The Project Physics Course

Text and Handbook **6**

The Nucleus

The Project Physics Course

Text and Handbook

Delete

p. 27 as nec. to make room for "Activities"
pp 28-9 if necessary
pp 90-1
pp 110-122 ("Reader...")
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UNIT 6 The Nucleus

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This Text-Handbook, Unit 6, is one of the many instructional materials developed for the Project Physics Course. These materials include Texts, Handbooks, Teacher Resource Books, Readers, Programmed Instruction booklets, Film Loops, Transparencies, 16mm films, and laboratory equipment.

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(Continued on p. 122)

Science is an adventure of the whole human race to learn to live in and perhaps to love the universe in which they are. To be a part of it is to understand, to understand oneself, to begin to feel that there is a capacity within man far beyond what he felt he had, of an infinite extension of human possibilities . . .

I propose that science be taught at whatever level, from the lowest to the highest, in the humanistic way. It should be taught with a certain historical understanding, with a certain philosophical understanding, with a social understanding and a human understanding in the sense of the biography, the nature of the people who made this construction, the triumphs, the trials, the tribulations.

I. I. RABI
Nobel Laureate in Physics

Preface

Background The Project Physics Course is based on the ideas and research of a national curriculum development project that worked in three phases. First, the authors—a high school physics teacher, a university physicist, and a professor of science education—collaborated to lay out the main goals and topics of a new introductory physics course. They worked together from 1962 to 1964 with financial support from the Carnegie Corporation of New York, and the first version of the text was tried out in two schools with encouraging results.

These preliminary results led to the second phase of the Project when a series of major grants were obtained from the U.S. Office of Education and the National Science Foundation, starting in 1964. Invaluable additional financial support was also provided by the Ford Foundation, the Alfred P. Sloan Foundation, the Carnegie Corporation, and Harvard University. A large number of collaborators were brought together from all parts of the nation, and the group worked together for over four years under the title *Harvard Project Physics*. At the Project's center, located at Harvard University, Cambridge, Massachusetts, the staff and consultants included college and high school physics teachers, astronomers, chemists, historians and philosophers of science, science educators, psychologists, evaluation specialists, engineers, film makers, artists and graphic designers. The teachers serving as field consultants and the students in the trial classes were also of vital importance to the success of Harvard Project Physics. As each successive experimental version of the course was developed, it was tried out in schools throughout the United States and Canada. The teachers and students in those schools reported their criticisms and suggestions to the staff in Cambridge, and these reports became the basis for the subsequent revisions of the course materials. In the Preface to Unit 1 *Text* you will find a list of the major aims of the course.

We wish it were possible to list in detail the contributions of each person who participated in some part of Harvard Project Physics. Unhappily it is not feasible, since most staff members worked on a variety of materials and had multiple responsibilities. Furthermore, every text chapter, experiment, piece of apparatus, film or other item in the experimental program benefitted from the contributions of a great many people. On the preceding pages is a partial list of contributors to Harvard Project Physics. There were, in fact, many other contributors too numerous to mention. These include school administrators in participating schools, directors and staff members of training institutes for teachers, teachers who tried the course after the evaluation year, and most of all the thousands of students who not only agreed to take the experimental version of the course, but who were also willing to appraise it critically and contribute their opinions and suggestions.

The Project Physics Course Today. Using the last of the experimental versions of the course developed by Harvard Project Physics in 1964–68 as a starting point, and taking into account the evaluation results from the tryouts, the three original collaborators set out to develop the version suitable for large-scale publication. We take particular pleasure in acknowledging the assistance of Dr. Andrew Ahlgren of Harvard University. Dr. Ahlgren was invaluable because of his skill as a physics teacher, his editorial talent, his versatility and energy, and above all, his commitment to the goals of Harvard Project Physics.

We would also especially like to thank Miss Joan Laws whose administrative skills, dependability, and thoughtfulness contributed so much to our work. The publisher, Holt, Rinehart and Winston, Inc. of New York, provided the coordination, editorial support, and general backing necessary to the large undertaking of preparing the final version of all components of the Project Physics Course, including texts, laboratory apparatus, films, etc. Damon, a company located in Needham, Massachusetts, worked closely with us to improve the engineering design of the laboratory apparatus and to see that it was properly integrated into the program.

In the years ahead, the learning materials of the Project Physics Course will be revised as often as is necessary to remove remaining ambiguities, clarify instructions, and to continue to make the materials more interesting and relevant to students. We therefore urge all students and teachers who use this course to send to us (in care of Holt, Rinehart and Winston, Inc., 383 Madison Avenue, New York, New York 10017) any criticism or suggestions they may have.

F. James Rutherford
Gerald Holton
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The energy released by nuclear reactions within stars makes them visible to us over vast distances. The sun, a typical star, converts the mass of over 4 billion kg of hydrogen into an equivalent amount of radiant energy each second.

UNIT 6

The Nucleus

CHAPTERS

21 Radioactivity
22 Isotopes
23 Probing the Nucleus
24 Nuclear Energy; Nuclear Forces

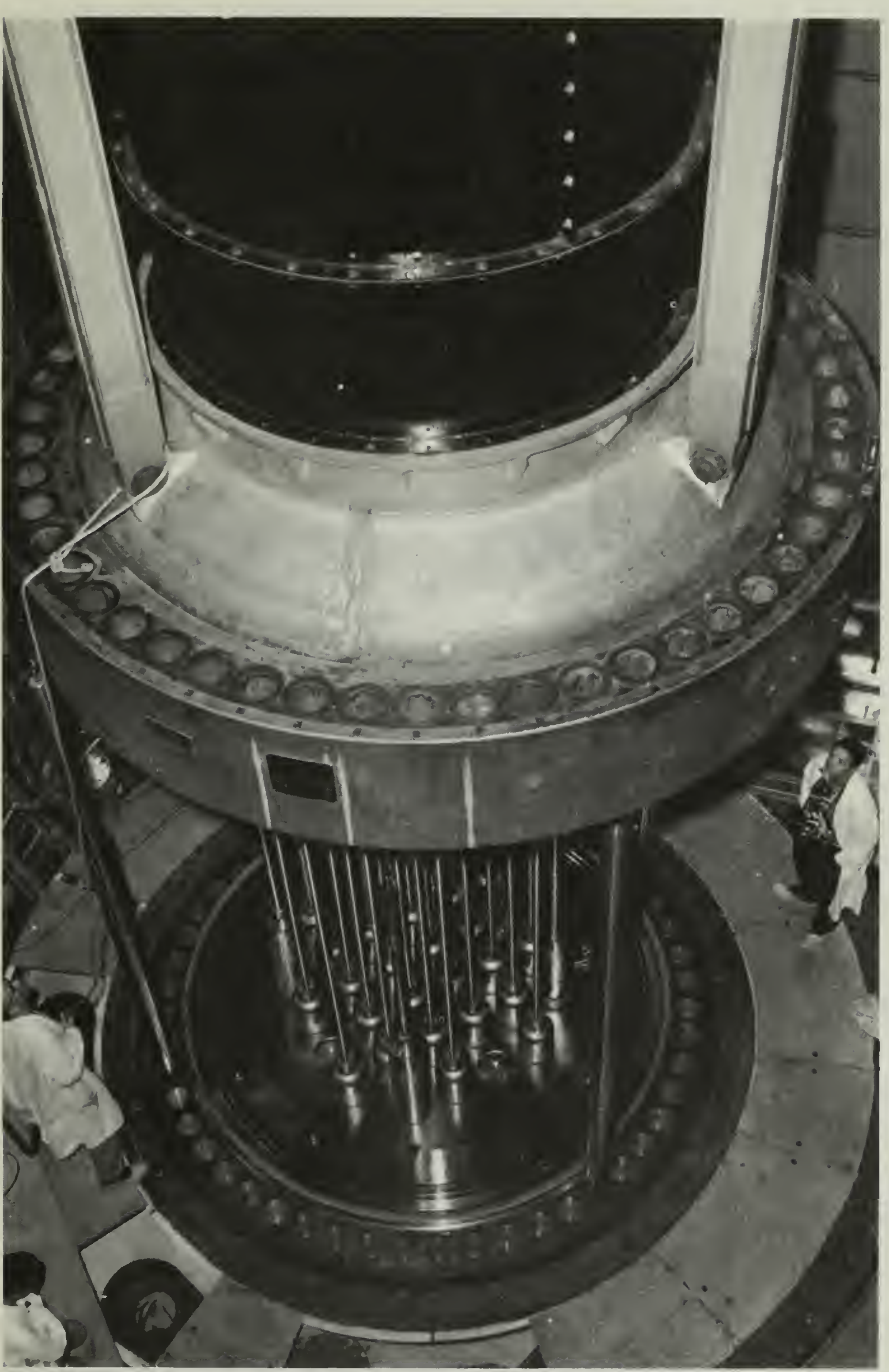
PROLOGUE In Unit 5 we learned that the atom consists of a very small, positively charged nucleus surrounded by electrons. Experiments on the scattering of α particles showed that the nucleus has dimensions of the order of 10^{-14} m. Since the diameter of an atom is of the order of 10^{-10} m, the nucleus takes up only a minute fraction of the volume of an atom. The nucleus, however, contains nearly all of the mass of the atom, as is also shown by the scattering experiments. The existence of the atomic nucleus and its properties raised new questions. Is the nucleus itself made up of still smaller units? If so, what are these units and how are they arranged in the nucleus? What methods can be used to get answers to these questions? What experimental evidence do we have to guide us?

We saw in Unit 5 that the study of the properties and structure of atoms needed new physical methods. The methods that could be used to study the properties of bodies of ordinary size, that is, with dimensions of the order of centimeters or meters, could not yield information about the structure of atoms. It is reasonable to expect that it is still more difficult to get information telling us what goes on inside the nucleus, which is such a small part of the atom. New kinds of experimental data must be obtained. New theories must be devised to help us correlate and understand the data. In these respects the study of the nucleus is still another step on the long road from the very large to the very small along which we have traveled in this course. In Unit 6 we shall dig deeper into the problem of the constitution of matter by studying the atomic nucleus.

One of the first and most important steps to an understanding of the atomic nucleus was the discovery of radioactivity in 1896. Our discussion of nuclear physics will, therefore, start with radioactivity. We shall see how the study of radioactivity led to additional discoveries, to the development of methods for getting at the nucleus, and to ideas about the constitution of the nucleus. In fact, the discovery that the atom has a nucleus was a consequence of the study of radioactivity. We shall examine the interaction between experiment and theory, and the step-by-step development of ideas about the nucleus. We shall try to see how particular experimental results led to new ideas, and how the latter, in turn, led to new experiments. This historical study is especially useful and interesting because nuclear physics is a new branch of physics, which has developed over a relatively short period of time. The reports and papers through which discoveries have been made known are readily available. The research is still going on, and at an ever-increasing rate. Progress in nuclear physics is closely related to modern technology, which both supplies tools for further research and applies some of the research in practical ways. Some of these practical applications have serious economic and political consequences. Newspapers report about them almost daily, and it is the citizen's duty to inform himself as well as he can about them in order to participate effectively in the decisions that affect his life.

Now that the use and control of nuclear technology is often front-page news, it may be hard to realize that the study of the atomic nucleus is connected with a chance discovery made in 1896. But it was that discovery which touched off the whole enterprise that we call nuclear physics, and it is there that we shall start.

The Yankee Atomic Electric nuclear power station in Rowe, Massachusetts.



Installation of the reactor vessel head at the Yankee Atomic Electric station.

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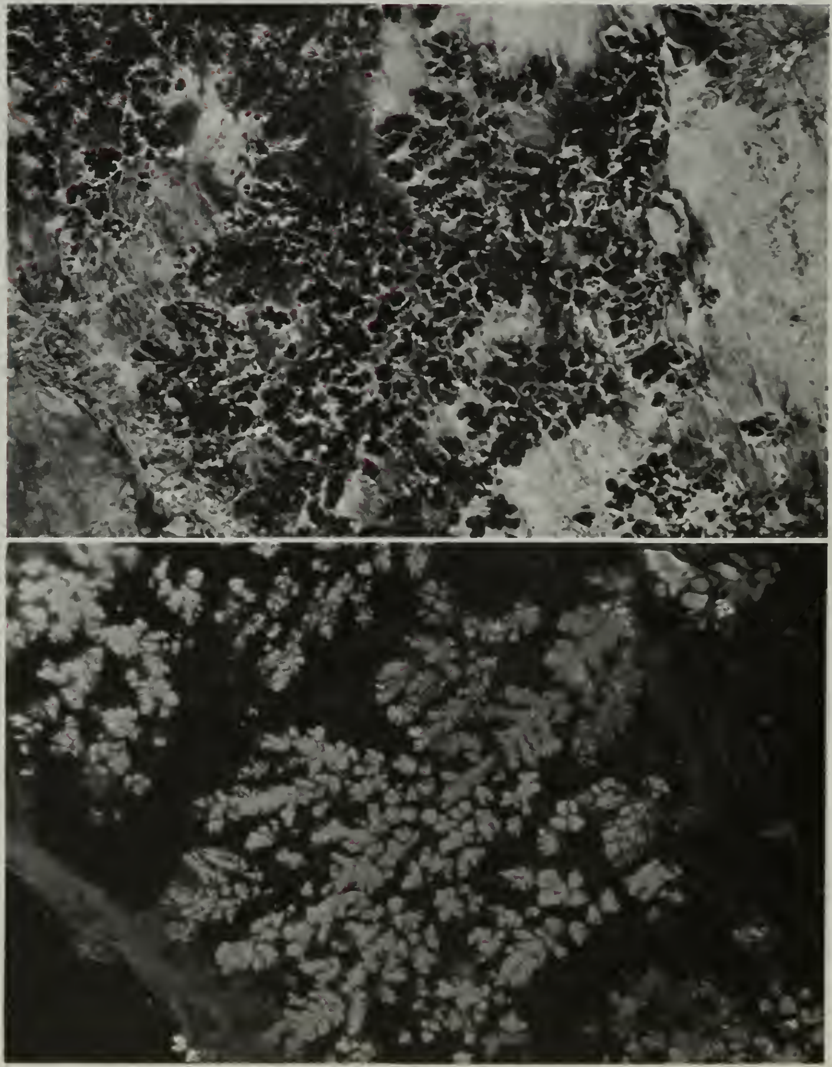


Above is a photograph of the polished surface of a uranium-bearing rock, photographed in reflected light. Below is an autoradiograph of the same surface made by placing the rock directly on a piece of film, packaging both in a light-tight container, and allowing the film to be exposed for about fifty hours. The whitish areas on that print correspond to radioactive areas on the rock.

CHAPTER TWENTY-ONE

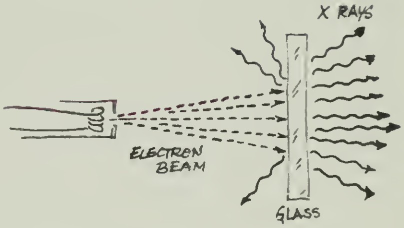
Radioactivity

21.1 Becquerel's discovery

A legendary chapter in physics began with the discovery of the phenomenon known as "radioactivity" early in 1896 by the French physicist Henri Becquerel. It was another of those "accidents" that illustrate how the trained and prepared mind is able to respond to an unexpected observation.

SG 21.1

Only two months before, in November 1895, Röntgen had discovered x rays. In doing so, he had unwittingly set the stage for the discovery of radioactivity. Röntgen had pointed out that x rays came from the glowing spot on a glass tube where a beam of cathode rays (high-speed electrons) was hitting. (See Secs. 18.2 and 18.6.) When the cathode-ray beam was turned off, the spot of light on the face of the glass tube disappeared, and also the x rays coming from that spot stopped.

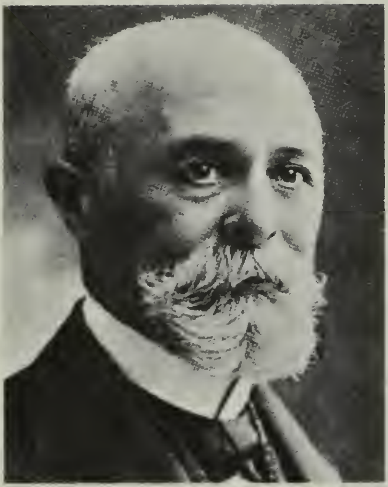


X-ray production by bombardment of electrons (cathode rays) on glass.

The emission of light by the glass tube when it is excited by the cathode ray beam is an example of the phenomenon called *fluorescence*, and was well known before Röntgen's work. A considerable amount of research had been done on fluorescence during the latter part of the nineteenth century. A substance is said to be fluorescent if it immediately emits visible light when struck by visible light of shorter wavelength, or by invisible radiations such as ultraviolet light, or by the beam of electrons that make up cathode rays. Fluorescence stops when the exciting light is turned off. (The term *phosphorescence* is generally applied to a related phenomenon, the emission of visible light which continues *after* the exciting light is turned off.)

Röntgen also showed that one method of detecting the presence of x rays was to let them expose a well-wrapped photographic plate. (See Sec. 18.6)

Röntgen's observation that the x rays also came from the spot which showed fluorescence raised the suspicion that there was a close connection between x rays and fluorescence or phosphorescence. Becquerel was fortunate in having the necessary materials and training to study this problem. In addition, he was the son and grandson of physicists who had made important contributions in the field of fluorescence and phosphorescence. In his Paris laboratory he had devised an instrument for examining materials



Henri Becquerel (1852-1908) received the 1903 Nobel Prize in physics (for the discovery of natural radioactivity) along with Pierre and Marie Curie (for the discovery of the radioactive elements radium and polonium).

in complete darkness a small fraction of a second after they had been exposed to a brilliant light. The question occurred to Becquerel: When bodies are made to fluoresce (or phosphoresce) in the visible region with sufficient intensity, do they also emit x rays in addition to the light-rays? He tested a number of substances by exposing them to sunlight; his method of checking whether they also emitted invisible x rays followed Röntgen's idea: to see if a well-wrapped photographic plate was exposed by such invisible rays. One of the samples Becquerel used happened to be a salt of the metal uranium, a sample of potassium-uranyl sulfate. In his words:

> I wrapped a . . . photographic plate . . . with two sheets of thick black paper, so thick that the plate did not become clouded by exposure to the sun for a whole day. I placed on the paper a crust of the phosphorescent substance, and exposed the whole thing to the sun for several hours. When I developed the photographic plate I saw the silhouette of the phosphorescent substance in black on the negative. If I placed between the phosphorescent substance and the paper a coin or a metallic screen pierced with an open-work design, the image of these objects appeared on the negative. The same experiment can be tried with a thin sheet of glass placed between the phosphorescent substance and the paper, which excludes the possibility of a chemical action resulting from vapors which might emanate from the substance when heated by the sun's rays.
>
> We may therefore conclude from these experiments that the phosphorescent substance in question emits radiations which penetrate paper that is opaque to light. . . .

In his published paper, Becquerel was careful to conclude from his experiment only that "penetrating radiations" were emitted from the phosphorescent substance. He did not write that the substance emitted x rays while it phosphoresced, because he had not fully verified that the radiations were x rays (though the radiations were transmitted through the black paper, just as x rays are), or that they were actually related to the phosphorescence (though he strongly suspected that they were). Before he could investigate these possibilities, he made this discovery:

As it turned out, and will be shown in Sec. 21.3, the Becquerel rays are not x rays.

> . . . among the preceding experiments some had been made ready on Wednesday the 26th and Thursday the 27th of February [1896]; and as on those days the sun only showed itself intermittently, I kept my arrangements all prepared and put back the holders in the dark in the drawer of the case, and left in place the crusts or uranium salt. Since the sun did not show itself again for several days, I developed the photographic plates on the 1st of March, expecting to find the images very feeble. On the contrary, the silhouettes appeared with great intensity. I at once thought that the action might be able to go on in the dark. . . .

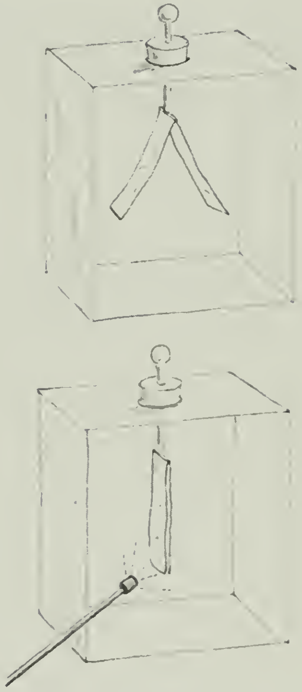
Further experiments verified this surprising thought: even when the uranium compound was not being excited by sunlight to phosphoresce, it continually emitted something that could penetrate black paper and other substances opaque to light, such as thin plates of aluminum or copper. Becquerel found that all the compounds of uranium—many of which were not phosphorescent at all—and metallic uranium itself had the same property. The amount of action on the photographic plate did not depend on what the particular compound of uranium was, but only on the amount of uranium present in it!

Becquerel also found that the persistent radiation from a sample of uranium did not appear to change, either in intensity or character, with the passing of time. Nor was a change in the activity observed when the sample of uranium or of one of its compounds was exposed to ultraviolet light, infrared light, or x rays. Moreover, the intensity of the uranium radiation (or "Becquerel rays," as they came to be known), was the same at room temperature (20°C), at 200°C and at the temperature at which oxygen and nitrogen (air) liquefy, about −190°C. Thus, these rays seemed to be unaffected by ordinary physical (and chemical) changes.

Becquerel also showed that the radiations from uranium produced ionization in the surrounding air. They could discharge a positively or negatively charged body such as an electroscope. So the uranium rays resemble x rays in two important respects: their penetrating power and their ionization power. Both kinds of rays were invisible to the unaided eye, but both affected photographic plates. Still, x rays and Becquerel rays differed in at least two important ways: compared to x rays, these newly discovered rays from uranium needed no cathode ray tube or even light to start them, and they could not be turned off. Becquerel showed that even after a period of three years a given piece of uranium and its compounds continued to emit radiations spontaneously.

The years 1896 and 1897 were years of high excitement in physics, to a large extent because of the great interest in the recently discovered x rays and in cathode rays. It quickly became evident that x rays could be used in medicine and they were the subject of much research. In comparison the properties of the Becquerel rays were less spectacular, and little work was done on them in the period from the end of May 1896 until the end of 1897. In any case, it seemed that somehow they are special cases of x-ray emission. Even Becquerel himself turned his attention to other work. But attention began to be attracted by the fact that the invisible rays from the uranium and its compounds appeared spontaneously without special preparation or electric devices.

Two questions were asked: first, what was the source of the energy creating the uranium rays and making it possible for them to penetrate opaque substances? And second, did any other of the seventy or more elements known then have properties similar to those of uranium? The first question was not answered for some time, although it was considered seriously. The second question was answered early in 1898 by the Curies, who by doing so, opened a whole new field of research in physical science.



The ionizing effect of the Becquerel rays could be demonstrated with a charged electroscope (upper sketch). When a sample of uranium is held near the electroscope leaves (lower sketch), the rays cause gas molecules in the air to ionize—that is, to become electrically charged. Ions, with a charge opposite to that on the leaves drift to the leaves and neutralize their charge. The time taken for the leaves to fall is a measure of the *rate* of *ionization of the gas*, and hence of the activity of the uranium source.

Q1 Why was Becquerel experimenting with a uranium compound? Describe his experiment.

Q2 How did uranium compounds have to be treated in order to emit the "Becquerel rays"?

Q3 What were the puzzling properties of the "Becquerel rays"? In what ways were they similar to x rays?

21.2 Other radioactive elements are discovered

One of Becquerel's colleagues in Paris was the physicist Pierre Curie, who had recently married a Polish-born physicist, Marie Sklodowska. Marie Curie undertook a systematic study of the Becquerel rays and looked for other elements and minerals that might emit them. Using a sensitive electrometer which her husband had recently invented, she measured the small electric current produced when the rays ionized the air. This current was assumed to be (and actually is) proportional to the intensity of the rays. With this new technique, she could give a numerical value to the ionizing effect produced by the rays, and these values were reproducible within a few percent from one experiment to the next with the same sample.

One of her first results was the discovery that the element thorium (Th) and its compounds emitted radiations with properties similar to those of the uranium rays. (The same finding was made independently in Germany by Gerhardt C. Schmidt, at about the same time.) The fact that thorium emits rays like those of uranium was of great importance; it showed that the mysterious rays were not a property peculiar just to one element. The discovery spurred the search for still other elements that might emit similar rays. The fact that uranium and thorium were the elements with the greatest known atomic masses indicated that the very heavy elements might have special properties different from those of the lighter elements.

The evident importance of the problems raised by the discovery of the uranium and thorium rays, led Pierre Curie to lay aside his researches in other fields of physics and work with his wife on these new problems. They began on a herculean task. First they found that the intensity of the emission from any thorium compound was directly proportional to the fraction by weight of the metallic element thorium present. (Recall that Becquerel had found a similar result for uranium compounds.) Moreover, the amount of radiation was independent of the physical conditions or the chemical combination of the active elements. These results led the Curies to the conclusion that the emission of the rays depended only on the presence of *atoms* of either of the two elements uranium or thorium. Atoms of other elements that were present were simply inactive, or absorbed some of the radiation.

These ideas were especially important because they helped the Curies interpret their later experiments. For example, in their studies of the radioactivity of minerals they examined pitchblende, an ore containing about 80 percent uranium oxide (U_3O_8). They found that the emission from pitchblende, as measured by its effect in ionizing air, was about four or five times as great as that to be expected from the amount of uranium in the ore. The other elements known at the time to be associated with uranium in pitchblende, such as bismuth and barium, had been shown to be not radioactive. If emission of rays is an atomic phenomenon, the unexpected activity of pitchblende could be explained only by the presence of another element in pitchblende, an element more active than uranium itself.

To explore this hypothesis, the Curies applied chemical separation processes to a large sample of pitchblende to try to isolate this hypothetical active substance. After each separation process, the products were tested, the inactive part discarded, and the active part analyzed further. Finally, the Curies obtained a highly active product which presumably consisted mainly of the unknown element. In a note titled "On a New Radioactive Substance Contained in Pitchblende," which they submitted to the French Academy of Sciences in July of 1898, they reported:

In this note the term "radioactivity" was used for the first time.

> By carrying on these different operations . . . finally we obtained a substance whose activity is about 400 times greater than that of uranium. . . .
>
> We believe, therefore, that the substance which we removed from pitchblende contains a metal which has not yet been known, similar to bismuth in its chemical properties. If the existence of this new metal is confirmed, we propose to call it *polonium*, after the name of the native country of one of us.

Compare the positions of polonium (Po) and bismuth (Bi) in the Periodic Table on p. 27.

Six months after the discovery of polonium, the Curies chemically separated another substance from pitchblende and found the emission from it so intense as to indicate the presence of still another new element even more radioactive than polonium! This substance had an activity per unit mass 900 times that of uranium, and was chemically entirely different from uranium, thorium or polonium. Spectroscopic analysis of this substance revealed spectral lines characteristic of the inactive element barium, but also a line in the ultraviolet region that did not seem to belong to any known element. The Curies reported their belief that the substance, "although for the most part consisting of barium, contains in addition a new element which produced radioactivity and, furthermore, is very near barium in its chemical properties." For this new element, so extraordinarily radioactive, they proposed the name *radium*.

Compare the positions of barium (Ba) and radium (Ra) in the Periodic Table.

A next step in making the evidence for the newly discovered elements more convincing was to determine their properties, especially their atomic masses. The Curies had made it clear that they had not yet been able to isolate either polonium or radium in pure metallic form, or even to obtain a pure sample of a compound of either element. From the substance containing the strongly radioactive substance that they called radium, they had separated a part consisting of barium chloride mixed with a presumably very


a.


b.

a. Marie Curie
b. c. Marie and Pierre
d. Marie, Iréne and Pierre
all three won Nobel prizes.

Pierre Curie (1859-1906) studied at the Sorbonne in Paris. In 1878 he became an assistant teacher in the physical laboratory there, and some years later, professor of physics. He was well known for his research on crystals and magnetism. He married Marie Sklodowska in 1895 (she was 28 years old). After their marriage, Marie undertook her doctoral research on radioactivity. In 1898 Pierre joined his wife in this work. Their collaboration was so successful that in 1903 they were awarded the Nobel Prize in physics, which they shared with Becquerel. Pierre Curie was run over and killed by a horse-drawn vehicle in 1906. Marie Curie was appointed to his professorship at the Sorbonne, the first woman to have this post.

In 1911 she was awarded the Nobel Prize in chemistry for the discovery of the two new elements, radium and polonium. She is the only person who has won two Nobel prizes in science. (Linus Pauling also won two Nobel prizes—one for chemistry and one for peace). The rest of her career was spent in the supervision of the Paris Institute of Radium, a center for research on radioactivity and the use of radium in the treatment of cancer.

Marie Curie died in 1934 of leukemia, a form of cancer of the leukocyte-forming cells of the body, probably caused by over-exposure to the radiations from radioactive substances.


c.


d.

small quantity of radium chloride. Additional separations gave an increasing proportion of radium chloride. The difficulty of this task is indicated by the Curies' remark that radium "is very near barium in its chemical properties," for it is very difficult to separate elements whose chemical properties are similar. Moreover, to obtain their highly radioactive substances in usable amounts, they had to start with a very large amount of pitchblende.

With an initial 100-kg shipment of pitchblende (from which the uranium salt had been removed to be used in the manufacture of glass) the Curies went to work in an abandoned woodshed at the School of Physics where Pierre Curie taught. Having failed to obtain financial support, the Curies made their preparations without technical help in this "laboratory." Marie Curie wrote later:

> I came to treat as many as twenty kilograms of matter at a time, which had the effect of filling the shed with great jars full of precipitates and liquids. It was killing work to carry the receivers, to pour off the liquids and to stir, for hours at a stretch, the boiling material in a smelting basin.

From the mixture of radium chloride and barium chloride they produced, only the average atomic mass of the barium and radium could be computed. At first an average value of 146 was obtained, as compared with 137 for the atomic mass of barium. After many additional purifications which increased the proportion of radium chloride, the average value for atomic mass rose to 174. Continuing the tedious purification process for four years, during which she treated several tons of pitchblende residue, Marie Curie was able to report in July 1902 that she had isolated 0.1 gram of radium chloride, so pure that spectroscopic examination showed no evidence of any remaining barium. She calculated the atomic mass of radium to be 225 (the present-day value is 226.03). The activity of radium is more than a million times that of the same mass of uranium.

The present yield of radium from one ton of high-grade uranium ore is about 0.2 g.

SG 21.2

Q4 How is the radioactive emission of an element affected by being combined into different chemical compounds?

Q5 Why did the Curies suspect the existence of another radioactive material in uranium ore, in addition to uranium itself?

Q6 What was the main difficulty in producing a pure sample of the element radium?

21.3 The penetrating power of the radiation: α, β and γ rays

Once the extraordinary properties of radium became known, they excited interest both inside and outside the scientific world, and the number of people studying radioactivity increased rapidly. The main question that attracted attention was: what are the mysterious radiations emitted by radioactive bodies?

In 1899, Ernest Rutherford, whose theory of the nuclear atom has been discussed in Chapter 19, started to seek answers to this question. Rutherford found that a sample of uranium emits at least two distinct kinds of rays—one that is very readily absorbed, which he called for convenience α rays (alpha rays), and the other more penetrating, which he called β rays (beta rays). In 1900 the French physicist P. Villard observed that the emission from radium contained rays much more penetrating than even the β rays; this type of emission was given the name γ (gamma) rays. The penetrating power of the three types of rays, as known at the time, is compared in the table below, first published by Rutherford in 1903:

See the article "Rutherford" in *Reader 6.*

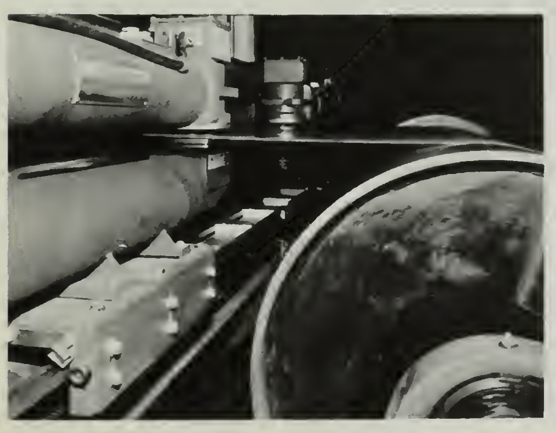
Appropriate thickness of aluminum required to reduce the radiation intensity to one-half its initial value

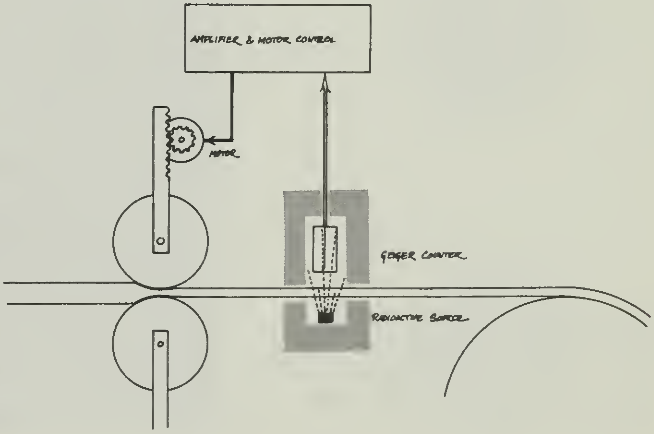
RADIATION TYPE	THICKNESS OF ALUMINUM
α	0.0005 cm
β	0.05
γ	8

So it turned out that the Becquerel rays were more complex than had been thought even before the *nature* of α, β and γ rays were ascertained. Of the three kinds of rays, the α rays are the most strongly ionizing and the γ rays the least. The power of penetration is inversely proportional to the power of ionization. This is to be expected: the penetrating power of the α rays from uranium is low because they expend their energy very rapidly in causing intense ionization. Alpha rays can be stopped—that is, completely absorbed—by about 0.006 cm of aluminum, by a sheet of ordinary writing paper, or by a few centimeters of air. Beta rays are completely stopped only after traveling many meters in air, or a centimeter in aluminum. Gamma rays can pass through many centimeters of lead, or through several feet of concrete, before being almost completely absorbed. One consequence of these properties of the rays is that heavy and expensive shielding is sometimes needed in the study or use of radiations, especially γ

SG 21.2

The absorption of β rays gives rise to many modern practical applications of radioactivity. One example is the thickness gauge illustrated in the photograph and drawing below. Sheet metal or plastic is reduced in thickness by rolling. The thickness is measured continuously and accurately by determining the intensity of the β rays that pass through the sheet. The rollers are adjusted so that the desired sheet thickness is obtained.

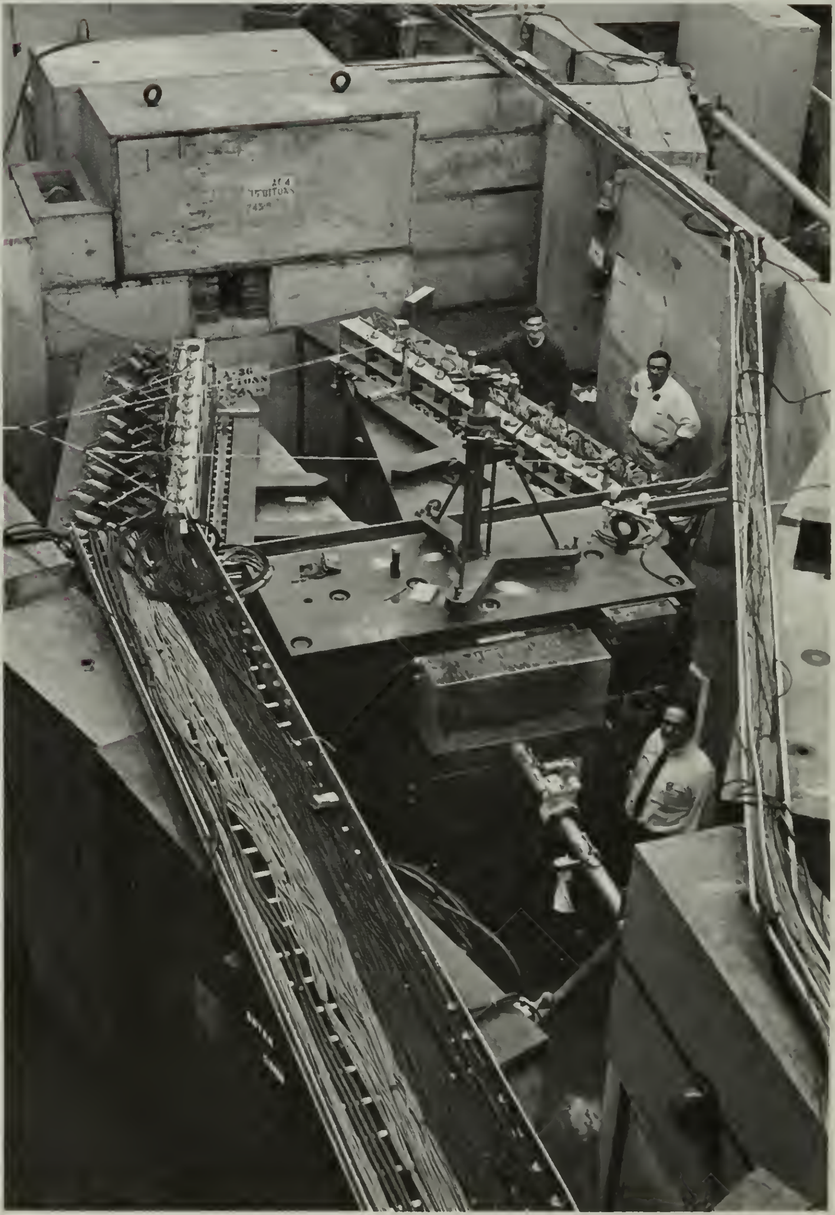




The rays ionize and, consequently, break down molecules in living cells.

rays, to protect people from harmful effects of the rays. In some cases these "radiation shields" are as much as 10 feet thick. Shown below is one example of shielding around a target at the output of an electron accelerator (where γ rays are created by a method different from radioactivity, as you shall see later in this unit).

Q7 List α, β and γ rays in order of the penetrating ability. Why is penetrating power inversely related to ionizing power?



Shielding around an experimental area through which passes a beam from a high-energy particle accelerator (The Cambridge Electron Accelerator).

21.4 The charge and mass of α, β and γ rays

Another method used to study the rays was to direct them through a magnetic field to see if they were deflected or deviated from their initial directions by the action of the field. This method, which came to provide one of the most widely used tools for the study of atomic and nuclear events, is based on the now familiar fact that a force acts on a charged particle when it moves across a magnetic field. As was discussed in Sec. 14.13, this force acts always at right angles to the direction of motion of the charged particle. The particle experiences a continual deflection and, if sent into a uniform field at right angles, moves along the arc of a circle. (It might be wise to review that section now.)

This property had been used in the 1890's by J. J. Thomson in his studies of cathode rays. He showed that these rays consist of very small negatively charged particles, or electrons (Chapter 18). Becquerel, the Curies and others found that the α, β and γ rays behaved differently from one another in a magnetic field. The behavior of the rays is illustrated in the diagram in the margin.

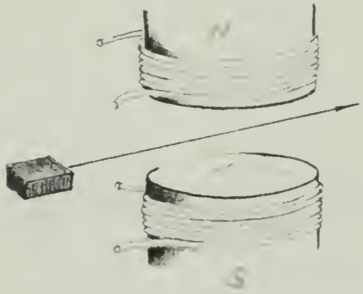
Suppose that some radioactive material, such as a sample of uranium, is placed at the end of a narrow hole in a lead block; a narrow beam consisting of α, β and γ rays escapes from the opening. If the beam enters a strong, uniform magnetic field (as in the last 2 drawings in the margin), the three types of rays will go along paths separated from one another. The γ rays continue in a straight line without any deviation. The β rays will be deflected to one side, moving in circular arcs of differing radii. The α rays will be deflected slightly to the other side, moving in a circular arc of large radius, but are rapidly absorbed in the air.

The direction of the deflection of the β rays in such a magnetic field is the same as that observed earlier in Thomson's studies of the properties of cathode rays. It was concluded, therefore, that the β rays, like cathode rays, consist of *negatively charged particles.* (The negative charge on the β particles was confirmed by the Curies in 1900; they caused the beam of the particles to enter an electroscope, which became negatively charged.) Since the direction of the deflection of the α rays was opposite to that of the β rays, it was concluded that the α rays consist of *positively charged particles*. Since the γ rays were not deflected, it was concluded that they were neutral, that is, had no electric charge; no conclusion could be drawn from this type of experiment as to whether the γ rays are, or are not, particles.

The deflection of a charged particle in electric and magnetic fields depends on both its charge and mass. Therefore, the ratio of charge to mass for β particles can be calculated from measured deflections in fields of known intensity.

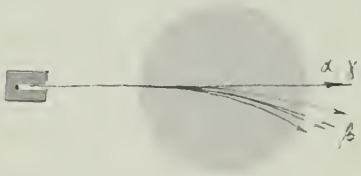
Becquerel, investigating β particles in 1900, used a procedure which was essentially the same as that used by J. J. Thomson in 1897 to obtain a reliable value for the ratio of charge q_e to mass m_e for the particles in cathode rays. (The fact that there was a

α, β and γ rays are separated from a sample of radioactive material by their passage through a magnetic field.

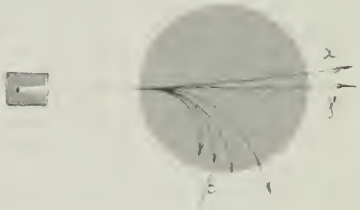


No magnetic field.

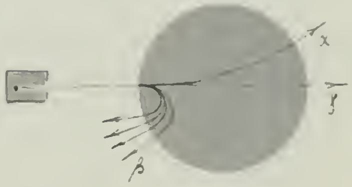
Weak magnetic field.



Stronger magnetic field.



Very strong magnetic field.



consistent single value establishing quantitatively the existence of the electron; (see Sec. 18.2.) By sending β rays through electric and magnetic fields, Becquerel was able to calculate the speed of the β particles. He obtained a value of q/m for β particles which was in close enough agreement with that found by Thomson for the electron to permit the deduction that the β particles are electrons.


(a) Electric field only (b) Magnetic field only (c) Both electric and magnetic field

Electric and magnetic fields can be set up perpendicularly so that the deflections they cause in a beam of charged particles will be in opposite directions. Particles moving at one certain speed will not be deflected, because the electric and magnetic forces on it balance.

SG 21.4–21.6

The nature of the α radiation was more difficult to establish. It was necessary to use a very strong magnetic field to produce measurable deflections of α rays. The value of q/m found for α particles (4.8×10^7 coul/kg) was about 4000 times smaller than q/m for β particles. The reason for the small q/m value could be a small value of q or a large value of m. Other evidence available at the time indicated that q for an α particle was not likely to be smaller than for a β particle. It was therefore concluded that m would have to be much larger for the α particle than for the β particle.

The value of q/m given above for α particles is just one half that of q/m found earlier for a hydrogen ion (see Table 17.4). The value would be explained in a reasonable way if the α particle were like a hydrogen molecule minus one electron (H_2^+), or else if it were a helium atom (whose mass was known to be about four times that of a hydrogen atom) without its two electrons (He^{++}). Other possibilities might have been entertained—for example, bare nuclei of carbon, nitrogen or oxygen would have about the same q/m ratio. In fact, however, the right identification turned out to be that of α particles with He^{++}, and we turn now to the clever experiment that provided the final proof.

Q8 What was the evidence that β particles are electrons?

Q9 What observation led to the suggestion that α particles are much more massive than β particles?

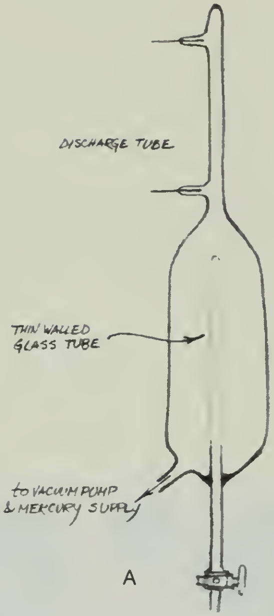
21.5 The identity of α rays: Rutherford's "mousetrap"

See Rutherford's essay "The Nature of the Alpha Particle" in *Reader 6*.

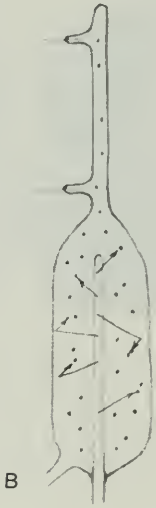
It was known that the gas helium was always found imprisoned in radioactive minerals. In addition, Sir William Ramsey and Frederick Soddy had discovered, in 1903, that helium was given off from a radioactive compound, radium bromide. This led Rutherford to advance the hypothesis that the α particle is a doubly-ionized helium atom—a He atom minus its two electrons—or, as we would now say, the nucleus of a helium atom. In a series of experiments from 1906 to 1909 he succeeded in proving the correctness of his hypothesis in several different ways. The last and most convincing of these experiments was made in 1909, with T. D. Royds, by constructing what Sir James Jeans later called "a sort of mousetrap for α particles."

The experiment used the radioactive element radon (Rn). Radon had been discovered by Pierre Curie and André Debierne in 1901; they had found that a gas was given off from radium. A small amount of the gas collected in this way was found to be a strong α emitter. The gas was shown to be a new element and was called "radium emanation" and later "radon." Ramsey and Soddy then found that when radon is stored in a closed vessel, helium always appears in the vessel also. Thus helium is given off not only by radium but also by radon.

Now Rutherford and Royds put a small amount of radon in a fine glass tube with a wall only one-hundredth of a millimeter thick. This wall was thin enough so that α particles could pass through it, but radon itself could not. The tube was sealed into a thick-walled, outer glass tube which had an electric discharge section at the top. (See sketch A in the margin.) The air was pumped out of the outer tube and the apparatus was allowed to stand for about a week. During this time, while α particles from the radon passed through the thin walls of the inner tube, a gas was found gradually to collect in the previously evacuated space (sketch B). Mercury was then pumped in at the bottom to compress the gas and confine it in the discharge tube (sketch C). When a potential difference was applied to the electrodes of the discharge tube, an electric discharge was produced in the gas. The resulting light was examined with a spectroscope, and the spectral lines seen turned out to be characteristic of helium. (In a separate control experiment, helium gas itself was put in the inner, thin-walled tube, and did not leak through the wall of the inner tube.)



Rutherford's "mousetrap" for identifying particles.



Now it was clear to Rutherford how to interpret his results: he could safely conclude that the helium gas that collected in the outer tube was formed from α particles that had passed into the outer tube.

But Rutherford's result implied conclusions more important than just the identity of α particles. Apparently, an atom of an element (radon) can spontaneously emit a fragment (an α particle) that is the nucleus of *another* element (helium). A startling idea, but only the beginning of more startling things to come.

Q10 How did Rutherford know that the gas which appeared in the tube was helium?

21.6 Radioactive transformations

The emission of α and β particles raised difficult questions with respect to existing ideas of matter and its structure. The rapid development of chemistry in the nineteenth century had made the atomic-molecular theory of matter highly convincing. According to this theory, a pure element consists of identical atoms, which are indestructible and unchangeable. But if a radioactive atom emits as substantial a fragment as an α particle (shown to be an ionized helium atom), can the radioactive atom remain unchanged? That did not seem plausible. Rather, it seemed that there must be a transformation in which the radioactive atom is changed to an atom of a different chemical element.

If an atom emits an α particle, a substantial part of its mass will be carried away by the α particle. What about the atoms which emit β particles? The β particle (shown to be an electron) is far less massive than the α particle; but its mass is not zero, and so a radioactive atom must also undergo some change when it emits a β particle. It was again difficult to escape the conclusion that radioactive atoms are, in fact, subject to division (into two parts of markedly unequal mass)—a conclusion contrary to the basic concept that the atom is indivisible.

The water is being boiled by the heat given off by a small capsule of cobalt 60. This capsule, the first ever made to produce heat from radioactive cobalt, was generating heat at the rate of 360 watts when this photo was taken.

Another fundamental question arose in connection with the energy carried by the rays emitted by radioactive substances. As early as 1903 Rutherford and Soddy, and Pierre Curie and a young co-worker, A. Laborde, noted that a sample of radium kept itself at a higher temperature than its surroundings merely by reabsorbing some of the energy of the α particles emitted by atoms inside the sample. (Curie and Laborde found that one gram of radium can produce about 0.1 kilocalories of heat per hour.) A sample of radium thus has the property that it can continue to release energy year after year, for hundreds and even thousands of years.

The continuing release of such a quantity of heat could not be explained by treating radioactivity as an ordinary chemical reaction. It was clear that radioactivity did not involve chemical changes in the usual sense: energy was emitted by samples of pure elements; energy emission by compounds did not depend on the type of molecule in which the radioactive element was present. The origin of the production of heat had to be sought in some deep changes *within* the atoms of radioactive elements, rather than in chemical reactions among atoms.

Rutherford and Soddy proposed a bold theory of *radioactive transformation* to explain the nature of these changes. They proposed that when a radioactive atom emits an α or a β particle, it really breaks into two parts—the α or β particle that was emitted, and a heavy leftover part which is physically and chemically different from the "parent" atom. There was a good deal of evidence for the last part of the assumption. For example, the formation of radon gas from radium was known as mentioned earlier. When the atomic mass of radon was determined, it turned out to be smaller than that of radium by just 4 atomic mass units, the mass of an α particle.

The idea of radioactive transformation can be represented by an "equation" similar to the kind used to represent chemical reactions. For example, if we use the symbols Ra and Rn to represent atoms of radium and radon, we can express the transformation of radium into radon as:

$$\mathrm{Ra} \longrightarrow \mathrm{Rn} + \mathrm{He}$$

Here He stands for the helium atom formed by the doubly-charged α particle when it picks up two electrons.

The process of transformation can be described as the transformation or "disintegration" or "decay" or "transmutation" of radium into radon, with the emission of an α particle.

Many decay processes in addition to the example just cited had been found and studied, by the Curies, by Rutherford and his co-workers, and by others, and these processes fitted easily into the kind of scheme proposed by Rutherford and Soddy. For example, Radon is radioactive also, emitting another α particle and thereby decaying into an atom of an element which was called "radium A" at the time. Radium A was later shown to be polonium (Po).

Rutherford and Soddy received Nobel Prizes in chemistry for their work on the radioactive transformation of one element into another.

$$\mathrm{Rn} \longrightarrow \mathrm{Po} + \mathrm{He}$$

Polonium is a solid, and it too is radioactive. In fact, the original "parent" radium atoms undergo a series or chain of transformations into new, radioactive, "daughter" elements, ending finally with a "daughter" element which is non-radioactive or stable.

SG 21.7

Q11 Why was radioactive decay believed not to be an ordinary chemical reaction?

Q12 Give an example of a radioactive transformation. Why is it contrary to the ideas of nineteenth-century chemistry?

21.7 Radioactive decay series

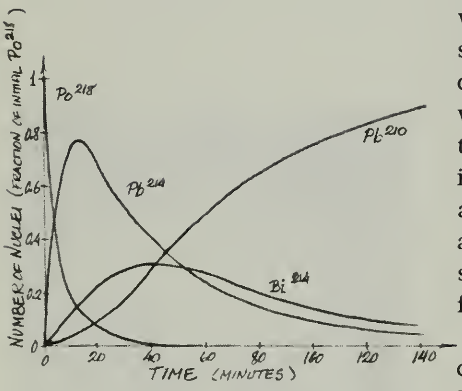
The decay of radium and its daughters was found eventually to lead to a stable end-product which was identified by its chemical behavior as *lead*. The chain beginning with radium has 10 members, some emitting α particles and others emitting β particles. Some gamma rays are emitted during the decay series, but gamma rays do not appear alone; they are emitted only together with an α particle or a β particle. Rutherford and Soddy also suggested that, since radium is always found in uranium ores, radium itself may be a member of a series starting with uranium as the ancestor of all the members. Research showed that this is indeed the case. Each uranium atom may in time give rise to successive daughter atoms, radium being the sixth generation and stable lead the fifteenth.

The table on p. 27 shows all the members of the so-called *uranium-radium series*. The meaning of some of the symbols will be discussed in later sections. The number following the name of an element, as in uranium 238, indicates the atomic mass. Notice that there are heavier and lighter varieties of the element, for example, uranium 238 and 235, polonium 218, 214, and 210. Much more will be said about these varieties in the next chapter.

Two other naturally occurring radioactive series have been found; one starts with thorium 232 and the other with uranium 235. (See SG 22.7 and 22.8, Chapter 22.)

Each member of the series differs physically and chemically from its immediate parent or daughters; it should, therefore, be possible to separate the different members in any radioactive sample. This is by no means impossible to do, but the separation problem was made difficult by the fact that the different radioactive species decay at different rates, some very slowly, some rapidly, others at intermediate rates. These rates and their meaning will be discussed in the next section, but the fact that the rates differ gives rise to important effects that can be discussed now.

An interesting example is supplied by that portion of the uranium series which starts with the substance called polonium 218. A pure sample of polonium 218 may be collected by exposing to the gas radon a piece of ordinary material such as a thin foil of aluminum. Some of the radon atoms decay into polonium 218 atoms which then stick to the surface of the foil. The graph at the left shows what becomes of the polonium 218. Polonium 218 (Po^{218}) decays into lead 214 (Pb^{214}), which decays into bismuth 214 (Bi^{214}), which decays into polonium 214 (not shown), then lead 210, etc. If the original sample contains 1,000,000 atoms of polonium 218 when it is formed, after twenty minutes it will contain about 10,000 Po^{218} atoms, about 660,000 Pb^{210} atoms, about 240,000 Bi^{214} atoms and about 90,000 Pb^{210} atoms. The number of Po^{214} atoms is negligibly small because most of the Po^{214} changes into Pb^{210} in a small fraction of a second.



A sample of pure, freshly separated radium (Ra 226) would also change in composition in a complicated way, but much more slowly. Eventually it would consist of a mixture of radium 226, radon 222, polonium 218, lead 214 and all the rest of the members of the chain down to, and including, stable "radium G" (lead 206).

SG 21.8

Similarly, a sample of pure uranium may contain, after a time, 14 other elements of which 13—all but the last, stable portion—contribute to the radioactive emission, each in its own way. In all such cases, a complicated mixture of elements results. After starting as a pure α emitter, a sample eventually emits many α particles, β particles and γ rays, apparently continuously and simultaneously.

It is evident that the separation of the different members of a radioactive chain will be difficult—especially if some members of the chain decay rapidly. The determination of the chemical nature and the radioactive properties of each member required great experimental ingenuity. One successful method depended on the skillful chemical purification of a particular radioactive substance, as the Curies had done with radium and polonium. For example, suppose that a sample has been obtained from which all the radioactive atoms except those of radium 226 have been removed. The sample immediately starts to give off radon gas. The latter can be drawn off and its properties examined before it becomes seriously contaminated by the disintegration of many of its atoms into polonium 218. If this is done, it turns out that radon decays (through several transformations) into lead much more quickly than radium decays into radon.

Q13 Give at least three reasons for the difficulty of separating decay products.

Q14 If you start with a sample made entirely of pure uranium

238 atoms, what emission is observed at the start? How will the emission change as time goes on?

21.8 Decay rate and half-life

In the last section we saw that of 1,000,000 polonium 218 atoms present in a freshly prepared sample of that radioactive substance, only about 10,000 would remain after twenty minutes, the rest having decayed into atoms of lead 214. It would take only three minutes following the preparation of the pure sample of Po^{218} or fifty percent of the atoms originally present in the sample to have decayed. In the case of radium (Ra^{226}), however, it would take 1620 years for half of the radium atoms in a freshly prepared sample of radium to be transformed into radon atoms.

In 1898 the Curies obtained a total of about 200 grams of radium. Seventy years later (1968) 194 grams of this remained as radium. The other six grams corresponded to 16×10^{21} radium atoms that have decayed into radon and subsequently into other elements during those 70 years.

These two examples illustrate the experimental fact that samples of radioactive elements show great differences in their rates of decay. These different rates are the result of *averages* of many individual, different decay events going on at random in a sample. Looking at *one* atom of any radioactive element, one never can tell when it will decay; some may decay as soon as they are produced, while others may never decay. Still, it has been found experimentally that there is a numerical value that describes the decay of a large group of atoms of one kind; a value which is unchangeable and always the same for any group of atoms of that kind. That value is the *fraction of those atoms that decay per second.* This number is almost completely independent of all physical and chemical conditions, such as temperature, pressure, and form of chemical combination. These remarkable properties of radioactivity deserve special attention, and the meaning of the italicized statement above will be discussed in detail because it is basic to our understanding of radioactivity.

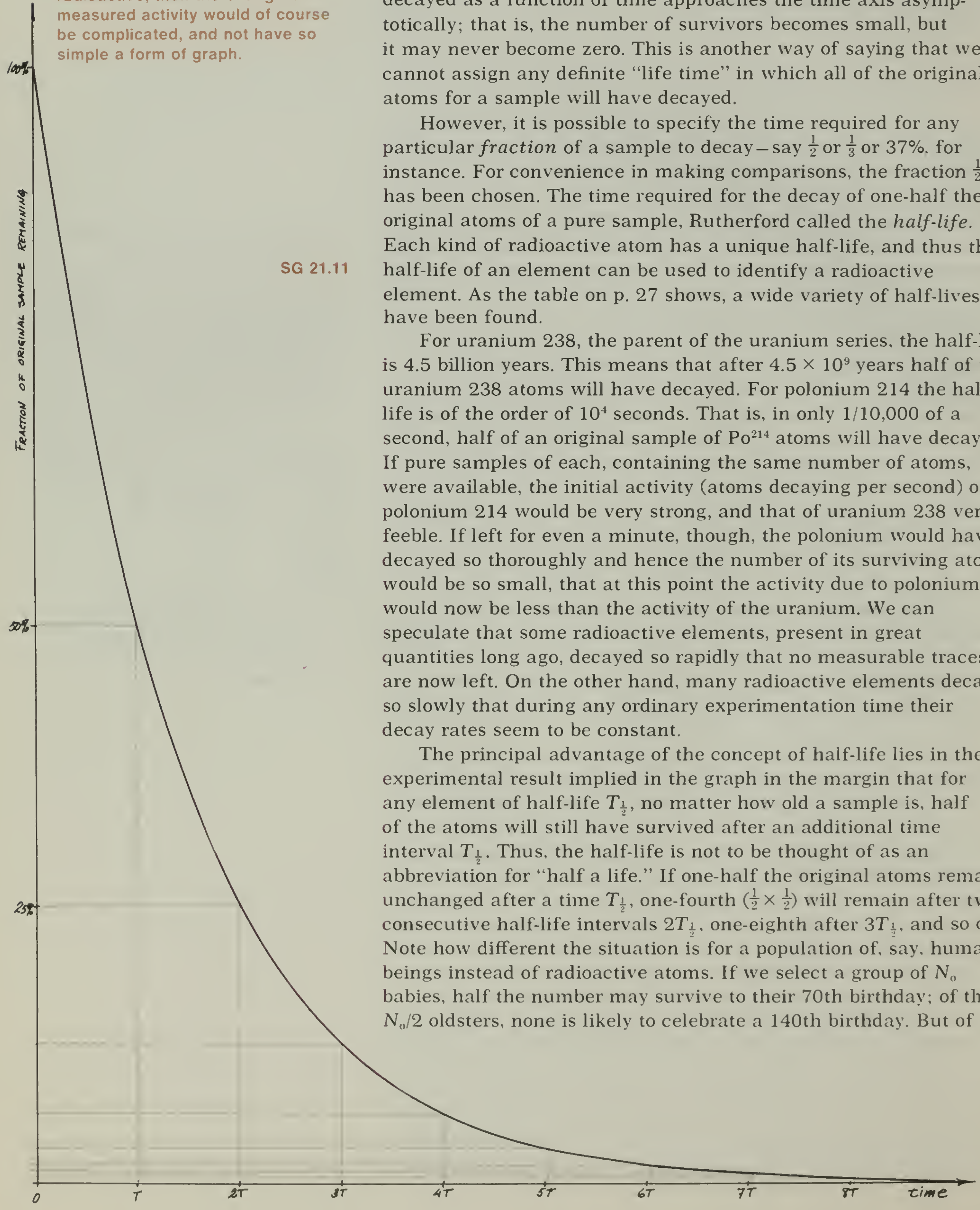
In a few cases, pressure and chemical combination have been found to make slight (and now well understood) differences in the rate of decay.

Say, for example, that 1/1000 of the atoms in a freshly-prepared pure sample decay during the first second. Then we expect that 1/1000 of the remaining atoms will decay during the next second, and 1/1000 of the atoms remaining after 10 seconds will decay during the eleventh second, and so on—in fact, during any subsequent second of time, 1/1000 of the atoms remaining at the beginning of that second will decay—at least until the number of remaining atoms becomes so small that statistical predictions start to become very uncertain.

SG 21.9, 21.10

Since the *fraction* of the atoms that decay per unit time is a constant for each element, the *number* of atoms that decay per unit time will decrease in proportion to the number of atoms remaining. Consequently, if the percentage of surviving, unchanged atoms is plotted as a function of time, a curve like the one on the next page is obtained. The number of atoms in a sample that decay per unit time is the *activity* of the sample. Thus, the graph on the next page also represents the way in which the measured activity of a sample would decrease with time.

If the daughter atoms were also radioactive, then the change of measured activity would of course be complicated, and not have so simple a form of graph.



The curve that shows the number of atoms that have not decayed as a function of time approaches the time axis asymptotically; that is, the number of survivors becomes small, but it may never become zero. This is another way of saying that we cannot assign any definite "life time" in which all of the original atoms for a sample will have decayed.

SG 21.11

However, it is possible to specify the time required for any particular *fraction* of a sample to decay – say $\frac{1}{2}$ or $\frac{1}{3}$ or 37%, for instance. For convenience in making comparisons, the fraction $\frac{1}{2}$ has been chosen. The time required for the decay of one-half the original atoms of a pure sample, Rutherford called the *half-life*. Each kind of radioactive atom has a unique half-life, and thus the half-life of an element can be used to identify a radioactive element. As the table on p. 27 shows, a wide variety of half-lives, have been found.

For uranium 238, the parent of the uranium series, the half-life is 4.5 billion years. This means that after 4.5×10^9 years half of the uranium 238 atoms will have decayed. For polonium 214 the half-life is of the order of 10^4 seconds. That is, in only 1/10,000 of a second, half of an original sample of Po^{214} atoms will have decayed. If pure samples of each, containing the same number of atoms, were available, the initial activity (atoms decaying per second) of polonium 214 would be very strong, and that of uranium 238 very feeble. If left for even a minute, though, the polonium would have decayed so thoroughly and hence the number of its surviving atoms would be so small, that at this point the activity due to polonium would now be less than the activity of the uranium. We can speculate that some radioactive elements, present in great quantities long ago, decayed so rapidly that no measurable traces are now left. On the other hand, many radioactive elements decay so slowly that during any ordinary experimentation time their decay rates seem to be constant.

The principal advantage of the concept of half-life lies in the experimental result implied in the graph in the margin that for any element of half-life $T_{\frac{1}{2}}$, no matter how old a sample is, half of the atoms will still have survived after an additional time interval $T_{\frac{1}{2}}$. Thus, the half-life is not to be thought of as an abbreviation for "half a life." If one-half the original atoms remain unchanged after a time $T_{\frac{1}{2}}$, one-fourth ($\frac{1}{2} \times \frac{1}{2}$) will remain after two consecutive half-life intervals $2T_{\frac{1}{2}}$, one-eighth after $3T_{\frac{1}{2}}$, and so on. Note how different the situation is for a population of, say, human beings instead of radioactive atoms. If we select a group of N_0 babies, half the number may survive to their 70th birthday; of these $N_0/2$ oldsters, none is likely to celebrate a 140th birthday. But of

The Mathematics of Decay

The *activity* of a sample, the number of disintegrations per second, the decay rate—these are alternative expressions for the same quantity. If we use the letter N to represent generally the number of atoms of a given kind present in a radioactive sample, then the activity is $\Delta N/\Delta t$, where ΔN is the number of atoms disintegrating in the time interval Δt. If, in a time interval Δt, ΔN atoms disintegrate out of a total number N, the *fraction* of atoms disintegrating is $\Delta N/N$. The *fraction of atoms disintegrating per unit time* is $\Delta N/N\big/\Delta t$. (This same quantity can be thought of also as the ratio of the activity to the total number, $\Delta N/\Delta t\big/N$.) This quantity, usually called λ, is analogous to the death rate in a human population. In the United States, for example, about 5,000 persons die each day out of a population of about 200,000,000. The death rate is therefore one person per 40,000 per day (or one person per day per 40,000).

The beautifully simple mathematical aspect of radioactive decay is that the fraction of atoms decaying per second does not change with time. If initially there are N_o atoms, and a certain fraction λ decay in one second, the actual number of atoms decaying in one second is λN_o. Then, at any later time t, when there are only N_t atoms remaining, the *fraction* that decay in one second will still be λ—but the *number* of atoms decaying in one second is now λN_t, a smaller number than before.

The constant fraction λ of atoms decaying per unit time is called the *decay constant*. The value of this constant λ can be found for each radioactive species. For example, λ for radium is 1.36×10^{-11} per second, which means that on the average 0.0000000000136 of the total number of atoms in any sample of radium will decay in one second.

We can represent the fact that λ is a constant by the expression

$$\lambda = \frac{\Delta N/\Delta t}{N} = \text{constant}$$

which we can rewrite as

$$\Delta N/\Delta t = \text{constant} \times N$$

$$\text{or } \Delta N/\Delta t \propto N$$

This form of the relation expresses clearly the fact that the decay rate depends directly on the number of atoms left.

By using calculus, a relation of this type can be turned into an expression for N as a function of elapsed time t:

$$\frac{N_t}{N_o} = e^{-\lambda t} \quad \text{or} \quad N_t = N_o e^{-\lambda t}$$

where N_o is the number of atoms at $t = 0$, N_t is the number remaining unchanged at time t, and e is a mathematical constant that is approximately equal to 2.718. The factor $e^{-\lambda t}$ has the value 1 when $t = 0$, and decreases toward 0 as t increases. Since the decay constant appears as an exponent, the decay is called "exponential" and takes the typical exponential form illustrated by the graph which frames page 22.

The relationship between the half-life $T_{\frac{1}{2}}$ and the decay constant λ can be derived as follows. We start by writing the exponential decay equation in logarithmic form. This is done by taking the logarithm of both sides of the equation:

$$\begin{aligned} \log \frac{N_t}{N_o} &= \log e^{-\lambda t} \\ &= -\lambda t \log e \end{aligned}$$

After a time equal to the half-life $T_{\frac{1}{2}}$, the ratio $N_t/N_o = \frac{1}{2}$. So we can substitute $\frac{1}{2}$ for N_t/N_o if we substitute $T_{\frac{1}{2}}$ for t in the above equation, and get

$$\log(\tfrac{1}{2}) = -\lambda T_{\frac{1}{2}} \log e$$

The value of $\log(\frac{1}{2})$ is -0.301 and the value of $\log e = 0.4343$; hence

$$-0.301 = -\lambda T_{\frac{1}{2}}\,(0.4343)$$

$$\text{and} \qquad \lambda T_{\frac{1}{2}} = 0.693$$

So the product of the decay constant and the half-life is always equal to 0.693. Knowing either one allows us to compute the other directly.

For example, radium 226 has a decay constant $\lambda = 1.36 \times 10^{-11}$ per second, so

$$\begin{aligned} (1.36 \times 10^{-11}\ \text{sec}^{-1})\, T_{\frac{1}{2}} &= 0.693 \\ T_{\frac{1}{2}} &= \frac{0.693}{1.36 \times 10^{-11}\ \text{sec}^{-1}} \\ T_{\frac{1}{2}} &= 5.10 \times 10^{10}\ \text{sec} \end{aligned}$$

Thus the half-life of radium 226 is 5.10×10^{10} sec (about 1620 years).

SG 21.12–21.15

N_0 radioactive atoms with a half-life of 70 years. $N_0/4$ will have remained intact after 140 years, $N_0/8$ after 210 years, etc. To put it differently, *the statistical probability of survival for atoms is unchanged by the age they have already reached*; in humans, of course, the probability of survival (say, for another year) depends strongly on age.

We have been considering the behavior not of individual atoms, but of a very large number of them. As we saw in considering the behavior of gases in Chapter 11, this allows us to use laws of statistics to describe the average behavior of the group. If a hundred thousand persons were to flip coins simultaneously just once, we could predict with good accuracy that about one-half of them would get heads. But we could not accurately predict that one particular person in this crowd would obtain heads on a single flip. If the number of coins tossed is small, the observed count is likely to differ considerably from the prediction of 50% heads. From experiments in radioactivity we can predict that a certain fraction of a relatively large number of atoms in a sample will survive in any given time interval—say $\frac{1}{2}$ will survive to reach the age T—but not whether a particular atom will be among the survivors. And as the sample of survivors decreases in size owing to disintegrations, our predictions become less precise. Eventually, when only a few unchanged atoms are left, we could no longer make useful predictions at all. In short, the disintegration law is a *statistical* law, and is thus applicable only to large populations of the radioactive atoms. Moreover, it makes no assumptions as to *why* the atoms disintegrate.

The use of this statistical law, in practice, is justified because even a minute sample of a radioactive element contains very many atoms. For example, one-millionth of a gram of uranium contains 3×10^{15} atoms.

In the discussion of the kinetic theory of matter we saw that it is a hopeless and meaningless task to try to describe the motions of each individual molecule; but we could calculate the *average* pressure of a gas containing a very large number of molecules. Similarly, in dealing with radioactivity we find that our inability to specify when each of the tremendous number of atoms in a normal sample will disintegrate makes a statistical treatment necessary—and useful.

Q15 Why can one not specify the life time of a sample of radioactive atoms?

Q16 How much of a substance will be left unchanged after a period equal to four times its half-life?

Q17 If, after many many half-lives, only two atoms of a radioactive substance remain, what will happen during an additional period equal to one half-life?

21.1 The Project Physics learning materials particularly appropriate for Chapter 21 include:

Experiments

Random Events
Range of α and β Particles
Half-life – I
Half-life – II
Radioactive Tracers

Activities

Magnetic Deflection of β Rays
Measuring the Energy of α Radiation
A Sweet Demonstration
Ionization of Radioactivity
Exponential Decay in Concentrations

Reader Article

The Nature of the Alpha Particle

Transparencies

Separation of α, β, γ Rays
Rutherford's α-Particle "Mousetrap"
Radioactive Disintegration Series

In addition, the following *Reader* articles are appropriate to Unit 6 in general:

Rutherford
The Privilege of Being a Physicist
One Scientist and His View of Science
The Development of the Space-Time View of Quantum Electrodynamics
Physics and Mathematics
Where Do We Go From Here?

21.2 Which of the Curies' discoveries would have been unlikely if they had used Becquerel's photographic technique for detecting radioactivity?

21.3 A spectroscopic examination of the γ rays from bismuth 214 shows that rays of several discrete but different energies are present. The rays are said to show a "line spectrum." The measured wavelength corresponding to one of the lines is 0.016Å.

(a) Show that the energy of each of the γ-ray photons responsible for that line is 1.2×10^{-13} J. (Hint – see Chapter 20.)
(b) What is the equivalent energy in electron volts?

21.4 Suppose that in the figure on p. 15 the magnetic field strength is 1.0×10^{-3}N/amp·m.

(a) What would be the radius of curvature of the path of electrons entering the magnetic field with a speed of 1.0×10^{7} m/sec? (The charge and mass of the electron are 1.6×10^{-19} coul and 9.1×10^{-31} kg respectively.)
(b) If α particles entered the magnetic field with the same speed as the electrons in part (a), what would be the radius of curvature of their orbit? (The mass of an α particle is $6.7 \times 10-27$ kg.)
(c) Compare your answers to parts (a) and (b).

21.5 The electric field in the figure on p. 16 is produced by + charge at top plate, − charge at bottom. What is the sign of charges in beam going through tube? What is direction of magnetic field (into page or out of page)?

21.6 If the electrons described in part (a) of SG 21.4 pass through crossed electric and magnetic fields as shown in part (c) of the figure on p. 16,

(a) what must be the strength of the electric field to just balance the effect of a magnetic field of strength 1.0×10^{-3}N/amp·m?
(b) what voltage must be supplied to the electric field deflecting plates to produce the electric field strength of part (a) of this problem if the plates are 0.10 m apart?
(c) what will happen to the α particles of SG 21.4 (b) moving through the crossed magnetic and electric fields of this problem?

21.7 For each part below, select the most appropriate radiation(s): α, β, or γ.

(a) most penetrating radiation
(b) most easily absorbed by aluminum foil
(c) most strongly ionizing radiation
(d) may require thick "radiation shields" for protection
(e) cannot be deflected by a magnet
(f) largest radius of curvature when traveling across a magnetic field
(g) highest q/m value
(h) important in Rutherford's and Royd's "mousetrap" experiment
(i) involved in the transmutation of radium to radon
(j) involved in the transmutation of bismuth 210 to polonium 210

21.8 Suggest an explanation for the following observations:

The English physicist Sir William Crookes discovered in 1900 that immediately after a strongly radioactive uranium-containing compound was purified chemically, the uranium compound itself showed much smaller activity, and the separate residue containing none of the uranium was strongly radioactive.

Becquerel found, in 1901, that in such a case the uranium compound regained its original activity after several months, while the residue gradually lost most of its activity during the same time.

21.9 A Geiger counter shows that the rate of emission of β particles from an initially pure sample of a radioactive element decreases to one-half the initial rate in 25 hours.

(a) What fraction of the original number of radioactive atoms is still unchanged at that time?
(b) What fraction of the original number will have disintegrated in 50 hours?

(c) What assumptions have you made in giving these answers? How might you check them?

21.10 It took 10 years for 10 percent of the atoms of a certain freshly prepared sample of radioactive substance to decay. How much of the material that is left unchanged will decay in the *next* 10 years?

21.11 Suppose at time t_0 a sample of pure radium consisted of 2.66×10^{21} atoms. (The half-life of radium is approximately 1600 years.)

(a) If N_t is the number of radium atoms in the sample at a time t, make a graph of N_t vs time covering a period of 8000 years.

(b) Show that at the end of 8000 years, 8.3×10^{19} radium atoms still remain in the sample

(c) From your graph, estimate the number of radium atoms in the sample after 4000 years.

21.12 The capsule containing cobalt 60, shown and described on p. 18, is reported to have an activity of 17,000 curies. One curie is defined as 3.70×10^{10} disintegrations per second.

(a) How much energy is released per disintegration in the cobalt 60?

(b) What would be the rate of heat production of that sample after 15 years? (The half-life of cobalt 60 is approximately 5 years.)

21.13 Radioactive isotopes in quantities of 10 micro-curies or less can be purchased for instructional purposes from the U.S. Atomic Energy Commission. How many disintegrations per second occur in a 10 micro-curie sample?

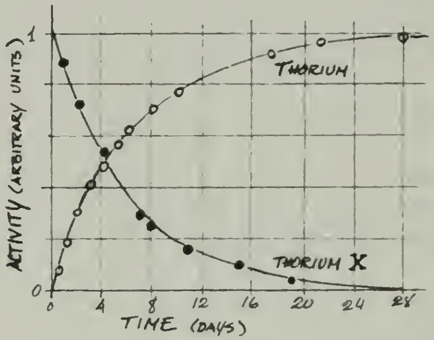
21.14 Below are the observed disintegration rates (counting rates) as a function of time for a radioactive sample.

TIME	COUNTING RATE (counts/min)	TIME (hr)	COUNTING RATE (counts/min)
0.0	. . . .	6.0	1800
0.5	9535	7.0	1330
1.0	8190	8.0	980
1.5	7040	9.0	720
2.0	6050	10.0	535
3.0	4465	11.0	395
4.0	3300	12.0	290
5.0	2430		

(a) Plot the data, and determine the approximate half-life of this substance.

(b) How many atoms decay each minute for each 10^6 atoms in this sample? (Use the relationship between λ and T derived on p. 23.) Does this number remain constant?

21.15 Rutherford and Soddy, working with samples of compounds of thorium, obtained results similar to those described in SG 21.8. Their results published in 1903, are shown below.



(a) What is the half-life of thorium X?

(b) In 1931 Rutherford was elevated to the British peerage, becoming "Baron Rutherford of Nelson." It is claimed that there is a connection between Rutherford's design of his coat of arms (shown below) and his work. What might the connection be?

RUTHERFORD OF NELSON.

Periodic Table of the Elements*

Locate on back inside cover. Add names of elements

Group→ Period ↓	I	II											III	IV	V	VI	VII	0
1	1.0080 H 1																	4.0026 He 2
2	6.939 Li 3	9.012 Be 4											10.811 B 5	12.011 C 6	14.007 N 7	15.999 O 8	18.998 F 9	20.183 Ne 10
3	22.990 Na 11	24.31 Mg 12											26.98 Al 13	28.09 Si 14	30.97 P 15	32.06 S 16	35.45 Cl 17	39.95 Ar 18
4	39.10 K 19	40.08 Ca 20	44.96 Sc 21	47.90 Ti 22	50.94 V 23	52.00 Cr 24	54.94 Mn 25	55.85 Fe 26	58.93 Co 27	58.71 Ni 28	63.54 Cu 29	65.37 Zn 30	69.72 Ga 31	72.59 Ge 32	74.92 As 33	78.96 Se 34	79.91 Br 35	83.80 Kr 36
5	85.47 Rb 37	87.62 Sr 38	88.91 Y 39	91.22 Zr 40	92.91 Nb 41	95.94 Mo 42	(99) Tc 43	101.07 Ru 44	102.91 Rh 45	106.4 Pd 46	107.87 Ag 47	112.40 Cd 48	114.82 In 49	118.69 Sn 50	121.75 Sb 51	127.60 Te 52	126.9 I 53	131.30 Xe 54
6	132.91 Cs 55	137.34 Ba 56	* 57–71	178.49 Hf 72	180.95 Ta 73	183.85 W 74	186.2 Re 75	190.2 Os 76	192.2 Ir 77	195.09 Pt 78	196.97 Au 79	200.59 Hg 80	204.37 Tl 81	207.19 Pb 82	208.98 Bi 83	210 Po 84	(210) At 85	222 Rn 86
7	(223) Fr 87	226.05 Ra 88	† 89–103															

*Rare-earth metals	138.91 La 57	140.12 Ce 58	140.91 Pr 59	144.27 Nd 60	(147) Pm 61	150.35 Sm 62	151.96 Eu 63	157.25 Gd 64	158.92 Tb 65	162.50 Dy 66	164.93 Ho 67	167.26 Er 68	168.93 Tm 69	173.04 Yb 70	174.97 Lu 71
† Actinide metals	227 Ac 89	232.04 Th 90	231 Pa 91	238.03 U 92	(237) Np 93	(242) Pu 94	(243) Am 95	(245) Cm 96	(249) Bk 97	(249) Cf 98	(253) E 99	(255) Fm 100	(256) Mv 101	(253) No 102	(257) Lw 103

*Numbers above the symbols are the average atomic masses (relative to carbon 12). The names of the elements and their symbols are listed on the following pages.

Uranium-radium decay series

OLD NAME	PRESENT NAME AND SYMBOL		MODE OF DECAY	HALF-LIFE
Uranium I	Uranium 238	${}_{92}U^{238}$	α	4.51 × 10^9 years
Uranium X_1	Thorium 234	${}_{90}Th^{234}$	β,γ	24.1 days
Uranium X_2	Protactinium 234	${}_{91}Pa^{234}$	β,γ	1.18 minutes
Uranium II	Uranium 234	${}_{92}U^{234}$	α	2.48 × 10^5 years
Ionium	Thorium 230	${}_{90}Th^{230}$	α,γ	8.0 × 10^4 years
Radium	Radium 226	${}_{88}Ra^{226}$	α,γ	1620 years
Radium Emanation	Radon 222	${}_{86}Rn^{222}$	α	3.82 days
Radium A	Polonium 218	${}_{84}Po^{218}$	α	3.05 minutes
Radium B	Lead 214	${}_{82}Pb^{214}$	β,γ	26.8 minutes
Radium C	Bismuth 214	${}_{83}Bi^{214}$	β,γ	19.7 minutes
Radium C′	Polonium 214	${}_{84}Po^{214}$	α	1.64 × 10^{-4} seconds
Radium D	Lead 210	${}_{82}Pb^{210}$	β,γ	21.4 years
Radium E	Bismuth 210	${}_{83}Bi^{210}$	β	5.0 days
Radium F	Polonium 210	${}_{84}Po^{210}$	α,γ	138.4 days
Radium G	Lead 206	${}_{82}Pb^{206}$	stable	

List of the Elements

Element	Symbol	Atomic Number	Year of Isolation or Discovery and Origin of Name*
Actinium	Ac	89	1900 Greek *aktis*, ray
Aluminum	Al	13	1825 Latin *alumen*, substance with astringent taste
Americium	Am	95	1944 America
Antimony	Sb	51	15th century, Greek *antimonos*, opposite to solitude
Argon	Ar	18	1894 Greek *argos*, inactive
Arsenic	As	33	13th century, Greek *arsenikon*, valiant
Astatine	At	85	1940 Greek *astatos*, unstable
Barium	Ba	56	1808 Greek *barys*, heavy
Berkelium	Bk	97	1949 Berkeley, California
Beryllium	Be	4	1797 mineral, beryl
Bismuth	Bi	83	15th century, German *Weisse Masse*, white mass
Boron	B	5	1808 Arabic *bawraq*, white
Bromine	Br	35	1826 Greek *bromos*, a stench
Cadmium	Cd	48	1817 Latin *cadmia*, calamine, a zinc ore
Calcium	Ca	20	1808 Latin *calcis*, lime
Californium	Cf	98	1950 State and University of California
Carbon	C	6	prehistoric, Latin *carbo*, coal
Cerium	Ce	58	1804 the asteroid Ceres, discovered 1803
Cesium	Cs	55	1860 Latin *caesius*, sky blue
Chlorine	Cl	17	1808 Greek *chloros*, grass green
Chromium	Cr	24	1797 Greek *chroma*, color
Cobalt	Co	27	1735 Greek *kobolos*, a goblin
Copper	Cu	29	prehistoric, Latin *cuprum*, copper
Curium	Cm	96	1944 Marie and Pierre Curie
Dysprosium	Dy	66	1886 Greek *dysprositos*, hard to get at
Einsteinium	Es	99	1952 Albert Einstein
Erbium	Er	68	1843 Ytterby, a mining town in Sweden where first sample found
Europium	Eu	63	1900 Europe
Fermium	Fm	100	1953 Enrico Fermi
Fluorine	F	9	1886 Latin *fluere*, to flow
Francium	Fr	87	1939 France
Gadolinium	Gd	64	1886 Johan Gadolin, Finnish chemist
Gallium	Ga	31	1875 Gaul, or France
Germanium	Ge	32	1886 Germany
Gold	Au	79	prehistoric, Anglo-Saxon gold, symbol from Latin *aurum*
Hafnium	Hf	72	1922 *Hafnia*, Latin for Copenhagen
Helium	He	2	1895 Greek *helios*, the sun
Holmium	Ho	67	1879 *Holmia*, Latin for Stockholm
Hydrogen	H	1	1766 Greek *hydro genes*, water former
Indium	In	49	1863 indigo-blue spectrum line
Iodine	I	53	1811 Greek *iodes*, violet-like
Iridium	Ir	77	1804 Latin *iridis*, rainbow
Iron	Fe	26	prehistoric, Anglo-Saxon *iren* or *isen*, symbol from Latin *ferrum*
Krypton	Kr	36	1898 Greek *kryptos*, hidden
Lanthanum	La	57	1839 Greek *lanthanien*, to be concealed
Lawrencium	Lw	103	1961 Ernest O. Lawrence, inventor of cyclotron
Lead	Pb	82	Prehistoric, middle English *led*, symbol from Latin *plumbum*
Lithium	Li	3	1817 Greek *lithos*, stone
Lutetium	Lu	71	1905 *Lutetia*, ancient name of Paris
Magnesium	Mg	12	1774 Latin *magnes*, magnet
Mendelevium	Md	101	1955 Dmitri Mendeleev, who devised first Periodic Table

List of the Elements (cont.)

Element	**Symbol**	**Atomic Number**	**Year of Isolation or Discovery and Origin of Name***
Mercury	Hg	80	prehistoric, Latin *Mercurius*, the gold and planet
Molybdenum	Mo	42	1782 Greek *molybdos*, lead
Neodymium	Nd	60	1885 Greek *neos*, new, and *didymos*, twin
Neon	Ne	10	1898 Greek *neos*, new
Neptunium	Np	93	1940 planet Neptune
Nickel	Ni	28	1750 German *Nickel*, a goblin or devil
Niobium	Nb	41	1801 Niobe, daughter of Tantalus
Nitrogen	N	7	1772 Latin *nitro*, native soda, and *gen*, born
Nobelium	No	102	1957 Alfred Nobel
Osmium	Os	76	1804 Greek *osme*, a smell, from the odor of its volatile tetroxide
Oxygen	O	8	1774 Greek *oxys*, sharp, and *gen*, born
Palladium	Pd	46	1803 planetoid Pallas, discovered 1801
Phosphorus	P	15	1669 Greek *phosphoros*, light bringer
Platinum	Pt	78	1735 Spanish *plata*, silver
Plutonium	Pu	94	1940 Pluto, the second planet beyond Uranus
Polonium	Po	84	1898 Poland, native country of co-discoverer Marie Curie
Potassium	K	19	1807 English *potash*, symbol Latin *kalium*
Praseodymium	Pr	59	1885 Greek *praseos*, leek green and *didymos*, a twin
Promethium	Pm	61	1947 Prometheus, fire bringer of Greek mythology
Protactinium	Pa	91	1917 Greek *protos* first, and actinium because it disintegrates into it
Radium	Ra	88	1898 Latin *radius*, ray
Radon	Rn	86	1900 because it comes from radium
Rhenium	Re	75	1924 Latin *Rhenus*, Rhine province of Germany
Rhodium	Rh	45	1804 Greek *rhodon*, a rose
Rubidium	Rb	37	1860 Latin *rubidus*, red
Ruthenium	Ru	44	1845 Latin *Ruthenia*, Russia
Samarium	Sm	62	1879 Samarski, a Russian engineer
Scandium	Sc	21	1879 Scandinavian peninsula
Selenium	Se	34	1817 Greek selene, moon
Silicon	Si	14	1823 Latin *silex*, flint
Silver	Ag	47	prehistoric, Anglo-Saxon *seolfor*, symbol from Latin *argentum*
Sodium	Na	11	1807 Medieval Latin *soda*, symbol from Latin *natrium*
Strontium	Sr	38	1808 town of Strontian, Scotland
Sulfur	S	16	prehistoric, Latin *sulphur*
Tantalum	Ta	73	1802 Tantalus of Greek mythology
Technetium	Tc	43	1937 Greek *technetos*, artificial
Tellurium	Te	52	1782 Latin *tellus*, the earth
Terbium	Tb	65	1843 Ytterby, town in Sweden
Thallium	Tl	81	1862 Greek *thallos*, a young shoot
Thorium	Th	90	1819 Scandinavian mythology, *Thor*
Thulium	Tm	69	1879 Latin Thule, most northerly part of the habitable world
Tin	Sn	50	prehistoric, origin of name unknown, symbol Latin *stannum*
Titanium	Ti	22	1791 Greek mythology, Titans, first sons of the earth
Tungsten	W	74	1783 Swedish *tung sten*, heavy stone, symbol from the mineral wolframite
Uranium	U	92	1789 Planet Uranus
Vanadium	V	23	1830 goddess *Vanadis* of Scandinavian mythology
Xenon	Xe	54	1898 Greek *xenos*, strange
Ytterbium	Yb	70	1905 Ytterby, a town in Sweden
Yttrium	Y	39	1843 Ytterby, a town in Sweden
Zinc	Zn	30	prehistoric, German *Zink*, akin to *Zinn*, tin
Zirconium	Zr	40	1824 Arabian *Zerk*, a precious stone

*adapted from Alfred Romer, *The Restless Atom*, Science Study Series, Doubleday Co., N.Y.

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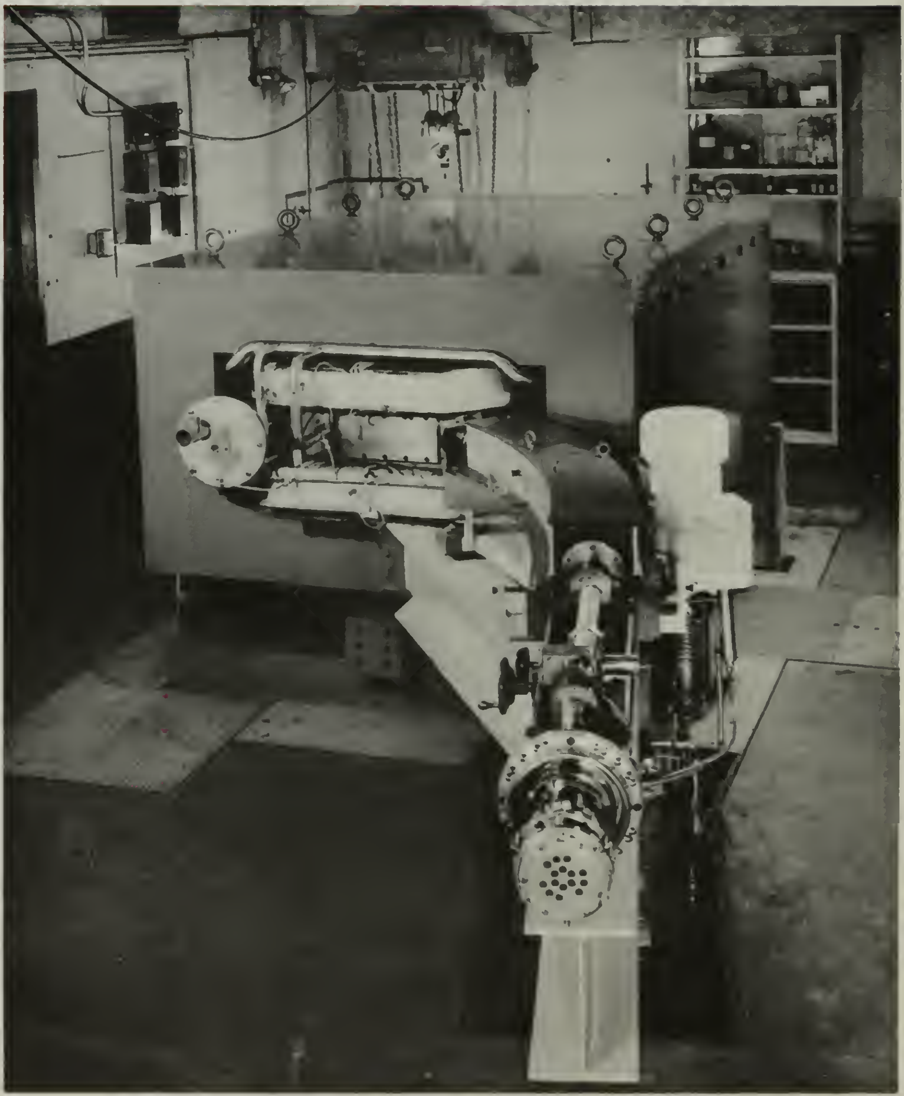


Partially assembled mass spectrograph in the laboratory of K.T. Bainbridge at Harvard University.

CHAPTER TWENTY-TWO

Isotopes

22.1 The concept of isotopes

The discovery that there are three radioactive series, each containing apparently new substances, raised a serious problem. In 1910 there were still some empty spaces in the periodic table of the elements, but there were not enough spaces for the many new substances. The periodic table represents an arrangement of the elements according to their chemical properties and, if it could not include the radioactive elements, it would have to be revised, perhaps in some drastic and fundamental way.

SG 22.1

The clue to the puzzle lay in the observation that some of the newly found materials that cropped up as members of a radioactive series had *chemical* properties identical with those of well-known elements, although some of their *physical* properties were different. For example, the "great-granddaughter" of uranium was found to have the same chemical properties as uranium itself. When both were mixed together, the two could not be separated by chemical means. No chemist had detected, by chemical analysis, any difference between these two substances. But the two substances, now known as uranium 238 and uranium 234, do differ from each other in certain physical properties. As the lower table on p. 27 shows, uranium 238 and 234 have quite different radioactive half-lives: 4.5×10^9 years and 2.5×10^5 years, respectively; and the mass of a uranium 234 atom must be smaller than that of a uranium 238 atom by the mass of one α particle and two β particles. Another pair of radioactive substances, radium B and radium G, were found to have the same chemical properties as lead: when mixed with lead they could not be separated from it by chemical means. These substances are now known as lead 214 and lead 206, respectively. But lead 214 is radioactive and lead 206 is stable, and the lower table on p. 27 indicates that the atoms must differ from each other in mass by the mass of two α particles and four β particles. There are many other examples of such physical differences among two or more radioactive substances with the same chemical behavior.

Soddy suggested a solution that threw a flood of light on the nature of matter and on the relationship of the elements in the periodic table. He proposed that a chemical element could be regarded as a pure substance only in the sense that all of its atoms have the same chemical properties. That is, a chemical element may in fact be a *mixture of atoms,* some having different radioactive behavior and different atomic masses, but all having the same chemical properties. This idea meant that one of the basic postulates of Dalton's atomic theory would have to be changed, namely the postulate that the atoms of a pure element are alike in *all* respects. According to Soddy, it is only in chemical properties that the atoms of a given element are identical. The several physically different species of atoms making up a particular element occupy the same place in the periodic table, that is, have the same atomic number Z. Soddy called them *isotopes* of the element, from the Greek *isos* and *topos* meaning *same* and *place* (same place in the periodic table). Thus uranium 238 and uranium 234 are isotopes of uranium; lead 214 and lead 206 are isotopes of lead.

The many species of radioactive atoms in the three radioactive series were shown by chemical analysis to be isotopes of one or another of the last eleven elements in the periodic table—from lead to uranium. For example, the second and fifth members of the uranium series were shown to be isotopes of thorium, with $Z = 90$; the 8th, 11th and 14th members turned out to be isotopes of polonium ($Z = 84$). The old names and symbols given to the members of radioactive series upon their discovery were therefore rewritten to represent both the chemical similarity and physical difference among isotopes. The present names for uranium X_1 and ionium, for example, are thorium 234 and thorium 230 (as shown in the lower table on p. 27) A modern "shorthand" form for symbolizing any species of atom, or *nuclide,* is also given in the same table (for example, ${}_{90}Th^{234}$ and ${}_{90}Th^{230}$ for two of the isotopes of thorium). The subscript (90 in both cases for thorium) is the atomic number Z—the place number in the periodic table; the superscript (234 or 230) is the mass number *A*—the approximate atomic mass in amu. Note that the chemical symbol (such as Th) adds nothing to the information given by the subscript.

This shorthand notation is explained further on page 40.

Q1 Why wasn't it necessary, after all, to expand the periodic table to fit in the newly discovered radioactive substances?

Q2 The symbol for the carbon 12 nuclide is ${}_{6}C^{12}$. What is the approximate atomic mass of carbon 12? What is its position in the list of elements?

22.2 Transformation rules

Two questions then arose: how do changes in chemical nature come about as an atom undergoes radioactive decay? And, more specifically, what determines whether the atomic number Z increases or decreases in a given radioactive transformation?

In 1913, the answers to these questions were given independently by Soddy in England and by A. Fajans in Germany. They each proposed two rules which systematized all the relevant observations for natural radioactivity. We call them the *transformation rules of radioactivity.* Recall that by 1913 Rutherford's nuclear model of the atom was generally accepted. Using this model, one could consider a radioactive atom to have an unstable nucleus which emits an α or β particle (sometimes with emission of a γ ray). Every nucleus has a positive charge Zq_e, where Z is the atomic number and q_e is the magnitude of the charge of an electron. The nucleus is surrounded by Z electrons which make the atom as a whole electrically neutral and determine the chemical behavior of the atom. An α particle has an atomic mass of about 4 units and a positive charge of 2 units, $+2q_e$. A β particle has a negative charge of one unit, $-q_e$, and very little mass compared with an α particle.

The transformation rules may now be stated as follows:

1. When a nucleus emits an α particle, the mass of the atom decreases by 4 atomic mass units, and the atomic number Z of the nucleus decreases by 2 units; the resulting atom belongs to an element two spaces back in the periodic table.

2. When a nucleus emits a β particle, the mass of the atom is changed very little, but the atomic number Z increases by one unit: the resulting atom belongs to an element one place forward in the periodic table. When only a γ ray is emitted, there is no change in the number corresponding to the atomic mass, and none in the atomic number. The lower table on p. 27 shows how these rules apply to the uranium-radium series, at least so far as the atomic number is concerned.

The Rutherford-Bohr model of the atom helps us to understand why a change in chemical nature occurs as a result of α or β emission. Emission of an α particle takes two positive charges from the nucleus, and the resulting new atom with its less positive nucleus can hold in its outer shells two fewer electrons than before, so two excess electrons drift away. The chemical behavior of atoms is controlled by the number of electrons, therefore the new atom acts chemically like an atom of an element with an atomic number two units *less* than that of the parent atom. On the other hand, in β emission the nucleus—and with it the whole atom—becomes *more* positively charged, by one unit. The number of electrons that the atom can hold around the nucleus has increased by one, and after it has picked up an extra electron to become neutral again, the atom acts chemically as an atom with an atomic number one unit greater than that of the atom before the radioactive change occurred.

By using the transformation rules, Soddy and Fajans were able to determine the place in the periodic table for every one of the substances (or nuclides) in the radioactive series; no revision of the periodic table was needed. Many of the nuclides between Z = 82 (lead) and Z = 92 (uranium) are now known to contain several isotopes each. These results were expected from the hypothesis of the existence of isotopes, but direct, independent evidence was also sought—and it was obtained in 1914.

Frederick Soddy (1877-1956), an English chemist, studied at Oxford, and went to Canada in 1899 to work under Rutherford at McGill University in Montreal. There the two worked out their explanation of radioactive decay. Soddy returned to England in 1902 to work with Sir William Ramsay, the discoverer of the rare gases argon, neon, krypton and xenon. Ramsay and Soddy showed, in 1903, that helium was continually produced by naturally radioactive substances. In 1921, Soddy was awarded the Nobel Prize in chemistry for his discovery of isotopes. He was a professor of chemistry at Oxford from 1919 to 1936.

Example of α and β decay:

$\text{Po} \rightarrow \text{Pb} + \alpha$

$\text{Th} \rightarrow \text{Pa} + \beta$

SG 22.2, 22.3

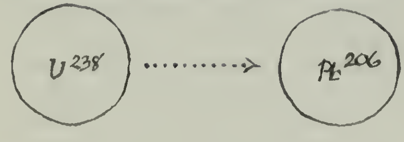
Q3 By how many units does the mass of an atom change during α decay? During β decay?

Q4 By how many units does the charge of a nucleus change during α decay? During β decay?

Q5 What are the transformation rules of radioactivity? Give an actual example of how they apply. How do these rules follow from the Rutherford-Bohr model of the atom?

22.3 Direct evidence for isotopes of lead

Soddy knew that the stable end product of the uranium-radium series had the chemical properties of lead, and that the end product of the thorium series also had the chemical properties of lead. But he realized that these end products should have atomic masses different from that of ordinary lead (that is, lead that was not produced from a radioactive series). This result follows from a simple calculation of the change in mass as an atom decays from the starting point of a radioactive series to the end point. The calculation may be simplified by ignoring beta decays in which no appreciable change in mass is involved.



There are four naturally occurring lead isotopes:

$_{82}Pb^{204}$
$_{82}Pb^{206}$
$_{82}Pb^{207}$
$_{82}Pb^{208}$

The first is found only as one of the isotopes of "ordinary" lead. Pb^{207} is also found as the end product of a decay chain starting with actinium.

SG 12.13 involves the fact that the decay of U is a distinct isotope of lead.

In the uranium series eight α particles, each with atomic mass of 4 units, are emitted. Therefore, the end product of the series starting from U^{238} is expected to have an atomic mass close to $238 - (8 \times 4) = 206$ units. In the thorium series, the end product derives from thorium 232, with an atomic mass of about 232 units, and six α particles are emitted along the way. It should therefore have an atomic mass close to $232 - (6 \times 4) = 208$ units. The average atomic mass of ordinary lead, found where there is no radioactive material evident, was known from chemical analysis to be 207.2 units.

The lead extracted from the mineral thorite, which consists mainly of thorium and contains only one or two per cent by mass of uranium, may be presumed to be the final product of the thorium series. The atomic mass of lead extracted from thorite should therefore be significantly different both from the atomic mass of lead extracted from a uranium mineral such as pitchblende, and from the atomic mass of ordinary lead.

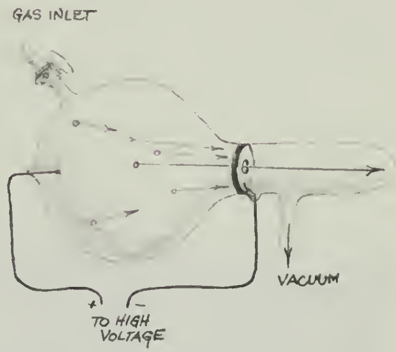
Here was a quantitative prediction, built on the transformation rules, which could be checked, and a number of chemists in Scotland, France, Germany, Austria and the United States attacked the problem. At Harvard University, T. W. Richards (later recipient of a Nobel Prize in chemistry) found atomic masses as low as 206.08 for samples of lead from ores rich in uranium. Chemists in Austria found samples of lead, in the ore uraninite, with an atomic mass of 206.04. Soddy and others found samples of lead from thorite with atomic masses as high as 207.08 and 207.9. The results left no doubt that uranium was transformed into a light isotope of lead, and thorium into a heavier isotope of lead.

Q6 On what grounds was the existence of different atomic masses of lead predicted?

22.4 Positive rays

It was hard to show that stable elements may be mixtures of isotopes. By definition, isotopes cannot be separated by ordinary chemical methods. Any attempt to separate a pair of isotopes must depend on a difference in some behavior which depends, in turn, on the difference between their atomic masses. Moreover, except for the very lightest elements, the difference in atomic mass is small compared to the atomic masses themselves. For the lead isotopes discussed in the last section the difference was only two units in about 200 units, or about one per cent. Any difference in a physical property between two isotopes having such a small mass difference would be expected to be very small, making separation difficult to achieve. Fortunately, when the question of the possible existence of isotopes of stable elements arose, a method was available which could answer the question. This method, developed by J. J. Thomson and extended by A. J. Dempster and others, depended on the behavior of positively charged ions when these are traveling in electric and magnetic fields.

In a cathode ray tube, electrons emitted from the cathode can knock electrons out of neutral atoms of gas with which they collide. It was thought that the positive ions produced in this way would accelerate toward the cathode and be neutralized there. In 1886, the German physicist Goldstein found that if a hole is made in the cathode, a ray passes through the cathode and emerges beyond it. The sketch in the margin is a schematic diagram of a discharge tube for producing such rays. If the cathode fits the tube tightly, so that no gas can enter the region behind it, and if the holes are so small that very little gas can get through them, a high vacuum can be produced on the right side, where the ray emerges. The ray then has quite a long range, and can be deflected by externally applied electric and magnetic fields. From the direction of the deflection, it could be concluded that the rays consist of positively charged particles. The rays were therefore called "positive rays," and were thought (correctly) to consist of positively charged ions of the atoms or molecules of the residual gas in the left side of the discharge tube.



Discharge tube for producing a beam of positive ions. The low-pressure gas between anode and cathode is ionized by the action of the electric field. The positive ions are accelerated by the electric field toward the cathode; there some of them will pass through a small hole and enter the well-evacuated region beyond, on the right side. That is where an external electric or magnetic field can be applied.

In this manner, Thomson prepared positive rays from different gases and used the observed deflection produced by external fields to determine the relative masses of the atoms of the gases. It was a crucially important method as we shall see. Rather than describe the details of Thomson's early apparatus we shall describe an improved type of instrument based on the early form, and one that is still in common use.

The modern instrument typically consists of two main parts: the first part accelerates and then selects a beam of ions all moving

J. J. Thomson (1856-1940) at work in the Cavendish Laboratory.

with the same speed; in the second part these ions pass through a magnetic field which deflects them from a straight path into several different curved paths determined by their relative masses. Ions of different mass are thus separated to such an extent that they can be detected separately. By analogy with the instrument that separates light of different wavelengths, the instrument that separates ions of different masses was called a *mass spectrograph.* Its operation (including how it can be used to measure q/m of ions) is explained on the opposite page. The details show what an ingenious and pretty piece of equipment this really is.

Thomson obtained results in his measurements of q/m for positive rays which were quite different from those that had been obtained for q/m of cathode-ray particles or β particles. Both the speeds of the ions and values of q/m were found to be smaller for gases with heavier molecules. These results are consistent with the idea that the positive rays are streams of positively ionized atoms or molecules.

Of course it would be very desirable if the values of q and m could be separately determined. The *magnitude* of q must be a multiple of the electron charge q_e, that is, it can only be q_e, or $2q_e$, or $3q_e$, $4q_e$, ... The greater the charge on an ion, the greater the magnetic force will be and, therefore, the more curved the path of the ions. So we expect that in the apparatus shown on p. 37, a doubly ionized atom (an ion with charge $+2q_e$) will follow a path with half the radius of that of a singly ionized atom of similar type; a triply ionized atom will trace out a semi-circular path with one-third the radius, etc. Thus, for each type of atom analyzed, the path with the largest radius will be that taken by the ions with the single charge q_e. Since q is therefore known for each of the paths, the mass of the ions can be determined from the values of q/m found for each path.

Thus, study of positive rays with the mass spectrograph made it possible to measure for the first time the masses of individual atoms. (With the electrolysis methods that had been available before, described in Sec. 17.7, it was possible to obtain only *average* masses for very large numbers of atoms.) The uncertainty of mass determinations made with modern mass spectrographs can be less than one part in a hundred thousand, that is, less than 0.001 percent. The difference in the masses of the isotopes of an element is thus easily detected, because in no case is it less than about 0.3 percent.

Some mass spectrometers are portable; small ones similar to this are carried aloft for analysis of the upper atmosphere.

Q7 The radius of curvature of the path of an ion beam in a magnetic field depends on both the mass and speed of the ions. How must a mass spectograph be constructed to allow separation of the ions in a beam by mass?

22.5 Separating isotopes

In Thomson's original instrument the uncertainty in measured mass of ions was about one percent, but this was small enough to

Principles of the operation of the mass spectrograph.

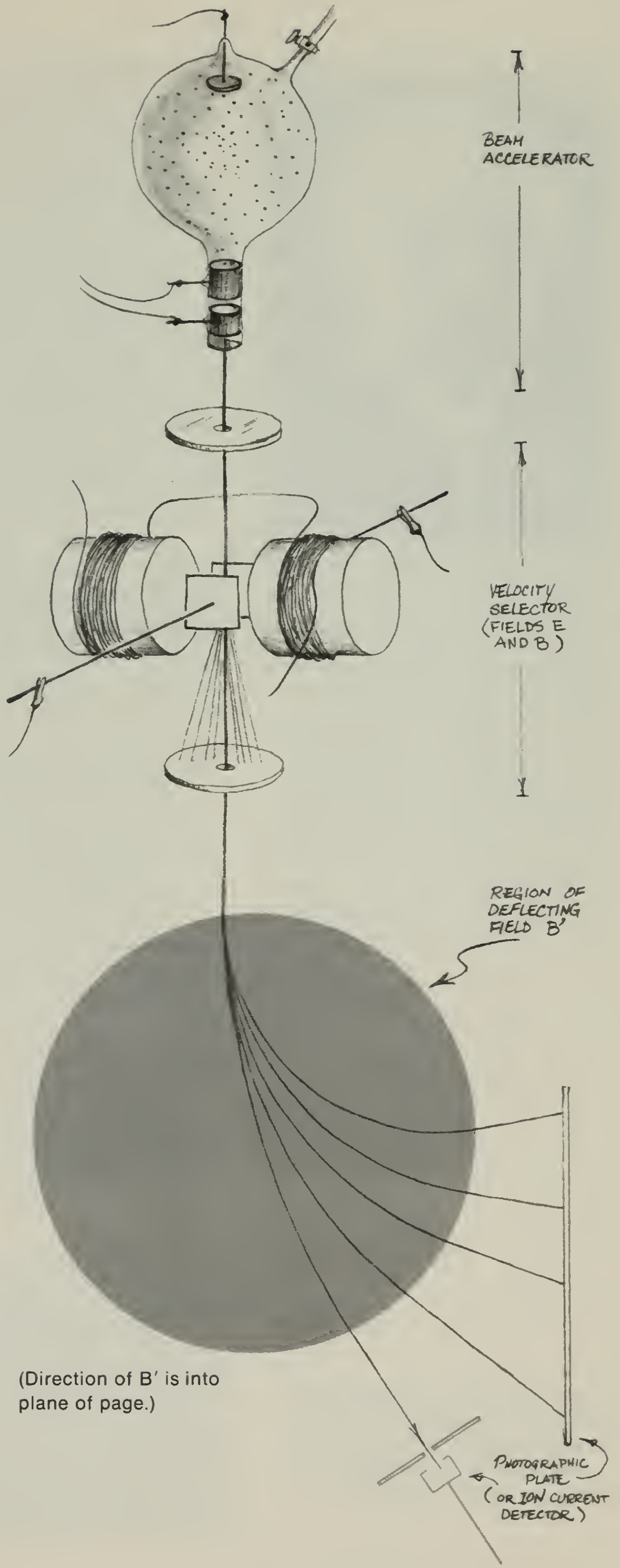
The magnetic separation of isotopes begins by electrically charging the atoms of a sample of material, for example by means of an electric discharge through a sample of gas. The resulting ions are then further accelerated by means of the electric potential difference between the lower pair of electrodes, and a beam emerges.

Before the different isotopes in the beam can be separated, there is usually a preliminary stage that allows only those ions with a certain velocity to pass through. In one type, the ion beam initially enters a region of crossed magnetic fields B and E, produced by current in coils and charged plates as shown. There, each ion experiences a magnetic force of magnitude qvB and an electric force of magnitude qE. The magnetic and electric forces act on an ion in opposite directions, and only for ions of a certain speed will the forces be balanced, allowing them to pass straight through the crossed fields and the hole in the diaphragm below them. For each of these ions, $qvB = qE$; so their speed $v = E/B$. Because only ions with this speed in the original direction remain in the beam, this portion of the first part of the apparatus is called a *velocity selector*.

The separation of isotopes in the beam is now accomplished in another magnetic field of strength B'. As the beam enters this field, the magnetic field causes a centripetal force to act on each ion, deflecting it into a circular arc whose radius R depends upon the ion's charge-to-mass ratio. That is, $qvB' = mv^2/R$, and so $q/m = v/B'R$.

The divided beams of ions fall on either a photographic plate (in a mass spectro*graph*) or a sensitive ion current detector (in a mass spectro*meter*), allowing the radii R of their deflections to be calculated from the geometry of the apparatus. Since v, B', and R can be determined from measurements, the charge-to-mass ratio of each beam of ions can be directly calculated.

Because this method uses electric and magnetic fields, it is called the *electromagnetic method of separation of isotopes.*



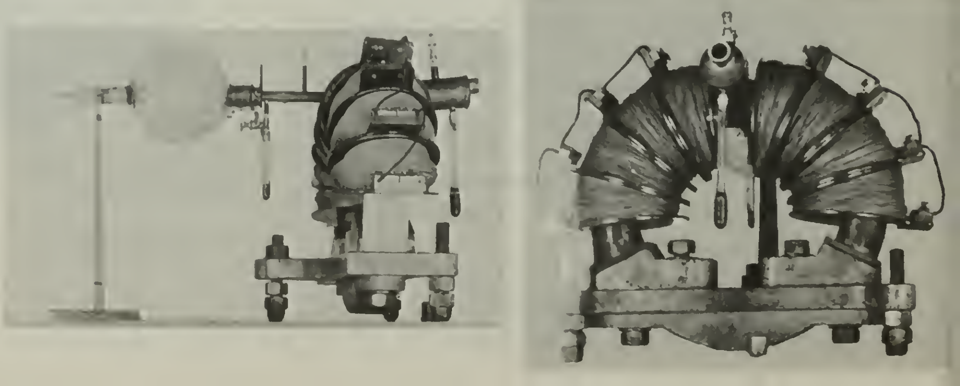
(Direction of B' is into plane of page.)

Francis William Aston (1877-1945) studied chemistry at the University of Birmingham. In 1910 he went to Cambridge to work under J. J. Thomson. He was awarded the Nobel Prize in chemistry, in 1922, for his work on isotopic mass determinations with the mass spectrograph. In disagreement with Rutherford, Aston pictured a future in which the energy of the atom would be tapped by man. In his Nobel acceptance speech he also spoke of the dangers involved in such a possibility. (Aston lived just long enough—by three months—to learn of the explosion of the nuclear bombs.)

permit Thomson to make the first observation of separated isotopes. He introduced a beam of neon ions from a discharge tube containing chemically pure neon into his mass spectrograph. The atomic mass of neon had been determined as 20.2 atomic mass units by means of the usual chemical methods for determining the atomic (or molecular) mass of a gas. Sure enough, at about the position on the photographic plate where ions of atomic mass 20 were expected to arrive, a dark line was observed when the plate was developed. But, in addition, there was also present nearby a faint line such as would indicate the presence of particles with atomic mass 22. No chemical element or gaseous compound was known which had this atomic or molecular mass. The presence of this line suggested, therefore, that neon might be a mixture of two isotopes, one with atomic mass 20, and the other with atomic mass 22. The average chemical mass 20.2 would result if neon contained about ten times as many atoms of atomic mass 20 as those of atomic mass 22.

The tentative evidence from this physical experiment that neon has two isotopes was so intriguing that Thomson's associate, F. W. Aston, looked for ways to sharpen the case for the existence of isotopes. It was well known from kinetic theory (see Sec. 11.5) that in a mixture of two gases with different molecular masses, the average molecular kinetic energy is the same for both. Therefore the lighter molecules have a higher average speed than the heavier molecules and collide more often with the walls of a container. If the mixture is allowed to diffuse through a porous wall from one container into another, the slower, heavier molecules are less likely to reach and pass through the wall. The portion of the gas sample that does not get through the wall will, therefore, contain more of the heavier molecules than the portion that does pass through the wall.

Aston allowed part of a sample of chemically pure neon gas to pass through such a wall. One pass accomplished only a slight separation of the lighter and heavier molecules, so a portion of the gas which had passed through the wall was passed through a porous wall again, and the same process was repeated many times. Aston measured the average atomic mass of each fraction of the gas by chemical means and found values of 20.15 atomic mass units for the fraction that had passed through the wall many times, and 20.28 units for the fraction that had been left behind in many tires. The difference in average atomic mass indicated that the neon was, indeed, a mixture of isotopes.



Two views of one of Aston's earlier mass spectrographs. The electromagnet was used to deflect a beam of charged atoms. Compare with sketch given on preceding page.

But even more impressive was the change in the relative intensities of the two traces (for atomic masses 20 and 22) in the mass spectrograph. The line corresponding to ions with 22 atomic mass units was more prominent in the analysis of the fraction of the gas that had been left behind, showing that this fraction was "enriched" in atoms of mass 22. The optical emission spectrum of the enriched sample was the same as that of the original neon sample—proving that no substance other than neon was present.

These results of separating isotopes at least partially by gas diffusion encouraged Aston to improve the method of determining the atomic masses of the isotopes of many elements other than neon. Today, the number and the atomic masses of virtually all naturally found isotopes of the whole list of elements have been determined. As an example, the figure below shows the mass spectrograph record obtained for the element germanium, indicating that this element has five isotopes. A picture of this kind is called a "mass spectrogram."

Although we cannot measure the mass of a *neutral* atom in a mass spectrograph (why not?), it is the custom to compute and list isotopic masses for neutral atoms, based on the measurement on ions.

A photographic record of the mass spectrum of germanium, showing the isotopes of mass numbers 70, 72, 73, 74, and 76.

Both the electromagnetic method and the gas-diffusion method of separating isotopes have been modified for large-scale applications. The electromagnetic method shown in principle on p. 37 is used by the United States Atomic Energy Commission to provide samples of separated isotopes for research. The gas diffusion method used by Aston in achieving a small degree of separation of the neon isotopes has been developed on an enormous scale to separate the isotopes of uranium in connection with the manufacture of nuclear bombs and the production of nuclear power.

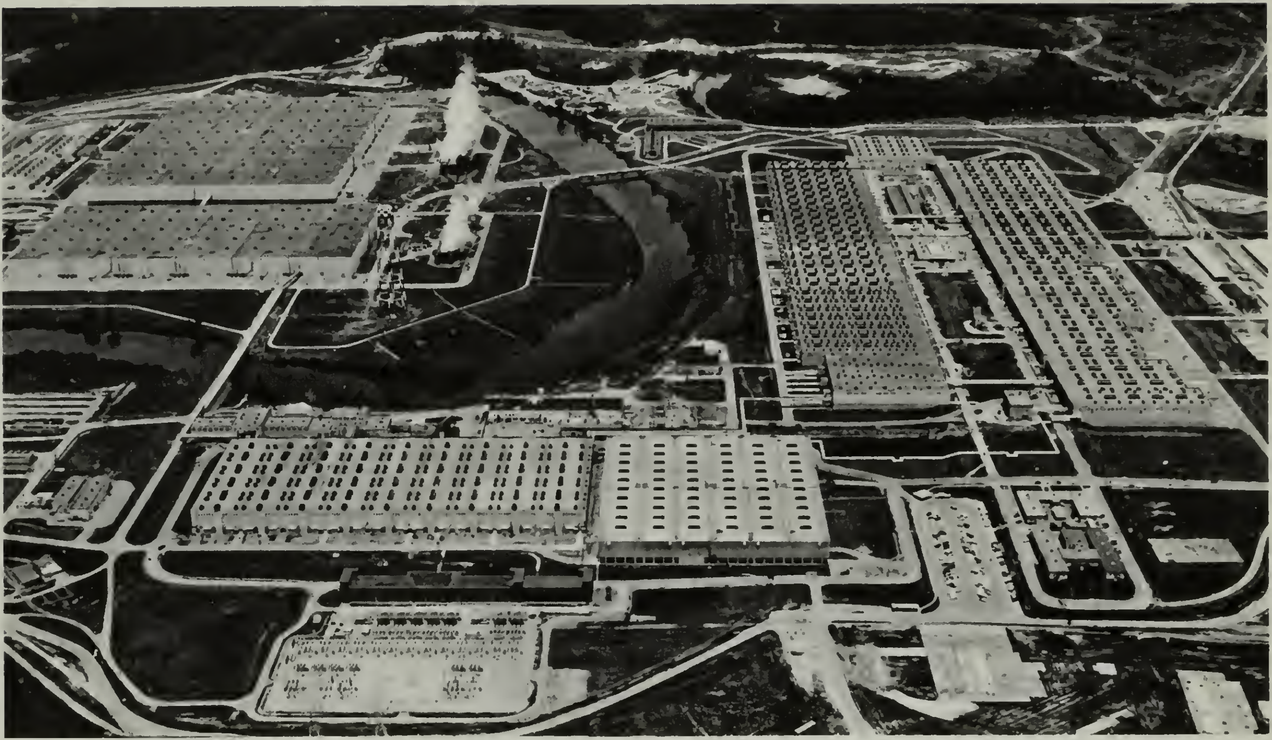
SG 22.5

Q8 What were three experimental results that supported the belief in the existence of two isotopes of neon?

Q9 Isotopes at a given speed are separated by the electromagnetic method in a mass spectrograph because more massive ions are deflected less than lighter ions going at the same speed. Why are isotopes separated in diffusing through a porous wall?

22.6 Summary of a useful notation for nuclides; nuclear reactions

It will be useful to summarize and recapitulate some ideas and notations. Because of the existence of isotopes, it was no longer possible to designate an atomic species only by means of the atomic number Z alone. To distinguish among the isotopes of an element some new symbols were introduced. One is the *mass number, A*, defined as the whole number closest to the measured atomic mass (see table on p. 42). For example, the lighter and heavier isotopes



The Atomic Energy Commission's Gaseous Diffusion Plant at Oak Ridge, Tennessee. The long buildings right of center made up the first plant.

of neon are characterized by the pairs of values: Z = 10, $A = 20$, and Z = 10, $A = 22$. (An element which consists of a single isotope can, of course, also be characterized by its Z and A values.)

These values of Z and A are determined by the properties of the atomic nucleus: according to the Rutherford-Bohr model of the atom, the atomic number Z is the magnitude of the positive charge of the nucleus in elementary charge units. The mass number A is very nearly equal to (but a bit less than) the atomic mass of the nucleus because the total mass of the electrons around the nucleus is very small compared to the mass of the nucleus.

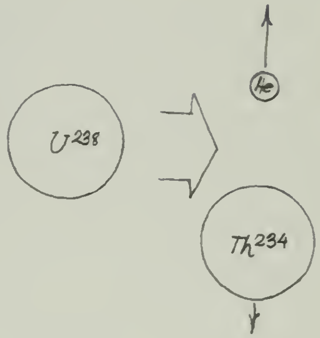
The term *nuclide* is used to denote an atomic species characterized by particular values of Z and A. An *isotope* is then one of a group of two or more nuclides, all having the same atomic number Z but different mass numbers A. A radioactive atomic species is called a radioactive nuclide, or radionuclide for short. A nuclide is usually denoted by the chemical symbol with a subscript at the lower left giving the atomic number, and a superscript at the upper right giving the mass number. In the symbol $_{Z}X^{A}$ for a certain nuclide, Z stands for the atomic number, X stands for the chemical symbol, and A stands for the mass number. For example, $_{4}Be^{9}$ is the nuclide beryllium with atomic number 4 and mass number 9; the symbols $_{10}Ne^{20}$ and $_{10}Ne^{22}$ represent the neon isotopes discussed above. The Z-value is the same for all the isotopes of a given element (X), and so is often omitted—except when it is needed for

The current international convention is to write both Z and A values on the *left*: ${}^{A}_{Z}X$. For purposes of clarity in this introductory text, the former convention, $_{Z}X^{A}$, is used.

balancing equations (as you will shortly see). Thus we often write Ne^{20} for $_{10}Ne^{20}$, or U^{238} for $_{92}U^{238}$.

The introduction of the mass number and the symbol for a nuclide makes it possible to represent radioactive nuclides in an easy and consistent way (as was done in the lower table on p. 27). In addition, radioactive decay can be expressed by a simple "equation" representing the changes that occur in the decay process. For example, the first step in the uranium-radium series, namely the decay of uranium 238 into thorium 234, may be written:

$$_{92}U^{238} \longrightarrow {}_{90}Th^{234} + {}_2He^4$$



The symbol $_2He^4$ stands for the helium nucleus (α particle); the other two symbols represent the initial and final atomic nuclei, each with the appropriate charge and mass number. The arrow stands for "decays into." The "equation" represents a *nuclear reaction*, and is analogous to an equation for a chemical reaction. The atomic numbers on the two sides of the equation must balance because the electric charge of the nucleus must be conserved: $92 = 90 + 2$. Also, the mass numbers must balance because of conservation of mass: $238 = 234 + 4$.

For another example, we see from the table of the uranium-radium series on p. 27, that $_{90}Th^{234}$ (thorium 234) decays by β emission, becoming $_{91}Pa^{234}$ (protactinium 234). Since a β particle (electron) has charge $-q_e$ and has an extremely small mass, the symbol $_{-1}e^0$ is used for it. This β decay process may then be represented by the equation:

$$_{90}Th^{234} \longrightarrow {}_{91}Pa^{234} + {}_{-1}e^0 + {}_0\bar{\nu}^0$$

There is also an antineutrino ($\bar{\nu}$) given off together with the β particle. The neutrino and antineutrino are two particles that will be discussed briefly in Sec. 23.6. *Z* and *A* are both zero for neutrinos and gamma rays: [illegible], γ

Q10 Write the complete symbol for the nuclide with atomic mass 194 and atomic number 78. Of which element is it an isotope?

Q11 Complete the following equation for α-decay. Tell what law or rule you have relied on.

$$_ZX^A \longrightarrow {}_2He^4 + {}_{Z-2}X^?$$

Q12 In the same way, complete the following equation for β-decay:

$$_ZX^A \longrightarrow {}_{-1}e^0 + {}_?X^A + {}_0\bar{\nu}^0$$

SG 22.6–22.9

22.7 The stable isotopes of the elements and their relative abundances

Mass spectra, such as the one of germanium shown on p. 39 have now been determined for all the elements that have at least one stable isotope. These are the elements with atomic numbers between 1 (hydrogen) and 83 (bismuth). A few of the results are listed on p. 42. The table also includes isotopes of the unstable (radioactive) elements uranium and thorium because they have such long half-lives that they are still present in large quantities in some rocks. Uranium has three naturally occurring isotopes, one of which, U^{235}, has the remarkable properties (to be discussed) that have made it important in military and political affairs as well as in science and industry. As can be seen in the table, the relative abundance of U^{235} is very low, and it must first be separated from the far more abundant U^{238} before it can be used in some applications. Such applications and some of their social effects will be discussed in Chapter 24.

Of the elements having atomic numbers between 1 and 83, only about one-fourth are single species; the others all have two or

Relative natural abundances and masses of some nuclides

The masses are given in atomic mass units (amu) based on ${}_6C^{12} = 12.000000$

ELEMENT	CHEMICAL SYMBOL	ATOMIC NUMBER Z	MASS NUMBER A	RELATIVE ABUNDANCE %	MASS OF NEUTRAL ATOM (amu)
Hydrogen	H	1	1	99.98	1.007825
		1	2	0.02	2.014102
Helium	He	2	4	100.00	4.002604
Lithium	Li	3	6	7.42	6.015126
		3	7	92.58	7.016005
Beryllium	Be	4	9	100.00	9.012186
Carbon	C	6	12	98.89	12.000000
		6	13	1.11	13.003354
Nitrogen	N	7	14	99.63	14.003074
		7	15	0.37	15.000108
Oxygen	O	8	16	99.76	15.994915
		8	17	0.04	16.999134
		8	18	0.20	17.999160
Neon	Ne	10	20	90.92	19.992440
		10	21	0.26	20.993849
		10	22	8.82	21.991385
Aluminum	Al	13	27	100.00	26.981535
Chlorine	Cl	17	35	75.53	34.968855
		17	37	24.47	36.965896
Platinum	Pt	78	190	0.01	189.9600
		78	192	0.78	191.9614
		78	194	32.90	193.9628
		78	195	33.80	194.9648
		78	196	25.30	195.9650
		78	198	7.21	197.9675
Gold	Au	79	197	100.00	196.9666
Lead	Pb	82	204	1.50	203.9731
		82	206	23.60	205.9745
		82	207	22.60	206.9759
		82	208	52.30	207.9766
Thorium	Th	90	232	100.00	232.0382
Uranium	U	92	234	0.006	234.0409
		92	235	0.720	235.0439
		92	238	99.274	238.0508

Mass of bare nucleus of hydrogen: 1.00727 amu
Mass of electron: 0.000549 amu

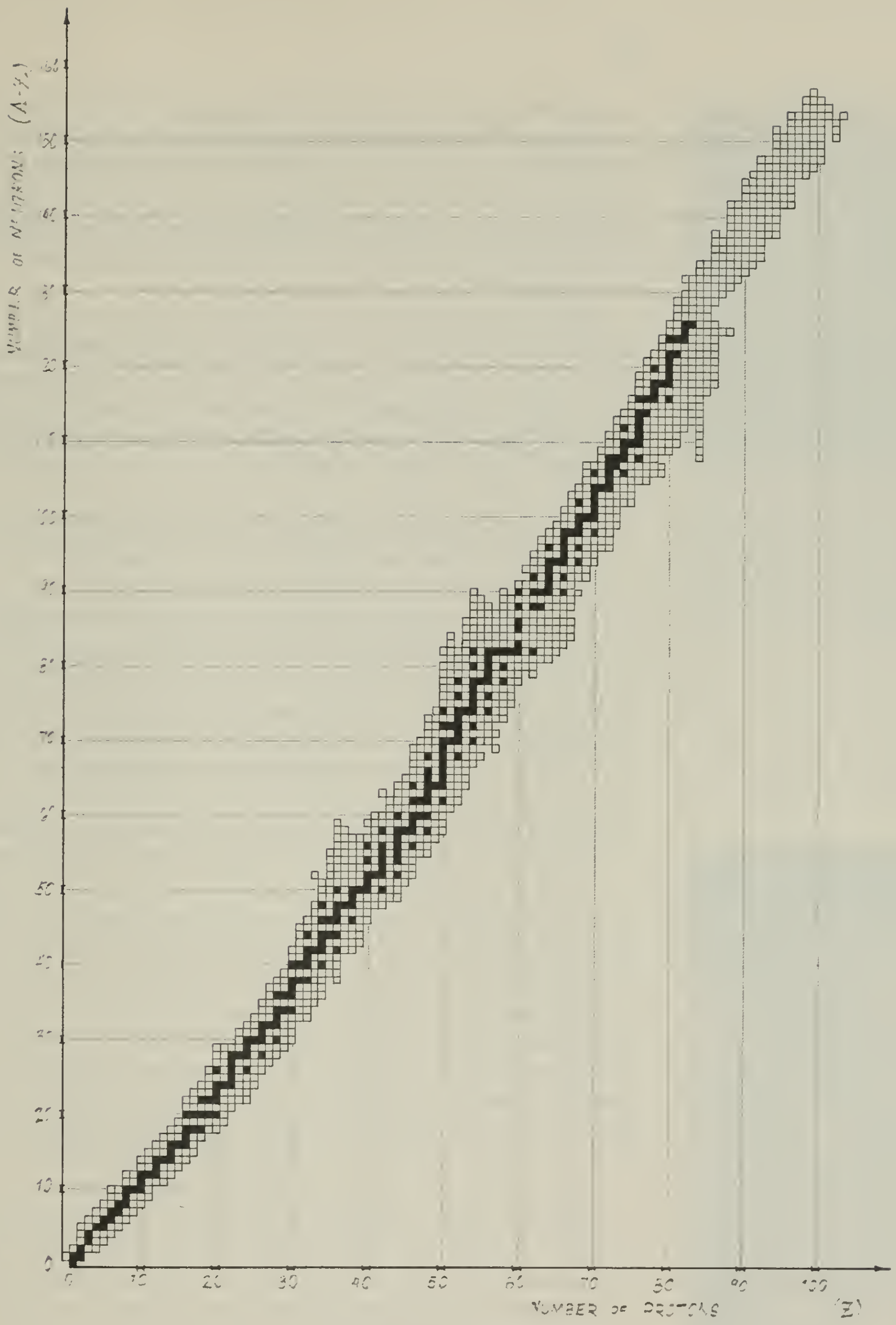
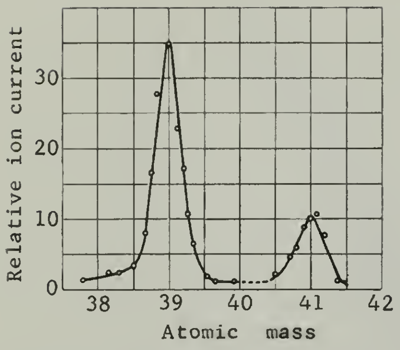


Chart of the known nuclides.
Each black square represents a stable, natural nuclide. Each open square represents a known unstable nuclide, with only a small number of these found naturally, the rest being man made. Note that all isotopes of a given element are found in a vertical column centered on the element's atomic number *Z*. (As will be seen in the next chapter, the *Z* number is the number of protons in the nucleus, and *A-Z*, the difference between the atomic mass and atomic number, is the number of neutrons.)



Record of determination of abundance of the isotopes of potassium in a mass spectrometer. In a mass spectrometer the current due to the ions is detected (see p. 37). Comparison of the current due to each isotope permits fairly precise estimates of the relative abundances of the isotopes.

more isotopes. As a result, the 83 elements together actually are made up of 284 naturally-occurring nuclides. All but 25 of these nuclides are stable. Many elements have only one stable nuclide, others have several, and tin has the greatest number, ten. Carbon and nitrogen each have two, and oxygen has three. The table on p. 42 shows that the isotope O^{16} has a very high relative abundance, the isotopes O^{17} and O^{18} being relatively rare.

There are 25 naturally occurring *unstable* nuclides not associated with the decay chains of the heavy radionuclides. They show only a small degree of radioactivity. The most common of these light nuclides is $_{19}K^{40}$, an isotope of potassium that has a relative abundance of only 0.012%. This isotope, which emits β particles, has so lengthy a half-life (1.3×10^9 years) that its presence makes it very useful for determining the ages of certain rocks. Such information, coupled with information on the decay of U^{238}, can be used to estimate the age of the earth.

Hydrogen, the lightest element, has two stable isotopes, of which the heavier one, with atomic mass number 2, has a relative abundance of only 0.02%. The hydrogen isotopes are exceptional in that the rare isotope has an atomic mass twice that of the common isotope. As a result, the differences between the properties of the two isotopes are more marked than in any other pair of isotopes. The hydrogen isotope of atomic mass number 2 has therefore been given its own name, *deuterium*, with the symbol D; sometimes it is called "heavy hydrogen." It occurs in so-called "heavy water" or "deuterium oxide," for which the formula is written $(_1H^2)_2O$ or D_2O.

The American chemist H. C. Urey received the 1934 Nobel Prize in chemistry for his discovery of "heavy" hydrogen.

Heavy water differs from ordinary water in some important respects: its density is 1.11 gram per cm^3 as compared with 1.00 for ordinary water; at one atmosphere pressure it freezes at 3.82°C and boils at 101.42°C (the corresponding temperatures for ordinary water being 0°C and 100°C). Naturally occurring water contains only about 1 atom of H^2 per 7000 atoms of H^1, but methods have been developed for enriching the fraction of H^2 and also for producing nearly pure D_2O in large amounts. Heavy water is important in some types of devices for the controlled release of nuclear energy, as will be explained in Chapter 24.

Interesting and important regularities have been discovered among the natural abundances, and some are still sources of puzzles. The number of nuclides with the various combinations of even and odd values of Z and *A* are listed below. It is evident that naturally occurring nuclides with even Z and even *A* are much more numerous than those with any other combination. Elements

Some Interesting Data Concerning Naturally Occurring Nuclides

	NUMBER OF STABLE ELEMENTS	NUMBER OF NUCLIDES Odd *A*	Even *A*	TOTAL	AVERAGE NO. OF ISOTOPES PER ELEMENT
Odd *Z*	40	53	8	61	1.5
Even *Z*	43	57	166	223	5.2
Total	83	110	174	284	3.4

with even Z have, on the average, more isotopes per element than those with odd Z. Every theory of the nucleus has to try to account for these regularities, which are related to the stability of atomic nuclei. Information of this kind is analogous to observations of the positions of planets, to data on chemical compounds, and to atomic spectra. All of these provide material for the building of theories and models.

Q13 What is deuterium?

Q14 What is "heavy water"?

Q15 Neon actually has three isotopes (see table on p. 42). Why did Thomson and Aston find evidence for only two isotopes?

This is a photograph of the oscilloscope display of a high-resolution mass spectrometer when both hydrogen and helium are present. The high peak, on the left, indicates the He^3 isotope of mass 3.016030 amu. The other peak indicates H^3, the extra-heavy hydrogen isotope, otherwise known as tritium, whose mass is 3.016049 amu. The mass difference between the two nuclides is therefore about two parts in 300,000. It is easily observable.

22.8 Atomic masses

The masses of most of the stable nuclides have been determined, and the results are of fundamental importance in quantitative work in nuclear physics and its applications. The standard of mass adopted by physicists for expressing the atomic mass of any nuclide was slightly different from that used by chemists for the chemical atomic weights. The chemists' scale was defined by assigning the value 16.0000 atomic mass units to ordinary oxygen. But, as can be seen in the table on p. 42, oxygen is a mixture of three isotopes, two of which, O^{17} and O^{18}, have very small abundances. For isotopic mass measurements, the value 16.0000 was assigned to the most abundant isotope, O^{16}, and this mass was used as the standard by physicists. For some years, up to 1960, the atomic mass unit, 1 amu, was defined as 1/16 of the mass of a neutral O^{16} atom. Since 1960, O^{16} has been replaced by C^{12} as the standard, and the atomic mass unit is now defined by both physicists and chemists as 1/12 of the mass of a neutral C^{12} atom. The main reason for the choice of carbon is that mass-spectrographic measurements of atomic masses are much more accurate than the older chemical methods. Carbon forms an exceptional variety of compounds, from light to very heavy, which can be used as comparison standards in the mass spectrograph.

SG 22.10–22.12

The results that have been obtained for the atomic masses of some elements of special interest are listed in the table on p. 42. Atomic masses can be determined with great accuracy, and, when expressed in atomic mass units, they all turn out to be very close to integers. For each nuclide, the measured mass differs from an integer by less than 0.06 amu. This result is known as Aston's *whole-number rule*, and provides the justification for using the mass number A in the symbol ${}_{Z}X^{A}$ for a nuclide or atom. As you will see in the next chapter, the explanation or physical basis for this rule is connected with the structure of the nucleus.

Q16 What nuclide is the current standard for atomic mass? Why has it been chosen?

22.1 The Project Physics learning materials particularly appropriate for Chapter 22 include the following *Transparencies:*
Radioactivity Displacement Rules
Mass Spectrometer
Chart of Nuclides
Nuclear Equations

22.2 Soddy's proposal of isotopes meant that not all atoms of the same element are identical. Explain why this proposal does *not* require that the atoms of a given element show differences in chemical behavior.

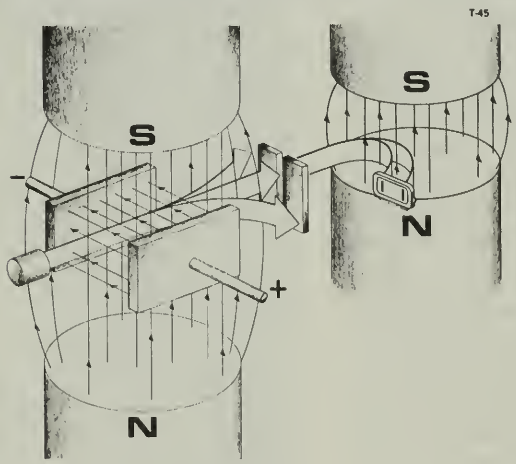
22.3 After Soddy's proposal of the existence of isotopes, how could one go about determining whether an apparently new element was really new and should be given a separate place in the periodic table, or was simply an isotope of an already known element?

22.4 At the National Bureau of Standards, in 1932, a gallon of liquid hydrogen was slowly evaporated until only about 1 gram remained. This residue allowed the first experimental check on existence of the "heavy" hydrogen isotope H^2.

(a) With the help of the kinetic theory of matter, explain why the evaporation should leave in the residue an increased concentration of the isotope of greater atomic mass.

(b) Why should the evaporation method be especially effective with hydrogen?

22.5 A mass spectrograph similar to that sketched below causes singly charged ions of chlorine 37 to travel a semi-circular path and strike a photographic plate (in the magnetic field at the right).



From the equation on p 37:

(a) show that the path radius is inversely proportional to the ion mass.

(b) if the path diameter for chlorine ions is about 1.0 m, how far apart will the traces of Cl^{37} and Cl^{35} be on the photographic plate?

(c) what would be the diameter of the orbit of lead 208 ions if the same electric and magnetic field intensities were used to analyze a sample of lead?

(d) the problems of maintaining a uniform magnetic field over surfaces larger than 1 square meter are considerable. What separation between lead 207 and lead 208 would be achieved if the diameter of the orbit of lead 208 were held to 1.000 meter?

22.6 Supply the missing data indicated by these transformation "equations:"

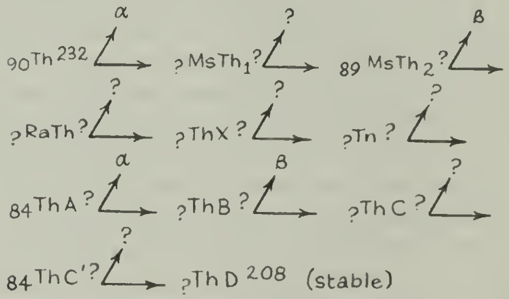
(a) ${}_{?}Pb^{212} \longrightarrow Bi^{212} + ?$

(b) ${}_{?}Bi^{212} \longrightarrow \quad + {}_{-1}e^{0}$

(c) $? \longrightarrow Pb^{208} + {}_{2}He^{4}$

22.7 A radioactive series, originally called the actinium series, is now known to start with the uranium isotope ${}_{92}U^{235}$. This parent member undergoes transmutations by emitting in succession the following particles: α, β, α, β, α, α, α, α, β, α, β. The last of these disintegrations yields ${}_{82}Pb^{207}$, which is stable. From this information, and by consulting the periodic table, determine the complete symbol for each member of the series. List the members of the series in a column, and beside each member give its mode of decay (similar to what was done in the Table on page 27).

22.8 In the following diagram of the thorium series, which begins with ${}_{90}Th^{232}$, the symbols used are those that were originally assigned to the members of the sequence:



Supply the missing data; then by consulting the periodic table replace the old symbols with the present ones. Indicate where alternative possibilities exist in the series.

22.9 From ${}_{94}Pu^{241}$, an isotope of plutonium produced artificially by bombarding uranium in a nuclear reactor, a radioactive series has been traced for which the first seven members are ${}_{94}Pu^{241}$, ${}_{95}Am^{241}$, ${}_{93}Np^{237}$, ${}_{91}Pa^{233}$, ${}_{92}U^{233}$, ${}_{90}Th^{229}$, and ${}_{88}Ra^{225}$. Outline the disintegration series for these first seven members, showing the modes of decay as in the preceding question.

22.10 A trace of radioactivity found in natural carbon makes it possible to estimate the age of materials were once living. The radioactivity of the carbon is due to the presence of a small amount of the unstable isotope, carbon 14. This isotope is created mainly in the upper atmosphere by transformation (induced by cosmic rays) of the stable isotope carbon 13 to carbon 14.

The rate of production of carbon 14 from carbon 13 matches the rate of beta-decay of carbon 14 into nitrogen 14, so the percentage of total carbon in the atmosphere consisting of carbon 14 is relatively constant. Now when carbon dioxide is used by plants in photosynthesis, the cell incorporates the isotopes of carbon in the same proportions as exist in the atmosphere. The activity of the carbon at that point amounts to 15.3 beta emissions per minute per gram of carbon. When the interaction of the living plant with the atmosphere stops, for example, when a branch is broken off a living tree for use as a tool, the radioactivity begins to decrease at a rate characteristic of carbon 14. This rate has been measured, and the half-life of carbon is known to be 5760 years. So if the activity is measured at some later time, and if the half-life of carbon 14 is known, then one can use the decay curve given on page 22 to determine the time elapsed since the branch was taken from the tree. For example, suppose the activity was found to have dropped from the normal rate of 15.3 to 9.2 beta emissions per minute per gram of carbon. Knowing the half-life, determine the time elapsed.

Repeat the procedure in SG 22.10 to calculate the age of charcoal found in an ancient Indian fire pit, if the activity of the carbon in the charcoal is now found to be 1.0 beta emissions per minute per gram of carbon. What assumption are you making in this part of the problem?

22.11 (a) Find the average atomic mass of carbon by calculating the "weighted average" of the atomic masses of the two natural carbon isotopes. (Use the data of the table on p. 42.)
(b) Find the average atomic mass of lithium.
(c) Find the average atomic mass of ordinary lead.

A 14,000-year-old burial site being uncovered by an archeological team near the Aswan Reservoir. The age of the burial site is determined by carbon-14 dating (described in SG 22.10) of scraps of wood or charcoal found in it.

22.12 The mass of a neutral helium atom is 4.00260 amu, and that of an electron is 0.00055 amu. From these data find the mass of the α particle in amu.

22.13 The age of a rock containing uranium can be estimated by measuring the relative amount of U^{238} and Pb^{206} in a sample of the rock. Consider a rock sample which is found to contain 3 times as many U^{238} atoms as Pb^{206} atoms.
(a) What fraction of the U^{238} contained in the sample when it was formed has decayed?
(b) Refer to the graph on p. 22 and estimate the fraction of a half-life needed for that fraction of the U^{238} to decay.
(c) How old is the rock?
(d) For this simple method to work it is necessary to assume that each U^{238} atom that decays appears as a Pb^{206} atom—in other words that the half-lives of all the intermediate substances in the uranium chain are negligible compared to that of U^{238}. Is this assumption a valid one?

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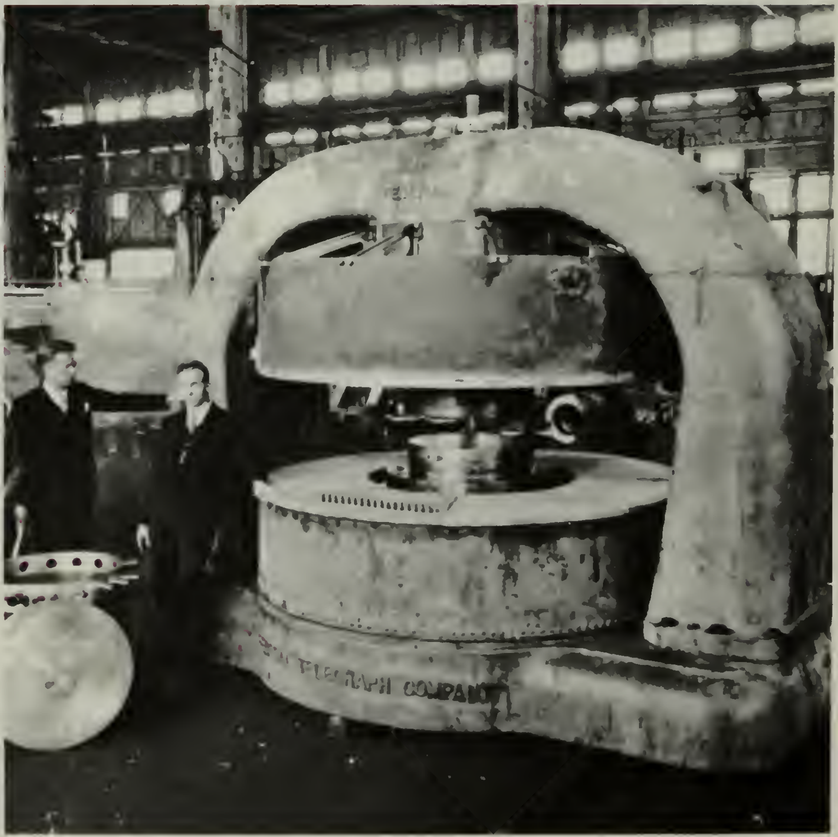


Ernest O. Lawrence (left) and M. S. Livingston (right) are shown standing beside the magnet for one of the earliest cyclotrons. Lawrence and Livingston invented the cyclotron in 1931, thereby initiating the development of high-energy physics in the United States.

CHAPTER TWENTY-THREE

Probing the Nucleus

23.1 The problem of the structure of the atomic nucleus

The discoveries of radioactivity and isotopes raised new questions about the structure of atoms—questions which involved the atomic nucleus. We saw in Sec. 22.2 that the transformation rules of radioactivity could be understood in terms of the Rutherford-Bohr model of the atom. But that model said nothing about the nucleus other than that it is small, has charge and mass, and may emit an α or a β particle. This implies that the nucleus has a structure which changes when a radioactive process occurs. The question arose: can we develop a theory or model of the atomic nucleus that will explain the facts of radioactivity and the existence of isotopes?

SG 23.1

The answer to this question makes up much of *nuclear physics*. The problem of nuclear structure can be broken into two questions: (1) what are the building blocks of which the nucleus is made, and (2) how are the nuclear building blocks put together? Answers to the first question are considered in this chapter. In the next chapter we shall take up the question of how the nucleus is held together. The attempt to solve the problem of nuclear structure, although not yet completed, has not only led to many new basic discoveries and to large-scale practical applications, but also has had important social and political consequences, stretching far beyond physics into the life of society in general. Some of these consequences will be discussed in Chapter 24.

The Project Physics supplemental unit *Elementary Particles* goes one step further, into the nature and structure of the subatomic particles themselves.

23.2 The proton-electron hypothesis of nuclear structure

The emission of α and β particles by radioactive nuclides suggested that a model of the nucleus might be constructed by starting with α and β particles as building blocks. Such a model would make it easy to see, for example, how a number of α particles could be emitted, in succession, in a radioactive series. But not all nuclei are radioactive, nor do all have masses that are

SG 23.2

multiples of the α-particle mass. For example, the nucleus of an atom of the lightest element, hydrogen, with an atomic mass of one unit (two units in the case of the heavy isotope), is too light to contain an α particle. So is the light isotope of helium, $_2He^3$.

Proton—from the Greek "protos" (first). It is not known who suggested the name originally—it is found in the literature as far back as 1908. In 1920 Rutherford's formal proposal of the name proton was accepted by the British Association for the Advancement of Science.

A positively charged particle with mass of one unit would seem to be more satisfactory as a nuclear building block. Such a particle does indeed exist: the nucleus of the common isotope of hydrogen. This particle has been named the *proton*. According to the Rutherford-Bohr theory of atomic structure, the hydrogen atom consists of a proton with a single electron revolving around it.

In the preceding chapter (Sec. 22.4), we discussed Aston's *whole-number rule,* which expressed the experimental result that the atomic masses of the nuclides are very close to whole numbers. This rule, together with the properties of the proton—for example, its single positive charge—made it appear possible that all atomic nuclei are made up of protons. Could a nucleus of mass number A consist of A protons? If this were the case, the charge of the nucleus would be A units; but, except for hydrogen, the nuclear charge Z is found to be always less than A—usually less than $\frac{1}{2}A$. To get around this difficulty, it was assumed that in addition to the protons, atomic nuclei contain just enough electrons to cancel the charge of the extra protons; that is, they were supposed to contain $A—Z$ electrons. These electrons would contribute only a small amount to the mass of the nucleus, but together with the protons they would make the net charge equal to +Z units, as required. It seemed thus plausible to consider the atom as consisting of a nucleus made up of A protons and $A—Z$ electrons, with A additional electrons outside the nucleus to make the entire atom electrically neutral. For example, an atom of $_8O^{16}$ would have a nucleus with 16 protons and 8 electrons, with 8 additional electrons outside the nucleus. This model of the nucleus is known as the *proton-electron hypothesis* of nuclear composition.

SG 23.3

The proton-electron hypothesis seemed to be consistent with the emission of α and β particles by atoms of radioactive substances. Since it was assumed that the nucleus contained electrons, explanation of beta decay was no problem: when the nucleus is in an appropriate state it may simply eject one of its electrons. It also seemed reasonable that an α particle could be formed, in the nucleus, by the combination of four protons and two electrons. (An α particle might exist already formed in the nucleus, or it might be formed at the instant of emission.)

The proton-electron hypothesis is similar to an earlier idea suggested by English physician William Prout in 1815. On the basis of the small number of atomic masses then known, he proposed that all atomic masses are multiples of the atomic mass of hydrogen, and that therefore all the elements might be built up of hydrogen. Prout's hypothesis was discarded when, later in the nineteenth century, the atomic masses of some elements were found to be fractional, in particular, those of chlorine (35.46 units) and copper (63.54 units). With the discovery of isotopes, however, it was realized that the fractional atomic masses of chlorine and copper, like that of neon, arise because these elements are *mixtures* of isotopes, with each separate isotope having an atomic mass close to a whole number.

Although the proton-electron hypothesis was satisfactory in some respects—as in accounting for the whole number rule for isotope masses, and in being consistent with the emission of α and β particles by radioactive nuclides—it led to serious difficulties and had to be given up. The existence of electrons inside the nucleus had to be ruled out for a number of reasons, not the least being that the more precise the mass measurements became, the further the mass of nuclei departed from that predicted by the proton-electron hypothesis.

Careful inspection of the modern values of nuclide masses (table 22.1) shows that nuclides can not be considered as simple conglomerates of hydrogen and electrons.

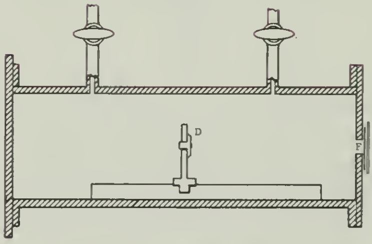
Q1 Why was the idea of hydrogen atoms being a basic building block of all atoms given up in the nineteenth century?

Q2 On the basis of the proton-electron hypothesis, what would a nucleus of ${}_6C^{12}$ contain?

Q3 Does the proton-electron hypothesis work out for, say, ${}_2He^4$?

23.3 The discovery of artificial transmutation

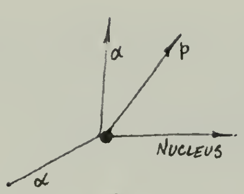
A path which led to a better understanding of nuclear composition was opened, almost by accident, in 1919. In that year Rutherford found that when nitrogen gas was bombarded with α particles from bismuth 214, swift particles were produced which could travel farther in the gas than did the α particles themselves. When these particles struck a scintillation screen, they produced flashes of light fainter than those produced by α particles, about the intensity that would be expected for positive hydrogen ions (protons). Measurements of the effect of a magnetic field on the paths of the particles suggested that they were indeed protons. Rutherford ruled out, by means of careful experiments, the possibility that the protons came from hydrogen present as an impurity in the nitrogen. Since the nitrogen atoms in the gas were the only possible source of protons, Rutherford concluded that an α particle, in colliding with a nitrogen nucleus, can occasionally knock a small particle—a proton—out of the nitrogen nucleus. In other words, Rutherford deduced that an α particle can cause the artificial disintegration of a nitrogen nucleus, with one of the products of the disintegration being a proton. But this process does not happen easily. The experimental results showed that only one proton was produced for about one million α particles passing through the gas.



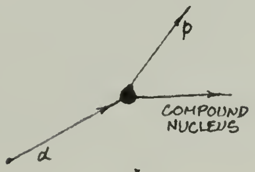
Rutherford's diagram of the apparatus used to detect the protons from disintegrations produced by α particles. The α source was on a movable stand D. Nitrogen nuclei in the nitrogen gas which filled the box are transmuted by the α particle. At the end of the box was a piece of silver foil F thick enough to stop α particles, but not protons. Behind the foil was a lead sulfide screen S which would show flashes of light when struck by protons. To see the flashes, the screen S had to be watched through a microscope with a dark-adapted eye.

Between 1921 and 1924, Rutherford and Chadwick extended the work on nitrogen to other elements and found evidence for the artificial disintegration of all the light elements, from boron to potassium, with the exception of carbon and oxygen. (These were later shown to undergo artificial disintegration.)

The next step was to determine the nature of the nuclear process leading to the emission of the proton. Two hypotheses were suggested for this process: (a) the nucleus of the bombarded atom loses a proton, "chipped off" as the result of a collision with a swift α particle; or (b) the α particle is *captured* by the nucleus of the atom it hits, forming a new nucleus which, a moment later, emits a proton. It was possible to distinguish experimentally between these two possible cases by using a device, called a "cloud chamber," which reveals the path or track of an individual charged particle. The cloud chamber was invented by C. T. R. Wilson and perfected by him over a period of years. In 1911 it became a major scientific instrument; a simplified diagram is shown at the left. (a) If a proton were being chipped off, four tracks should be seen in a photograph of a disintegration event: the track of an α particle before the collision, the track of the same α particle after collision, and the tracks of both the proton and the recoiling nucleus after collision. In case (b), on the other hand, the α particle should disappear in the collision, and only three tracks would be seen: that of the α particle before collision, and the tracks of the proton and recoil nucleus after the collision. The choice between the two possibilities was settled in 1925 when P. M. S. Blackett studied the tracks produced when particles passed through nitrogen gas in a cloud chamber. He found, as shown in the photograph below, that the only tracks which could be seen for artificial disintegration were those of the incident α particle, a proton, and the recoil nucleus. The absence of a track corresponding to the presence of an α particle after the collision proved that the α particle disappeared completely and that case (b) is the correct interpretation of artificial disintegration.



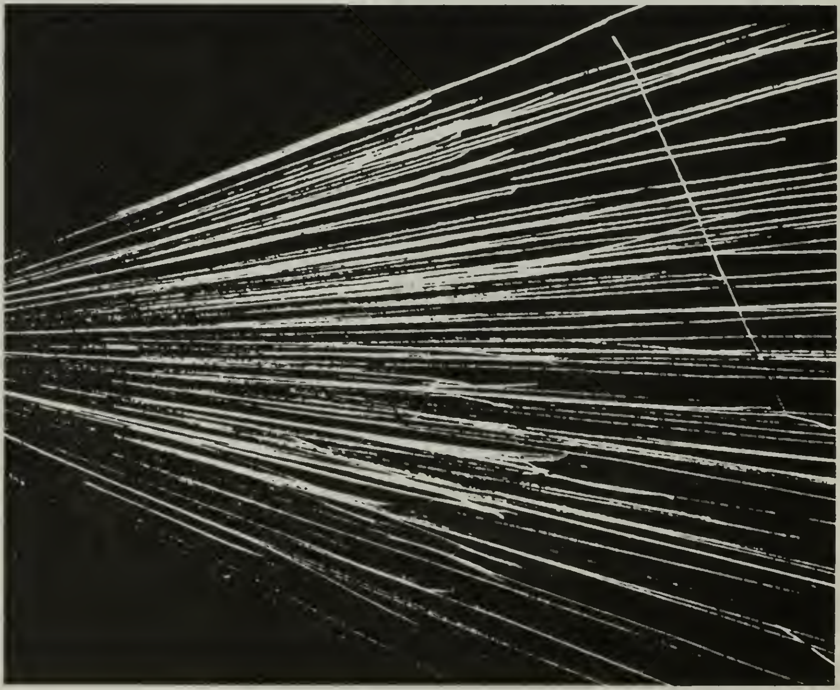
a



b

The Wilson cloud chamber. When the piston is moved down rapidly the gas in the cylinder cools and becomes supersaturated with water vapor. The water vapor will condense on the ions created along the path of a high-energy charged particle, thereby making the track. For his invention of the cloud chamber, C. T. R. Wilson (1869-1959) of Scotland shared the 1927 Nobel Prize in physics with Arthur H. Compton. (See also page 65 margin)

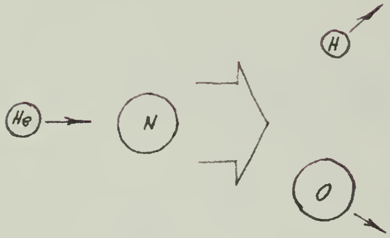
The process in which an α particle is absorbed by a nitrogen



α-particle tracks from a source at the left, in a cloud chamber filled with nitrogen gas. At the far right, one α particle has hit a nitrogen nucleus; a proton is ejected upward toward the left, and the resulting oxygen nucleus recoils downward to the right. (From P. M. S. Blackett, 1925) nucleus and a proton is emitted may be represented by an "equation" which is analogous to the representation used near the end of Sec. 22.6 to represent radioactive decay. The equation expresses the fact that the total mass number is the same before and after the collision (that is, there is conservation of mass number), and the fact that the total charge is the same before and after the collision (there is conservation of charge). The atomic number, the mass number, and the nuclear charge are known for the target nucleus ${}_7N^{14}$, for the incident α particle ${}_2He^4$, and for the proton ${}_1H^1$. The product nucleus will therefore have the atomic number $7 + 2 - 1 = 8$ (which is the atomic number for oxygen), and will have the mass number $14 + 4 - 1 = 17$. Hence the product nucleus must be ${}_8O^{17}$, an isotope of oxygen. The disintegration process may therefore be represented by the nuclear reaction:

See "The Tracks of Nuclear Particles" in *Reader 6.*

$${}_2He^4 + {}_7N^{14} \longrightarrow {}_8O^{17} + {}_1H^1$$



This reaction shows that a transmutation of an atom of one chemical element into an atom of another chemical element has taken place. The transmutation did not occur spontaneously, as it does in the case of natural radioactivity, but was man-made; it was produced by exposing target atoms (nuclei) to projectiles emitted from a radioactive nuclide. In the paper in which he reported this first artificially produced nuclear reaction, Rutherford said:

SG 23.4

> The results as a whole suggest that, if α particles—or similar projectiles—of still greater energy were available for experiment, we might expect to break down the nuclear structure of many of the lighter atoms.

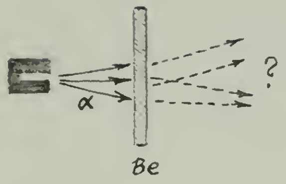
This call for greater energies of "projectiles" was soon answered by the construction of accelerators. (See Sec. 23.7.)

The further study of reactions involving light nuclei led (as you shall see in the next section) to the discovery of a new particle—the *neutron*—and to a better theory of the constitution of the nucleus. Many types of reactions have been observed with nuclei of all masses, from the lightest to the heaviest, and the possibilities indicated by Rutherford have been realized to an extent far beyond what he would have imagined in 1919.

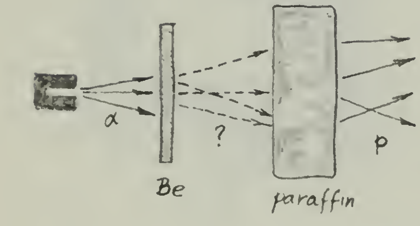
Q4 What evidence showed that the bombarding α particle was temporarily *absorbed* by the nitrogen nucleus, rather than that it simply broke up and bounced off?

23.4 The discovery of the neutron

In 1920 Rutherford suggested that a proton inside the nucleus might have an electron tied to it so closely as to form a neutral particle. Rutherford even suggested the name "neutron" for this hypothetical particle. Physicists looked for neutrons, but the search presented at least two difficulties: (1) they could find no naturally occurring neutron-emitting materials; and (2) the methods used for detecting atomic particles all depended on effects of the electric charge of the particles – and so could not be applied directly to neutral particles. Until 1932, the search for neutrons was unsuccessful.



The proof of the existence of neutrons came in 1932 as the climax of a series of experiments on nuclear reactions made by physicists in different countries. The discovery of the neutron is a good example of how physicists operate – how they think about problems and arrive at solutions; it is an excellent "case history" in experimental science. Working in Germany in 1930, W. G. Bothe and H. Becker found that when samples of boron or of beryllium were bombarded with α particles, they omitted radiations which appeared to be of the same kind as γ rays, at least insofar as the γ rays had no electric charge. Beryllium gave a particularly marked effect of this kind. Observations by physicists in Germany, France and Great Britain showed that the radiation from the beryllium penetrated further (through lead, for example) than any γ radiation found up to that time, and had an energy of about 10 MeV. The radiation was thus much more energetic than the γ rays (that is, high-energy photons) previously observed, and, as a result, aroused much interest.



Among those who investigated this radiation were the French physicists Frédéric Joliot and his wife Irène Curie, a daughter of the discoverers of radium. They studied the absorption of the radiation in paraffin, a material rich in hydrogen. They found in the course of their experiments that the radiation from beryllium, when it fell on paraffin, ejected large numbers of hydrogen nuclei – protons – from the paraffin. The energies of these protons were found to be about 5 MeV. Using the principles of conservation of momentum and energy, they calculated the energy a γ ray would need if it were to transfer 5 MeV to a proton in a collision. The result was about 50 MeV, a value much greater than the 10 MeV that had been measured for the radiation. In addition, the number of protons produced was found to be much greater than that predicted on the assumption that the radiation consisted of γ rays.

James Chadwick (born 1891) received the Nobel Prize in Physics in 1935 for his discovery of the neutron.

These discrepancies (between the results of two sets of experiments, and between theory and experiment) left physicists in a dilemma. Either they could conclude that the conservation principles of momentum and of energy did not apply to the collisions between the radiation and the protons in the paraffin, or they could adopt another hypothesis about the nature of the radiation. Now, if there is any one thing physicists do not want to do it is to give up the principles of conservation of momentum and of energy. These principles are so basic to scientific thought and have proven so useful that physicists tried very hard to find an alternative to giving them up.

The English physicist James Chadwick found similarly perplexing results for recoiling nuclei from several other light elements, including helium, lithium, carbon, nitrogen, and argon.

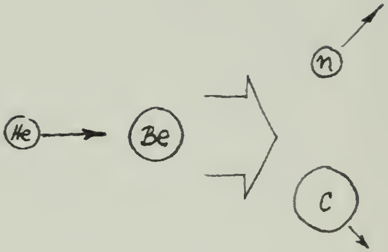
In 1932 Chadwick proposed a successful alternative hypothesis about the nature of the radiation. His first published report of his hypothesis is reproduced on the next page. In a later, more complete paper, "The Existence of a Neutron," he said:

> If we suppose that the radiation is not a quantum radiation [γ ray], but consists of particles of mass very nearly equal to that of the proton, all the difficulties connected with the collisions disappear, both with regard to their frequency and to the energy transfers to different masses. In order to explain the great penetrating power of the radiation, we must further assume that the particle has no net charge. We must suppose it to consist of a proton and electron in close combination, the 'neutron' discussed by Rutherford in his Bakerian Lecture of 1920.

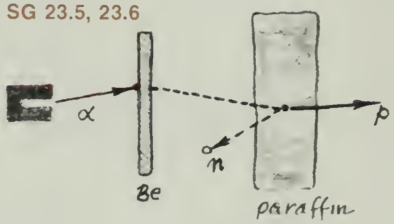
Thus, according to Chadwick's hypothesis, when an element such as beryllium is bombarded with α particles, a nuclear reaction can take place that produces neutrons:

$$_2He^4 + {}_4Be^9 \longrightarrow {}_6C^{12} + {}_0n^1$$

Here, the symbol $_0n^1$ represents the neutron postulated by Chadwick, with zero charge, and mass number equal to 1. Such neutrons then, because they have no electric charge, could penetrate bricks of a material as dense as lead without giving up their energy. When neutrons go through paraffin, there would occasionally be head-on collisions with hydrogen nuclei—protons. The recoiling protons could then be observed because of the ionization they produce. Thus Chadwick's chargeless particle hypothesis could account in a qualitative way for the observed effects of the mysteriously penetrating radiation.



SG 23.5, 23.6



Paraffin wax contains 14 hydrocarbon compounds ranging from $C_{18}H_{38}$ to $C_{32}H_{66}$.

His estimate that the particle's mass must be nearly equal to the mass of a proton was made by applying the laws of conservation of momentum and energy to the case of perfectly elastic collisions—simply applying the laws that worked well for the case of interacting billiard balls and other objects treated in "classical" physics. In a perfectly elastic head-on collision between two bodies, as you saw in Chapter 9, almost all of the kinetic energy of the initially moving body will be transferred to the initially stationary body only if the bodies have approximately equal masses. In collisions that are not precisely head-on, less kinetic energy will be transferred. Therefore, on the *average*, a kinetic energy of about 5 MeV for the recoiling protons would be about right for collisions produced by neutrons with energies about 10 MeV, if the neutron and proton masses were approximately equal.

As explained in *Text* Sec. 14.8. the electron-volt (eV) is a unit of energy.

1KeV = 10 eV

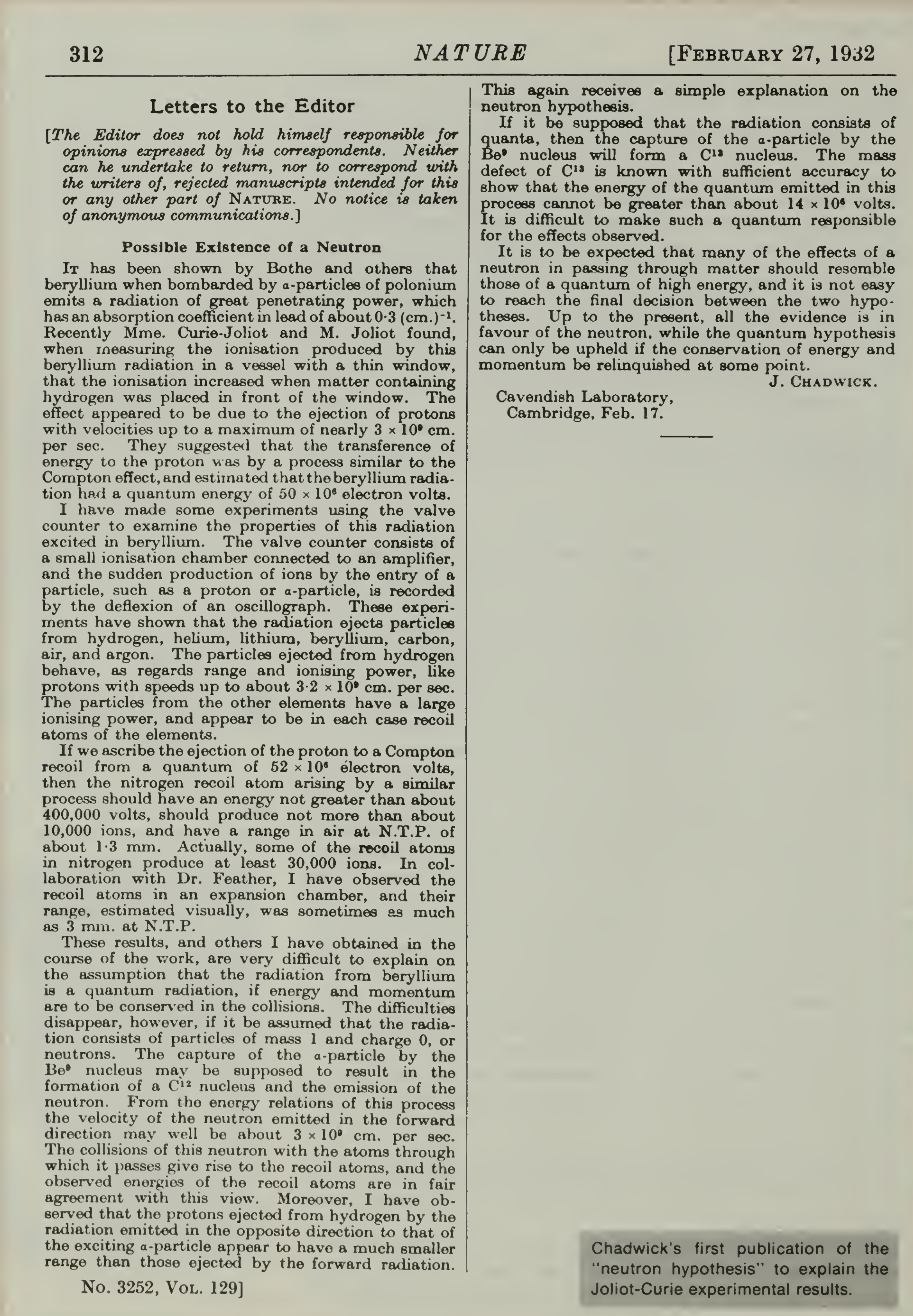
1MeV = 10 eV

1BeV = 10 eV

Chadwick was able to make a more precise calculation of the neutron's mass by applying the conservation laws to data on collisions with nuclei of different masses; the details of the derivation are shown on page 57.

Chadwick found the mass of the neutron to be 1.16 amu. The difficulties of measuring the kinetic energies of the recoiling nuclei made this only an approximate value, but it was good enough to

SG 23.7, 23.8



Letters to the Editor

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Possible Existence of a Neutron

It has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

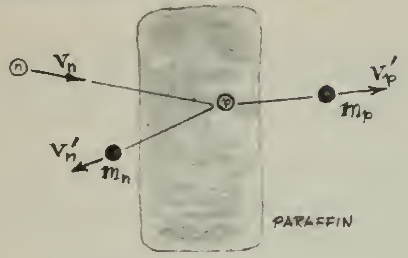
It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. Chadwick.

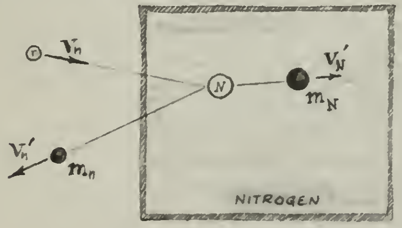
Cavendish Laboratory,
Cambridge, Feb. 17.

Chadwick's first publication of the "neutron hypothesis" to explain the Joliot-Curie experimental results.

Determining the Neutron's Mass



(a) The sketch above represents an elastic collision of a neutron (*n*) and a proton (*p*). If it were a head-on collision, the neutron would rebound straight back and the proton would be seen to emerge along the *same* line. To determine the mass of the neutron, m_n, we return to the principles of conservation of kinetic energy and conservation of momentum, which provide two algebraic equations that must both hold. The case is particularly simple if we consider a perfectly elastic head-on collision. As shown at the right, an expression for the proton's recoil speed v_p' can be derived by combining the equations algebraically (solving the momentum equation for v_n, substituting the resulting expression for v_n' in the energy equation, expanding, collecting terms, and solving for v_p'). However, this expression includes the term v_n, the neutron's initial speed, which cannot be measured directly. We can eliminate v_n from the equation by analyzing another collision and combining the results with what we already have.



(b) The sketch above represents a perfectly elastic collision between a neutron (*n*) and a nitrogen nucleus (*N*). When the collision is head-on, we can write energy and momentum equations similar to what we wrote before, but this time *leading to an expression for the recoil speed of the nitrogen nucleus,* v_N'. This expression also includes the unmeasurable quantity v_n.

CONSERVATION OF ENERGY

$$\tfrac{1}{2} m_n v_n^2 = \tfrac{1}{2} m_n v_n'^2 + \tfrac{1}{2} m_p v_p'^2$$

CONSERVATION OF MOMENTUM

$$m_n v_n = m_n v_n' + m_p v_p'$$

$$v_n' = \frac{m_n v_n - m_p v_p'}{m_n}$$

$$\tfrac{1}{2} m_n v_n^2 = \tfrac{1}{2} m_n \left(\frac{m_n v_n - m_p v_p'}{m_n} \right)^2 + \tfrac{1}{2} m_p v_p'^2$$

$$m_n v_n^2 = \frac{m_n^2 v_n^2 - 2 m_n m_p v_n v_p' + m_p^2 v_p'^2}{m_n} + m_p v_p'^2$$

$$m_n^2 v_n^2 = m_n^2 v_n^2 - 2 m_n m_p v_n v_p' + m_p^2 v_p'^2 + m_n m_p v_p'^2$$

$$m_p^2 v_p'^2 + m_n m_p v_p'^2 = 2 m_n m_p v_n v_p'$$

$$m_p v_p' + m_n v_p' = 2 m_n v_n$$

$$v_p' = \frac{2 m_n v_n}{m_p + m_n}$$

CONSERVATION OF ENERGY

$$\tfrac{1}{2} m_n v_n^2 = \tfrac{1}{2} m_n v_n'^2 + \tfrac{1}{2} m_N v_N'^2$$

CONSERVATION OF MOMENTUM

$$m_n v_n = m_n v_n' + m_N v_N'$$

$$v_N' = \frac{2 m_n v_n}{m_N + m_n}$$

$$\frac{v_p'}{v_N'} = \frac{m_N + m_n}{m_p + m_n}$$

$$m_n = \frac{m_N v_N' - m_p v_p'}{v_p' - v_N'}$$

(c) The v_p equation and v_N' equation are then combined algebraically (eliminating v_n), and solved for m_n. The expression for m_n now contains only terms which can be measured—so the mass of the neutron, m_n, can be calculated. Note that we use here nothing but the ideas developed for ordinary elastic collisions. (See SG 23.7 and 23.8).

show that the neutron has a mass very close to that of the proton; thus Chadwick's hypothesis did indeed offer a satisfactory solution to the problem of the "radiation" emitted when beryllium or boron was bombarded with particles.

Much research has been done since 1932 on the properties of neutrons and on the interactions between neutrons and atoms. An entire branch of study called *neutron physics* has been developed. Neutron physics deals with the production of neutrons, their detection and their interaction with atomic nuclei and with matter in bulk. This research has led, among other things, to the discovery of nuclear fission, to be discussed in Chapter 24.

The best methods now available for determining the neutron mass give 1.008665 amu (based on the scale $C^{12} = 12$ exactly).

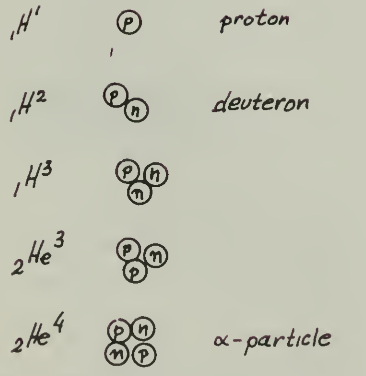
Q5 Why could the penetrating radiation from bombarded beryllium not be considered γ rays?

Q6 Why did the mass of a neutron have to be found by measurements on protons the neutrons ejected in collision?

Q7 How could the principles of conservation discussed in Unit 3 be used to find the mass of the neutron?

23.5 The proton-neutron theory of the composition of atomic nuclei

The discovery of the neutron, with an atomic mass close to one unit and with no electric charge, confirmed Rutherford's suggestion that the atomic nucleus is made up of protons and neutrons. This hypothesis was soon used as the basis of a detailed theory of the nucleus by Heisenberg in 1932, and is still the basis of attempts to describe the properties and structure of the nucleus. According to the proton-neutron hypothesis, the nucleus of an atom having atomic number Z and mass number *A* consists of Z protons and $A - Z$ neutrons. The nuclei of the isotopes of a given element differ only in the number of neutrons they contain. Thus the nucleus of the hydrogen isotope of mass number 1 contains one proton; the nucleus of the hydrogen isotope of mass number 2 contains one proton and one neutron (that nucleus is called a deuteron). The nucleus of the neon isotope Ne^{20} contains 10 protons and 10 neutrons, while that of Ne^{22} contains 10 protons and 12 neutrons. The atomic number Z identified with the charge in the nucleus, is the number of protons in the nucleus. The mass number *A* is the total number of protons and neutrons. If we use the term *nucleons* to refer to both kinds of nuclear particles, then *A* is simply the number of nucleons.



See models of the nucleus in Unit 6.

SG 23.9, 23.10

Is the proton-neutron hypothesis for the structure of nuclei fully consistent with the facts of radioactivity, such as α and β emission and the transformation rules? If two protons and two neutrons could combine, the resulting particle would have $Z = 2$ and $A = 4$, just the properties of the α particle. The emission of two protons and two neutrons (in the combined form of an α particle) would be consistent with the first transformation rule of radioactivity. (The α particle might exist as such in the nucleus, or it might be formed at the instant of emission; the latter possibility is now considered more likely.) But if the nucleus consists of protons and neutrons, where could a β particle come from? This question is more difficult to answer than that of the origin of an α particle. The second transformation rule of radioactivity provides a clue: when a nucleus emits a β particle, its charge Z increases by one unit while its mass number A remains unchanged. This would happen, if a neutron were to change into a proton and a β particle.

This idea was not a return to the proton-electron hypothesis discussed in Sec. 23.2. Physicists had already come to the conclusion that electrons are not present in the nucleus, so β decay was not considered to be a simple separation of a proton and electron; it would have to be a *transformation* of a neutron that *created* a proton and electron. However, there were additional experimental data that raised difficulties for such a simple transformation idea.

Q8 According to the proton-neutron theory of the nucleus, what is in the nucleus of ${}_7N^{14}$?

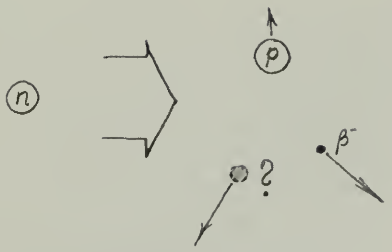
Q9 Describe an ordinary helium atom in terms of the three elementary particles: the proton, the neutron, and (outside the nucleus) the electron.

Q10 If nuclei do not contain β particles, how can β emission be explained?

23.6 The neutrino

The description of β decay in terms of the transformation of a neutron in the nucleus is part of one of the most fascinating stories in modern physics: the prediction and eventual discovery of the particles called the neutrino and the antineutrino. Quantitative studies of the energy relations in β decay during the 1920's and 1930's raised a difficult and serious question. Methods were devised for determining the energy change in a nucleus during β decay. According to the principle of conservation of energy, the energy lost by the nucleus should be equal to the energy carried off by the β particle. But, the kinetic energy of the β particles had a whole range of measured values, all smaller than the amount of energy lost by the nucleus: some of the energy lost by the nucleus seemed to have disappeared. Measurements made on a large number of β-emitters indicated that on the average about two-thirds of the energy lost by the β-decaying nuclei seemed to disappear. Attempts to find the missing energy failed. For example, some physicists thought that the missing energy might be carried off by γ rays; but no such γ rays could be detected experimentally. The principle of conservation of energy seemed to be violated in β decay. Similar discrepancies were found in measurements of the momentum of the emitted electron and the recoiling nucleus.

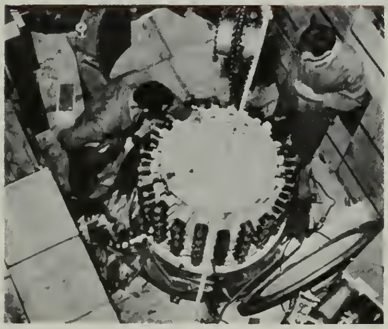
As in the case of the experiments that led to the discovery of the neutron, physicists tried very hard to find an alternative to accepting the failure of the principles of conservation of energy and momentum. The Austrian physicist Wolfgang Pauli suggested in 1933 that another, hitherto unnoticed particle, is emitted in β decay along with the electron, and that this particle carries off the missing energy and momentum. This hypothetical particle could have no electric charge, because the positive charge of the proton and the negative charge of the β particle together are equal to the zero charge of the original neutron. The mass-energy balance in the decay of the neutron indicated that the rest mass of the hypothetical particle should be very small—much smaller than the mass of an electron, and possibly even zero. The combination of zero electric charge, and zero or nearly zero mass, would make the particle extremely hard to detect.



We now know that a *free* neutron—a neutron separated from an atom—sooner or later decays into a proton, an electron, and a neutrino. (The half-life of a beam of free neutrons has been measured to be 12 minutes.)

The Italian physicist Enrico Fermi called the suggested particle the *neutrino* ("little neutral-one" in Italian). In 1934 Fermi constructed a theory of β decay based on Pauli's suggestion. This theory has been successful in describing all the known facts of β decay. From 1934 on, the neutrino was accepted as a "real" particle for two reasons, both theoretical: it saved the principle of conservation of energy in β decay, and it could be used successfully both to describe the results of experiments in β decay and to predict the results of new experiments. (See "Conservation Laws" in *Reader* 6.)

Many unsuccessful attempts were made to capture neutrinos over a period of 25 years. Finally, in 1956, neutrinos were detected in an experiment using the extremely large flow of neutrinos that comes out of a nuclear reactor (see Chapter 24). The detection of neutrinos is an indirect process that involves detecting the products of a reaction *provoked* by a neutrino. The reaction used was a reverse β decay—the production of a proton from a neutron. Because the proper meeting of a proton, an electron, and a neutrino at the same place and same time is an exceedingly unlikely event—and the resulting neutron difficult to detect—"catching" the neutrinos required a very elaborate and sensitive trap. (See photo at the left.) Again the faith of physicists in the principle of conservation of energy was justified.



The first detection of neutrinos was in this tank. Reactions provoked by neutrinos cause flashes of light in the liquid with which the tank is filled. The flashes are detected by the photoelectric tubes which stud the tank wall. This work was done by two American physicists, Clyde Cowan and Frederick Reines.

There is one more complication: it is now known that there are several kinds of neutrinos. The one involved in β decay (as discussed so far) is now referred to as an *anti-neutrino*, and is denoted by the symbol $\bar{\nu}$ (Greek letter "nu" with a bar over it). The transformation of a neutron during β-emission is then written:

$$_1n^0 \longrightarrow {}_1p^1 + {}_{-1}e^0 + \bar{\nu}$$

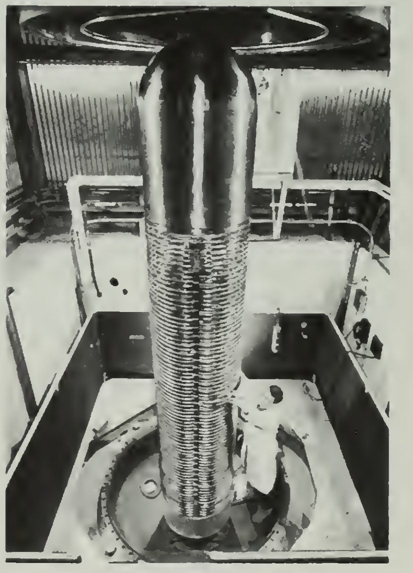
Q11 Why was an almost undetectable particle invented to patch up the theory of β decay?

23.7 The need for particle accelerators

Up to 1932 the study of nuclear reactions was limited by the kind of projectile that could be used to bombard nuclei: only α particles from the naturally radioactive nuclides could bring about reactions. Progress was limited because α particles could be obtained only in beams of low intensity and with fairly low kinetic energies. These relatively low-energy particles could produce transmutations only in light elements. When heavier elements are bombarded with α particles, the repulsive electric force exerted by the greater charge of the heavy nucleus on an α particle makes it difficult for the α particle to reach the nucleus. The probability of a nuclear reaction taking place becomes very small or zero. But because the interest in nuclear reactions was great, physicists in many countries sought methods of increasing the energy of charged particles to be used as projectiles.

First stage of a 750-kilovolt proton accelerator.

There were advantages to be gained in working with particles that have only one positive charge—the proton or the deuteron (the nucleus of the deuterium or heavy hydrogen atom). Having but a single charge, these particles would experience smaller repulsive electric forces than would α particles in the neighborhood of a nucleus, and thus would be more successful in getting close enough to produce transmutations—even of *heavy* (and therefore high-charge) target nuclei. Protons or deuterons could be obtained from positive-ray tubes, but their energies were rather low. Some device was needed to accelerate these particles to higher energies, as Rutherford was among the first to ask (see p. 57). Such devices might also offer other advantages: the speed (and energy) of the bombarding particles could be controlled by the experimenter; and very intense projectile beams might be obtained. It would then be possible to find how nuclear reactions depend on the energy of the bombarding particles.



A Van de Graaff generator, built on a vertical axis.

Since 1930, many devices for accelerating charged particles have been invented and developed. In each case, the particles used (electrons, protons, deuterons, α particles or heavy ions) are accelerated by an electric field. In some cases a magnetic field is used to control the path of particles, that is, to steer them. The simplest type (like the Van de Graaff machine shown at the right) has a single high-voltage step—these cannot be practically operated above about 10 million volts, so they cannot be used to increase electron or proton energies above about 10 MeV.

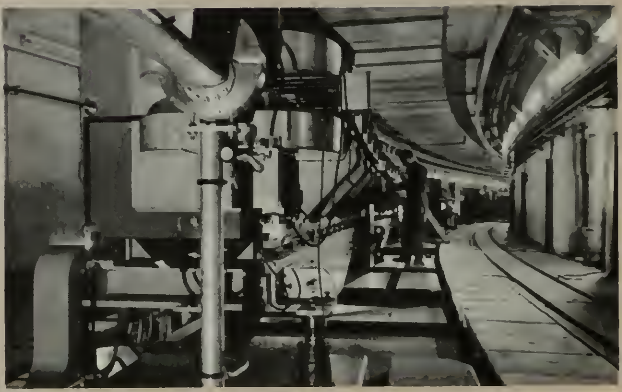
Another type (like the Linac on p. 62) has a long series of low voltage steps—some of these produce electron energies up to 20 BeV. A third general type uses magnetic fields to hold the particles in a circular path, returning them over and over to the same low-voltage accelerating fields. The first machine of this type was the cyclotron (see the photograph on p. 48). Other circular types are illustrated on pp. 62 and 63. The most recent of these will produce 7 BeV electrons or 500 BeV protons! Accelerators have become basic tools for research in nuclear and high-energy physics; their operation, and the way a typical recent experiment was actually done, are the subject of the two Project Physics films, *Synchrotron*, and *People and Particles*. Also, accelerators are used in the production of radioactive isotopes, and serve as radiation sources for medical and industrial purposes.

SG 23.16

See "The Evolution of the Cyclotron" and "The Cyclotron as Seen by . . ." in *Reader 6*.

a

c



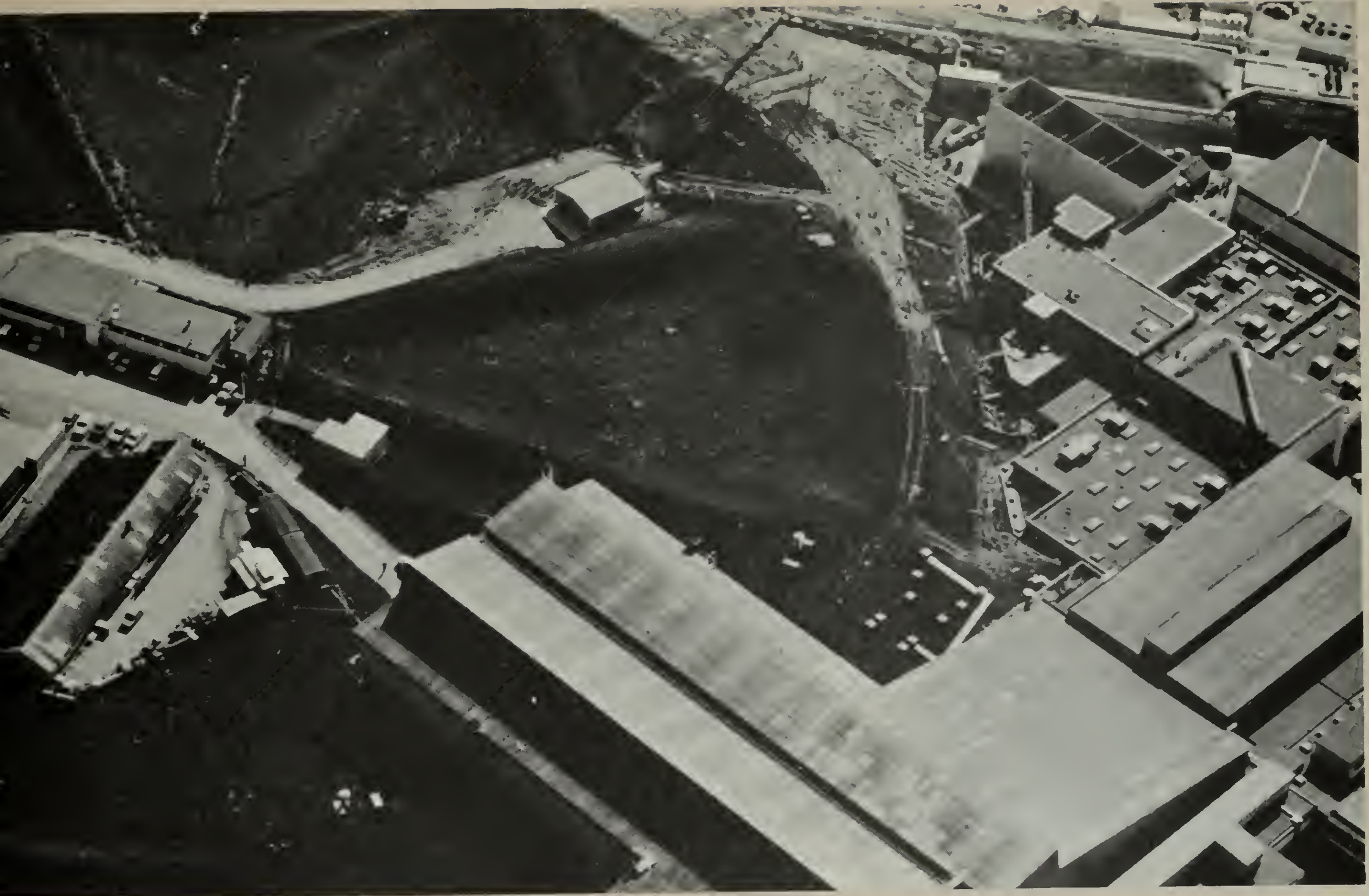
d

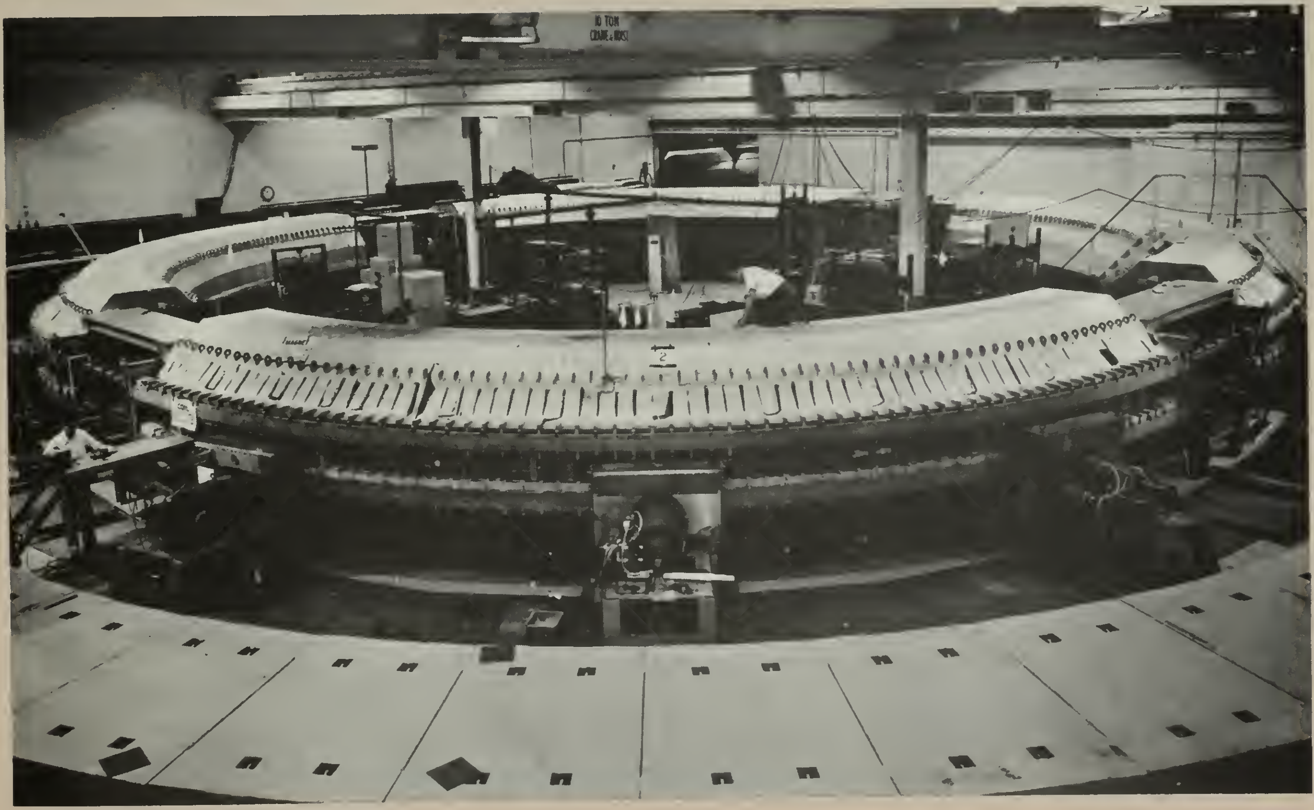
b

a and **b:** outside and inside the Stanford "Linac" (linear accelerator).

c and **d:** outside and inside the CERN proton-synchrotron at Gene va. (See "CERN" in *Reader 6.*) The evacuated ring in which the protons are accelerated is at the upper left of photograph d.

e: the Brookhaven Cosmotron, in operation from 1952 to 1967, and now superceded by larger accelerators at Brookhaven.





e

Major Types of Particle Accelerators

TYPE	PRINCIPLE OF OPERATION	MAXIMUM ENERGY	PARTICLES	NOTES AND EXAMPLES OF USE
ONCE-THROUGH ACCELERATION				
Cockcroft-Walton	direct high voltage potential	≃ 4 MeV	various	commercially available
Van de Graaff generator	high voltage by transport of charges on moving belt	≃ 3 MeV ≃ 14 MeV	electrons protons	commercially available
Linear accelerator	successive application of high frequency voltages	≃ 10 MeV per particle	heavy ions	Lawrence Radiation Laboratory and Yale University
Linear accelerator	pulsed high frequency wave	≃ 20 BeV	electrons	Stanford University, two miles long
CYCLIC ACCELERATION				
Betatron	magnetic induction (electrons in an evacuated tube accelerated by variable field of electromagnet)	≃ 300 MeV	electrons	largest machine is at University of Illinois
Cyclotron	voltage of constant frequency applied to particles in fixed magnetic field	≃ 12 MeV ≃ 24 MeV ≃ 48 MeV	protons deuterons He-nuclei	commercially available; numerous installations, including some built by students at high schools
Synchro-cyclotron	voltage of variable frequency applied to particles in fixed magnetic field	≃ 750 MeV	protons	184-inch unit at Lawrence Radiation Laboratory, Berkeley
Electron synchrotron	voltage of constant frequency applied to particles orbiting in variable magnetic field	≃ 7 BeV	electrons	Hamburg, Germany (7.5 BeV); Cambridge Electron Accelerator (6 BeV) operated by Harvard and M.I.T.
Proton synchrotron	synchronized voltage of high frequency applied to particles orbiting in variable magnetic field	≃ 12 BeV	protons	6.2 BeV "Bevatron" at Lawrence Radiation Laboratory; 3 BeV Cosmotron at Brookhaven; 3 BeV at Princeton; and 12.5 BeV synchrotron at Argonne National Laboratory
Alternating gradient synchrotron	same as synchrotron except successive segments of magnetic field have opposite curvature	≃ 30 BeV	protons	Brookhaven National Laboratory (Long Island), and CERN, Switzerland (where a 300 BeV accelerator is in design stage)
		≃ 76 BeV	protons	Serpukhov, U.S.S.R. (Also a 1000 BeV accelerator in design stage)
Strong-focusing synchrotron	″	≃ 500 BeV	protons	Enrico Fermi Laboratory, Batavia, Illinois (in construction)

The table on p. 64 summarizes the major types of particle accelerators now being used or planned. One of the latter is a 200 to 500 BeV particle accelerator being built for completion in about 1973 or 1974. It is being paid for with approximately $240 million appropriated from public funds through the Atomic Energy Commission. Such "machines" are among the most complex and grandiose structures ever built by man. Indeed, they are monuments to his imagination and ingenuity, his ability to reason and to collaborate in groups on peaceful projects that further the understanding of nature. Basically, the "machines" are tools to help us find out as much as we can about the structure of nuclear particles and the forces holding them together.

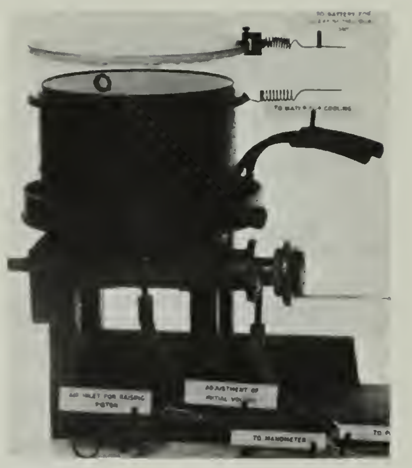
With the discovery of the neutron in 1932 it was believed that three "elementary" particles act as the building blocks of matter: the proton, the neutron, and the electron. We have mentioned the existence of new particles, such as neutrinos and antineutrinos. As high-energy accelerators became available, additional "elementary" particles were discovered, one after another. On page 175 is a list of some of these particles; they are grouped into "families" according to their properties. Most of these particles exist only briefly—typical lifetimes are of the order of 10^{-8} second or less. A whole new field, high-energy physics, has evolved, and the aim of the high-energy physicist of today is to discern the order and structure behind the large number of "elementary" particles that have been discovered.

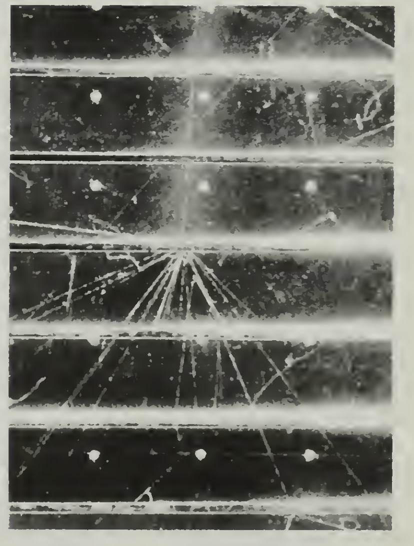
How do we detect these particles? We have already mentioned a number of methods by which we can observe and measure radioactive emissions. They include the electroscope and the electrometer employed since the early days of radioactivity, the Geiger counter (see *Text* Sec. 19.3), and the Wilson cloud chamber. In addition we now have various types of ionization chambers, scintillation counters, photographic emulsions (see "The Tracks of Nuclear Particles" in *Reader* 6), semiconductor devices, spark chambers (see "The Spark Chamber" in *Reader* 6), and bubble chambers (some of which are displayed on the next two pages). One of the supplemental units in the Project Physics Course, entitled *Elementary Particles*, further describes in detail the devices, and the discoveries made with them.

Q12 Why can low-energy α particles cause transmutations only in nuclei of relatively small atomic number?

Q13 Why are protons more effective projectiles for producing nuclear reactions than are α particles or heavy ions?

Q14 What are some of the devices for producing high-energy particles to be used as projectiles? What are some devices for detecting nuclear reactions induced by such projectiles?



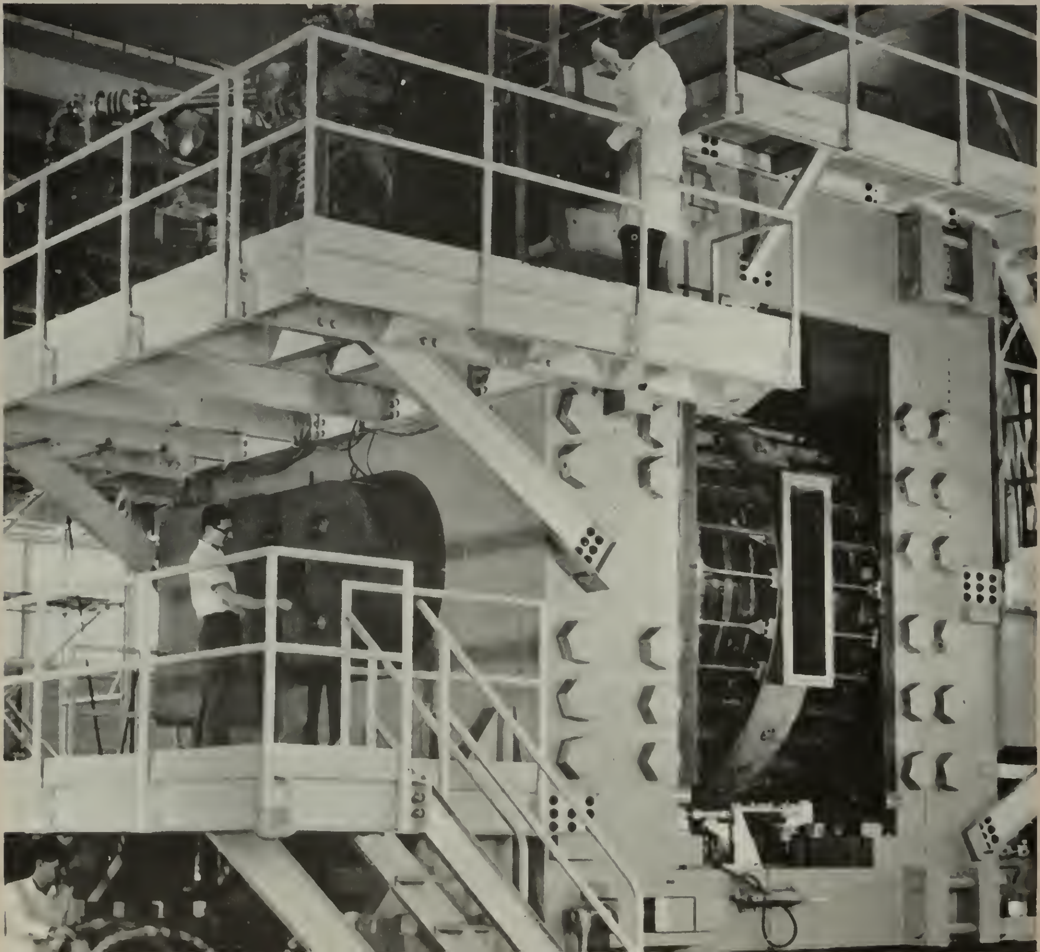


The top photograph shows C. T. R. Wilson's cloud chamber. (See also p. 52.) The middle photograph shows particle tracks in a cloud chamber. (The positively and negatively charged ions had separated before the cloud was formed, so the track shows up as two vertical streaks.) In the bottom photograph high voltages between the plates in a spark chamber cause sparks to jump along the ionized trails left by high-energy charged particles.

Above: The tiny bubble chamber, 3 cm long, invented by D. A. Glaser in 1952. (Note the particle track.) Glaser was 26 at the time, and later was awarded the Nobel Prize for his invention.

Below: the 200-cm Bubble Chamber Assembly at the Brookhaven National Laboratory.

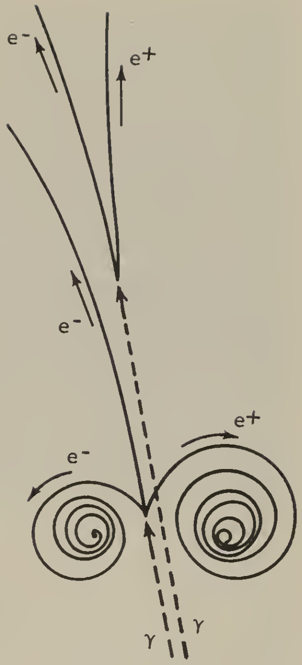
Right: The viewing of a projected, enlarged photograph made of particle tracks in a bubble chamber.

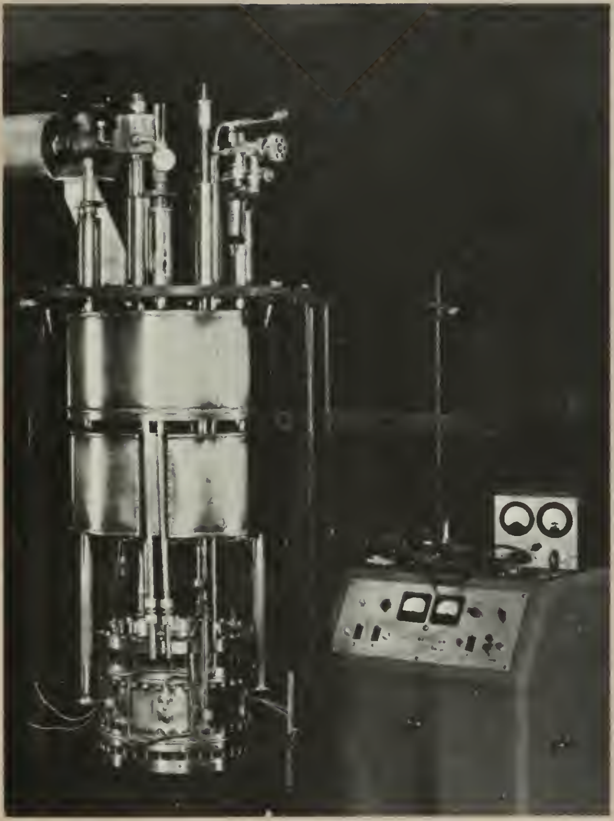


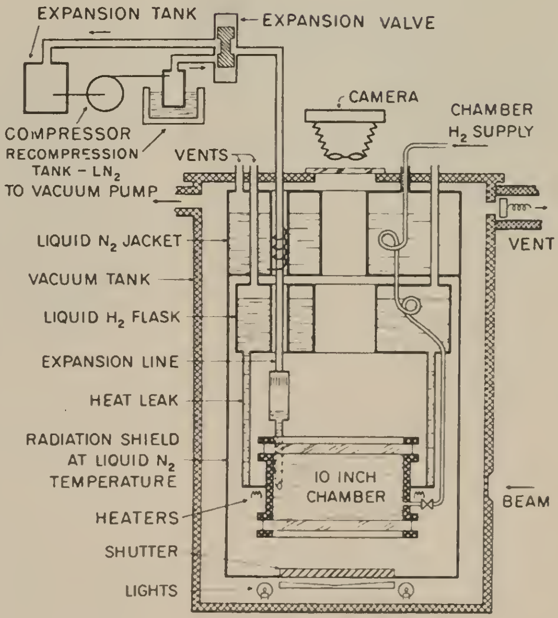
The bubble chamber photo at the left illustrates one of the major discoveries of modern physics, the interconversion of energy and matter (to be discussed in Chapter 20.) The diagram at the right shows the significant tracks recorded in the photo. In the upper left, an electron-positron pair is formed by a gamma ray (not visible in bubble chamber pictures) interacting with a hydrogen nucleus. (The discovery of positrons is described briefly on p. 70.) An applied magnetic field causes the electron and the positron to be deflected in opposite directions. (In what direction was the magnetic field?)

In the lower left of the same photo a gamma ray forms another electron-positron pair; the additional electron (third track, upward) was knocked out of a hydrogen atom during this process.

The bubble chamber photo was taken in a 10″ liquid-hydrogen bubble chamber at the Lawrence Radiation Laboratory of the University of California. The chamber is shown below at the left, with the liquid nitrogen shield removed. The accompanying diagram at the right gives some of the details of the bubble chamber and its auxiliary equipment.







23.8 Nuclear reactions

The development of the cyclotron and other particle accelerators led to great advances in the study of nuclear reactions. Nearly all of the stable nuclides have now been bombarded with protons, deuterons, α particles, neutrons and γ rays, and hundreds of nuclear reactions have been examined. Examples of reactions induced by α particles and protons have already been discussed.

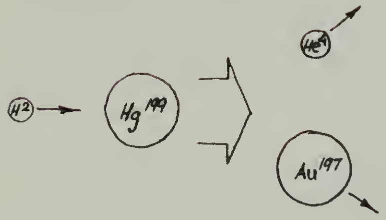
We discuss the transmutation into gold only as an example of a nuclear reaction; a more useful reaction is the transmutation of gold into something else—for example:

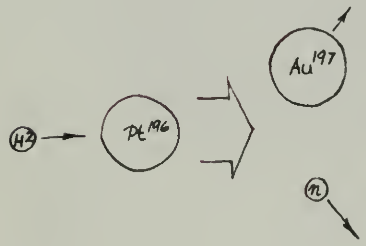
$$_{79}Au^{197} + {_0}n^1 \longrightarrow {_{80}}Hg^{19} + {_{-1}}e^0$$

This reaction can be used to obtain pure samples of a single mercury isotope. (It's alchemy turned upside down.)

Since the first known alchemical writings during the third or fourth centuries A.D., and throughout the historical development of chemistry, the dream of transmuting materials (usually into gold) has always haunted some people. In most nuclear reactions one element is indeed changed into another: so in a sense the ancient dream of the alchemist has come true. But it is unlikely to make a fortune for anyone. It is possible to transmute various elements into gold, but such transformations are of course completely different, both in method and purpose, from the attempts of the ancient alchemists. (Moreover, they are all entirely uneconomical methods for "making gold.")

Gold has only one stable isotope found in nature—$_{79}Au^{197}$; other gold isotopes can be made, but are radioactive. We can also illustrate two types of nuclear reactions induced by deuterons, both resulting in the stable isotope of gold:





$$_1H^2 + {_{80}}Hg^{199} \longrightarrow {_{79}}Au^{197} + {_2}He^4$$

$$_1H^2 + {_{78}}Pt^{196} \longrightarrow {_{79}}Au^{197} + {_0}n^1$$

In both cases we need an accelerator to produce high-energy deuterons; in bombarding a mercury isotope we produce α particles besides our desired gold. In bombarding platinum we produce neutrons in addition to the gold.

The last reaction, in which a *neutron* was produced, is an example of reactions which have become especially important because of the usefulness of the neutrons. Neutrons can be produced when nuclei are bombarded with protons, deuterons, or α particles, as in the reactions:

$$_{28}Ni^{58} + {_1}H^1 \longrightarrow {_{29}}Cu^{58} + {_0}n^1$$

$$_6C^{12} + {_1}H^2 \longrightarrow {_7}N^{13} + {_0}n^1$$

$$_4Be^9 + {_2}He^4 \longrightarrow {_6}C^{12} + {_0}n^1$$

The neutrons produced by such bombardment can, in turn, be used to induce other nuclear reactions. As we noted before, neutrons are especially effective as "bullets," because they have no electric charge. They are not subject to repulsive electrostatic forces in the neighborhood of a positively charged nucleus, and are therefore more likely to penetrate nuclei than are protons, deuterons, or α particles.

Because of the neutron's lack of electrical charge, many more reactions have been induced by neutrons than by any other kind of particle. Enrico Fermi was the first to undertake a systematic program of research involving the use of neutrons as projectiles in nuclear reactions. Starting in 1934, he and his group bombarded many elements, from the lightest to the heaviest, with neutrons, and studied the properties of the nuclides produced. The research described in the Prologue to Unit 1 was done as part of this program.

A typical neutron-induced reaction, again one resulting in gold, is:

$$_{0}n^{1} + {}_{80}Hg^{198} \longrightarrow {}_{79}Au^{197} + {}_{1}H^{2}$$

In another, a very common type of neutron-induced reaction, the neutron is captured and a γ ray is emitted, as in the following example:

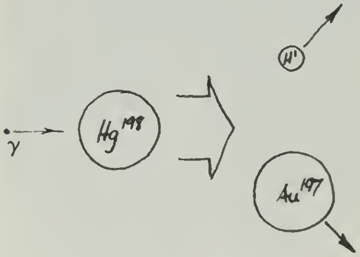
$$_{0}n^{1} + {}_{78}Pt^{196} \longrightarrow {}_{78}Pt^{197} + \gamma$$

Note that since there is no change in the atomic number, the element here remains the same. An isotope of the target nucleus is produced with a mass number greater by one unit than that of the target nucleus. The new nucleus so produced has more energy than it needs to be stable, and is said to be produced in an "excited state." It returns to its lowest energy state by emitting one or more γ rays.


In this bubble chamber picture, a neutron is produced at the bottom, at the end of the $\frac{1}{2}$" long track, near the + mark. This neutron in turn causes a reaction near the center of the plate. (Neutral particles do not leave tracks in bubble chambers.)

Some nuclei can also undergo reactions when bombarded with γ rays; an example, for illustration's sake once again resulting in gold, is the reaction:

$$\gamma + {}_{80}Hg^{198} \longrightarrow {}_{79}Au^{197} + {}_{1}H^{1}$$



In this case, the energy of the γ ray excites the mercury target nucleus which becomes unstable, ejects a proton, and thereby becomes a gold nucleus.

The amount of gold that can be produced by the above reaction is very small; we have simply tried to illustrate some typical artificial transmutations. The examples we have given barely suggest the rich variety of such reactions that have been observed. The products of these reactions may change as the energy of the bombarding particles changes. Nuclear reactions are important, not only because they indicate our ability to produce new nuclides, but also because they provide important data about nuclear structure. A model of nuclear structure, to be successful, must enable us to predict the results of these nuclear reactions, just as a successful model of atomic structure must allow us to predict the results of chemical reactions.

SG 23.11
SG 23.12

Q15 What property of neutrons makes them particularly useful for producing nuclear reactions?

Q16 Complete the following equation for a nuclear reaction: $_{13}Al^{27} + {}_{1}H^{2} \longrightarrow {}_{0}n^{1} + {}_{?}Si^{?}$.

23.9 Artificially induced radioactivity

In the discussion of nuclear reactions so far we have only hinted at an interesting discovery. We have shown in the last section that the capture of a neutron by platinum 196 results in platinum 197 and the emission of a γ ray. As is listed in the table on p. 42, six different isotopes of platinum are found in nature—but platinum 197 is not among these. The question arises: is platinum 197, produced by neutron capture, stable? The answer is no; it is radioactive and decays by the emission of a β particle to gold 197 (the only stable gold isotope):

$$_{78}\mathrm{Pt}^{197} \longrightarrow {}_{79}\mathrm{Au}^{197} + {}_{-1}\mathrm{e}^{0} + \bar{\nu}$$

The half life of platinum 197 is 20 hours.

The production of radioactive platinum 197 in a nuclear reaction is an example of *artificially induced radioactivity.* This phenomenon was discovered in 1934 by Irène Curie and F. Joliot. They were studying the effects of α particles on the nuclei of light elements. When they bombarded boron, magnesium, and aluminum with α particles from polonium, they observed the immediate ejection of protons and neutrons from the bombarded nuclei, as expected. But, in addition to these particles, *positive electrons*, or *positrons*, also were observed to be emitted. The positron is a particle whose mass is the same as that of the electron, and whose charge has the same magnitude but opposite sign to that of the electron.

One of the earliest records of a "shower" of electrons and positrons; it shows their tracks curving in opposite directions in a strong magnetic field. The shower was caused by cosmic rays, and was recorded in a Wilson cloud chamber, taken to an altitude of 4.3 km.

The positron had been discovered earlier by the American physicist C. D. Anderson in 1932 while studying cosmic rays. (Cosmic rays are highly penetrating radiations which originate outside the earth and consist of protons, electrons, neutrons, photons, and other particles.) Employing a cloud chamber situated in a magnetic field, Anderson observed some tracks which, judged by the density of ionization along the track, could have been produced only by high-speed particles having the same mass and *magnitude* of charge as an electron; but the curvature was opposite in direction to that of high-speed electron tracks. Anderson concluded that the particles producing them must have been positively charged electrons, to which the name positron was given (symbol β^{+}, or ${}_{1}\mathrm{e}^{0}$).

In the Joliot-Curie experiment, the production of positrons along with neutrons as a result of the bombardment of a light element with α particles seemed to indicate that a new type of nuclear reaction was occuring. Further experiments by this couple showed that the light-element targets *continued to emit positrons*, even after the source of the α particles had been removed. When the rate of emission of the positrons was plotted against time elapsed since removal of the α particle source, curves were obtained, for each target, similar to the curves obtained in natural β radioactivity. (The half-life of the emitter was found to be 2.5 min). The results seemed to show that an initially stable nuclide had been changed into a radioactive one. In the case of the bombardment of ${}_{13}\mathrm{Al}^{27}$ by α particles, which produced neutrons as well as a new radioactive material, a nuclear reaction would produce a nuclide of mass number 30 (= 27 + 4 − 1) and atomic number 15 (= 13 + 2 − 0) – hence an isotope of phosphorus. The reaction would be:

$$_{13}\mathrm{Al}^{27} + {}_2\mathrm{He}^4 \longrightarrow {}_0\mathrm{n}^1 + {}_{15}\mathrm{P}^{30}$$

Irene Curie and F. Joliot in their laboratory. They were married in 1926. In 1935 they shared the Nobel Prize for chemistry.

Curie and Joliot ran chemical separations similar to those made in the study of the naturally radioactive elements, and showed that the target, after bombardment, indeed contained a small amount of phosphorus, and an isotope that was radioactive. Now, phosphorus occurs in nature only as $_{15}\mathrm{P}^{31}$; no isotope of phosphorus with mass number 30 had ever been found to occur naturally. It was reasonable to suppose that if P^{30} were made in a nuclear reaction, it would not be stable but radioactive. If it decayed by emission of a positron, that reaction would be expressed in the following manner:

$$_{15}\mathrm{P}^{30} \longrightarrow {}_{14}\mathrm{Si}^{30} + {}_1\mathrm{e}^0 + \nu$$

where $_{14}\mathrm{Si}^{30}$ is a known isotope of silicon, $_1\mathrm{e}^0$ represents a positron and ν is a neutrino.

This kind of decay implies that a proton in the nucleus may be transformed into a neutron that remains in the nucleus, a positron that is emitted, and a neutrino:

$$_1\mathrm{p}^1 \longrightarrow {}_0\mathrm{n}^1 + {}_1\mathrm{e}^0 + \nu$$

In sum, after the discovery that the bombardment of light nuclides by α particles can lead to radioactive products, it was found that nuclear reactions induced by protons, deuterons, neutrons and photons can also result in radioactive products. As in the case of the natural radionuclides, an artificial radionuclide can be characterized by its half-life and the type of radiation it emits. When the products of nuclear reactions are radioactive they can be traced in chemical separations by means of their characteristic half-lives or decay products. (They can not be traced chemically because very small amounts are involved – often less than a millionth of a gram.) The special branch of chemistry that deals with the separation and identification of the radioactive products of nuclear reactions is called radiochemistry, and has become an important part of nuclear science. The breadth of this field is indicated by the fact that since 1935 about 1200 artificially radioactive nuclides have been made and identified, many of which are in use in research and industry.

Among the various modes of decay of artificial radioactive nuclides are α, β^-, β^+, γ emissions and capture of an orbital electron by the nucleus.

SG 23.13 – 23.16

Q17 Complete the following equation for a positive β-decay: $_7\mathrm{N}^{13} \longrightarrow {}_1\mathrm{e}^0 + {}_?\,?^?$
How many neutrons and protons were there in the nitrogen nucleus before decay? How many in the resulting product nucleus afterward?

23.1 The Project Physics learning materials particularly appropriate for Chapter 23 include the following:

Activity
Neutron Detection Problem Analogue
Film Loop
Collisions With an Object of Unknown Mass
Films
People and Particles
Synchrotron
Reader Articles
Some Personal Notes on the Search for the Neutron
Antiprotons
The Tracks of Nuclear Particles
The Spark Chamber
The Evolution of the Cyclotron
The Cyclotron As Seen By . . .
CERN
Conservation Laws
The Fall of Parity
Can Time Go Backward?
Particle Accelerators

23.2 Why would it be difficult to explain the nucleus of ${}_{92}U^{235}$ as a mixture of alpha particles and electrons?

23.3 On the basis of the proton-electron hypothesis of nuclear composition, how many protons would you expect to find in the ${}_{92}U^{235}$ nucleus? How many electrons?

23.4 Complete the following nuclear equations:

(a) ${}_5B^{10} + {}_2He^4 \longrightarrow (\quad) + {}_1H^1$
(b) ${}_{11}Na^{23} + {}_2He^4 \longrightarrow (\quad) + {}_1H^1$
(c) ${}_{13}Al^{27} + {}_2He^4 \longrightarrow (\quad) + {}_1H^1$
(d) $(\quad) + {}_2He^4 \longrightarrow {}_{17}Cl^{35} + {}_1H^1$
(e) $(\quad) + {}_2He^4 \longrightarrow {}_{20}Ca^{42} + {}_1H^1$

23.5 Complete the following nuclear equations:

(a) ${}_3Li^6 + {}_1H^1 \longrightarrow {}_2He^4 + (\quad)$
(b) ${}_4Be^9 + {}_1H^1 \longrightarrow {}_2He^4 + (\quad)$
(c) ${}_4Be^9 + {}_1H^1 \longrightarrow (\quad) + {}_1H^2$
(d) ${}_5B^{11} + {}_2He^4 \longrightarrow {}_7N^{14} + (\quad)$

23.6 Complete the following nuclear equations (consult periodic table of elements for atomic numbers of indicated nuclides):

(a) $Al^{27} + {}_0n^1 \longrightarrow Al^{28} + (\quad)$
(b) $Al^{27} + {}_1H^2 \longrightarrow {}_1H^1 + (\quad)$
(c) $Al^{27} + {}_1H^1 \longrightarrow {}_2He^4 + (\quad)$
(d) $Al^{27} + {}_1H^2 \longrightarrow {}_2He^4 + (\quad)$

What aspect of nuclear reactions do equations (b) and (d) illustrate?

23.7 (a) Explain briefly why the maximum speed gained by nitrogen nuclei in collisions with neutrons is roughly 10 times less than that gained by hydrogen nuclei in collisions with neutrons?

(b) Where in this course was the physics needed for this problem first developed?

23.8 One major disadvantage of indirect methods of measurement is that the experimental uncertainty is often larger. If Chadwick had measured a maximum speed of 3.2×10^9 cm/sec for hydrogen nuclei (a change of only 3%), and 4.7×10^8 cm/sec for nitrogen nuclei (no change), what would be the calculated mass of the neutron? By what percentage would the calculated mass of the neutron change due to the 3% shift in the speed measurement.

23.9 Indicate the mass number *A*, the atomic number Z, the number of protons and the number of neutrons for each of the following nuclei: (Make a similar table in your notebook if you may not write in this book.)

	A	Z	number of protons	number of neutrons
H^1				
H^2				
He^4				
Li^7				
C^{13}				
U^{238}				
Th^{234}				
Th^{230}				
Pb^{214}				
Pb^{206}				

23.10 How many electrons are there in a neutral atom of
(a) platinum 196?
(b) gold 198?
(c) mercury 198?
(d) mercury 199?

23.11 Complete the following nuclear reaction equations:

(a) ${}_{11}Na^{23} + {}_1H^2 \longrightarrow {}_1H^1 + (\quad)$
(b) ${}_{11}Na^{23} + {}_0n^1 \longrightarrow \gamma + (\quad)$
(c) ${}_{12}Mg^{24} + {}_0n^1 \longrightarrow {}_1H^1 + (\quad)$
(d) ${}_{12}Mg^{26} + {}_1H^2 \longrightarrow {}_2He^4 + (\quad)$

What aspect of nuclear reactions do these equations illustrate?

23.12 Describe the following reactions in *words*:

${}_{13}Al^{27} + {}_0n^1 \longrightarrow {}_{12}Mg^{27} + {}_1H^1.$

${}_{12}Mg^{27} \longrightarrow {}_{13}Al^{27} + {}_{-1}e^0 + \overline{\nu} + \gamma \; (T_{\frac{1}{2}} = 9.5 \text{ min})$

23.13 It is often necessary to infer information in the absence of direct evidence. Thus when a hunter following the tracks of a rabbit in the snow finds that the tracks suddenly stop with no evidence of other tracks or of hiding places, he may infer something about the possible presence of owls or eagles.

The bubble chamber photograph at the right shows, among other things, the tracks of two nuclear particles that originate or terminate at a point in the lower center. Describe interactions that might occur at that point in terms of your knowledge of the law of conservation of momentum.

23.14 How may the discovery of artificially radioactive nuclides have helped the development of theories of nuclear structure?

23.15 If you have seen one or more of the films *Synchrotron, People and Particles,* and *The World of Enrico Fermi,* write an essay on either
(a) the way research teams work together in modern high-energy physics, or
(b) the reasons why some parts of modern experimental physics require large "machines" to do research, or
(c) why in many major countries millions of dollars of public money are appropriated to build and run these machines.

23.16 Compare the mass of a neutral helium atom with the sum of the masses of four hydrogen nuclei plus two electrons outside (to get a neutral helium atom). What conclusions do you draw?

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24.10 The strength of nuclear forces 99
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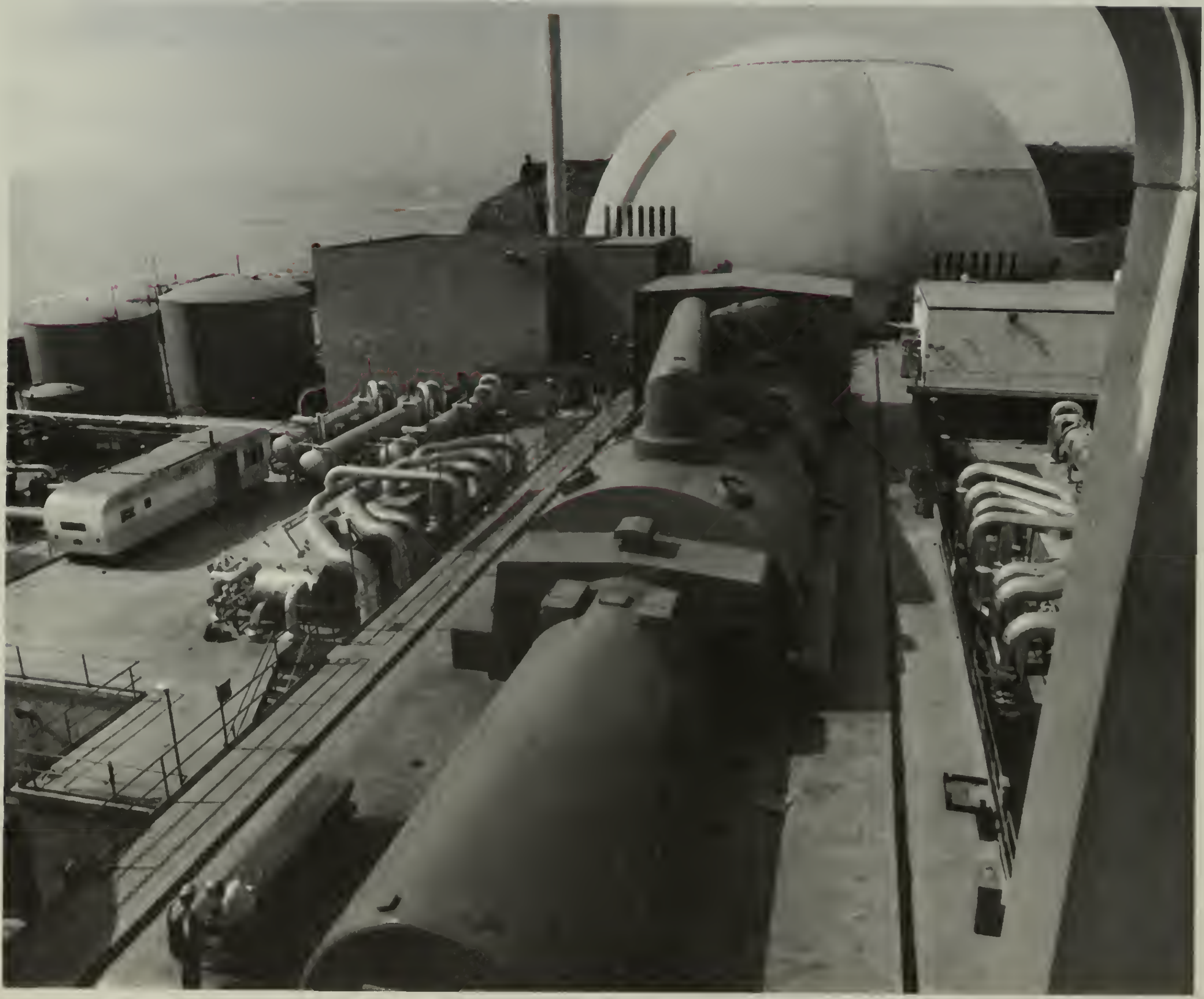


CHAPTER TWENTY-FOUR

Nuclear Energy; Nuclear Forces

24.1 Conservation of energy in nuclear reactions

SG 24.1

In the discussion of nuclear reactions in the last chapter, the emphasis was on the transformations of nuclei and on the properties of the nuclides formed. But there is another property of these reactions that is important—the absorption or release of energy.

You know that in some chemical reactions energy must be supplied from the outside to keep the reaction going, while in others energy is liberated. The formation of water from oxygen and hydrogen is an example of a reaction in which energy is liberated; the reaction between these two gases is usually violent, and heat is given off. We may conclude that the water which is formed has less energy than did the substances of which the water is made. On the other hand, when water is decomposed by electrolysis, electrical energy must be supplied by passing a current through the water, and the products of the reaction—the oxygen and hydrogen liberated—have more energy than the water.

In both kinds of chemical reactions, we neglect the small amount of energy that may be required to trigger the reaction.

Nuclear reactions too may absorb energy, or liberate energy. One main reason for the interest in nuclear reactions is the fact that the amount of energy absorbed or liberated per nucleus involved can be greater by a factor of a million or more than the amount involved per atom in a chemical reaction. Nuclear fission and nuclear fusion (discussed later in this chapter) are two special kinds of nuclear reactions in which the energy release is exceptionally large; hence these types of reactions have made them important in industrial and military applications.

It would be a good idea to reread Sec. 20.1 in Unit 5, to review the relativistic relationship of mass and energy. Two important ideas for this chapter are: (a) the mass of a moving body is greater than the rest mass by KE/c^2, and (b) a body at rest has an energy of m_0c^2.

Since there is an equivalence between mass and energy, a large release of energy in a nuclear reaction will be accompanied by corresponding changes in the total rest mass of the interacting

In this nuclear-electric power plant, a controlled fission reaction inside the domed housing supplies heat energy for operation of a steam turbine which drives an electrical generator.

nuclei. Therefore the relation of $E = mc^2$ plays an important part in interpreting nuclear reactions.

In this chapter we shall examine the mass and energy relations in nuclear reactions. This study will show how some of the ideas and experimental information of the last three chapters are linked together.

Q1 Is energy always liberated in a nuclear reaction?

24.2 The energy of nuclear binding

As early as 1927 Aston concluded from his measurements with a mass spectrograph that when two light nuclei combine to form a heavier one, the new nucleus weighs less than the sum of the original ones.

Our concepts of atomic and nuclear structure—that an atom consists of a nucleus surrounded by electrons and that the nucleus is made up of protons and neutrons—led to a fundamental question: is the mass of a neutral atom equal to the sum of the masses of the protons, neutrons, and electrons that make up the neutral atom? This question can be answered precisely because the masses of the proton, the neutron, and the electron are known, as are the masses of nearly all the atomic species. A survey of the known atomic masses shows that, for each kind of atom, the atomic mass is always *less* than the sum of the masses of the constituent particles in their free states. The simplest atom containing at least one proton, one neutron, and one electron is deuterium, $_1H^2$; in this case we have for the masses:

rest mass of one proton = 1.007276 amu
rest mass of one neutron = 1.008665
rest mass of one (orbiting) electron = 0.000549
total rest mass of constituent particles in free state = 2.016490 amu

rest mass of deuterium atom = 2.014102 amu
difference (Δm) = 0.002388 amu

Although the difference in rest mass, Δm, may appear small, it corresponds to a significant energy difference, because of the factor c^2 in the relation $E = mc^2$. The difference Δm in mass corresponds to the difference ΔE in energy according to the relation: $\Delta E = \Delta mc^2$. A convenient conversion factor from atomic mass (expressed in amu) to energy (expressed in MeV) is, as shown in the margin, 1 amu = 931 MeV. If we therefore think of a deuterium atom being made with a proton and a neutron combine (and are joined by a tiny electron), then an amount of mass 0.002388 amu will have to be "lost" in the process. This means that an amount of energy equal to 0.002388 amu × 931 MeV/amu = 2.22 MeV has to be somehow radiated away from this system of combining particles, before they settle down as a deuterium atom.

The energy equivalent of 1 atomic mass unit:

$1 \text{ amu} = 1.66 \times 10^{-27}\text{kg}$
$\Delta E = \Delta mc^2$
$= (1.66 \times 10^{-27}\text{kg}) \times (3 \times 10^{8}\text{m/sec})^2$
$= 14.9 \times 10^{-11} \text{ joules}$

But $1 \text{ MeV} = 1.60 \times 10^{-12} \text{ joules}$

$$\Delta E = \frac{14.9 \times 10^{-11} \text{ joules}}{1.6 \times 10^{-13} \text{ joules/MeV}} = 931 \text{ MeV}$$

SG 24.2

The expected energy loss calculated from the difference in rest mass can be compared with the result of a direct experiment. When hydrogen is bombarded with neutrons, a neutron can be captured in the reaction:

$$_0n^1 + {}_1H^1 \rightarrow {}_1H^2 + \gamma$$

This reaction produces no particle fragments having large kinetic energy, so the mass of 0.002388 amu by which $_1H^2$ is lighter than $_0n^1 + _1H^1$ must be carried away by the γ ray. The energy of the γ ray has been determined experimentally, and is found to be 2.22 MeV, just as predicted! The inverse reaction, in which deuterium is bombarded with γ rays, has also been studied:

$$_1H^2 + \gamma \quad \rightarrow \quad _1H^1 + _0n^1$$

When the energy of the γ rays is less than 2.22 MeV, this reaction cannot occur. But if we use γ rays of energy 2.22 MeV or greater, the reaction does occur: the proton and neutron separate and can be detected.

Following the "capture" of a neutron by the nucleus $_1H^1$, energy is liberated in a γ ray. The energy 2.22 MeV is called the *binding energy* of the deuteron. It can be thought of as the energy released when a proton and neutron combine to form a nucleus. To get the inverse reaction (when $_1H^2$ is bombarded with γ rays), energy must be absorbed. So one can think of the binding energy as the amount of energy *needed* to break the nucleus up into its constituent nuclear particles.

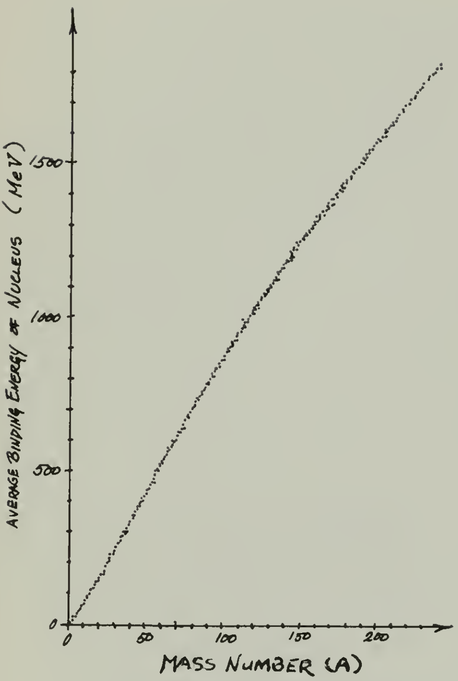
The concept of binding energy was, of course, already implied in earlier parts of the course, though not applied to nuclear physics. For example, the earth is held in orbit around the sun and would need to be given a certain additional amount of kinetic energy to escape from the sun, which binds it by gravitational attraction. In a hydrogen atom, the electron needs 13 eV before it can escape from the nucleus that binds it by an electric attraction. And conversely, when a bare $_1H^1$ nucleus captures an electron and becomes a stable, ordinary neutral atom of hydrogen, the system must give up an amount of energy equal to 13 eV by radiation—exactly the observed energy of the photon emitted in this process of electron capture.

Q2 When energy is "liberated" during a nuclear reaction, what becomes of it?

Q3 What is the definition of binding energy for the case of the deuteron nucleus?

24.3 Nuclear binding energy and stability

The calculation of nuclear binding energy made for deuterium can be extended to all other nuclear species. But it is first necessary to explain a convention: in practice, physicists make such calculations for neutral atoms rather than for bare atomic nuclei. (Experimental values of masses found from mass-spectrographic measurements are for atoms that are missing only one or two electrons.) Since an atom contains electrons orbiting around the nucleus as well as the protons and neutrons inside the nucleus, the mass of one electron outside the nucleus must be included for every proton inside the nucleus in the calculations.



Nuclear binding energy as a function of the number of particles in the nucleus.

The following example illustrates the calculations that allow finding the nuclear binding energy of an atom. Let us compare the actual mass of a carbon-12 atom with the sum of the masses of its component particles:

rest mass of 6 hydrogen atoms (includes 6 protons and 6 electrons)	6 × 1.007825 =	6.04695 amu
rest mass of 6 neutrons	6 × 1.008665 =	6.05199
total rest mass of particles		= 12.09894
rest mass of carbon-12 atom		= 12.00000
difference in rest mass (Δm)		= 0.09894

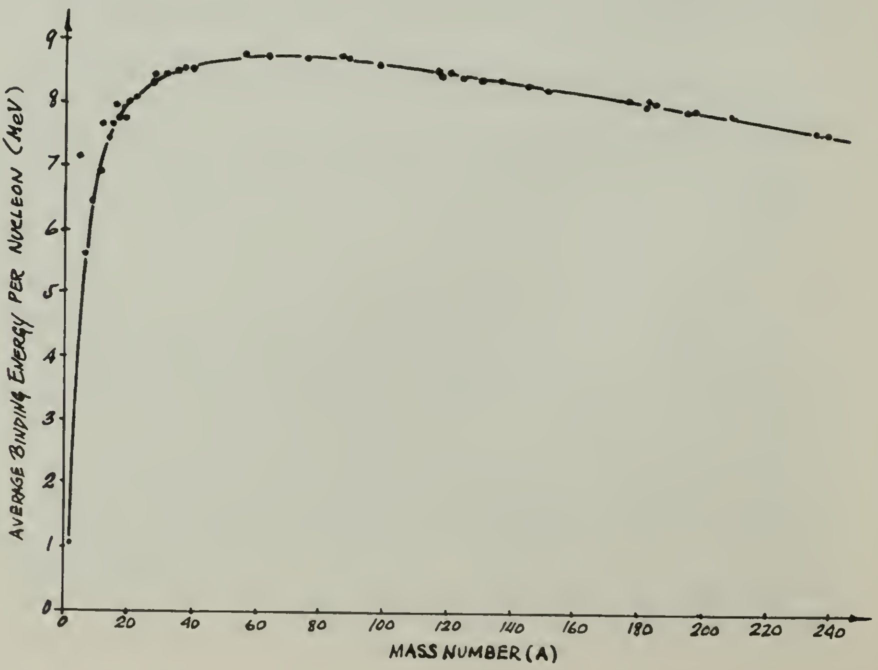
corresponding energy=

0.09894 amu × 931 MeV/amu = 92.1 MeV

In the same manner one can calculate the nuclear binding energy of any stable atom. The figure in the margin shows in graphic form how the nuclear binding energy for stable nuclides actually increases with increasing atomic mass, as more particles are added to form the nucleus. The term *nucleons* refers to both protons and neutrons, so we can say that the binding energy of the nucleus increases with the number of nucleons. But as you see, the answer is not a straight line. Such experimental data have important implications.

The implications can be seen more clearly if we calculate the *average binding energy per particle*. In the case of the carbon-12 example, we found the total binding energy to be 92.1 MeV. Since we are dealing with 12 particles inside the nucleus (6 protons and 6 neutrons), the average binding energy per particle in 92.1 MeV/12 or 7.68 MeV. In the graph at the bottom of the page, the values of average binding energy per particle (in MeV) are plotted

Notice the unusually high position (above the curve) of the dot near 7.1 MeV, compared to its neighbors. The point is for He^4. The relatively high value of the binding energy of their nucleus is related to its unusually great stability.



Average nuclear binding energy per particle as a function of the number of particles in the nucleus.

against the number of particles in the nucleus (mass number, A). The significance of the graph lies in its striking shape.

Note that the binding energy per particle starts with a low value for deuterium (the first point), and then increases rapidly. Some nuclei in the early part of the curve, for example He^4, C^{12}, and O^{16}, have exceptionally high values as compared with their neighbors. More energy would have to be supplied to remove a particle from one of them than from one of their neighbors. We would therefore expect He^4, C^{12} and O^{16} to be exceptionally stable. There is evidence in favor of this conclusion: for example, the fact that the four particles making up the He^4 nucleus are emitted as a single unit, the α particle, in radioactivity. The curve has a broad maximum, extending from approximately $A = 50$ to $A = 90$ and then drops off for the heavy elements. Thus ${}_{29}Cu^{63}$ near the maximum is found to have a binding energy per particle of about 8.75 MeV, while ${}_{92}U^{235}$, near the high-A end of the curve, has a value of 7.61 MeV. It follows that the nuclei in the neighborhood of the maximum of the curve, like those of copper, should be more difficult to break up than those of uranium.

SG 24.3

Remember: high binding energy per particle means lots of energy needed per particle to take the nucleus apart into its constituent nucleons.

The idea of binding energy should now make it clear why atomic masses, when precisely measured, turn out not to be exactly whole-number multiples of the mass of a hydrogen atom, even though nuclei are just collections of identical protons and neutrons. When those particles combined to make a nucleus, their total rest mass was reduced by an amount corresponding to the binding energy—and the average binding energy varies from nuclide to nuclide, as shown in the lower graph on p. 78.

With the information we now have about the nuclear binding energy, we shall be able to calculate and predict the energy needed for or released in nuclear reactions. (The average binding energy curve has other important implications which we shall mention later.)

Q4 Which would be more stable, a nuclide with a high *total* binding energy, or a nuclide with a high *average* binding energy per nucleon?

24.4 The mass-energy balance in nuclear reactions

In the previous section we used a very simple nuclear reaction to introduce the concept of binding energy. In this section we shall use a more complicated reaction to show an important relation between the binding energy and the energy liberated in a nuclear reaction.

We shall analyze the mass-energy balance in the reaction of a proton with lithium 7:

$$ {}_1H^1 + {}_3Li^7 \rightarrow {}_2He^4 + {}_2He^4 $$

This reaction has historical interest: it was the first case of a nuclear disintegration brought about by artifically accelerated particles; and the analysis of the reaction provided one of the earliest quantitative tests of Einstein's mass-energy relation. The reaction was a good one to analyze because the masses of the proton, the α particle and the lithium atom were known, and the kinetic energies of the incoming proton and the two resulting α particles could be measured accurately (by their ionizing effects).

REST MASSES

	before		*after*
Li^7	7.016005 amu	He^4	4.002604 amu
H^1	1.007825 amu	He^4	4.002604 amu
	8.023830 amu		8.005208 amu

difference

$$\begin{array}{rr} & 8.023830 \text{ amu} \\ - & \underline{8.005208 \text{ amu}} \\ \Delta m = & 0.018622 \text{ amu} \end{array}$$

$$0.018622 \text{ amu} \times 931 \text{ MeV/amu} = 17.3 \text{ MeV}$$

rest mass of Li^7 atom = 7.016005 amu
rest mass of H^1 atom = 1.007825 amu
rest mass of He^4 atom = 4.002604 amu

The energy we expect to be released in the reaction may be calculated by finding the difference in rest masses before and after the nuclear reaction takes place. The rest mass of the products is less by 0.018622 amu compared with the rest mass of the initial atoms, corresponding to a deficit of 17.3 MeV. The corresponding deficit in energy, 17.3 MeV, appears as the kinetic energy of the two α particles emitted. (In fact the incident proton also has kinetic energy, so that the 17.3 MeV represents the *difference* between the kinetic energies of the two emitted α particles and the kinetic energy of the incident proton.)

When the experiment is made, one finds full agreement between the expected kinetic energy deficit calculated from the data for the rest masses and the experimental value found for the kinetic energies. This agreement shows that the mass-energy relation is valid. There is a release of energy when the lithium atom is broken up, and this release shows up at the expense of some of the rest mass of its fragments. This experiment was first done in 1932; since then, hundreds of nuclear transformations have been studied, and the results have invariably agreed with the mass-energy relationships calculated by means of the equation $\Delta E = \Delta mc^2$.

The balance of rest mass and kinetic energy can be related to the idea of binding energy. In the lower graph on page 78, the average binding energy per nucleon of the lithium-7 nucleus is given as 5.6 MeV. Since lithium 7 has seven particles in the nucleus, the total nuclear binding energy is 7 × 5.6 MeV = 39.2 MeV. The incident proton has no binding energy. The nuclear binding energy of each α particle (He^4 nucleus) is 28.3 MeV making a total of 56.6 MeV for the two α particles. The difference between the binding energies before and after shows how much more tightly the nucleons in the product fragments are bound: 56.6 MeV − 39.2 MeV = 17.4 MeV: consequently there have to be 17.4 MeV of energy released in the reaction, appearing as kinetic energy of the fragments. This checks closely with the experimentally found kinetic energies.

SG 24.4

Analysis of many nuclear reactions verifies this general rule: *When the total binding energy of the products exceeds that of the reactants, energy is liberated.* We can express this also as when the products of a nuclear reaction have greater average binding energy per particle than the reactants do, energy is liberated. This rule is a summary of the fact that energy will be liberated in a nuclear reaction when the products lie higher on the average binding energy curve than the reactants do.

SG 24.5–24.7

The shape of the average binding energy curve, which drops off at both ends, indicates therefore that there are two general nuclear reaction processes by which one can hope to release energy from nuclei: combining light nuclei into a more massive nucleus, or splitting up heavy nuclei into nuclei of medium mass. In either process the products would have greater average binding energy, so energy would be released. A process in which two nuclei join together to form a heavier nucleus is called *nuclear fusion*. A process in which a heavy nucleus splits into fragments of intermediate mass is called *nuclear fission*. Both fusion and fission have been shown to occur, and the technology of fission has been simplified and exploited in many countries. Fission reactions can be made to take place slowly (as in a nuclear power plant) or very rapidly (as in a nuclear explosion).

Q5 Would breaking up a heavy nucleus into very many light nuclei result in the liberation of energy?

24.5 Nuclear fission: discovery

The discovery of nuclear fission is an example of an unexpected result of great practical importance, obtained during the course of research carried on for reasons having nothing to do with the possible usefulness of the discovery. It is also an excellent example of the combined use of physical and chemical methods in nuclear research, and of the effectiveness of team work. After Joliot and Curie showed that some products of nuclear reactions are radioactive (Sec. 23.9), Fermi and his colleagues in Italy undertook a systematic study of nuclear reactions induced by neutrons. One of the purposes of this research was to produce new nuclides. As a result, many new radioactive nuclides were made and their half-lives determined. One nuclear reaction used successfully in this study was the capture of a neutron followed at once by the emission of a γ ray. For example, when aluminum is bombarded with neutrons, the following reaction occurs:

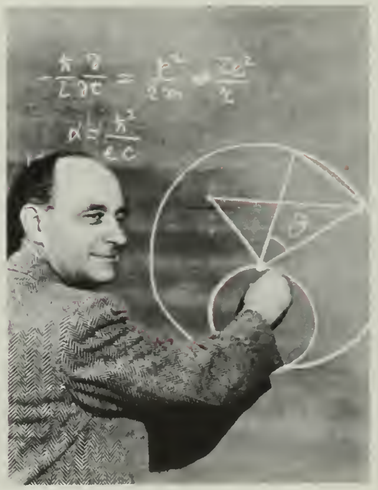
$$_0n^1 + {}_{13}Al^{27} \rightarrow {}_{13}Al^{28} + \gamma$$

Aluminum 28 is radioactive, with a half-life of 2.3 minutes, decaying by β emission into silicon:

$$_{13}Al^{28} \rightarrow {}_{14}Si^{28} + {}_{-1}e^0 + \bar{\nu}$$

As a result of these two reactions, a nuclide ($_{14}Si^{28}$) is produced with values of Z and A each greater by one unit than those of the initial nucleus. Fermi thought that if neutrons bombarded uranium – the atomic species having the largest value of Z known then – an entirely *new* element might be formed by the β decay of the heavier uranium isotope:

A few of the problems encountered by Fermi in his work on these reactions were described in the Prologue to Unit 1. The supplemental Project Physics Unit "Discoveries in Physics" goes into more detail on the discovery of fission.



Enrico Fermi.

SG 24.8

$$_0n^1 + {}_{92}U^{238} \rightarrow {}_{92}U^{239} + \gamma$$

$$_{92}U^{239} \rightarrow {}_{93}(?)^{239} - {}_{-1}e^0 + \bar{\nu}$$

He also speculated that the new nuclide denoted by $_{93}(?)^{239}$ in turn might also undergo β decay:

$$_{93}(?)^{239} \rightarrow {}_{94}(?)^{239} + {}_{-1}e^0 + \bar{\nu}$$

In this way, two new elements might be produced (one with $Z = 93$, one with $Z = 94$). If these reactions could really be made to occur, the result would be the man-made production of an element, or elements, not previously known to exist—*transuranium elements*.

Fermi found in 1934 that the bombardment of uranium with neutrons actually produced new radioactive elements in the target as shown by the emission of rays and a decay activity that defined new, relatively short half-lives. The new elements were at first assumed to be the hypothesized transuranium elements.

The results aroused much interest, and in the next five years a number of workers experimented with the neutron bombardment of uranium. Many different radioactive half-lives were found for the radiation from the target, but attempts to identify these half-lives with particular elements led to great confusion. The methods used were similar to those used in the study of the natural radioactive elements (Sec. 21.7). But the difficulty was even greater because a radioactive nuclide formed in a nuclear reaction is usually present in the target area only in an extremely small amount, possibly as little as 10^{-12} grams; special techniques to separate these small quantities had to be developed.

The reason for the confusion was found early in 1939 when Otto Hahn and Fritz Strassmann, two German chemists, showed definitely that one of the supposed transuranium elements was actually an isotope of *barium* ($_{56}Ba^{139}$), identified by its half-life of 86 minutes and its chemical behavior. Another nuclide resulting from the neutron bombardment of uranium was identified as lanthanum ($_{57}La^{140}$), with a half-life of 40 hours.

The production of the nuclides $_{56}Ba^{139}$ and $_{57}La^{140}$ from uranium, a nuclide with the atomic number 92 and an atomic mass of nearly 240, required an unknown kind of nuclear reaction, one in which the heavy nucleus is split almost in half. Nothing like it had been known to exist before. If such a process really occurred, it would also have to be possible to find "the other half," that is, to find nuclides with mass between 90 and 100 and atomic numbers of about 35. Indeed, Hahn and Strassmann were able to find in the target material a radioactive isotope of strontium ($Z = 38$) and one of yttrium ($Z = 39$) which fulfilled these conditions, as well as isotopes of krypton ($Z = 36$) and xenon ($Z = 54$). It was clear from the chemical evidence that the uranium nucleus, when bombarded with neutrons, can indeed split into two nuclei of intermediate atomic mass.

Although Hahn and Strassmann showed that isotopes of intermediate mass did appear, they hesitated to state the conclusion

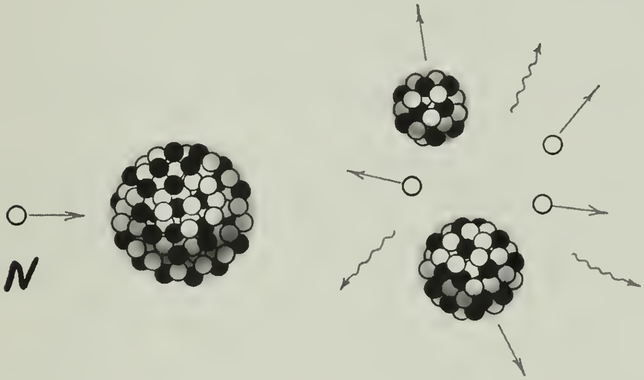
Starting about six years after Fermi's speculation of 1934, it was found possible, by a variety of methods, to create transuranium elements. The new elements up to $Z = 103$, are listed below. A tiny sample of one of them, curium 244—dissolved in a test tube of water, is shown in the 5-minute exposure above (by light produced when the radiation interacts with the surrounding matter).

$_{92}U$	Uranium
$_{93}Np$	Neptunium
$_{94}Pu$	Plutonium
$_{95}Am$	Americium
$_{96}Cm$	Curium
$_{97}Bk$	Berkelium
$_{98}Cf$	Californium
$_{99}Es$	Einsteinium
$_{100}Fm$	Fermium
$_{101}Md$	Mendelevium
$_{102}No$	Nobelium
$_{103}Lw$	Lawrencium

that the uranium nucleus could be split. In their historic report, dated January 9, 1939, they said:

> On the basis of these briefly presented experiments, we must, as chemists, really rename the previously offered scheme and set the symbols Ba, La, Ce in place of Ra, Ac, Th. As "nuclear chemists" with close ties to physics, we cannot decide to make a step so contrary to all existing experience of nuclear physics. After all, a series of strange coincidences may, perhaps, have led to these results.

The step which Hahn and Strassmann could not bring themselves to take was taken on January 16, 1939 by two Austrian physicists, Lise Meitner and Otto R. Frisch. They suggested that the neutron provoked a disintegration of the uranium nucleus into "two nuclei of roughly equal size," a process which they called "nuclear fission" by analogy to the biological division, or fission, of a living cell into two parts. On the basis of comparison of the low average binding energy per nucleon of uranium with the higher average binding energy per nucleon of the products, they predicted that the fragments would have high kinetic energy. This was soon verified experimentally. Shortly afterward, it was found that transuranium elements may, after all, *also* be formed when uranium is bombarded with neutrons. In other words the capture of a neutron by uranium sometimes leads to fission, and sometimes leads to β decay. The β decay results in the formation of isotopes of elements of atomic number 93 and 94 – later, named *neptunium* and *plutonium*. The presence of both types of reaction – fission, and neutron capture followed by β decay – was responsible for the difficulty and confusion in the analysis of the effects of neutrons on the uranium target. Now, the interpretation of the experiments opened two new fields of scientific endeavor: the physics and chemistry of the transuranium elements, and the study of nuclear fission.



Schematic diagram representing uranium fission.

Lise Meitner and Otto Hahn

Lise Meitner, born in Austria, joined Otto Hahn in 1908 in a research collaboration that lasted thirty years. In 1938, Miss Meitner was forced to leave Germany by the Hitler regime. She was in Sweden when she published the first report on fission with her nephew, O. R. Frisch.

Otto R. Frisch

The discovery of nuclear fission inspired research workers all over the world, and much new information was obtained within a short time. It was found that the uranium nucleus, after capturing a neutron, can split into one of more than 40 different pairs of fragments. Radio-chemical analysis showed that nuclides resulting from fission have atomic numbers between 30 and 63 and mass numbers between 72 and 158.

Yet nuclides of medium mass are not the only fission products. Neutrons also are emitted in fission; the average number of neutrons emitted is usually between 2 and 3. The following reaction indicates only one of the many ways in which a uranium nucleus can split:

SG 24.9, 24.10

$${}_0n^1 + {}_{92}U^{235} \quad \rightarrow \quad {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\ {}_0n^1$$

${}_{56}Ba^{141}$ and ${}_{36}Kr^{92}$ are not "natural" nuclides, and are not stable; they are radioactive and decay by β emission. For example, ${}_{56}Ba^{141}$ can decay into ${}_{59}Pr^{141}$ by successive emission of three β particles, as shown by the following scheme (the numbers in parentheses are the half-lives):

$${}_{56}\mathrm{Ba}^{141} \xrightarrow[\text{(18 min)}]{{}_{-1}e^{\circ}} {}_{57}\mathrm{La}^{141} \xrightarrow[\text{(3.6 hr)}]{{}_{-1}e^{\circ}} {}_{58}\mathrm{Ce}^{141} \xrightarrow[\text{(32 days)}]{{}_{-1}e^{\circ}} {}_{59}\mathrm{Pr}^{141}$$

Similarly, ${}_{36}Kr^{92}$ is transformed into ${}_{40}Zr^{92}$ by four successive β decays. See SG 24.11.

It has been found that only certain nuclides can undergo fission. For those which can, the probability that a nucleus will split when bombarded depends on the energy of the neutrons used in the bombardment. The nuclides ${}_{92}U^{235}$ and ${}_{94}Pu^{239}$ can undergo fission when bombarded with neutrons of *any* energy even 0.01 eV or less. On the other hand, U^{238} and Th^{232} undergo fission only when bombarded with neutrons having kinetic energies of 1 MeV or more.

Plutonium 239 (${}_{94}Pu^{239}$) is produced by the capture of a neutron by ${}_{92}U^{238}$ and the subsequent emission of two β particles, as was discussed on p. 82.

The energy released in the fission of a nucleus is about 200 MeV. This value can be calculated either by comparing atomic rest masses of reactants and products, or from the average binding energy curve of the graph on p. 78. The energy release in fission is more than 20 times larger than in the more common nuclear reactions where it is usually less than 10 MeV, and more than a million times larger than in chemical reactions.

Under appropriate conditions the neutrons released in fission can, in turn, cause fission in neighboring uranium atoms, and a process known as a *chain reaction* can develop in a sample of uranium. The combination of the large energy release in fission and the possibility of a chain reaction is the basis of the large-scale use of nuclear energy.

Q6 What two successive reactions can result in the appearance of a transuranium element?

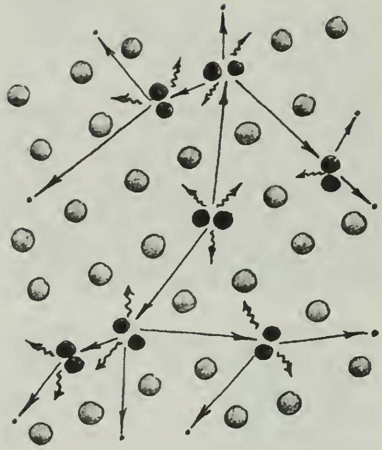
Q7 What product of the fission process makes a chain reaction possible?

24.6 Nuclear fission: controlling chain reactions

For a chain reaction in a sample of uranium to continue at an even rate, there must be a favorable balance between the net *production* of neutrons by fissions, and the *loss* of neutrons due to the following three processes:

1. capture of neutrons by uranium without fission resulting;
2. capture of neutrons by other materials in the sample or the structure containing the sample;
3. escape of neutrons from the sample without being captured.

If too *many* neutrons escape from or are absorbed in the structure or assembly (called a "reactor") there will not be enough to sustain the chain reaction. If too *few* neutrons escape or are absorbed, the reaction will continue to build up more and more. The design of nuclear reactors as energy sources involves finding proper sizes, shapes, and materials to maintain or control a balance between neutron production and neutron loss.



A schematic diagram of the beginning of a chain reaction. The nucleus in the center has fissioned into 2 parts, releasing also gamma rays and neutrons. Some of the neutrons are captured by other nuclei, promoting further fissioning with the accompanying release of more neutrons. . . and so on.

Since the nucleus occupies only a tiny fraction of an atom's volume, the chance of a neutron colliding with a uranium nucleus is small, and a neutron can go past the nuclei of billions of uranium (or other) atoms while moving a few inches. If the reactor assembly is small, a significant percentage of the fission neutrons can escape from the assembly without causing further fissions. The "leakage" of neutrons can be so large that a chain reaction cannot be sustained. The number of neutrons produced is proportional to the *volume*, but the number of neutrons that escape is proportional to the *surface area.* As the linear size L of the assembly is increased, the volume and area increase in proportion to L^3 and L^2; so neutron *production* increases with size more rapidly than neutron *escape* does. For a given combination of materials—uranium and other structural materials which may be needed—there is a size of the reactor, called the critical size, for which the net production of neutrons by fission is just equal to the loss of neutrons by non-fission capture and escape. If the size of the reactor assembly is smaller than this critical size, a chain reaction cannot be sustained. The design of a reactor of reasonable dimensions with given materials which will correspond to critical size is an important part of research in the field of "nuclear engineering."

SG 24.12

Another important consideration in the design of nuclear reactors is the fact that fission is much more probable when U^{235} is bombarded with *slow* neutrons than when it is bombarded with fast neutrons. The neutrons released in fission generally come out at very high speeds having kinetic energies from about 0.01 MeV to nearly 20 MeV, with an average kinetic energy of about 2 MeV. But the fast neutrons can be slowed down in the reactor by the addition of material to which the neutrons can lose energy in collisions. The material should be relatively low in atomic mass so that the neutrons will transfer a significant fraction of their energy in elastic collision; but the material should not also capture and absorb many neutrons. Pure carbon in the form of graphite, and also water and beryllium meet these requirements. These substances are called *moderators* because they slow down—moderate—the newly produced neutrons to lower speeds at which the probability of causing additional fission is high.

Although nuclear reactors can be built in which the fissions are induced by fast neutrons, it has been easier to build reactors with materials in which the fissions are induced by slow neutrons.

We have described (Sec. 23.4) how neutrons lose nearly all their kinetic energy in a headon collision with a hydrogen nucleus—but most collisions will not be head-on.

Hydrogen atoms in water are very effective in slowing down neutrons because the mass of a hydrogen nucleus is nearly the same as that of a neutron and because the number of hydrogen atoms per unit volume is high. A neutron can lose a large fraction of its energy in a collision with a hydrogen nucleus and only about 20 collisions are needed, on the average, to slow down the fast neutron to energies under 1 eV. However, neutrons can also be captured by the hydrogen nucleus in the reaction:

$${}_1H^1 + {}_0n^1 \quad \rightarrow \quad {}_1H^2 + \gamma$$

The probability of this reaction occurring instead of an elastic collision is high enough so that it has been found impossible to achieve a chain reaction with natural uranium and ordinary water.

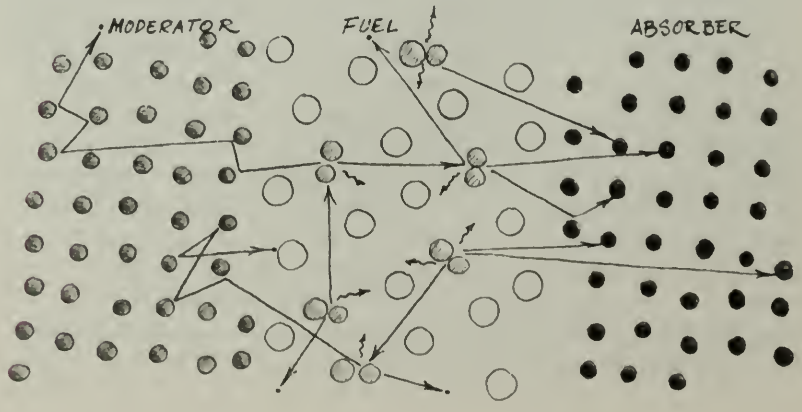
Heavy water: $(H^2)_2O$, or D_2O.

$${}_1H^2 + {}_0n^1 \xrightarrow{\text{(low probability)}} {}_1H^3 + \gamma$$

But there are other ways to make reactors. We note, for example, that the absorption of a neutron by a deuterium nucleus—such as the nucleus of the heavy isotope of hydrogen, found in heavy water—has an extremely small probability. Neutrons do not lose as much energy per collision with H^2 nuclei, but this disadvantage is overbalanced by the much lower absorption rate—so a chain reaction can be achieved easily with natural uranium and heavy water. Reactors with natural uranium as the fuel and heavy water as the moderator have been built in the United States, Canada, France, Sweden, Norway and other countries.

The contrast between the nuclear properties of hydrogen ${}_1H^1$ and deuterium (${}_1H^2$ or ${}_1D^2$) has important implications for the development of nuclear reactors. Heavy water is much more expensive than ordinary water, but when it is used with natural uranium (mostly U^{238}), a chain reaction can be achieved efficiently. Ordinary water can be used, if uranium enriched in the isotope U^{235} is used instead of natural uranium. Many reactors "fueled" with enriched uranium and moderated with ordinary water have been built in the United States. In fact, this general reactor type has been used in nearly all the large nuclear power plants built so far, and in the reactors used in nuclear-powered ships.

Carbon in the form of graphite has been used as a moderator



Schematic diagram of three types of functions fulfilled by parts of a nuclear reactor.

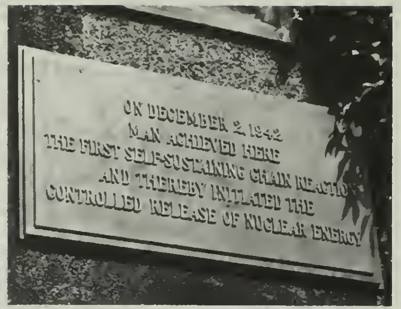
in many reactors, including the earliest ones. It is not as good a slowing-down agent as water or heavy water; about 120 collisions with carbon atoms are needed to slow down a fast neutron with an initial energy of 2 MeV to the energy of about 0.025 eV desired; in heavy water only about 25 collisions are needed. Although carbon in the form of graphite is not the best moderator and absorbs some neutrons, it does permit a chain reaction to occur when lumps of natural uranium (cylindrical rods, for example) are arranged in a large mass of graphite. The determination of just how this could be done was one of the main problems that had to be solved before the world's first chain reaction was achieved by a team under Enrico Fermi in December 1942 at the University of Chicago. (It was a crucial experiment because until its success it was by no means certain that a chain reaction was really possible.) Many graphite-moderated reactors are now in operation throughout the world. Their chief purpose will be discussed in the next section.

The control of a reactor is relatively simple. If fission is occurring too frequently, a few "control" rods are inserted into the reactor. The rods consist of a material (such as cadmium or boron) that absorbs slow neutrons, thereby reducing the number of neutrons in the moderator. Removal of the control rods will allow the rate of the reactor to go up. The sketch at the bottom of the opposite page illustrates the basic reactions that occur in a nuclear reactor in which uranium is the fissionable material.

Q8 What is a "moderator"?

Q9 What is an advantage and a disadvantage of using water as a moderator in nuclear reactors?

Q10 How can the rate of reaction be controlled in a reactor?



The west wall of the football stands of Stagg Field, University of Chicago. Squash courts under these stands were used as the construction site of the first nuclear reactor. Below is an artist's sketch of that graphite-moderated reactor during the experimental run on December 2, 1942, when it first became self-sustaining.

24.7 Nuclear fission: large-scale energy release and some of its consequences

The large-scale use of nuclear energy in chain reactions was accomplished in the United States between 1939 and 1945. The work was done under the pressure of World War II, as a result of the cooperative efforts of large numbers of scientists and engineers. The workers in the United States included Americans, Britons, and European refugees from fascist-controlled countries.

Fission occurs less than one billionth of a second after the neutron is captured.

The aim was to produce a so-called *atomic* (more properly, *nuclear*) bomb, essentially an uncontrolled nuclear reactor in which an extensive chain reaction occurs throughout the material in a few millionths of a second. This differs therefore from the controlled nuclear reactor, in which the operating conditions are so arranged that the energy from fission is released at a much slower and essentially constant rate. In the controlled reactor the fissionable material is mixed with other materials in such a way that, on the average, only *one* of the neutrons emitted in fission causes the fission of another nucleus; in this way the chain reaction just sustains itself. In a nuclear bomb the fissionable material is pure (that is, not mixed with a moderator) and the device is designed so that nearly all of the neutrons emitted in each fission can cause fissions in other nuclei.

Recall that fission of U^{235} can occur with neutrons of any speed, but fission of U^{238} requires high-speed neutrons.

Nuclear reactors were used during World War II to produce raw materials for one kind of nuclear bomb, namely to manufacture Pu^{239} from U^{238}. These reactors were designed in such a way that some of the neutrons from the fission of U^{235} were slowed down sufficiently *not* to cause fission in U^{238} atoms. (In natural uranium only about $\frac{3}{4}$ % of the atoms are U^{235}.) Instead, the neutrons were absorbed by U^{238} nuclei to form Pu^{239} through the reactions described in the previous section.

Pu^{239} acts similar to U^{235}; both materials can sustain a rapid, uncontrolled chain reaction. Nuclear bombs have been made of both materials; a single nuclear bomb, using U^{235}, destroyed the city of Hiroshima, Japan, on August 6, 1945; another bomb, using ${}_{94}Pu^{239}$, destroyed the city of Nagasaki three days later. Since the end of World War II in 1945, the technology of fission has been further developed in two different directions. One direction has been military. Other countries besides the United States have made nuclear weapons, including (as of 1970) the United Kingdom, the Soviet Union, France, and China. The enormous death-dealing capability of these weapons, and the ever-larger numbers of bombs of many varieties that have been accumulating all over the globe, have increased and made more dangerous the tensions existing throughout the world and have emphasized critically the need for the peaceful settlement of international disputes.

From the beginning, scientists have been prominently involved in activities to alert their government and fellow citizens to the moral and practical problems raised by the nuclear weapons race. See *Reader 6*, "Report to the Secretary of War" by James Franck and colleagues.

One incidental problem has been that of the radioactive *fallout* from bomb tests. In the explosion of a nuclear bomb, large amounts of radioactive fission products are scattered. These materials can be blown by winds from one part of the world to another and carried down from the atmosphere by rain or snow. Some of the radioactive materials are long-lived; they may be absorbed in growing foodstuffs and eaten by animals and people. It is known that such radioactive materials can cause harmful genetic effects as well as somatic effects. One of the most abundant and long-lived products of the fission of either U^{235} or Pu^{239} is strontium 90 ($_{38}Sr^{90}$). This isotope of strontium is similar to $_{20}Ca^{40}$ in its chemical properties. Hence when Sr^{90} from radioactive fallout enters the body, it finds its way into bone material. It decays by emission of 0.54-MeV β particles (half-life = 28 years), which can injure cells and cause leukemia, bone tumor, and possibly other forms of damage, particularly in growing children.

Genetic effects of radiation: effects producing changes in cells which will affect offspring of exposed individual.
Somatic effects: all effects caused by radiation to an exposed individual during his lifetime.

A grain of radioactive dust from the atmosphere caused these α-particle tracks in a photographic emulsion (enlarged 2000 times).

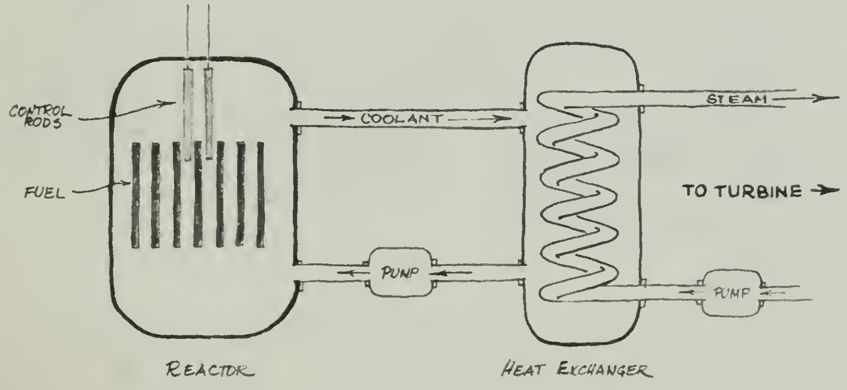
There has been much research and discussion concerning possible harm to present and future generations. Partly as the result of petitions and protests organized by scientists, the United States, the United Kingdom, the Soviet Union and most other nations (but not France and China) agreed in 1963 to a moratorium on further bomb tests in the atmosphere. Though it allowed continuation of tests underground, the atmospheric test ban treaty was rightly considered a great step forward in simultaneously curbing radioactive pollution and increasing somewhat the chances for further arms control treaties. For example, it is said to have helped pave the way to the treaty, in effect since 1970, by which most nations agreed not to disseminate nuclear weapons to "non-nuclear" nations.

The second direction in which the use of nuclear energy has been pushed on a large scale has been in the production of electrical power from the energy released in fission. The increasing need for electrical energy is an important aspect of modern life. The amount of electricity used in an advanced industrial country, such as the United States, has been doubling approximately every ten years since about 1900. Although there are still large supplies of coal, oil, and natural gas, it is evident that additional sources of energy will be needed, and nuclear energy from fission can fill this need. Moreover, such energy plants avoid the chemical pollution of their environment, since this method of energy release does not involve combustion.

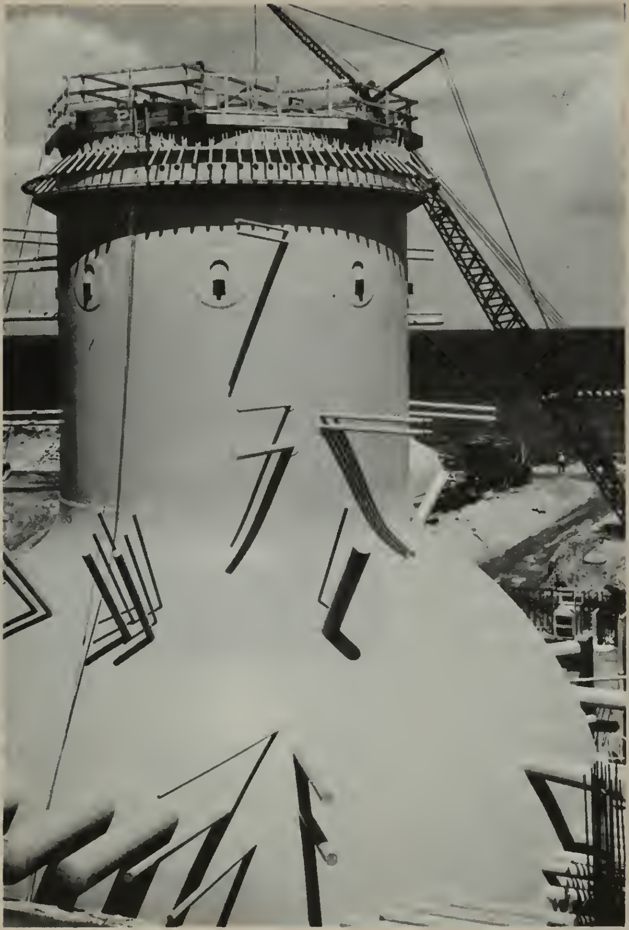
See "The Nuclear Energy Revolution" in *Reader 6.*

If proper controls are seriously applied, two remaining sources of pollution can also be avoided in such plants: thermal pollution by heating the water of streams or lakes used for cooling the reactor, and leakage of small quantities of radioactive materials from the reactor.

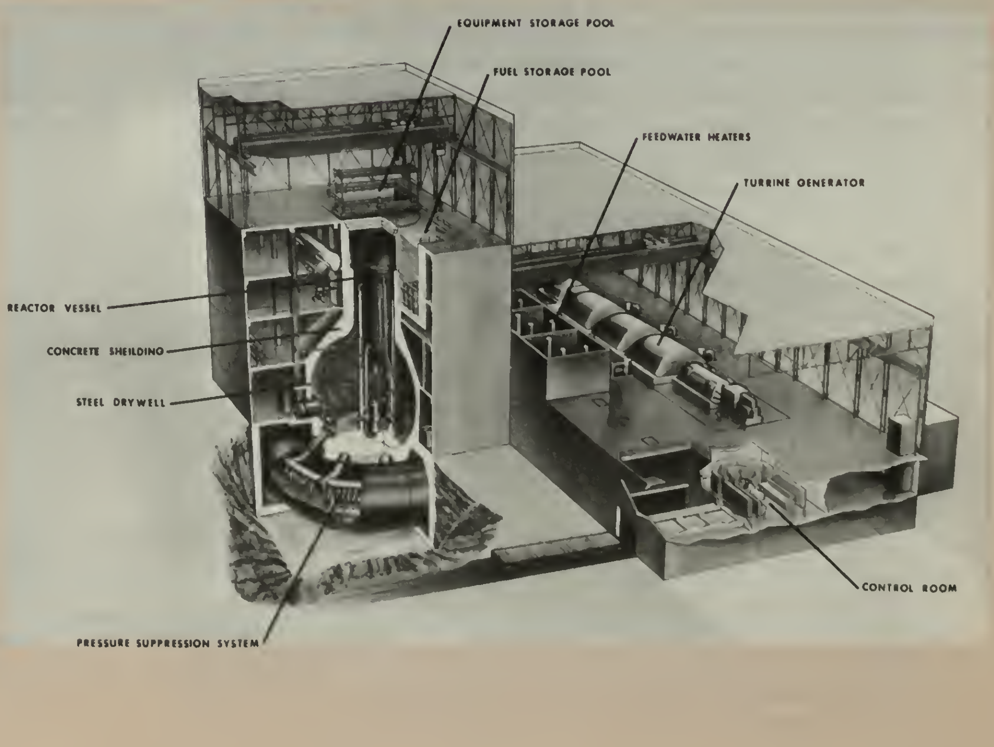
In almost all present systems of nuclear power production, the reactor is a source of heat for running steam turbines; the turbines drive electrical generators just as they do in conventional power stations.

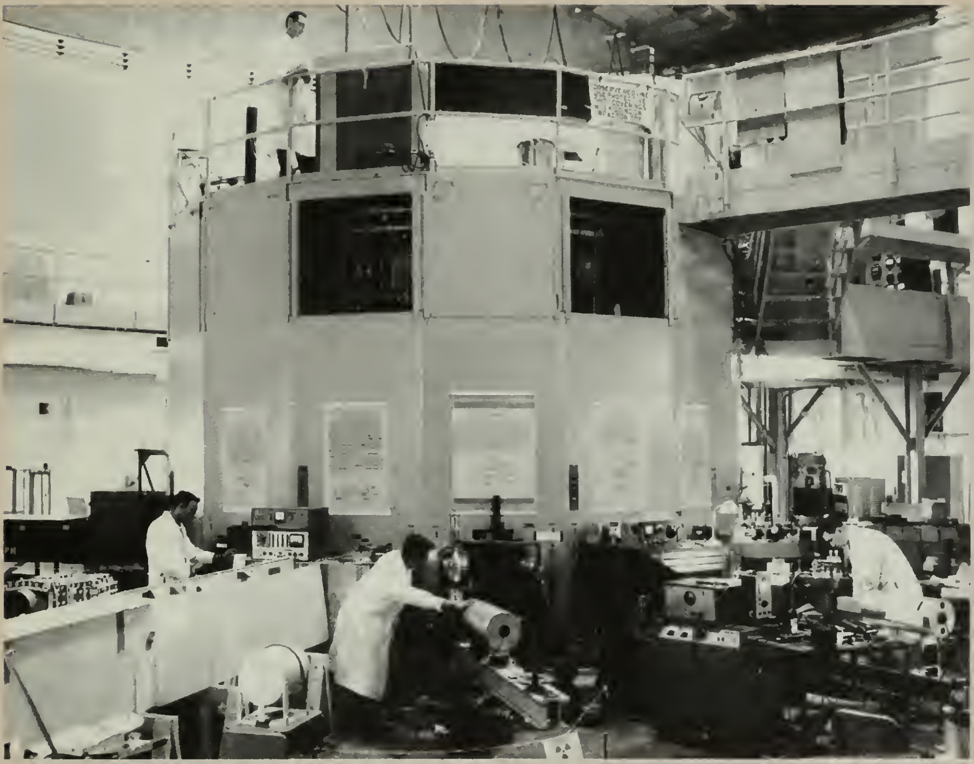


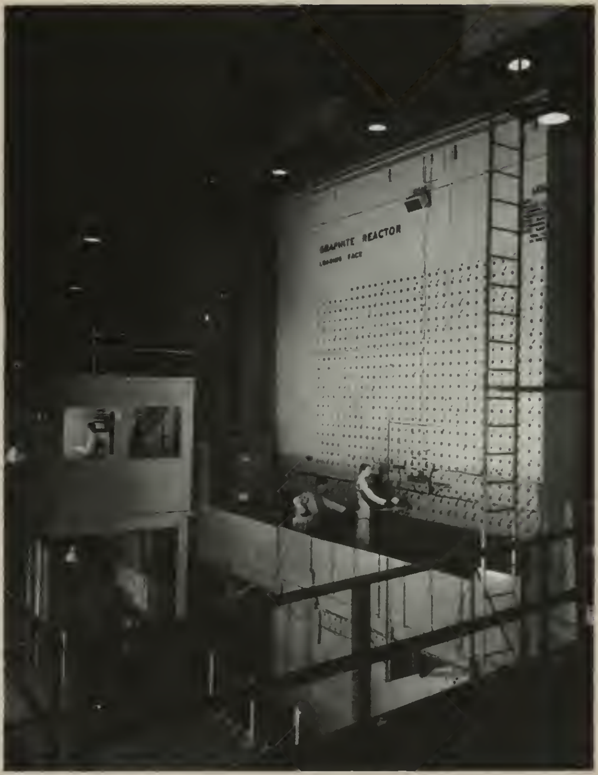
Heat produced in a reactor (by the flying fission fragments) does not directly turn water to steam. As this simplified diagram indicates, the water is heated in a "heat exchanger" by a fluid that circulates through the reactor core.



The photograph at the left illustrates one type of commercial installation for converting the heat energy from a fission chain reaction into electrical energy. This steel "drywell" is the housing for the nuclear reactor at the Nine Mile Point generating station, near Oswego on Lake Ontario. The cutaway drawing below shows the reactor, turbine-generator and other components of a similar installation at the Dresden nuclear power station at Joliet, Illinois.







Above is a small research reactor at M.I.T. in Cambridge, Mass.
At the right, technicians load "fuel" slugs containing fissionable materials into the A.E.C.'s graphite-moderated reactor at Oak Ridge, Tennessee.

See "Twentieth Birthday of the Atomic Age" and "Calling all Stars" in *Reader 6.*

For a variety of reasons, some administrative and some technical, but mostly connected with the "Cold War" with the Soviet Union that started after World War II and intensified during the early fifties, the U.S. Atomic Energy Commission (AEC) did not emphasize applied research on nuclear-electric power systems until President Eisenhower so directed in 1953. By that time America's first experimental breeder reactor (EBR-1) had demonstrated for two years in Idaho that electric power could be produced in significant amounts while simultaneously producing (or "breeding") plutonium in a U^{238} blanket around the neutron-and-energy-producing core of U^{235} and moderator.

"Manhattan District" was the code name given to the bomb-development project during World War II.

Not until fully twenty years after the Manhattan project reached its goals could one say that the age of nuclear-electric generation of power had arrived. Nuclear energy sources became economically competitive with hydroelectric and fossil-fuel sources (coal, oil, natural gas) in the early 1960's when costs per kilowatt-hour from nuclear energy sources became as low as one-half cent. More than half of the total new electric power plant construction in the United States is now committed to nuclear sources. The United Kingdom and France also successfully used reactors to generate commercial electric power. Thus there finally are strong reasons for optimism concerning the new source of energy through nuclear fission.

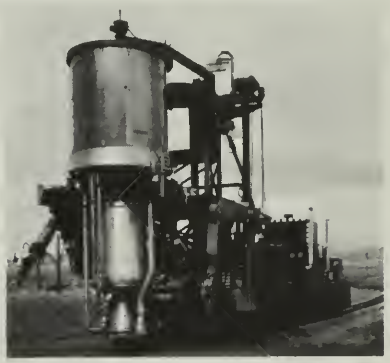
Such a new source was clearly needed, for along with the population explosion and the depletion of fossil fuels, an energy

Below is shown a model of a plant for producing both nuclear power and desalted water, designed to be built on a man-made island off the coast of southern California. It will generate electricity at the rate of 1.8 million kilowatts and also produce, by distillation, 150 million gallons of fresh water daily for use in cities, industries, and agriculture.

shortage threatened to limit mankind's future development. Nuclear power reactors, now entering a third generation of development, also show promise of being able to furnish energy economically for desalting sea water, to convert atmospheric nitrogen into powdered fertilizers, and to make fluid fuels from hydrocarbons in low-grade coal. If all this can be done cheaply enough with breeder reactors that produce at least as much fissionable material as they "burn," then indeed the war-born nuclear technology at last can have the beneficial impact on all human society that is desperately needed.

In the meantime, the social costs of the nuclear energy revolution have already been very high—in human lives, in money, and in the anxiety of life under the threat of nuclear war. In some ways these are analogous problems to the human price of industrialization after the development of the steam engine (Unit 3). At the same time, the potential benefit to man is great. As in the past, the decisions that will be necessary in the future development of nuclear power cannot be made on the basis of physics alone. Science can help to illuminate alternatives on which essentially political decisions can be based, but it cannot and should not be used by itself to choose among them. Responsible scientific opinion must be supplemented by political insight and a broad humanistic view of society. But at the very least, responsible citizens must have some understanding of the scientific principles that will underlie the alternatives among which they must choose.

A blast of exhaust (above) from an experimental nuclear rocket engine (below).



Among the many problems for public policy raised by developments in nuclear power is the Plowshare Program of the AEC. The crater at the left was part of Plowshare's research into the possibility of creating lakes, harbors and sea-level canals between oceans by exploding nuclear devices. The problems raised include those of pollution, the dangers of diversion of such devices for war purposes, and the wisdom of engaging on some large-scale projects that may end up moving mountains to serve the purposes of relatively small groups rather than all who will be affected by such transformations.

Chronology of Some Developments in Nuclear Science and Technology

1896	Becquerel discovers unstable (radioactive) atoms.
1899	Isolation of radium by Curies.
1905	Einstein's statement of equivalence of mass and energy.
1911	Rutherford discovers nucleus.
1919	Rutherford achieves transmutation of one stable chemical element into another.
1920-1925	Improved mass spectrographs show that changes in mass per nuclear particle accompanying nuclear reactions account for energy released by nucleus.
1931	Lawrence and Livingston construct first cyclotron.
1932	Chadwick identifies neutrons.
1934	Fermi's group in Rome finds radioactivity induced by neutrons.
1939	Evidence of uranium fission by Hahn and Strassmann, identification of fission products by Meitner and Frisch.
1940	Discovery of neptunium and plutonium at the University of California.
1942	Achievement of first self-sustaining nuclear reaction, University of Chicago.
1945	First test of a nuclear device, at Alamagordo, New Mexico, followed by the dropping of nuclear bombs in Hiroshima and Nagasaki, at the end of World War II.
1946	President Truman signs the bill creating the U.S. Atomic Energy Commission.
	First shipment of radioactive isotopes from Oak Ridge to hospital in St. Louis, Mo.
1951	First significant amount of electricity (100 kilowatts) produced from nuclear energy at testing station in Idaho.
1952	First detonation of a hydrogen bomb, Eniwetok Atoll, Pacific Ocean.
1953	President Eisenhower announces U.S. Atoms-for-Peace program and proposes establishment of an international atomic energy agency.
1954	First nuclear-powered submrine, *Nautilus*, commissioned.
1955	First United Nations International Conference on Peaceful Uses of Atomic Energy held in Geneva, Switzerland.
1956	First commercial power plant begins operation at Calder Hall, England.
1957	Shippingport Atomic Power Plant in Pennsylvania reaches full power of 60,000 kilowatts.
	International Atomic Energy Agency formally established.
1959	First nuclear-powered merchant ship, the *Savannah*, launched at Camden, New Jersey.
1961	A radioactive isotope-powered electric generator placed in orbit, the first use of nuclear power in space.
1963	President Kennedy signs the Limited Test Ban Treaty for the United States
1964	President Johnson signs law permitting private ownership of certain nuclear materials.
1966	Beginning of the rapid development of nuclear power plants in the U.S.
1968	"Non-proliferation" agreement, signed by the United States, the Soviet Union and other countries, limiting the number of countries possessing nuclear weapons.
1970	"Non-proliferation" agreement ratified.

24.8 Nuclear fusion

Fusion reactions have been produced in the laboratory by bombarding appropriate light target materials with, for example, high-energy deuterons from a particle accelerator. In these reactions nuclei result which are heavier than the nuclei of either the "projectiles" or the targets; there are usually also additional particles released—and energy. Some typical examples of fusion reactions, together with the energy liberated in each reaction, are:

$$
\begin{aligned}
{}_1H^2 + {}_1H^2 &\rightarrow {}_1H^3 + {}_1H^1 + 4\ \text{MeV}\\
{}_1H^2 + {}_1H^2 &\rightarrow {}_2He^3 + {}_0n^1 + 3.3\ \text{MeV}\\
{}_1H^2 + {}_1H^3 &\rightarrow {}_2He^4 + {}_0n^1 + 17.6\ \text{MeV}\\
{}_1H^2 + {}_2He^3 &\rightarrow {}_2He^4 + {}_1H^1 + 18.3\ \text{MeV}
\end{aligned}
$$

In the first of the above equations, the heavier product nucleus is an isotope of hydrogen, called tritium, with mass number $A = 3$; it has been found in small traces in nature, is radioactive with half-life of about 12 years, and it decays by beta emission into ${}_2He^3$, an isotope of helium.

Although the energy liberated in a single fusion is less than in a single fission, the energy released *per unit mass* is much greater. The mass of about 50 helium atoms is approximately equal the mass of one uranium atom: 50 × 17.6 MeV is 1040 MeV—compared to 200 MeV for a typical fission

When a target containing tritium is bombarded with deuterons, ${}_2He^4$ can be formed, as in the third equation above, liberating 17.6 MeV of energy. Of this energy, 14.1 MeV appears as kinetic energy of the neutron and 3.5 MeV as kinetic energy of the product nucleus.

The fusion of tritium and deuterium offers the possibility of providing large sources of energy, for example, in electric power plants. Deuterium occurs in water with an abundance of about one part in seven thousand hydrogen atoms, and can be separated from the lighter isotope. One gallon of water contains about one-eighth of a gram of deuterium which can now be separated at a cost of about 4 cents. If this small amount of deuterium could be made to react under appropriate conditions with tritium (perhaps produced by the reaction discussed above), the energy output would be equivalent to that from about 300 gallons of gasoline. The total amount of deuterium in the oceans is estimated to be about 10^{17} kilograms, and its energy content would be about 10^{20} kilowatt-years. If deuterium and tritium could be used to produce energy, they would provide an enormous source of energy.

There are, however, some difficult problems to be solved before fusion reactions are likely to be useful as steady sources of energy; some of these should be discussed at least briefly. The nuclei which react in the fusion processes are positively charged and repel one another because of the repulsive electric force. The nuclei must, therefore, be made to collide with a high relative speed to overcome the repulsive force tending to keep them apart. Experiments have shown that this can occur when the particles have kinetic energies of about 0.1 MeV or more. The nuclei must also be confined in a region where they can undergo many collisions without escaping, or being absorbed by the walls bounding the region, or losing energy by collisions with too many "cooler" (less energetic) molecules.

SG 24.13, 24.14

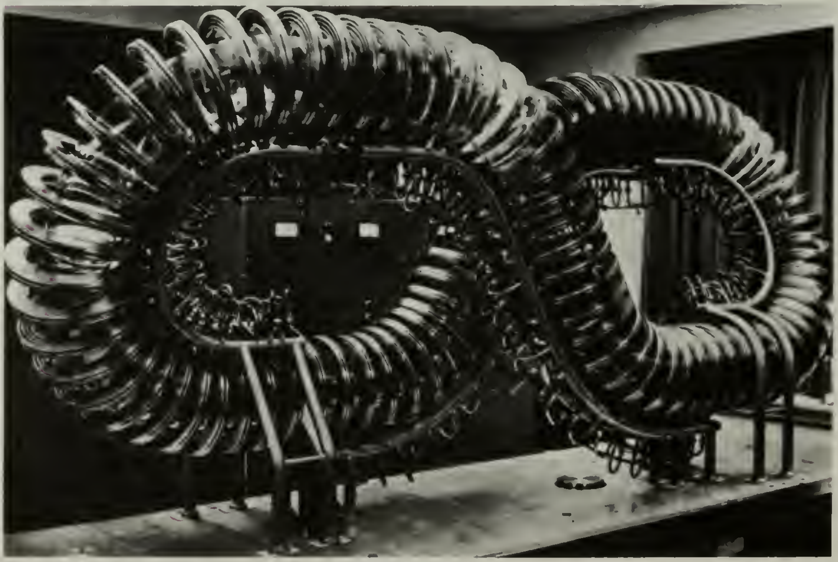
There must be enough collisions per unit time so that fusion can occur at a rate that will yield more energy than that needed to cause the collisions. The combination of these requirements means that the nuclei must be contained at a temperature of the order of 100 million degrees.

A *plasma* is an ionized gas in which positively and negatively charged particles move about freely.

At the temperature required for fusion, the atoms have been stripped of their electrons, and the resulting nuclei and separated electrons are said to form a *plasma*. No wall made of ordinary material can contain a hot plasma at 10^8 °K (the wall would be vaporized instantly!). But the charged particles of a plasma could, in theory, be contained in an appropriately designed magnetic field. The first problem to be solved, therefore, is to contain the plasma of deuterium and tritium nuclei in a magnetic field, while accelerating the nuclei by means of an electric field to the required kinetic energy (or temperature). The behavior of the charged particles in a plasma is complicated; there are many kinds of instabilities that make the plasma difficult to contain properly and long enough. These problems of the release of energy to form a *controlled* and sustained fusion reaction have not yet been solved on a practical scale, but research on them is being carried on in many countries. There is considerable international cooperation in this research, including visits of research teams between the United States, Britain, France, and the U.S.S.R. Although the effort and expense are great, the possible pay-off in terms of future power resources is enormous.

Q11 Why are very high temperatures required to cause fusion reactions?

Q12 How could extremely hot gases be kept from contacting the wall of a container?



A demonstration model of a "Stellarator." The figure-eight shape enables strong magnetic fields to contain a continuous plasma stream in which, it is hoped, a controlled fusion reaction might be made to occur.

Pen drawing by Vincent van Gogh.

24.9 Fusion reactions in stars

One of the most fascinating aspects of nuclear physics is the study of the sources of the energy of different types of stars. The sun is an example. In the sun, the fusion process results in the production of a helium nucleus from four protons. The net results of the reactions can be written as:

$$4\ {}_1H^1 \rightarrow {}_2He^4 + 2\,{}_{+1}e^0 + 26\ \text{MeV}$$

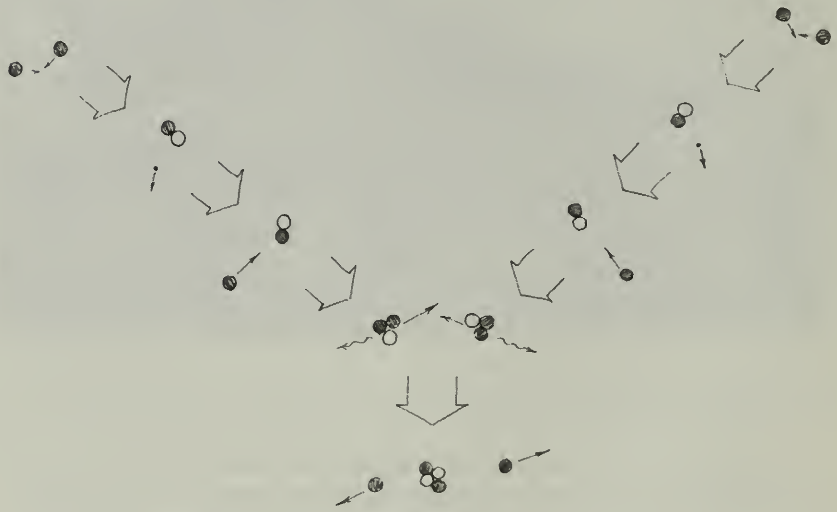
SG 24.15

The reaction does not take place in a single step but can proceed through different sets of reactions whose net results are summarized in the above equation; in each case, the overall amount of energy released is 26 MeV.

The fusion of four protons into a helium nucleus is the main source of the energy of the sun. Chemical reactions cannot provide energy at large enough rates (or for long enough duration!) to account for energy production in the sun, but nuclear fusion reactions can. Hydrogen and helium together make up about 99 percent of the sun's mass, with approximately twice as much H as He. There is plenty of hydrogen to supply the sun's energy for many millions of years to come.

For details see SG 24.16, 24.17, and 24.18.

But by which of the several possible sets of reactions does the transformation of hydrogen into helium take place? The direct process of four protons colliding to form a helium nucleus has been ruled out because the probability for such a reaction under solar conditions is too low. It may happen, but not often enough for the amount of energy released. A more likely set of reactions is the process represented in the sketch on the next page. When the temperature is about 10^7 °K, the kinetic energies are large enough to overcome the electric repulsion between protons, and fusion of two protons ($_1H^1$) takes place. The nuclear reaction results in a deuteron ($_1H^2$), a positron ($_{+1}e^0$), and a neutrino. As soon as a deuteron is formed, it reacts with another proton resulting in helium 3 ($_2He^3$) and a γ ray. The helium-3 nuclei fuse with each other, forming α particles and two protons. In each of these reactions energy is released, resulting in 26 MeV for the complete cycle of four protons forming a helium nucleus.



One form of proton-proton fusion chain which releases energy in stars:

- ● protons
- ○ neutrons
- · positrons
- ⟿ γ-rays

The rates of the reaction depend on the number of nuclei per unit volume and on the temperature; the higher the temperature, the faster the thermal motion of the particles and the more frequent and energetic the collisions. At the temperature of the sun's interior, which has been estimated to be 10 to 20 million degrees, the kinetic energies resulting from the thermal motion are in the neighborhood of 1 KeV.

See "Power from the Stars" in *Reader 6.*

The release of large amounts of energy by means of fusion processes *on earth* has so far been possible only in thermonuclear explosions, such as hydrogen bombs. A hydrogen bomb consists of a mixture of light elements with a fission bomb. The high particle energies produced by the fission reaction serve to initiate the fusion reaction. The explosion of a fission bomb produces a temperature of about 5×10^7 °K, which is sufficiently high to make fusion possible. The fusion reactions then release additional large amounts of energy. The total energy release is much greater than would be liberated by the fission bomb alone. Moreover, while there is a sort of upper limit beyond which fission bombs become not much more destructive (because they disperse the extra fissionable material before it can undergo fission), there seems to be no such upper limit to the size—and hence the destructive power—of fusion weapons.

The lack of an upper limit on the destructiveness of fusion bombs is one of the reasons why scientists such as Oppenheimer, Fermi, and Rabi advised against making such weapons, at least as long as there was any reasonable hope for international arms control agreements.

Q13 Is the ratio of the amount of hydrogen to the amount of helium in the sun increasing or decreasing?

24.10 The strength of nuclear forces

The large energies involved in nuclear reactions, a million or more times larger than the energies involved in chemical (molecular) reactions, indicate that the forces holding the nucleus together are very much stronger than the forces that hold molecules together. Another clue to the magnitude of nuclear forces is the density of a typical nucleus. The work of Rutherford and his colleagues on the scattering of α particles showed that atomic nuclei have radii in the neighborhood of 10^{-13} cm to 10^{-12} cm; this means that the volume of an atomic nucleus may be as small as 10^{-39} to 10^{-36} cm^3. Now, the mass of one of the lighter atoms is of the order of 10^{-24} gram, and this mass is almost all concentrated in the nucleus, with the result that the density of the nucleus may be as high as 10^{12} to 10^{14} grams per cubic centimeter. Densities of such magnitude are thousands of billions of times beyond the limits of our ordinary experience, since the greatest densities of ordinary material are in the neighborhood of 20 grams per cubic centimeter (uranium, gold, lead). It is evident that the forces that hold the atomic nucleus together must be very different from any forces we have considered so far. The search for understanding of these forces is one of the most important problems of modern physics. Although a good deal has been learned about nuclear forces, the problem is far from solved.

Information about nuclear forces has been obtained in several ways. It is possible to deduce some of the properties of nuclear forces from the known properties of atomic nuclei, for example, from the binding-energy curve of the graph on p. 78. That curve shows that the average binding energy per nucleon has nearly the same value for all but the lightest nuclei – about 8 MeV per nucleon. In other words, the *total* binding energy of a nucleus is roughly proportional to the number of nucleons. Now, if every particle in the nucleus were to exert a force on every other particle, it would be expected that the energy of the interactions, and therefore the binding energy, would be approximately proportional to the number of interacting pairs. But the number of pairs of nucleons goes up nearly in proportion to the square of the number of nucleons, so the binding energy calculated by assuming such interacting pairs is very different from the experimental results. To deal with this contradiction it is necessary to assume that a nuclear particle does not interact with all other nuclear particles, but only with a limited number of them, that is, only with its nearest neighbors. For this to be the case the nuclear forces must have a *short range:* the nuclear forces must fall off very rapidly as the distance between two nucleons increases. This decrease must be more rapid than the $1/r^2$ decrease of the gravitational force between two particles, or the $1/r^2$ decrease of the Coulomb electric force between two charges.

The chief problem studied by the team of physicists in the documentary film *People and Particles* is whether the electric force between charged particles at very small distances varies inversely as the square of the distance. (It does.)

The presence of protons in the nucleus also tells us something about nuclear forces. Since there are only positively charged and neutral particles in the nucleus, the electric forces must be repulsive. The nucleus is very small, of the order of 10^{-12} cm in diameter; therefore these repulsive forces must be enormous. Why then do the pieces that make up the nucleus not fly apart? It seems reasonable to assume that the electric repulsion is overcome at very small distances by very strong attractive forces between the nuclear particles. Information about such specifically nuclear forces can be obtained by studying the scattering of protons or neutrons by materials containing protons. Scattering experiments and the theory needed to account for their results form an important branch of nuclear physics. They show that such attractive nuclear forces do indeed exist. Many of the properties of these forces are now known. But the problems of nuclear forces and how they hold the nucleus together lie at the frontier of nuclear research.

See "Models of the Nucleus" in *Reader 6.*

In the absence of a complete theory of nuclear forces and structure, models of the nucleus have been developed. Several models are in use, each for a specific aspect of nuclear phenomena, because no one model adequately describes the whole wide range of phenomena, from particle emission in radioactive decay to nuclear reactions and fission. Two of the most prominent of these models are described briefly in the next two sections: the liquid drop model and the shell model.

Q14 Why is it assumed that there are special nuclear forces to hold the nucleus together?

Q15 Why is it assumed that the nuclear force is very short-range?

24.11 The liquid-drop nuclear model

In the liquid-drop model the nucleus is regarded as analogous to a charged drop of liquid. This model was suggested because the molecules in a liquid drop are held together by short-range forces, as the nucleons in a nucleus appear to be. According to this model, the particles in the nucleus, like the molecules in a drop of liquid, are in continual random motion. In analogy with the evaporation of molecules from the surface of a liquid drop, a group of nuclear particles may thus pick up enough energy through chance collisions with other nucleons to overcome the attractive nuclear forces and escape from the nucleus; this process would correspond to spontaneous α emissions.

This model has been especially useful in describing nuclear reactions: a particle may enter the nucleus from outside and impart enough additional kinetic energy to the protons and neutrons to permit the escape of a proton or a neutron, or a combination such as a deuteron or an α particle. A detailed quantitative theory of nuclear reactions based on this idea has been developed.

The usefulness of the liquid-drop model is well shown in its ability to account for fission. As we know, when a sample of U^{235} is bombarded with slow neutrons, that is, neutrons whose kinetic energy is very small, a U^{235} nucleus may capture a neutron to form a U^{236} nucleus. We can calculate the energy made available inside the nucleus by the captured neutron:

mass of U^{235} nucleus = 235.04393 amu
mass of neutron = 1.00867 amu
total mass = 236.05260 amu

mass of (unexcited) U^{236} nucleus = 236.04573 amu
difference in mass = 0.00687 amu
corresponding excess energy = 0.00687 amu × 931 MeV/amu
= 6.4 MeV

Therefore, at the instant when the neutron is captured, the U^{236} nucleus formed has this additional energy, 6.4 MeV, which is called the *excitation energy* due to the neutron capture. This energy is several MeV, even though the kinetic energy of the neutron (less than 1 eV) is relatively so small that it can be neglected in this calculation.

What happens to the excited U^{236} nucleus? This problem was studied theoretically in 1939 by Niels Bohr, who had come to the U.S., and John A. Wheeler, an American physicist. They showed that, according to the liquid-drop model, the U^{236} should be able to act like a drop of water when the latter is "excited" by being given mechanical energy. The nucleus can be deformed into an elongated or dumbell-like shape whose two (charged) parts may be beyond the range of the nuclear forces of attraction. The electric force of repulsion between the two parts of the deformed nucleus can overcome the short-range attractive forces, causing the nucleus to split, that is, to undergo fission, and causing the fragments to separate with high speeds. Each of the fragments will then quickly assume a spherical (or nearly sperical) form because within it the attractive nuclear forces again predominate. A schematic picture of a possible sequence of stages is sketched below.

The liquid-drop model gives a simple answer to the question: why do some nuclides (U^{235} and Pu^{239}) undergo fission with slow neutrons while others (Th^{232} and U^{238}) undergo fission only with fast neutrons? The answer is that a certain minimum amount of energy must be available to a nucleus to deform it enough so that the repulsive electric forces can overcome the attractive nuclear forces. This amount, called the *activation energy*, can be calculated with the aid of the mathematical theory of the liquid-drop model. When U^{235} captures a neutron to make U^{236}, the excitation energy of the U^{236} nucleus is greater than the energy required for fission, even if the exciting neutron has very low kinetic energy. This calculation was made by Bohr and Wheeler in 1939; they found that their model

Fission sometimes occurs spontaneously—but so rarely that we can neglect it for our treatment predicted, correctly, that U^{235} undergoes fission with slow neutrons. The theory also predicted that when U^{238} captures a slow neutron to form U^{239} the excitation energy is *smaller* than the activation energy by 0.9 MeV. Hence U^{238} should not undergo fission unless bombarded with neutrons with kinetic energies of 0.9 MeV or more. The correctness of this prediction was verified by experiment.

SG 24.19, 24.20

Q16 According to the liquid-drop model, what kind of force is responsible for fission of a nucleus?

Q17 Why does U^{238} require *fast* neutrons to provoke fission? Why does fission occur in U^{239} with *slow* neutrons?

24.12 The shell model

Another nuclear model is required to account for other properties of the nucleus—properties that could not be accounted for by the liquid-drop model. We mentioned in Sec. 22.7 that nuclides with even numbers of neutrons and protons are more stable than nuclides that contain odd numbers of either protons or neutrons. Detailed experimental studies of nuclear stability have shown that nuclei having 2, 8, 20, 50 or 82 protons, or 2, 8, 20, 50, 82 or 126 neutrons are unusually numerous and stable. These nuclei have greater binding energies than closely similar nuclei. When the exceptional properties of nuclei with these numbers of protons and neutrons became clear, in 1948, no available theory or model of the nucleus could account for this situation. The numbers 2, 8, 20, 50, 82 and 126 were referred to as "magic numbers."

It was known from the study of chemical properties that atoms with atomic numbers 2, 10, 18, 36, 54, and 86—gases helium to radon—have special chemical stability. This property was explained in the Bohr-Rutherford model of the atom by the idea that the electrons around each nucleus tend to arrange themselves in concentric shells, with each shell able to contain only a certain maximum number of electrons: 2 for the innermost shell, 8 for the next, and so on. An especially stable atom is one with a full electron shell on the outside. Although the Bohr-Rutherford model has been replaced by a more successful one based on quantum mechanics, the idea of shells still provides a useful picture, and a nuclear model—the *nuclear-shell model*—has been developed to deal with the observation that some nuclei are particularly stable.

In the nuclear shell model it is assumed that protons can, in a rough way of speaking, arrange themselves in shells, and that neutrons can, independently, do likewise; in the "magic-number" nuclei the shells are filled. The model has been worked out in great detail on the basis of quantum mechanics, and has been successful in correlating the properties of nuclides that emit α or β particles and γ photons, and in describing the electric and magnetic fields around nuclei. But the nuclear-shell model does not help us understand fission, and there are fundamental differences between this model and the liquid-drop model. For example, the shell model emphasized definite patterns in which nucleons are arranged, while the liquid-drop model pictures the nuclear material in random motion. Each model is successful in accounting for some nuclear phenomena, but fails for others.

When two seemingly contradictory theories or models must be used in a field of physics, a strong effort is put into trying to develop a more general viewpoint, or theory, which can include the two as special cases. Such a nuclear theory is being developed; it is called the *collective model*, and one of the physicists who has worked on this model is the Danish physicist Aage Bohr, the son of Neils Bohr. This model represents an advance beyond the shell and liquid-drop models in correlating nuclear data. It also has limits; thus, it does not answer fundamental questions about nuclear forces, which are still among the chief problems in the physics of our times.

Q18 According to the shell model, what gives nuclei having a "magic number" of protons and neutrons their special properties?

Q19 Which is better, the liquid-drop or the shell model of the nucleus?

The upper portion of the photo above shows normal plant cell chromosomes divided into 2 groups. Below that the same cell is shown after x-ray exposure. Fragments and bridges between groups are typical radiation-induced abnormalities.

24.13 Biological and medical applications of nuclear physics

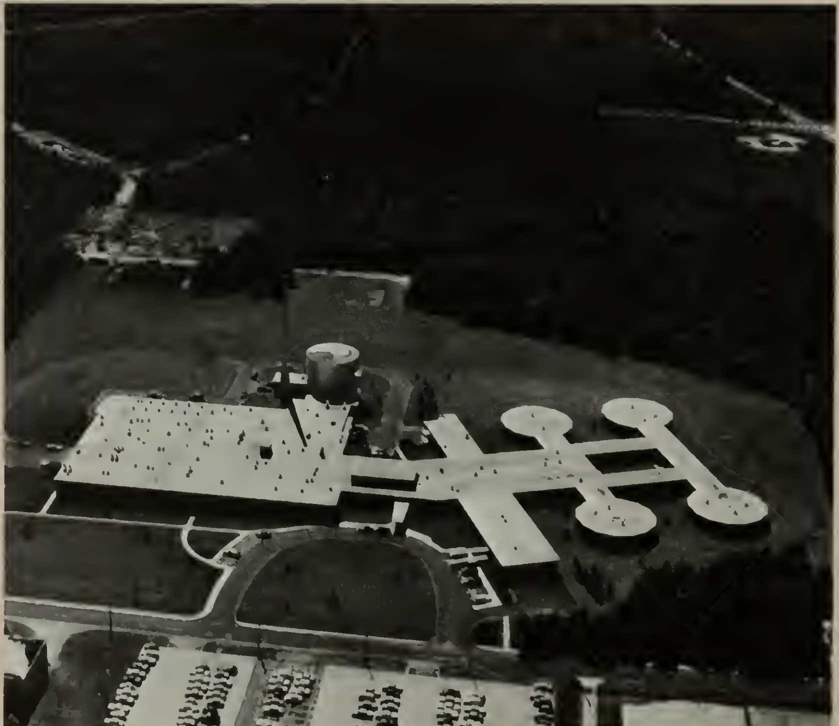
In Sec. 24.7 we mentioned military applications of nuclear energy, and the use of nuclear energy as a source of electric power for cities, industries, and agriculture. There are many other applications which may, in the long run, turn out to be more important than some of those. These may be included under the general heading of *radiation biology* and *radiation medicine*. The fields of science indicated by these names are broad and we can only indicate, by means of a few examples, some of the problems that are being worked on. In this work, radiations are used in the study of biological phenomena, in the diagnosis and treatment of disease, and in the improvement of agriculture.

The physical and chemical effects of various kinds of radiations on biological materials are being studied to find out, for example, how radiation produces genetic changes. Since it has been discovered that many of the key chemical processes in cells are organized by single chains of molecules, it is clear that a single particle of radiation can, by breaking a chemical bond in such a chain, cause a permanent and perhaps disastrous change in the cell.

An autoradiograph of a fern frond made after the plant had taken in a solution containing radioactive sulfur ($_{16}S^{35}$).

The metabolism of plants and animals is being studied with the aid of extremely small amounts of radioactive nuclides called *isotopic tracers*, or "tagged atoms." A radioactive isotope (for example, C^{14}) acts chemically (and therefore physiologically) like a stable isotope (C^{12}). Hence a radioactive tracer can be followed with counters as they go through various metabolic processes. The role of micronutrients (elements that are essential, in extremely small amounts, for the well-being of plants and animals) can be studied in this way. Agricultural experiments with fertilizers containing radioactive isotopes have shown at what point in the growth of a plant the fertilizer is essential. In chemistry, radioactive isotopes

Damaged trees surround a radioactive cesium 137 capsule which had been kept there for nearly 6 months in an experiment to study the effects of ionizing radiation on biological systems.



The Medical Research Center of Brookhaven National Laboratory on Long Island, New York. The research reactor is housed in the cylindrical structure at the rear; beside it is a stack which exhausts the air used to cool the reactor.

help in the determination of the details of chemical reactions and of the structure of complex molecules, such as proteins, vitamins and enzymes.

Perhaps the most rewarding uses of radioisotopes have been in medical research, diagnosis, and therapy. For example, tracers can help to determine the rate of flow of blood through the heart and to the limbs, thus aiding in the diagnosis of abnormal conditions. Intense doses of radiation can do serious damage to all living cells, but diseased cells are often more easily damaged than normal cells. Radiation can, therefore, be used to treat some diseases, such as cancer. Some parts of the body take up particular elements preferentially. For example, the thyroid gland absorbs iodine easily. Specially prepared radioisotopes of such elements can be administered to the victims of certain diseases, thus supplying desired radiation right at the site of the disease. This method has been used in the treatment of cancer of the thyroid gland, blood diseases and brain tumors and in the diagnosis of thyroid, liver and kidney ailments.

Some Typical Isotope Applications

ISOTOPE	HALF-LIFE	IMPORTANT USES
${}_1H^9$	11 years	Used as a tag in organic substances.
${}_6C^{14}$	4700 years	Used as a tag in studying the synthesis of many organic substances. When ${}_6C^{14}$ is incorporated in food material, its presence can be traced in the metabolic products.
${}_{11}Na^{24}$	15 hours	Useful in a wide variety of biochemical investigations because of its solubility and chemical properties.
${}_{15}P^{32}$	14 days	For the study of bone metabolism, the treatment of blood diseases and the specific uptake in tumor tissue.
${}_{16}S^{35}$	87 days	Has numerous chemical and industrial applications.
${}_{27}Co^{60}$	5.3 years	Because of its intense γ emission, may be used as a low-cost substitute for radium in radiography and therapy.
${}_{53}I^{131}$	8 days	For the study of thyroid metabolism and the treatment of thyroid diseases.

SG 24.21

The table above summarizes the use of a few radioisotopes, most of which are produced by neutron bombardment in nuclear reactors. Such uses suggest the promise that nuclear physics holds for the future. Indeed, they symbolize the meaning of science at its best: *research in science lays open to our understanding the secrets of nature—and from the application of his knowledge to human needs, all mankind can benefit.*

EPILOGUE In this unit we have traced the development of nuclear physics from the discovery of radioactivity to current work in nuclear fission and fusion. Radioactivity provided the starting place and tools to work with. In radioactivity we found the naturally occurring transmutation of elements, and so were led to achieve artificial transmutations. The naturally occurring radioactive series pointed to the existence of isotopes, both radioactive and stable. Artificial transmutation has increased by many hundreds the number of nuclear species available for study and use.

Nuclear physicists and chemists study the reactions of the stable and radioactive nuclides. The collection and correlation of a vast body of experimental data now available remind us of the work of the nineteenth-century chemists and spectroscopists. Nuclear models are built, changed, and replaced by newer and, perhaps, better models. But the detailed nature of nuclear forces is still the subject of much research, especially in the field of high-energy physics.

Yet that is only one of the fields that remains to be explored. The nucleus also has magnetic properties which affect the behavior of atoms. Sometimes it helps to study these properties when the atoms of matter are at very low temperatures, as close to absolute zero as we can get them. Nuclear physics overlaps with solid-state physics and with low-temperature physics; at low temperatures wonderful things happen—and quanta again help us to understand them.

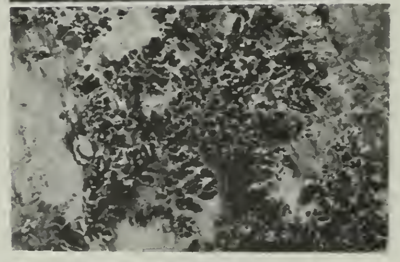
The study of light through the development of devices such as the laser attracts many physicists. These devices are made possible by, and contribute to, our increasing understanding of how complex atomic systems jump from one energy to another—and how they can be made to change where and when we want them to.

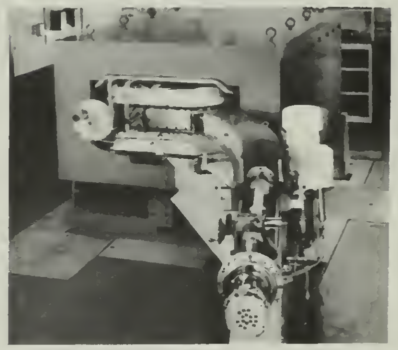
The properties of liquids are still only imperfectly understood. Thales of Miletus was perhaps the first man on record to make a large-scale scientific speculation when he proposed, over twenty-six centuries ago, that maybe everything in the world is basically made of water in combinations of its various states. Thales was wrong, but even today we are trying to develop an adequate theory of the behavior of water molecules.

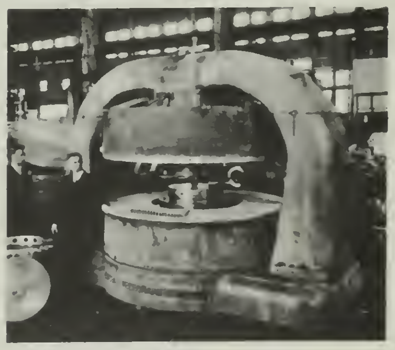
All the subjects we have mentioned touch on engineering, where physics and other disciplines are put to use to fashion the "man-made world". All of the engineering fields involve physics. Nuclear engineering and space engineering are the most recent and, at the moment, perhaps the most glamorous. But today the chemical engineer, the mechanical engineer and the metallurgist all use the physicist's way of understanding the properties of atoms and atomic nuclei, because it is no longer enough to know only the properties of matter in bulk.

The radiations we have talked about—α, β, and γ rays—are tools for industry, biology and medicine. They help to cure, preserve, study, understand. Neutrons are not only constituents of the nucleus, they are also probes for studies in science and in industry.

So our study of atoms and nuclei, indeed our whole course, has been an introduction not only to physics but also to the many fields with which physics is closely linked. It has been an introduction to an ever-expanding world in which much is known and understood; where much more—and perhaps the most wonderful part—is waiting to be discovered.







24.1 The Project Physics learning materials particularly appropriate for Chapter 24 include:

Film
The World of Enrico Fermi

Transparency
Binding Energy Curves

Reader Articles
New World of Nuclear Power
Models of the Nucleus
Power from the Stars
Success
The Nuclear Energy Revolution
A Report to the Secretary of War
Calling All Stars
Tasks for a World Without War

24.2 Suppose that a nucleus of ${}_6C^{13}$ is formed by adding a neutron to a ${}_6C^{12}$ atom. Neglecting any kinetic energy the neutron may have, calculate the energy that becomes available to the nucleus due to the absorption of that neutron to make ${}_6C^{13}$; the atomic masses of C^{12} and C^{13} (in an unexcited state) are 12.000000 and 13.003354 amu.

24.3 The atomic mass of He^4 is 4.00260 amu; what is the average binding energy per particle?

24.4 Suppose that a proton with relatively small kinetic energy induces the following reaction:

$$ {}_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4 $$

If the lithium nucleus were initially at rest, what would be the relative directions of the two α particles? What would be the kinetic energy of each α particle?

24.5 The first nuclear transmutation (obtained by Rutherford in 1919) was the reaction:

$$ {}_7N^{14} + {}_2He^4 \rightarrow {}_8O^{17} + {}_1H^1 $$

The atomic masses involved are:

N^{14}: 14.003074 amu
O^{17}: 16.999134 amu
He^4: 4.002604 amu
H^1: 1.007825 amu

Is energy absorbed or released in this reaction? How much energy (in MeV) is absorbed or released?

24.6 In an experiment on the reaction given in SG 24.5, the α particles used had a kinetic energy of 7.68 MeV, and the energy of the protons was 5.93 MeV. What was the energy of the "recoiling" O^{17} nucleus?

24.7 Calculate the amount of energy (in MeV) liberated in the following nuclear reaction:

$$ {}_7N^{14} + {}_1H^2 \rightarrow {}_7N^{15} + {}_1H^1 $$

The atomic masses are:

N^{14}: 14.003074 amu
H^2: 2.014102 amu
N^{15}: 15.000108 amu
H^1: 1.007825 amu

24.8 Appreciable amounts of the uranium isotope ${}_{92}U^{233}$ do not occur outside the laboratory; ${}_{92}U^{233}$ is formed after the thorium nucleus ${}_{90}Th^{232}$ has captured a neutron. Give the probable steps leading from ${}_{90}Th^{232}$ to ${}_{92}U^{233}$.

24.9 Use the graph at the top left hand corner of p. 78 to find the binding energies for U^{235}, Ba^{141} and Kr^{92}. Use these values to show that the energy released in the fission of U^{235} is approximately 200 MeV.

24.10 Possible end-products of U^{235} fission, when provoked by capture of slow neutrons, are ${}_{57}La^{139}$ and ${}_{42}Mo^{95}$. This reaction may be described by the equation:

$$ {}_{92}U^{235} + {}_0n^1 \rightarrow {}_{57}La^{139} + {}_{42}Mo^{95} + 2\,{}_0n^1 + 7({}_{-1}e^0) $$

The mass of ${}_{57}La^{139}$ is 138.8061 amu; that of ${}_{42}Mo^{95}$ is 94.9057 amu. How much energy is released per atom in this particular fission? (The mass of the seven electrons may be neglected.)

24.11 Write a set of equations that describe the decay of the fission product ${}_{36}Kr^{92}$ into ${}_{40}Zr^{92}$.

24.12 Loss of neutrons from a structure containing fissionable material depends on its shape as well as its size. For some shapes, it is impossible to reach a critical size because the neutron loss through the surface is too great. With what shape would a mass of fissionable material suffer the *least* loss of neutrons by passage through the surface? The *most*?

24.13 Why are the high temperatures produced by the explosion of a fission bomb necessary to initiate fusion in a thermonuclear device?

24.14 It is generally agreed that stars are formed when vast clouds of hydrogen gas collapse under the mutual gravitational attraction of their particles. How might this process lead to fusion reactions beginning in such stars? (Hint: The cloud has gravitational potential energy.)

24.15 One of the energy sources in the sun is the production of helium nuclei by four protons as described in Sec. 24.9: $4\,_1H^1 \rightarrow {}_2He^4 + 2\,_{+1}e^0$. Show that about 27 MeV of energy are released in each cycle.

24.16 Fusion reactions in the sun convert a vast amount of hydrogen into radiant energy each second.

(a) Knowing that the energy output of the sun is 3.90×10^{26} joules/sec, calculate the rate at which the sun is losing mass.

(b) Convert the value 3.90×10^{26} joules/sec to horsepower. (Recall that 1 horsepower is equivalent to 746 watts.)

24.17 A source of energy in the sun may be the "carbon cycle," proposed by Hans Bethe, which is outlined below.

(a) Complete the six steps of the cycle.

(b) After a cycle has been completed, which nuclides used in the cycle have been changed (and in what ways), and which have come out the same as they entered the cycle?

$_6C^{12} + {}_1H^1 \rightarrow (\qquad) + \gamma$

$(\qquad) \rightarrow {}_6C^{13} + {}_{+1}e^0 + \nu$

$_6C^{13} + {}_1H^1 \rightarrow (\qquad) + \gamma$

$(\qquad) + {}_1H^1 \rightarrow {}_8O^{15} + \gamma$

$_8O^{15} \rightarrow (\qquad) + {}_{+1}e^0 + \nu$

$(\qquad) + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4$

24.18 Another reaction which may take place in the sun is:

$$He^3 + He^4 \rightarrow Be^7 + \gamma$$

The atomic mass of He^3 is 3.016030 amu, and that of Be^7 is 7.016929. Is energy absorbed or released? How much energy?

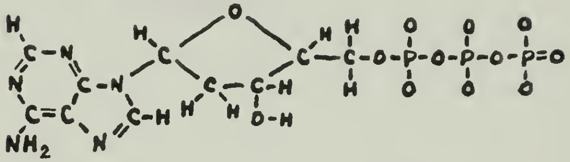
24.19 The atomic masses of $_{92}U^{233}$ and $_{92}U^{234}$ are 233.039498 and 234.040900 amu. The activation energy for the fission of the nucleus $_{92}U^{234}$ is 4.6 MeV. Is U^{233} fissionable by slow neutrons?

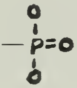
24.20 Bombardment of $_{94}Pu^{241}$ with slow neutrons sometimes leads to the reaction:

$$_{94}Pu^{241} + {}_0n^1 \rightarrow {}_{94}Pu^{242} + \gamma$$

The atomic masses of Pu^{241} and Pu^{242} are 241.056711 amu and 242.058710 amu. The activation energy of Pu^{241} is 5.0 MeV. Is Pu^{241} fissionable with slow neutrons?

24.21 The chemical structural formula for the energy carrying adenosine triphosphate (ATP) molecule in living cell is



Energy is provided to some other molecule when the end phosphate group (—  $-\overset{O}{\underset{O}{P}}=O$) is transferred to it, changing the ATP to adenosine *di*phosphate (ADP). Energy from the oxidation of food is used to attach new phosphate groups to the ADP, changing it once again to ATP. Suggest a procedure by which you could determine the rate at which new molecules of ATP are formed.

24.22 Write an essay on one of the following topics:

(a) The various ways a citizen can help assure that technological innovations will be made and used in a manner benefiting society as a whole.

(b) The differences between technology and basic science.

(c) The responsibilities of scientists to society.

(d) The responsibilities of society to further science.

(e) The fields of physics or related sciences in which you may want to do further study.

109
4
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FM
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17
126
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A perspective on the Project Physics Course: a letter from the Directors.

Harvard University
Cambridge, Massachusetts

Harvard Project Physics

Dear Student,

While taking this introductory course in physics you have worked through a great deal of the content and development of the physical sciences. You now have a good headstart for further study of physics as well as other fields such as astronomy, chemistry, engineering, and the history of science. You are now no longer an "outsider," but are knowledgeable about many of the main currents of scientific advance over the past centuries.

Even if you cannot yet solve the detailed problems that a professional physicist may be working on, you do now share with him much of the cultural heritage of modern physical science. Therefore you can, if you wish, make an important decision: if you found yourself intrigued or even just curious about any part of the material in this course, you should consider going more deeply into these fields as part of your further schooling--whether or not science will be your eventual career.

But in addition to physics, and in addition to the way men and women make discoveries in science, you have also learned something about the place of science in society. By now you should have some answers if anyone should ask "Why physics?" or "What is the relevance of science?"

It would have been impossible to do justice to these important questions when you started this course. Now you have first-hand knowledge on which to base your own answers. We, who have worked for years together with literally hundreds of colleagues and students in our participating try-out schools, to fashion these books, lab experiments, film, etc., would like to share with you some of our own answers to these questions, as a kind of epilogue to the whole Project Physics Course. We hope you may agree with at least some of our opinions.

What special reasons are there for thinking that physics, among all the sciences, is of basic importance? What is the relevance of science today? We believe there are at least five parts to a complete answer, and for each part there were examples in the course materials you have now studied. The fact that the questions about "relevance" have in the last few years almost become cliches does not change the need to be clear about the subject. So let us attack it head-on.

Relevance 1: The intellectual excitement of physics

At some points during the year--often, we hope--you yourself have felt the intellectual excitement that accompanies understanding human achievements of the kind that have been chronicled here. This sort of excitement can be derived from the explanation of the motion of planets in our solar system, just as it can from the discovery of the internal structure in Shakespeare's King Lear. You may have felt it, keenly and suddenly, when a theory showed the connection between apparently separate parts of experience, or when a lab experiment succeeded after many tries, or when the computed planetary orbit closed, or when a long derivation that seemed to ramble on and on came suddenly to a resolution like a Bach fugue.

At such a moment, one catches a glimpse that the sort of knowledge which physics leads to can crystallize the confused world of phenomena. Here is a way to see nature's clarity, here is the place to find the necessity which guides all things. Remember how lyrical Kepler became when he found the law that (T^2/R^3) is a constant? One must not dismiss such a moment of emotion. It does belong in science, too. It is a real and profound experience, an intellectual excitement that every scientist has when he discovers something new, or even when he just reads for the first time of a beautiful piece of work done by someone else. If we did not treasure such experiences, life would grow dull indeed. The joy of intellectual engagement in the deepest phenomena of the material world, and the joy of discovering therein the success of one's own rational and intuitive faculties--these are among the most relevant and enobling activities one can pursue.

In the Text and in the Reader, you have often encountered remarks by scientists praising the simplicity of physics, the fact that there are only a few really deep laws but that they suffice to deal with the myriad of apparently different observations. From the very beginning, from Chapter 1 where we quickly abandoned the gyrations of a falling leaf as a useful beginning for the study of motion, we learned to look for simple commonalities in all behavior. We have been seeking overall principles that will unify many diverse cases, whether it be a falling leaf in one's backyard or the turning of an unseen solar system at the edge of the universe. Nothing is more astonishing than that it *is* possible to have such a universal physics! The most distant hydrogen atom is built on exactly the same principle as the one nearest you--as seen by the fact that both emit the same wavelengths of light. All the laws of physics that govern the structure of matter and its behavior in space and time have that universality.

Einstein once expressed these thoughts in a memorable way. Physical theory, he said, has two ardent desires: To gather up as far as possible all pertinent phenomena and their connections; and to help us

> not only to know how nature is and how her transactions are carried through, but also to reach as far as possible the utopian and seemingly arrogant aim of knowing *why nature is*

> thus and not otherwise.....Thereby one experiences, so to speak, that God Himself could not have arranged those connections in any other way than that which factually exists, anymore that it would be in His power to make the number 4 into a prime number. This is the Promethean element of the scientific experience....Here has always been for me the particular magic of scientific effort.

Three and a half centuries earlier, Johannes Kepler had used almost the same words. In the preface of his first book he announced that he wanted to find out, with respect to the number, positions, and motions of the planets, "Why they are as they are, and not otherwise." To a friend he wrote at about the same time that with regard to numbers and quantity "our knowledge is of the same kind as God's, at least insofar as we can understand something of it in this mortal life."

These were by no means sacrilegious thoughts. On the contrary, it was a pious man who wrote this. As Kepler often stated--and many scientists since that day have agreed with him--the world that God made stands before our minds as a kind of puzzle, for us to solve in order that we may prove we are worthy of the mind given to us for that very purpose.

We hope to have shown that physics is neither an isolated, bloodless body of facts and theories with mere vocational usefulness, nor a glorious entertainment for an elite of mathematical wizards. (As a matter of fact, some of the best physicists, including several whose accomplishments are detailed in this course, were themselves not particularly good at mathematics.) Physics is the study of what makes the whole world go, and we think it is too beautiful to be kept secret from anyone, no matter what his eventual career plans may be. To live with more joy and intelligence, one has to know the world in which one lives, and this surely includes the majestic yet simple order physicists have found in our universe. Without such a study, as Galileo said, one may be lost in a labyrinth and not even know it. To be ignorant of physics may leave one unprepared for living in one's own time--as an intelligent spectator in the human adventures of our time no less than as an effective wage-earner and citizen.

Relevance 2: Immediate practical benefits to society

A second, very different way of seeing the relevance of science is in terms of the effect science sometimes has in helping to prepare the base for technological advance. We speak here not of the long-range, slower effects of which more will be said later, but the quick "spin-off," the intentional use of basic science "for the relief of man's estate," in the phrase of the seventeenth-century philosopher Francis Bacon.

Many students and critics of science seem to have only this particular aspect in mind when they use the word "relevance." However, useful though science can be in this sense, it would be quite wrong to settle merely for the assistance physics can give, say, to the study of such problems as pollution. We say this for two reasons: First of all there really is, and need be relatively little connection between today's basic physics research and current technological advance. The gadgets and devices being produced today by industry, even if they are as sophisticated as those used for space exploration, rely very little on new research in basic physics or on the discovery of new laws. They are mostly based on applications of well-known laws and of techniques developed long ago. On the contrary, people who do basic research in physics find themselves nowadays much more often in the position of having to <u>oppose</u> new plans for large-scale technological "advance" (whether it be a widely deployed ABM system, or excavation by use of nuclear devices, or supersonic transport planes, all of them gadgets that in the opinion of the majority of physicists have more long-range dangers than benefits).

In fact, contrary to folklore, the connection between basic physics and technical advance is generally indirect or roundabout. Only rarely is a basic advance made consciously as a prelude to a major technical improvement. The physicist H.B.G. Casimir illustrated this proposition by giving examples of progress made as a result of the work of scientists who did <u>not</u> set out to work for specific well-defined practical aims:

> One might ask whether basic circuits in computers might have been found by people who wanted to build computers. As it happens, they were discovered in the 1930's by physicists dealing with the counting of nuclear particles because they were interested in nuclear physics....
>
> One might ask whether there would be nuclear power because people wanted new power sources, or whether the urge to have new power would have led to the discovery of the nucleus. Only it didn't happen that way, and there were the Curies, and Rutherford, and Fermi, and a few others....
>
> One might ask whether induction coils in motorcars might have been made by enterprises which wanted to make motor transport, and whether then they would have stumbled on the laws of induction. But the laws of induction had been found by Faraday many decades before that....
>
> Or whether, in an urge to provide better communication, one might have found electromagnetic waves. They weren't found that way. They were found by Hertz who emphasized the beauty of physics and who based his work on the theoretical considerations of Maxwell. I think there is hardly any example of twentieth-century innovation which is not indebted in this way to basic scientific thought.

There is also another reason why it would be quite wrong to seek relevance for science merely in the rare immediate benefits to technology. Technological advance all too often brings with it major social problems that arise as unforeseen by-products, and these problems cannot be cured or even properly understood through <u>existing</u>

scientific or technological or political means alone. Rather, such cures depend to a large extent on making new, basic scientific advances. To put it differently, at the heart of social problems created by technological advance is the absence of some specific basic scientific knowledge. This fact gives a whole new mandate and a new range of expectations for basic scientific research.

Examples come readily to mind. Thus, it is quite customary to say that the population explosion is in part caused by the advance of medical science (owing to better sanitation, innoculation, antibiotics, etc.). But one can equally well claim that the population explosion is bound to overwhelm us precisely because we do not yet have at hand sufficient knowledge in pure science. That is to say, the complex problem of over-population is due in a large degree to our current ignorance of the basic process of conception--its biophysics, biochemistry, physiology. No wonder that attempts at controlling population are so halting. What is astonishing, rather, is that the first medical school laboratory in the United States specifically designed to study the whole range of scientific problems in the process of reproduction is only now being built.

Similarly, it is sometimes said that progress in physics is "responsible" for the threatening arms race. But it is more accurate to say that arms control treaties were difficult to achieve in good part because of insufficient knowledge of geophysics that made inspection through seismographs of suspected illegal weapons tests difficult and uncertain. A better understanding of geophysics, it turned out, was needed before different nations would consider it safe to enter in arms control treaties that outlaw weapons tests.

The problem of bringing food to hungry people in arid lands that are near the sea, as in Peru or India or Egypt, is to a large extent political, as are most of the problems mentioned above. But it is also a problem of basic science: Before it is possible to design much more economical desalination plants, a more fundamental understanding of the structure of liquids--one of the much-neglected problem areas in current physics and chemistry--and of the phenomena of materials moving through membranes will be needed. And turning to pollution, that is of course also the result of greed, stupidity, apathy, and the consequent lack of law enforcement; but to clean up smog-ridden areas more effectively will require greater basic knowledge than we have today of the physics and chemistry of combustion and of meteorology. And in the meantime, to this day the most effective and insufficiently used device for getting rid of pollution due to solid particles is the electrostatic precipitator, working on the scientific principles we discussed in Unit 4, and known since 1600.

These remarks should serve to oppose two widely current but erroneous notions: one, that basic science is an unnecessary luxury, and should be supported only if it is directed to immediate practical applicability (--as the quotation bv Casimir above indicates, things just don't happen that way); and second, that one way of stopping the abuses that come as by-products of technical innovation is to stop science (--whereas in fact curing the abuses depends on scientific advances yet to be made).

Relevance 3: Long-range social benefits

Turning from the immediate to the long-range effects of science that give it relevance, we have seen ample evidence that every person alive today, whether or not he or she has studied science, is intellectually a child of Copernicus and Galileo, Newton and Faraday, Einstein and Bohr. Our imagination and intellectual tools were indeed shaped to a large degree by the advances in the knowledge of physics they and their contemporaries made, long before we were born. Thus the material in the Unit 2 Text and Reader showed how the Copernican and Newtonian world view triumphed in the West, and indeed how the recognition that a uniform law holds sway over all matter everywhere helped to overcome hierarchical thinking, thereby preparing the mind for self-reliant democracy. And again, in Unit 3, we saw that the successes of statistics and of the concepts of energy prepared the ground for the modernization of the Newtonian worldview.

In addition to the long-range influence of science upon the mind--the kind of influence that Newton's work had on the imagination of the poets and theologians from the eighteenth century onward--there are also the more material long-range effects we studied in connection with the advances made by James Watt, Michael Faraday, and Enrico Fermi. From an understanding of how the steam engine works flowed a century-long transformation of society which now is studied under the name of the Industrial Revolution. From Faraday's "toys" came electric motors and generators and, in time, the electric-powered elevators, trains and subways that facilitated the upward and sideways growth of cities. Similarly, the experiments of Fermi's group on neutron-induced artificial radioactivity prepared for the study of nuclear fission, and this in turn led to the design of new sources of energy that will turn out to be the only means for meeting the frantically growing energy needs of our society.

Even more than is true for the immediate practical influences, it usually is impossible to foresee ahead of time the long-range effects of science upon social change. To avoid possible negative effects and to capitalize on positive ones, there is only one policy available: to exert uncompromising watchfulness, as citizens and scientists--calling attention to current flagrant abuses of scientific knowledge or skills, and keeping up-to-date on scientific advance so as to be ready to keep it from being derailed and abused in the future.

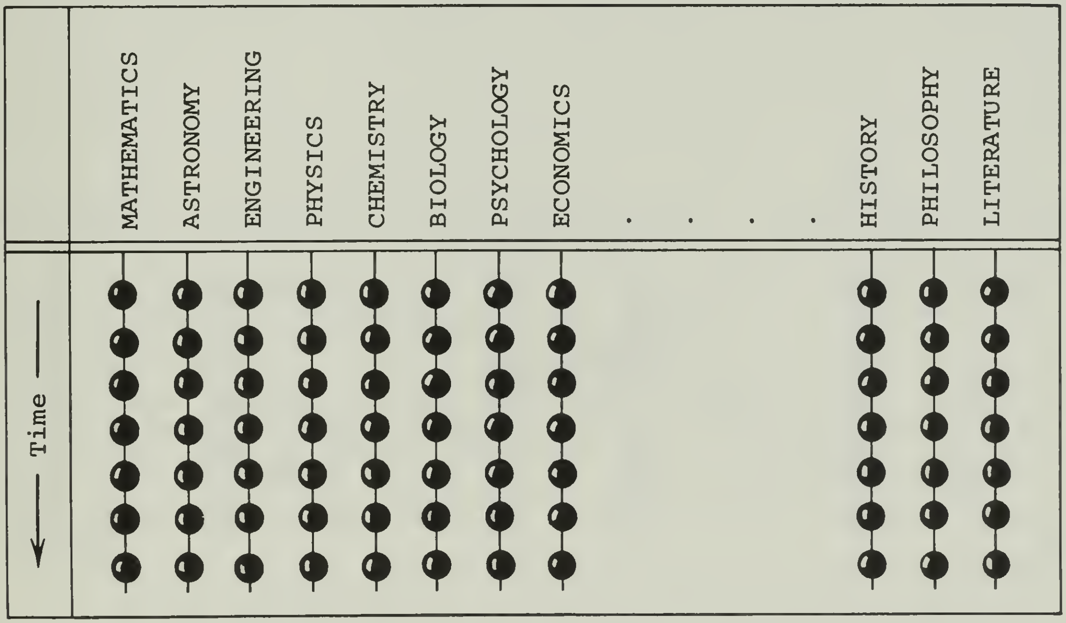
Relevance 4: Science as a study that is connected to all other fields

The fourth meaning of the word "relevance" refers to science not as merely a technical study but as one part of the general humanistic development of mankind. We agree fully with the Nobel Prize physicist I.I. Rabi, quoted in the Preface to the Text:

> Science should be taught at whatever level, from the lowest to the highest, in the humanistic way. By which I mean it

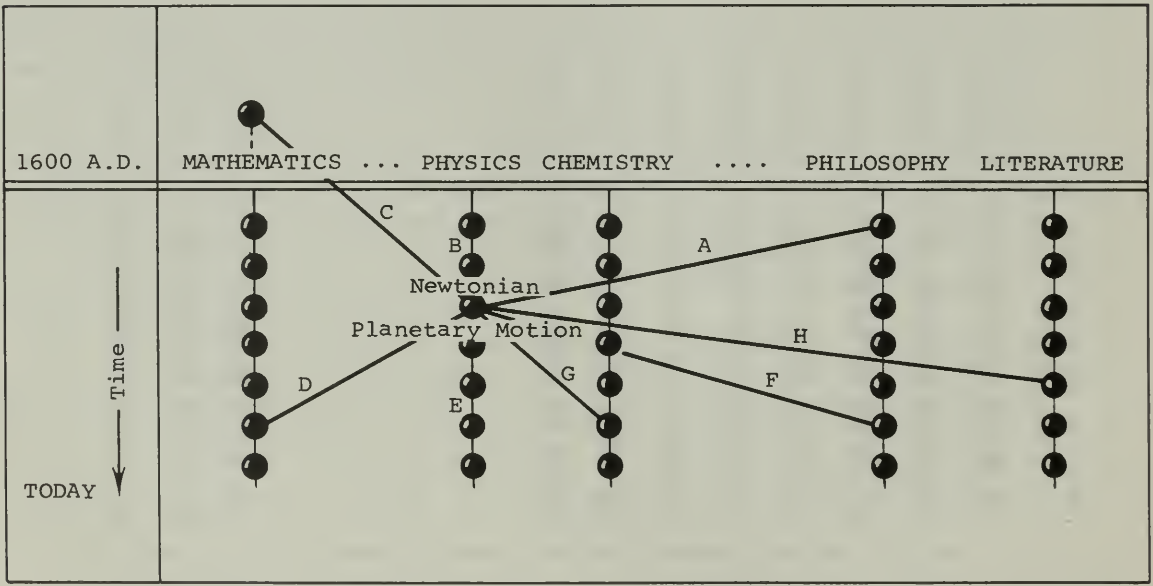
> should be taught with a certain historical understanding, with a social understanding and a human understanding, in the sense of the biography, the nature of the people who made this construction, the triumphs, the trials, the tribulations.

We can illustrate the need for this sense of humanistic interconnectedness by means of a simple diagram. The physics course as traditionally given in many high schools and colleges is like a string of beads. One subject follows another, from Galileo's kinematics to the most recent advances in nuclear physics--the usual sequence that more or less parallels the historical development of the science, whether this is made explicit or not. But few if any connections are shown with other achievements of human beings who are not physicists, with sciences other than physics, and with studies and activities other than science. And all too often the materials studied in the other courses--in chemistry, in biology, in literature, etc.--also hang there by themselves like so many separate strings of beads.



There are some advantages in such a string-of-beads presentation of a course. For example, it is convenient to teach. But ignoring connections that do exist among all these fields does not do justice to the actual state of affairs. A research project in experimental physics, for example, sooner or later draws on material not only from almost every part of a physics course, but also from mathematics, metallurgy, chemical thermodynamics, electronic engineering, computer technology, and many other fields of science--not to speak of group psychology, accounting, and skill in writing a good article about the work. Moreover, nobody who has engaged in actual scientific work can fail to see the influence that advances made in science can have in terms of social and practical consequences. "Pure" physics is an invention that exists only in the most old-fashioned classrooms. If you pick up a real problem in physics (or any other science) there extends from it connections to a number of expected and unexpected problems in fields that at first glance seem to "belong" to other professions.

In this course you have seen many evidences of these connections to subject matter of the kind not usually referred to in physics courses. Think back, for example, to our case study in Unit 2 of Newtonian mechanics as applied to planetary motion, a subject that is one of the "beads" on the physics chain. Newton had studied theology and philosophy and those ideas echoed in the Principia in his sections on the nature of time and space (in the Figure below, link A to philosophy). Within physics itself, Newton brought to a culmination the work of Kepler and Galileo (link B). Much of the established mathematics in Newton's work came from the Greeks (link C). New mathematics, particularly the basic ideas of calculus, were invented by Newton to aid his own progress, thereby advancing the progress of mathematics (link D).



Within physics, all who follow Newton will use his laws and approach (link E). His effects on the philosophy of the deist theologians (link F), on Dalton's atomic models in chemistry (link G), and on the artistic sensibilities of the 18th century in which Newton swayed the muses (link H), were documented in the <u>Text</u> and in the <u>Reader</u> articles.

The same kind of web extends around every one of the chief topics we have discussed in this course. Think of the link from philosophy to the work of Oersted, Ampère, and Faraday in electricity (through their interest in Nature Philosophy). Think of the link reaching from nuclear physics back along the chain to the classical physics of three centuries earlier (as in the discussion of how the mass of the neutron was determined), and the links sideways, to biology, engineering, and politics, through the various applications and by-products of nuclear reactors.

Such links exist between all fields. No doubt you found that some of the topics and persons discussed in our course came up also in other courses you have been taking. If we drew all links between fields on the intellectual map, we would see that instead of the separate strings of beads there really exists a coherent crystal, or, if you will, a tapestry, a fabric of ideas. This view of the relevance of science has deeply penetrated our course: Science is now seen to be in dynamic interaction with the total intellectual activity of an age. In a deep sense, science is part of the study of history and of philosophy, and it may underlie the work of the artist just as it penetrates into the explanation a mother gives to her child of the way things move.

If we therefore tried to think away the whole string with the heading "Physics," the history of Western thought would be almost incomprehensible. We could not understand--and in fact would not have had--much of the work of a John Locke and a Voltaire and an Alexander Pope who, among many others, were frankly inspired by the work of the physicists of their time. Conversely, philosophy, mathematics, and other fields would be far emptier studies without their fulfillment and extension through the work of philosopher-scientists such as Mach, Einstein, and Bohr. Eliminating physics would of course also make nonsense of the history of industrial development following upon Watt's steam engine, Volta's battery, Faraday's motors and generators, etc. A neighboring science such as chemistry could not have developed without models of gases and theories of atomic structure that were largely the work of physicists. In short, if you pull out the thread marked "Physics" from the tapestry, the fabric would unravel like an old sweater; and the same would be true if any of the other threads were pulled out. On this view, therefore, the relevance of any field of knowledge, including science, is that it is an integral part of the total growth of thought.

All too often students have to discover the existence of the fabric of ideas for themselves. For it is a bad habit of some academics to teach their own subject as if it had nothing to do with others. But it is precisely by seeing these connections between fields that one becomes educated rather than only trained. We have made these links explicit in our course in the hope of providing an educational experience that, in a similar manner, you can and should obtain in all your courses.

Relevance 5: Science as a style of life

Modern science is not an elite enterprise for only a self-educated few; nowadays there are literally millions of men and women engaged in it. In the United States alone there are nearly 50,000 people who contribute to physics, and each does so in an individual way. Some prefer to follow their thoughts entirely alone, some are surrounded by students or collaborate with groups of colleagues. Some are in small university laboratories, some in large industrial enterprises. Some accentuate the sober rationality and objectivity which it is possible to achieve in scientific work, others pursue their work with a passion and a daring that makes one dizzy to follow them. Some have no academic degree at all, others are laden with diplomas. But they all share gives a style or way of looking at the world and of life, and this fact science a relevance in addition to the four we have mentioned above. This style has a number of earmarks or components; in concluding this letter, let us list just four:

A. By and large, these people feel at home in the world of nature. It makes sense to them, and they are comfortable with it while knowing full well that the most surprising and important findings in their field are still to be made in the future. To them the world is not a succession of incoherent, unique events. Knowledge about nature gives them a sense of the relations of things--how the world hangs together in an ecological manner. But such knowledge does not "explain away" the phenomena or dull the excitement about them, any more than knowing the rules of baseball makes you less involved in watching the game than you would be if you were ignorant of them. Of course nobody knows all there is to know even about a single one of the sciences. But still, you can feel quite at home in a city even if you have personally walked through only a few percent of all the streets there; if you know the pattern in outline, plus the crucial details of some regions within it, you no longer feel a stranger.

B. Under Relevance 1 above we stressed the intellectual interest in science for society as a whole, but there is also a personal aspect for every scientist or student: Here is a chance to devote one's professional life to something one loves to do. Those who have selected a science for their career, and who are at all good at it, are on a road through a changing landscape along which each can select his own problems to work on. (If only this were possible for people everywhere, so many of whom are trapped in dull routines others have decided for them!) We speak here of science as doing, not just what is contained in books, any more than art is only what is contained in museums and libraries. Being a scientist can be a way of spending one's professional life, day by day, in what one likes to do and does well. It's not like reading a play, or watching it, but like writing it and acting in it. And much of the same satisfaction goes to those who spend most of their lives not as research scientists but as teachers, in high school or college--those who have found that their chief satisfaction is helping young people to realize what role science can play in their lives.

C. Each professional group has its own values, and the values of day-by-day life in science were illustrated in the course also. Nowhere more than in science is intellectual merit and skill honored. No matter who he is, the scientist is taken seriously by his peers for what he can do. Consequently, some minority groups have broken through the unjust social obstacles first by showing their excellence in scientific work. There is in science a great amount of room at the top, as well as an atmosphere of belonging to an international and cosmopolitan community.

One "minority" group that has been of particular concern to scientists is that made up of young people. A whole set of social inventions and devices operates in the life of science in order to recognize and reward talent as early as possible. As you saw again and again (in the Text and in the biographical remarks, in the documentary films People and Particles and The World of Enrico Fermi), the young scientist is welcome and is brought as quickly as possible to participate at the growing edge of new science. As a member of a team he may in some subject be the expert or teacher for others who are his seniors. And unlike the situation in many other fields, it is widely recognized in science that a person is at his best in terms of imaginative contributions while still young.

D. More and more, scientists have recognized that discovery of new knowledge and the teaching of established knowledge do not fulfill all their responsibilities. Rather, scientists are prominent among those who take part in the process of examining the immediate social consequences of scientific and technical advance; their knowledge of science adds to their obligations of citizenship. Most of them, and particularly the young, therefore feel that there is a happy complementarity between taking part in developing the human values of a democratic society and taking part in the growth of science.

* * *

The five meanings of relevance we have now set forth are of course closely related to one another in many ways. They can all be present in the actual lives of actual people. In preparing the materials of this course we have tried to catch our own excitement about physics, its relevance, and its relations to the rest of the world of thought and action--and we hope you have shared some of that excitement with us.

With all good wishes,

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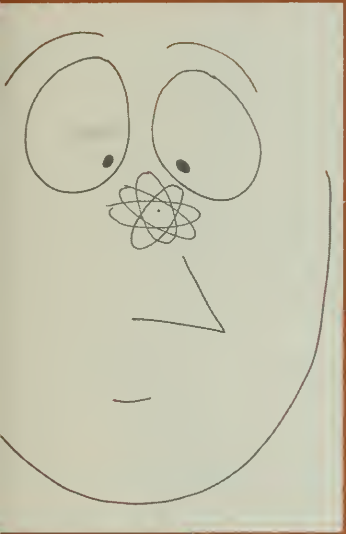
The Project Physics Course

Handbook 6

The Nucleus



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Chapter 21 Radioactivity

EXPERIMENT 45 RANDOM EVENTS

In Unit 6, after having explored the random behavior of gas molecules in Unit 3, you are learning that some atomic and nuclear events occur in a random manner. The purpose of this experiment is to give you some firsthand experience with random events.

What is a random event?

Dice are useful for studying random behavior. You cannot predict with certainty how many spots will show on a single throw. But you are about to discover that you *can* make useful predictions about a large number of throws. If the behavior of the dice is truly random, you can use probability theory to make predictions. When, for example, you shake a box of 100 dice, you can predict with some confidence how many will fall with one spot up, how many with two spots up, and so on. Probability theory has many applications. For example, it is used in the study of automobile traffic flow, the interpretation of faint radar echoes from the planets, the prediction of birth, death, and accident rates, and the study of the breakup of nuclei. An interesting discussion of the rules and uses of probability theory is found in George Gamow's article, "The Law of Disorder," in *Reader 3*.

The theory of probability provides ways to determine whether a set of events are random. An important characteristic of all truly *random* events is that each event is independent of the others. For example, if you throw a legitimate die four times in a row and find that a single spot turns up each time, your chance of observing a single spot on the fifth throw is no greater or smaller than it was on the first throw.

If events are to be independent, the circumstances under which the observations are made must never favor one outcome over another. This condition is met in each of the following three parts of this experiment. You are expected to do only one of these parts, (a), (b), or (c). The section "Recording your data" that follows the three descriptions applies to all parts of the experiment. Read this section in preparing to do any part of the experiment.

(a) Twenty-sided dice

A tray containing 120 dice is used for this experiment. Each die has 20 identical faces (the name for a solid with this shape is *icosahedron*). One of the 20 faces on each die should be marked; if it is not, mark one face on each die with a felt-tip pen.

Q1 What is the probability that the marked face will appear at the top for any one throw of one die? To put it another way, *on the average* how many marked faces would you expect to see face up if you roll all 120 dice?

Now try it, and see how well your prediction holds. Record as many trials as you can in the time available, shaking the dice, pouring them out onto the floor or a large tabletop, and counting the number of marked faces showing face up. (See Fig. 21-1.)

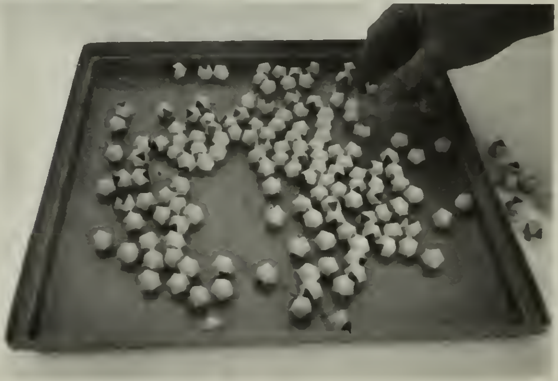


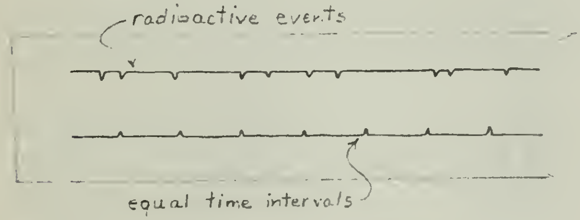
Fig. 21-1 Icosahedral dice in use.

The counting will go faster if the floor area or tabletop is divided into three or four sections, with a different person counting each section and another person recording the total count. Work rapidly, taking turns with others in your group if you get tired, so that you can count at least 100 trials.

(b) Diffusion cloud chamber

A cloud chamber is a device that makes visible the trail left by the particles emitted by radioactive atoms. One version is a transparent box filled with supercooled alcohol vapor. When an α particle passes through, it leaves a trail of ionized air molecules. The alcohol molecules are attracted to these ions and they condense into tiny droplets which mark the trail.

Your purpose in this experiment is not to learn about the operation of the chamber, but simply to study the randomness with which the α particles are emitted. A barrier with a narrow opening is placed in the chamber near a radioactive source that emits α particles. Count the number of tracks you observe coming through the opening in a convenient time interval, such as 10 seconds. Continue counting for as many intervals as you can during the class period.



A convenient method of counting events in successive time intervals is to mark them in one slot of the "drag-strip" recorder, while marking seconds (or ten second intervals) in the other slot.

(c) Geiger counter

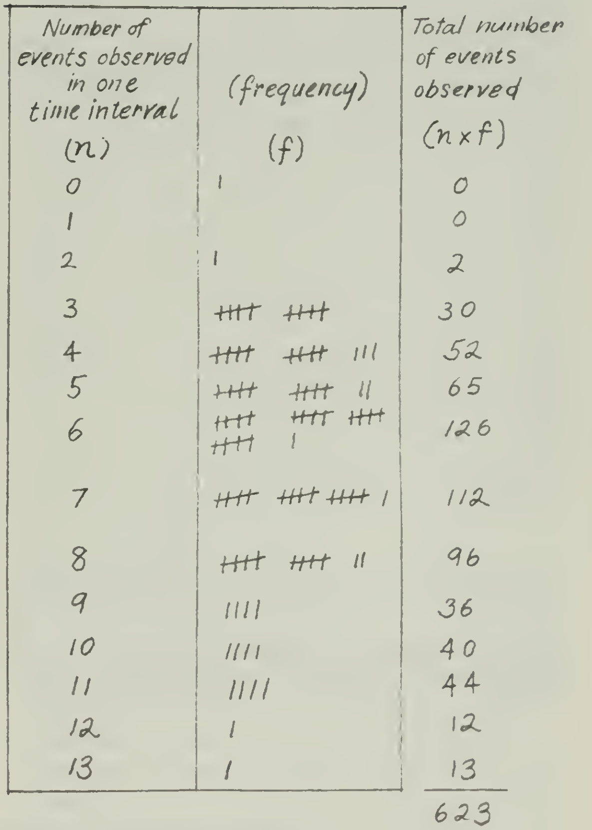
A Geiger counter is another device that detects the passage of invisible particles. A potential difference of several hundred volts is maintained between the two electrodes of the Geiger tube. When a β particle or a γ ray ionizes the gas in the tube, a short pulse of electricity passes through it. The pulse may be heard as an audible click in an earphone, seen as a "blip" on an oscilloscope screen, or read as a change in a number on an electronic scaling device. When a radioactive source is brought near the tube, the pulse rate goes up rapidly. But even without the source, an occasional pulse still occurs. These pulses are called "background" and are caused by cosmic radiation and by a slight amount of radioactivity always present in objects around the tube.

Use the Geiger counter to determine the rate of background radiation, counting over and over again the number of pulses in a convenient time interval, such as 10 seconds.

Recording your data

Whichever of the three experiments you do, prepare your data record in the following way:

Down the left-hand edge of your paper write a column of numbers from 0 to the highest number you ever expect to observe in one count. For example, if your Geiger counts seem to range from 3 to 20 counts in each time interval, record numbers from 0 to 20 or 25.



Number of events observed in one time interval (n)	(frequency) (f)	Total number of events observed (n×f)
0	|	0
1		0
2	|	2
3	𝍸 𝍸	30
4	𝍸 𝍸 |||	52
5	𝍸 𝍸 |||	65
6	𝍸 𝍸 𝍸 𝍸 |	126
7	𝍸 𝍸 𝍸 |	112
8	𝍸 𝍸 ||	96
9	||||	36
10	||||	40
11	||||	44
12	|	12
13	|	13
		623

Fig. 21-2 A typical data page.

To record your data, put a tally mark opposite each number in the column for each time this number occurred. Continue making tally marks for as many trial observations as you can make during the time you have. When you are through, add another column in which you multiply each number in the first column by the number of tallies opposite it. Whichever experiment you did, your data sheet will look something like the sample in Fig. 21-2. The third column shows that a total of 623 marked faces (or pulses or tracks) were observed in the 100 trials. The *average* is 623 divided by 100, or about 6. You can see that most of the counts cluster around the mean.

This arrangement of data is called a *distribution table.* The distribution shown was obtained by shaking the tray of 20-sided dice 100 times. Its shape is also typical of Geiger-counter and cloud-chamber results.

A graph of random data

The pattern of your results is easier to visualize if you display your data in the form of a bar graph, or *histogram,* as in Fig. 21-3.

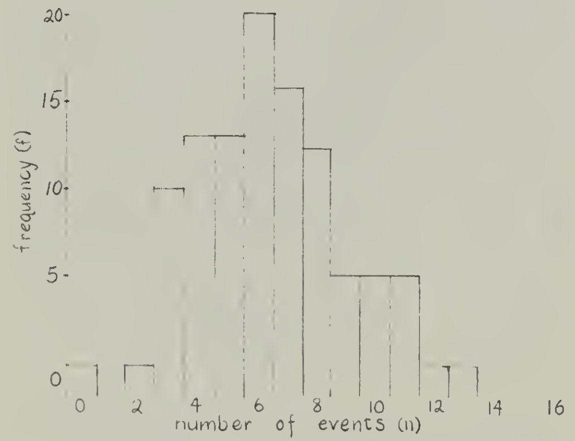


Fig. 21-3 The results obtained when a tray of 20-sided dice (one side marked) were shaken 100 times.

If you were to shake the dice another set of 100 times, your distribution would not be exactly the same as the first one. However, if sets of 100 trials were repeated several times, the *combined* results would begin to form a smoother histogram. Fig. 21-4 shows the kind of result you could expect if you did 1,000 trials.

Compare this with the results for only ten trials shown in Fig. 21-5. As the number of trials increases, the distribution generally becomes smoother and more like the distribution in Fig. 21-4.

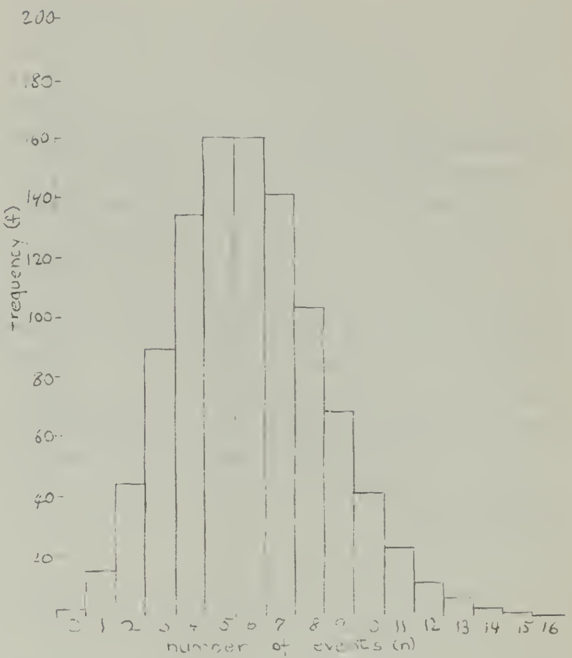


Fig. 21-4 The predicted results of shaking the dice 1000 times. Notice that the vertical scale is different from that in Fig. 21-3. Do you see why?

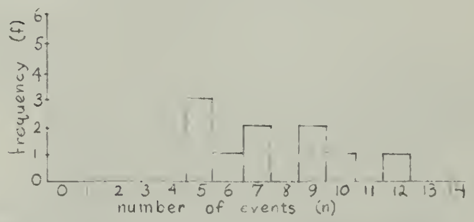


Fig. 21-5 Results of shaking the dice ten times.

Predicting random events

How can data like these be used to make predictions?

On the basis of Fig. 21-4, the best prediction of the number of marked faces turning up would be 5 or 6 out of 120 rolls. Apparently the chance of a die having its marked face up is about 1 in 20—that is, the probability is $\frac{1}{20}$.

But not all trials had 5 or 6 marked faces showing. In addition to the average of a distribution, you also need to know something about how the data spread out around the average. Examine the histogram and answer the following questions:

Q2 How many of the trials in Fig. 21-4 had from 5 to 7 counts?

Q3 What fraction is this of the total number of observations?

Q4 How far, going equally to the left and right of the average, must you go to include half of all the observations? to include two-thirds?

For a theoretical distribution like this (which your own results will closely approximate as you increase the number of trials), it turns out that there is a simple rule for expressing the spread: If the average count is A, then $\frac{2}{3}$ of the counts will be between $A - \sqrt{A}$ and $A + \sqrt{A}$. Putting it another way, about $\frac{2}{3}$ of the values will be in the range of $A \pm \sqrt{A}$.

Another example may help make this clear. For example, suppose you have been counting cloud-chamber tracks and find that the average of a large number of one-minute counts is 100 tracks. Since the square root of 100 is 10, you would find that about two-thirds of your counts would lie between 90 and 110.

Check this prediction in Fig. 21-4. The average is 6. The square root of 6 is about 2.4. The points along the base of the histogram corresponding to 6 ± 2.4 are between 3.6 and 8.4. (Of course, it doesn't really make sense to talk about a fraction of a marked side. One would need to round off to the nearest whole numbers, 4 and 8.) Therefore the chances are about two out of three that the number of marked sides showing after any shake of the tray will be in the range 4 to 8 out of 120.

Q5 How many of the trials did give results in the range 4 to 8? What fraction is this of the total number of trials?

Q6 Whether you rolled dice, counted tracks, or used the Geiger counter, inspect your results to see if $\frac{2}{3}$ of your counts do lie in the range $A \pm \sqrt{A}$.

If you counted for only a *single* one-minute trial, the chances are about two out of three that your single count C will be in the range $A \pm \sqrt{A}$, where A is the true average count (which you would find over many trials). This implies that you can predict the true average value fairly well even if you have made only a single one-minute count. The chances are about two out of three that the single count C will be within $\sqrt{A}$ of the true average A. If we assume C is a fairly good estimate of A, we can use $\sqrt{C}$ as an estimate of $\sqrt{A}$ and conclude that the chances are two out of three that *the value obtained for* C *is within* $\pm\sqrt{C}$ *of the true average.*

You can decrease the uncertainty in predicting a true average like this by counting for a longer period. Suppose you continued the count for ten minutes. If you counted 1,000 tracks the expected "two-thirds range" would be about $1000 \pm \sqrt{1000}$ or 1000 ± 32. The result is 1000 ± 32 counts in *ten* minutes, which gives an average of 100 ± 3.2 counts per minute. If you counted for still longer, say 100 minutes, the range would be $10{,}000 \pm \sqrt{10{,}000}$ or 10,000 ± 100 counts in *100* minutes. Your estimate of the average count rate would be 100 ± 1 counts per minute. The table below lists these sample results.

Notice that although the range of uncertainty in the *total* count increases as the count goes up, it becomes a smaller *fraction* of the total count. Therefore, the uncertainty in the *average* count rate (number of counts per minute) decreases.

SAMPLE RESULTS AND ESTIMATED "TWO-THIRDS RANGES"

TIME min	TOTAL COUNT	EXPECTED UNCERTAINTY	AVERAGE COUNT per min	EXPECTED UNCERTAINTY per min
1	100	±10	100	±10
10	1000	±32	100	±3.2
100	10000	±100	100	±1.0

(The percent uncertainty can be expressed as $\frac{\sqrt{C}}{C}$, which is equal to $\frac{1}{\sqrt{C}}$. In this expression, you can see clearly that the percent uncertainty goes down as C increases.)

You can see from these examples that the higher the total count (the longer you count or the more dice-rolling trials you do) the more precisely you can estimate the true average. This becomes important in the measurement of the activity of radioactive samples and many other kinds of random events. To get a precise measure of the activity (the average count rate), you must work with large numbers of counts.

Q7 If you have time, take more data to increase the precision of your estimate of the mean.

Q8 If you count 10 cosmic ray tracks in a cloud chamber during one minute, for how long would you expect to have to go on counting to get an estimate of the average with a "two-thirds range" that is only 1% of the average value.

This technique of counting over a longer period to get better estimates is fine as long as the true count rate remains constant. But it doesn't always remain constant. If you were measuring the half-life of a short-lived radioactive isotope, the activity rate would change appreciably during a ten-minute period. In such a case, the way to increase precision is still to increase the number of observations—by having a larger sample of material or putting the Geiger tube closer to it—so that you can record a large number of counts during a short time.

Q9 In a small town it is impossible to predict whether there will be a fire next week. But in a large metropolitan area, firemen know with remarkable accuracy how many fires there will be. How is this possible? What assumption must the firemen make?

EXPERIMENT 46
RANGE OF α AND β PARTICLES

An important property of particles from radioactive sources is their ability to penetrate solid matter. In this experiment you will determine the distances α and β particles can travel in various materials.

α particles are most easily studied in a cloud chamber, a transparent box containing super-cooled alcohol vapor. Since the α particles are relatively massive and have a double positive charge, they leave a thick trail of ionized air molecules behind them as they move along. The ions then serve as centers about which alcohol condenses to form tracks of visible droplets.

β particles also ionize air molecules as they move. But because of their smaller mass and smaller charge, they form relatively few ions, which are farther apart than those formed by α's. As a result, the trail of droplets in the chamber is much harder to see.

A Geiger counter, on the other hand detects β particles better than α particles. This is because α particles, in forming a heavy trail, lose all their energy long before they get through even the thin window of an ordinary Geiger tube. β particles encounter the atoms in the tube window also, but they give up relatively less energy so that their chances of getting through the wall are fairly good.

For these reasons you count α particles using a cloud chamber and β particles with a Geiger counter.

Observing α particles

Mark off a distance scale on the bottom of the cloud chamber so that you will be able to estimate, at least to the nearest $\frac{1}{2}$ cm, the lengths of the tracks formed (Fig. 21-6). Insert a source of α radiation and a barrier (as in the preceding experiment on random events) with a small slot opening at such a height that the tracks form a fairly narrow beam moving parallel to the bottom of the chamber. Put the cloud chamber into operation according to the instructions supplied with it.

Practice watching the tracks until you can report the length of any of the tracks you see.

Fig. 21-6

When you are ready to take data, count and record the number of α's that come through the opening in the barrier in one minute. Measure the opening and calculate its area. Measure and record the distance from the source to the barrier.

Actually you have probably not seen all the particles coming through the opening, since the sensitive region in which tracks are visible is rather shallow and close to the chamber floor. You will probably miss the α's above this layer.

The range and energy of α particles

The maximum range of radioactive particles as they travel through an absorbing material depends on several factors, including the density and the atomic number of the absorber. The graph (Fig. 21-7) summarizes the results

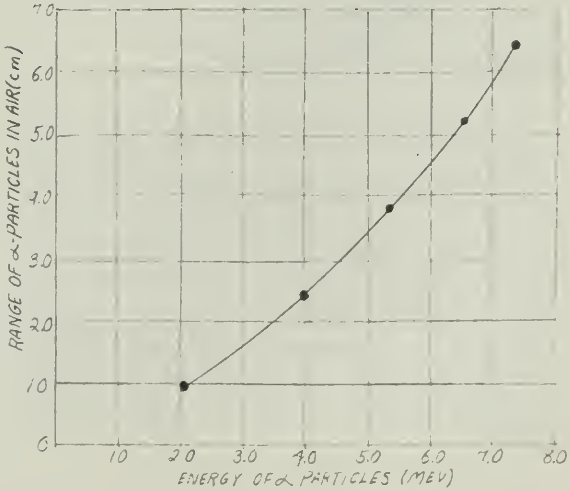


Fig. 21-7 Range of α-particles in air as a function of their energy.

of many measurements of the range of α particles traveling through air. The range-energy curve for particles in air saturated with alcohol vapor, as the air is in your chamber, does not differ significantly from the curve shown. You are therefore justified in using Fig. 21-7 to get a fair estimate of the kinetic energy of the α particles you observed.

Q1 Was there a wide variation in α-particle energies, or did most of the particles appear to have about the same energy? What was the energy of the α particle that caused the longest track you observed?

Now calculate the rate at which energy is being carried away from the radioactive source. Assume that the source is a point. From the number of α particles per minute passing through an opening of known area at a known distance from the source, estimate the number of α particles per minute leaving the source in *all* directions.

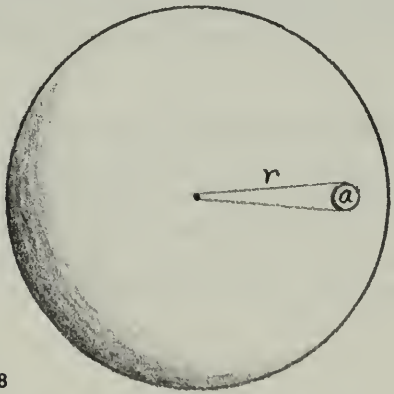


Fig. 21-8

For this estimate, imagine a sphere with the source at its center and a radius r equal to the distance from the source to the barrier. (Fig. 21-8.) From geometry, the surface area of the entire sphere is known to be $4\pi r^2$. You know the approximate rate c at which particles are emerging through the small opening, whose area a you have calculated. By proportion you can find the rate C at which the particles must be penetrating the total area of the sphere:

$$\frac{C}{c} = \frac{4\pi r^2}{a}$$

(The α-particle source is not a point, but probably part of a cylinder. This discrepancy, combined with a failure to count those particles that pass above the active layer, will introduce an error of as much as a factor of 10.)

The total number of particles leaving the source per minute, multiplied by the average energy of the particles, is the total energy lost per minute.

To answer the following questions, use the relationships

$$1 \text{ MeV} = 1.60 \times 10^{-13} \text{ joules}$$

$$1 \text{ calorie} = 4.18 \text{ joules}$$

Q2 How many joules of energy are leaving the source per minute?

Q3 How many calories per minute does this equal?

Q4 If the source were placed in one gram of water in a perfectly insulated container, how long would it take to heat the water from 0° C to 100° C?

Q5 How many joules per *second* are leaving the source? What is the power output in watts?

Observing β particles

After removing all radioactive sources from near the Geiger tube, count the number of pulses caused by background radiation in several minutes. Calculate the average background radiation in counts per minute. Then place a source of β radiation near the Geiger tube, and determine the new count rate. (Make sure that the source and Geiger tube are not moved during the rest of the experiment.) Since you are concerned only with the particles from the source, subtract the average background count rate.

Next, place a piece of absorbing material (such as a sheet of cardboard or thin sheet metal) between the source and the tube, and count again. Place a second, equally thick sheet of the same material in front of the first, and count. Keep adding absorbers and recording counts until the count rate has dropped nearly to the level of background radiation.

Plot a graph on which the horizontal scale is the total thickness (number of) absorbers and the vertical scale is the number of β's getting through the absorber per minute.

In addition to plotting single points, show the uncertainty in your estimate of the count rate for each point plotted. You know that because of the random nature of radioactivity, the count rate actually fluctuates around some average value. You do not know what *true* average value is; it would ideally take an infinite number of one-minute counts to determine the "true" average. But you know that the distribution of a great number of one-minute counts will have the property that two-thirds of them will differ from the average by less than the square root of the average. (See Experiment 45.)

For example, suppose you have observed 100 counts in one given minute. The chances are two out of three that, if you counted for a very long time, the mean count rate would be between 90 and 110 counts (between $100 - \sqrt{100}$ and $100 + \sqrt{100}$ counts). For this reason you would mark a vertical line on your graph extending from 90 counts up to 110. In this way you avoid the pitfall of making a single measurement and assuming you know the "correct" value. (For an example of this kind of graph see notes for Film Loop 9 in Unit 1 *Handbook*.)

If other kinds of absorbing material are available, repeat the experiment with the same source and another set of absorbers. For sources that emit very low-energy β rays, it may be necessary to use very thin materials, such as paper or household aluminum foil.

Range and absorption of β particles

Examine your graph of the absorption of particles.

Q6 Is it a straight line?

Q7 What would the graph look like if (as is the case for α particles) all β particles from the source were able to penetrate the same thickness of a given absorber material before giving up all their energy?

Q8 If you were able to use different absorbing materials, how did the absorption curves compare?

Q9 What might you conclude about the kinetic energies of β particles?

EXPERIMENT 47 HALF-LIFE—I

The more people there are in the world, the more people die each day. The less water there is in a tank, the more slowly water leaks out of a hole in the bottom.

In this experiment, you will observe three other examples of quantities that change at a rate that depends on the total amount of the quantity present. The objective is to find a common principle of change. Your conclusions will apply to many familiar growth and decay processes in nature.

If you experimented earlier with rolling dice and with radioactive decay (Experiment 45), you were studying random events you could observe one at a time. You found that the fluctuations in such small numbers of random events were relatively large. But this time you will deal with a large number of events, and you will find that the outcome of your experiments is therefore more precisely predictable.

Part A. Twenty-sided Dice

Mark any two sides of each 20-sided die with a (washable) marking pen. The chances will therefore be one in ten that a marked surface will be face up on any one die when you shake and roll the dice. When you have rolled the 120 dice, *remove* all the dice that have a marked surface face up. Record the number of dice you removed (or line them up in a column). With the remaining dice, continue this process of shaking, rolling, and removing the marked dice at least twenty times. Record the number you remove each time (or line them up in a series of columns).

Plot a graph in which each roll is represented by one unit on the horizontal axis, and the number of dice *removed* after each roll is plotted on the vertical axis. (If you have lined up columns of removed dice, you already have a graph.)

Plot a second graph with the same horizontal scale, but with the vertical scale representing the number of dice *remaining* in the tray after each roll.

You may find that the numbers you have recorded are too erratic to produce smooth curves. Modify the procedure as follows: Roll the dice and count the dice with marked surfaces face up. Record this number but do not remove the dice. Shake and count again. Do this five times. Now find the mean of the five numbers, and remove that number of dice. The effect will be the same as if you had actually started with 120 × 5 or 600 dice. Continue this procedure as before, and you will find that it is easier to draw smooth curves which pass very nearly through all the points on your two graphs.

Q1 How do the shapes of the two curves compare?

Q2 What is the ratio of the number of dice removed after each shake to the number of dice shaken in the tray?

Q3 How many shakes were required to reduce the number of dice in the tray from 120 to 60? from 60 to 30? from 100 to 50?

Part B. Electric Circuit

A capacitor is a device that stores electric charge. It consists of two conducting surfaces placed very close together, but separated by a thin sheet of insulating material. When the two surfaces are connected to a battery, negative charge is removed from one plate and added to the other so that a potential difference is established between the two surfaces. (See Sec. 14.6 of Unit 4 *Text*.) If the conductors are disconnected from the battery and connected together through a resistor, the charge will begin to flow back from one side to the other. The charge will continue to flow as long as there is a potential difference between the sides of the capacitor. As you learned in Unit 4, the rate of flow of charge (the current) through a conducting path depends both on the resistance of the path and the potential difference across it.

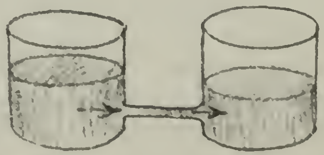
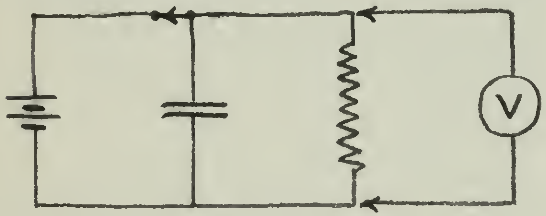


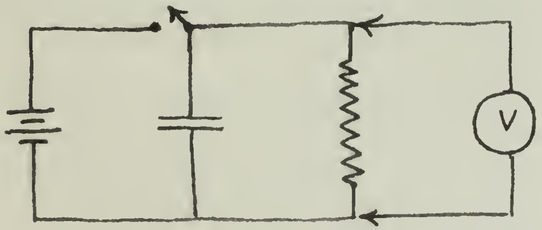
Fig. 21-9 An analogy: The rate of flow of water depends upon the difference in height of the water in the two tanks and upon the resistance the pipe offers to the flow of water.

To picture this situation, think of two partly filled tanks of water connected by a pipe running from the bottom of one tank to the bottom of the other (Fig. 21-9). When water is transferred from one tank to the other, the additional potential energy of the water is given by the difference in height, just as the potential difference between the sides of a charged capacitor is proportional to the potential energy stored in the capacitor. Water flows through the pipe at the bottom until the water levels are the same in the two tanks. Similarly, charge flows through the conducting path connecting the sides of the capacitor until there is no potential difference between the two plates.

Connect the circuit as in Fig. 21-10, close the switch, and record the reading on the voltmeter. Now open the switch and take a series of voltmeter readings at regular intervals. Plot a graph, using time intervals for the horizontal axis and voltmeter readings for the vertical.



(a) Charging the capacitor



(b) discharging through the resistor

Fig. 21-10

Q4 How long does it take for the voltage to drop to half its initial value? from one-half to one-fourth? from one-third to one-sixth?

Repeat the experiment with a different resistor in the circuit. Find the time required for the voltage to drop to half its initial value. Do this for several resistors.

Q5 How does the time required for the voltage to drop to half its initial value change as the resistance in the circuit is changed?

Part C. Short-lived Radioisotope

Whenever you measure the radioactivity of a sample with a Geiger counter, you must first determine the level of background radiation. With no radioactive material near the Geiger tube, take a count for several minutes and calculate the average number of counts per minute caused by background radiation. This number must be subtracted from any count rates you observe with a sample near the tube, to obtain what is called the *net count rate* of the sample.

The measurement of background rate can be carried on by one member of your group while another prepares the sample according to the directions given below. Use this measurement of background rate to become familiar with the operation of the counting equipment. You will have to work quite quickly when you begin counting radiation from the sample itself.

First, a sample of a short-lived radioisotope must be isolated from its radioactive parent material and prepared for the measurement of its radioactivity.

Although the amount of radioactive material in this experiment is too small to be considered at all dangerous (unless you drink large quantities of it), it is a very good idea to practice caution in dealing with the material. Respect for radioactivity is an important attitude in our increasingly complicated world.

The basic plan is to (1) prepare a solution which contains several radioactive substances, (2) add a chemical that absorbs only one of the radioisotopes, (3) wash most of the solution away leaving the absorbing chemical on a piece of filter paper, (4) mount the filter paper close to the end of the Geiger counter.

(1) Prepare a funnel-filter assembly by placing a small filter paper in the funnel and wetting it with water.

Pour 12 cc of thorium nitrate solution into one graduated cylinder, and 15 cc of dilute nitric acid into another cylinder.

(2) Take these materials to the filter flask

which has been set up in your laboratory. Your teacher will connect your funnel to the filter flask and pour in a quantity of ammonium phosphomolybdate precipitate, $(NH_4)_3PMo_{12}O_{40}$. The phosphomolybdate precipitate adsorbs the radioisotope radioactive elements present in the thorium nitrate solution.

(3) Wash the precipitate by sprinkling several cc of distilled water over it, and then *slowly* pour the thorium nitrate solution onto the precipitate (Fig. 21-11). Distribute the solution over the whole surface of the precipitate. Wash the precipitate again with 15 cc of dilute nitric acid and wait a few moments while the pump attached to the filter flask dries the sample. By the time the sample is dry, the nitric acid should have carried all the thorium nitrate solution through the filter. Left behind on the phosphomolybdate precipitate should be the short-lived daughter product whose radioactivity you wish to measure.

Fig. 21-11

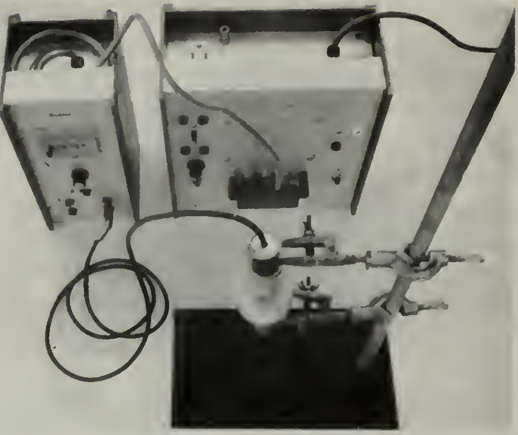
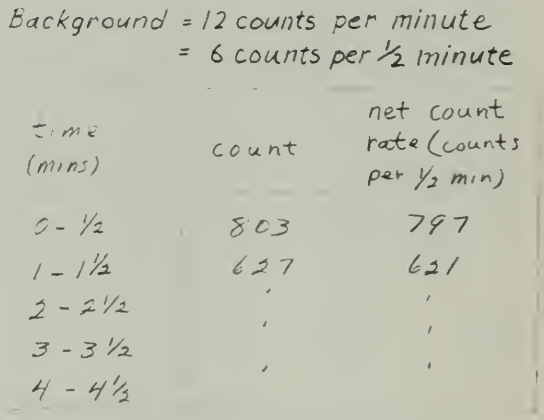


Fig. 21-12



Background = 12 counts per minute
= 6 counts per ½ minute

time (mins)	count	net count rate (counts per ½ min)
0 - ½	803	797
1 - 1½	627	621
2 - 2½	'	'
3 - 3½	'	'
4 - 4½	'	'

Fig. 21-13

(4) As soon as the sample is dry, remove the upper part of the funnel from the filter flask and take it to the Geiger counter. Make sure that the Geiger tube is protected with a layer of thin plastic food wrapping. Then lower it into the funnel carefully until the end of the tube almost touches the precipitate (Fig. 21-12).

You will probably find it convenient to count for one period of 30 seconds in each minute. This will give you 30 seconds to record the count, reset the counter, and so on, before beginning the next count. Record your results in a table like Fig. 21-13. Try to make about ten trials.

Plot a graph of *net* count rate as a function of time. Draw the best curve you can through all the points. From the curve, find the time required for the net count rate to decrease to half its initial value.

Q6 How long does it take for the net count rate to decrease from one-half to one-fourth its initial value? one-third to one-sixth? one-fourth to one-eighth?

Q7 The half-life of a radioisotope is one of the important characteristics which helps to identify it. Using the *Handbook of Chemistry and Physics*, or another reference source, identify which of the decay products of thorium is present in your sample.

Q8 Can you tell from the curve you drew whether your sample contains only one radioisotope or a mixture of isotopes?

Discussion

It should be clear from your graphs and those of your classmates that the three kinds of quantities you observed all have a common property: It takes the same time (or number of rolls of the dice) to reduce the quantity to half its initial value as it does to reduce from a half to a fourth, from a third to a sixth, from a fourth to an eighth, etc. This quantity is the *half-life*.

In the experiments on the "decay" of twenty-sided dice with two marked faces, you knew beforehand that the "decay rate" was one-tenth. That is, over a large number of throws an average of one-tenth of the dice would be removed for each shake of the tray.

The relationship between the half-life of a process and the decay constant λ is discussed on the gray page *Mathematics of Decay* in Chapter 21 of the *Text*. There you learned that for a large number of truly random events, the half life $T_{\frac{1}{2}}$ is related to the decay constant λ by the equation:

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

Q9 From the known decay constant of the dice, calculate the half-life of the dice and compare it with the experimental value found by you or your classmates.

Q10 If you measured the half-life for capacitor discharge or for radioactive decay, calculate the decay constant for that process.

EXPERIMENT 48 HALF LIFE—II

Look at the thorium decay series in the table below. One of the members of the series, radon 220, is a gas. In a sealed bottle containing thorium or one of its salts, some radon gas always gathers in the air space above the thorium. Radon 220 has a very short half-life (51.5 sec). The subsequent members of the series (polonium 214, lead 210, etc.) are solids. Therefore, as the radon 220 decays, it forms a solid deposit of radioactive material in the bottle. In this experiment you will measure the half-life of this radioactive deposit.

Although the amount of radioactive material in this experiment is too small to be considered at all dangerous (unless you drank large quantities of it), it is a very good idea to practice caution in dealing with the material.

THE THORIUM DECAY SERIES

NAME	SYMBOL	MODE OF DECAY	HALF-LIFE
Thorium 232	$_{90}Th^{232}$	α	1.39×10^{10} yrs.
Radium 228	$_{88}Ra^{228}$	β	6.7 years
Actinium 228	$_{89}Ac^{228}$	β	6.13 hours
Thorium 228	$_{90}Th^{228}$	α	1.91 years
Radium 224	$_{88}Ra^{224}$	α	3.64 days
Radon 220	$_{86}Rn^{220}$	α	51.5 sec
Polonium 216	$_{84}Po^{216}$	α	0.16 sec
Lead 212	$_{82}Pb^{212}$	β	10.6 hours
Bismuth 212	$_{83}Bi^{212}$	α or β*	60.5 min
Polonium 212	$_{84}Po^{212}$	α	3.0×10^{-7} sec
Thallium 208	$_{81}Tl^{208}$	β	3.10 min
Lead 208	$_{82}Pb^{208}$	Stable	3.10 min

*Bismuth 212 can decay in two ways: 34 per cent decays by α emission to thallium 208; 66 per cent decays by β emission to polonium 212. Both thallium 208 and polonium 212 decay to lead 208.

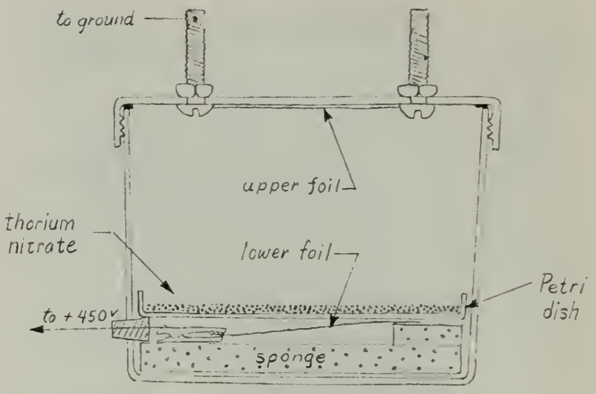


Fig. 21-14

Respect for radioactivity is an important attitude in our increasingly complicated world.

The setup is illustrated in Fig. 21-14. The thorium nitrate is spread on the bottom of a sealed container. (The air inside should be kept damp by moistening the sponge with water.) Radon gas escapes into the air of the container, and some of its decay products are deposited on the upper foil.

When radon disintegrates in the nuclear reaction

$$_{86}Rn^{220} \rightarrow {}_{84}Po^{216} + {}_{2}He^{4}$$

the polonium atoms formed are ionized, apparently because they recoil fast enough to lose an electron by inelastic collision with air molecules.

Because the atoms of the first daughter element of radon are ionized (positively charged), you can increase the amount of deposit collected on the upper foil by charging it negatively to several hundred volts. Although the electric field helps, it is not essential; you will get some deposit on the upper foil even if you don't set up an electric field in the container.

After two days, so much deposit has accumulated that it is decaying nearly as rapidly as the constant rate at which it is being formed.

Therefore, to collect a sample of maximum activity, your apparatus should stand for about two days.

Before beginning to count the activity of the sample, you should take a count of the background rate. Do this far away from the vessel containing the thorium. Remove the cover, place your Geiger counter about one mm above the foil, and begin to count. Make sure, by adjusting the distance between the sample and the window of the Geiger tube, that the initial count rate is high—several hundred per minute. Fix both the counter and the foil in position so that the distance will not change. To get fairly high precision, take a count over a period of at least ten minutes (see Experiment 45). Because the deposit decays rather slowly, you can afford to wait several hours between counts, but you will need to continue taking counts for several days. Make sure that the distance between the sample and the Geiger tube stays constant.

Record the net count rate and its uncertainty (the "two-thirds" range discussed in Experiment 45). Plot the net count rate against time.

Remember that the deposit contains several radioactive isotopes and each is decaying. The net count rate that you measure is the sum of the contributions of all the active isotopes. The situation is not as simple as it was in Experiment 46, in which the single radioactive isotope decayed into a *stable* isotope.

Q1 Does your graph show a constant half-life or a changing half-life?

Look again at the thorium series and in particular at the half-lives of the decay products of radon. Try to interpret your observations of the variation of count rate with time.

Q2 Which isotope is present in the greatest amount in your sample? Can you explain why this is so? Make a sketch (like the one on page 22 of Unit 6 *Text*) to show approximately how the relative amounts of the different isotopes in your sample vary with time. Ignore the isotopes with half-lives of less than one minute.

You can use your measurement of count rate and half-life to get an estimate of the amount of deposit on the foil. The activity, $\frac{\Delta N}{\Delta t}$, depends on the number of atoms present, N:

$$\frac{\Delta N}{\Delta t} = \lambda N.$$

The decay constant λ is related to the half-life $T_{\frac{1}{2}}$ by

$$\lambda = \frac{0.693}{T_{\frac{1}{2}}}$$

Use your values of counting rate and half-life to estimate N, the number of atoms present in the deposit. What mass does this represent? (1 amu = 1.7×10^{-27} kg.) The smallest amount of material that can be detected with a chemical balance is of the order of 10^{-6} gram.

Discussion

It is not too difficult to calculate the speed and hence the kinetic energy of the polonium atom In the disintegration

$$_{86}\mathrm{Rn}^{220} \quad \rightarrow \quad _{84}\mathrm{Po}^{216} + {_2}\mathrm{He}^4$$

the α particle is emitted with kinetic energy 6.8 MeV. Combining this with the value of its mass, you can calculate v^2 and, therefore, v. What is the momentum of the α particle? Momentum is of course conserved in the disintegration. So what is the momentum of the polonium atom? What is its speed? What is its kinetic energy?

The ionization energy—the energy required to remove an outer electron from the atom—is typically a few electron volts. How does your value for the polonium atom's kinetic energy compare with the ionization energy? Does it seem likely that most of the recoiling polonium atoms would ionize?

EXPERIMENT 49
RADIOACTIVE TRACERS

In this group of experiments, you have the opportunity to invent your procedures yourself and to draw your own conclusions. Most of the experiments will take more than one class period and will require careful planning in advance. You will find below a list of books and magazine articles that can help you.

A Caution

All these experiments take cooperation from the biology or the chemistry department, and require that safety precautions be observed very carefully so that neither you nor other students will be exposed to radiation.

For example, handle radioisotopes as you would a strong acid; if possible, wear disposable plastic gloves, and work with all containers in a tray lined with paper to soak up any spills. Never draw radioactive liquids into a pipette by mouth as you might do with other chemical solutions; use a mechanical pipette or a rubber bulb. Your teacher will discuss other safety precautions with you before you begin.

None of these activities is suggested just for the sake of doing tricks with isotopes. You should have a question clearly in mind before you start, and should plan carefully so that you can complete your experiment in the time you have available.

Tagged Atoms

Radioactive isotopes have been called tagged atoms because even when they are mixed with stable atoms of the same element, they can still be detected. To see how tagged atoms are used, consider the following example.

A green plant absorbs carbon dioxide (CO_2) from the air and by a series of complex chemical reactions builds the carbon dioxide (and water) into the material of which the plant is made. Suppose you tried to follow the steps in the series of reactions. You can separate each compound from the mixture by using ordinary chemical methods. But how can you trace out the chemical steps by which each compound is transformed into the next when they are all jumbled together in the same place? Tagged atoms can help you.

Put the growing green plant in an atmosphere containing normal carbon dioxide, to which has been added a tiny quantity of CO_2 molecules which contain the radioactive isotop carbon 14 in place of normal carbon 12. Less than a minute later the radioactivity can be detected within some, but not all, of the molecules of complex sugars and amino acids being synthesized in the leaves. As time goes on, the radioactive carbon enters step by step into each of the carbon compounds in the leaves.

With a Geiger counter, in effect, one can watch each compound in turn to detect the moment when radioactive molecules begin to be added to it. In this way, the mixture of compounds in a plant can be arranged in their order of formation, which is obviously a useful clue to chemists studying the reactions. Photosynthesis, long a mystery, has been studied in detail in this way.

Radioactive isotopes used in this manner are called *tracers*. The quantity of tracer material needed to do an experiment is astonishingly small. For example, compare the amount of carbon that can be detected by an analytical balance with the amount needed to do a tracer experiment. Your Geiger counter may, typically, need 100 net counts per minute to distinguish the signal from background radiation. If only 1% of the particles emitted by the sample are detected, then in the smallest detectable sample, 10,000 or 10^4 atoms are decaying each minute. This is the number of atoms that decay each minute in a sample of only 4×10^{-4} micrograms of carbon 14. Under ideal conditions, a chemical balance might detect one microgram.

Thus, in this particular case, measurement by radioactivity is over ten thousand times more sensitive than the balance.

In addition, tracers give you the ability to find the precise location of a tagged substance *inside* an undisturbed plant or animal. Radiation from thin sections of a sample placed on photographic film produces a visible spot. (Fig. 21-14.) This method can be made so precise that scientists can tell not only which *cells* of an organism have taken in the tracer, but also which *parts* of the cell (nucleus, mitochondria, etc.).

Choice of Isotope

The choice of which radioactive isotope to use in an experiment depends on many factors, only a few of which are suggested here.

Carbon 14, for example, has several properties that make it a useful tracer. Carbon compounds are a major constituent of all living organisms. It is usually impossible to follow the fate of any one carbon compound that you inject into an organism, since the added molecules and their products are immediately lost in the sea of identical molecules of which the organism is made. Carbon 14 atoms, however, can be used to tag the carbon compounds, which can then be followed step by step through complex chains of chemical processes in plants and animals. On the other hand, the carbon 14 atom emits only β particles of rather low energy. This low energy makes it impractical to use carbon 14 inside a large liquid or solid sample since all the emitted particles would be stopped inside the sample.

The half-life of carbon 14 is about 6000 years, which means that the activity of a sample will remain practically constant for the duration of an experiment. But sometimes the experimenter prefers to use a short-lived isotop so that it will rapidly drop to negligibly low activity in the sample—or on the laboratory table if it gets spilled.

Some isotopes have chemical properties that make them especially useful for a specific kind of experiment. Phosphorus 32 (half-life 14.3 days) is especially good for studying the growth of plants, because phosphorous is used by the plant in many steps of the growth process. Practically all the iodine in the human body is used for just one specific process—the manufacture of a hormone in the thyroid gland which regulates metabolic rate. Radioactive iodine 131 (half-life 8.1 days) has been immensely useful as a tracer in unravelling the steps in that complex process.

The amount of tracer to be used is determined by its activity, by how much it will be diluted during the experiment, and by how much radiation can be safely allowed in the laboratory. Since even very small amounts of radiation are potentially harmful to people, safety precautions and regulations must be carefully followed. The Atomic Energy Commission has established licensing procedures and regulations governing the use of radioisotopes. As a student you are permitted to use only limited quantities of certain isotopes under carefully controlled conditions. However, the variety of experiments you can do is still so great that these regulations need not discourage you from using radioactive isotopes as tracers.

One unit used to measure radioactivity of a source is called the *curie*. When 3.7×10^{10} atoms within a source disintegrate or decay in one second, its activity is said to be one curie (c). (This number was chosen because it was the approximate average activity of 1 gram of pure radium 226.) A more practical unit for tracer experiments is the microcurie (μc) which is 3.7×10^4 disintegrations per second or 2.2×10^6 per minute. The quantity of radioisotope that students may safely use in experiments, without special license, varies from 0.1 μc to 50 μc depending on the type and energy of radiation.

Notice that even when you are restricted to 0.1 μc for your experiments, you may still expect 3700 disintegrations per second, which would cause 37 counts a second in a Geiger counter that recorded only 1% of them.

Q1 What would be the "$\frac{2}{3}$ range" in the activity (disintegrations per minute) of a 1 μc source?

Q2 What would be the "$\frac{2}{3}$ range" in counts per minute for such a source measured with a Geiger counter that detects only 1% of the disintegrations?

Q3 Why does a Geiger tube detect such a small percentage of the β particles that leave the sample? (Review that part of Experiment 46 on the range of β particles.)

Part A. Autoradiography

One rather simple experiment you can almost certainly do is to re-enact Becquerel's original discovery of radioactivity. Place a radioactive object—lump of uranium ore, luminous watch dial with the glass removed, etc.—on a Polaroid film packet or on a sheet of x-ray film in a light-tight envelope. A strong source of radiation will produce a visible image on the film within an hour, even through the paper wrapping. If the source is not so strong, leave it in place overnight. To get a very sharp picture, you must use unwrapped film in a completely dark room and expose it with the radioactive source pressed firmly against the film.

(Most Polaroid film can be developed by placing the packet on a flat surface and passing a metal or hard-rubber roller firmly over the pod of chemicals and across the film. Other kinds of film are processed in a darkroom according to the directions on the developer package.)

This photographic process has grown into an important experimental technique called *autoradiography*. The materials needed are relatively inexpensive and easy to use, and there are many interesting applications of the method. For example, you can grow plants in soil treated with phosphorus 32, or in water to which some phosphorus 32 has been added, and make an autoradiograph of the roots, stem, and leaves (Fig. 21-15). Or each day take a leaf from a fast-growing young plant and show how the phosphorous moves from the roots to the growing tips of the leaves. Many other simple autoradiograph experiments are described in the source material listed at the end of this experiment.

Fig. 21-15 Autoradiograph made by a high school student to show uptake of phosphorus-32 in coleus leaves.

Part B. Chemical Reactions and Separations

Tracers are used as sensitive indicators in chemical reactions. You may want to try a tracer experiment using iodine 131 to study the reaction between lead acetate and potassium iodide solutions. Does the radioactivity remain in the solute or is it carried down with the precipitate? How complete is the reaction?

When you do experiments like this one with liquids containing β sources, transfer them carefully (with a special mechanical pipette or a disposable plastic syringe) to a small, disposable container called a planchet, and evaporate them so that you count the dry sample. This is important when you are using β sources since otherwise much of the radiation would be absorbed in the liquid before it reached the Geiger tube.

You may want to try more elaborate experiments involving the movement of tracers through chemical or biological systems. Students have grown plants under bell-jars in an atmosphere containing radioactive carbon dioxide, fed radioactive phosphorus to earthworms and goldfish, and studied the metabolism of rats with iodine 131.

Some Useful Articles

"Laboratory Experiments with Radioisotopes for High School Demonstrations," edited by S. Schenberg; U.S. Atomic Energy Commission, 1958. Order from Superintendent of Documents, Government Printing Office, Washington, D.C. 20402 for thirty-five cents.

"Radioactive Isotopes: A Science Assembly Lecture." Illustrated. Reprints of this article available from *School Science and Mathematics*, P.O. Box 246, Bloomington, Indiana 47401 for twenty-five cents.

"Radioisotope Experiments for the Chemistry Curriculum" (student manual 17311) prepared by U.S. Atomic Energy Commission.

Order from Office of Technical Services, Washington, D.C. 20545, for two dollars. (A companion teacher's guide is also available at one dollar from the same source.)

American Biology Teacher, August 1965, Volume 27, No. 6. This special issue of the magazine is devoted to the use of radioisotopes and contains several articles of use in the present exercise on tracers. Order single copies from Mr. Jerry Lightner, P.O. Box 2113, Great Falls, Montana 59401 for seventy-five cents.

Scientific American, May 1960. The Amateur Scientist section (by C. L. Stong), page 189, is devoted to a discussion of "how the amateur scientist can perform experiments that call for the use of radioactive isotopes." Copies of the magazine are available in many libraries or can be obtained from Scientific American, 415 Madison Ave., New York, New York 10017. (Reprints of this article are not available).

Scientific American, March 1953. The Amateur Scientist section is on "scintillation counters and a home-made spinthariscope for viewing scintillations."

"Low Level Radioisotope Techniques," John H. Woodburn, *The Science Teacher* magazine, November 1960. Order from The Science Teacher, 1201 16th Street, N.W., Washington, D.C. 20036. Single copies are one dollar.

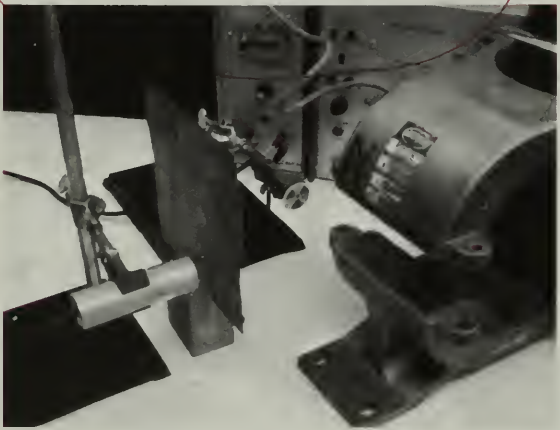
Safe disposal of radioactive wastes with long half-lives is becoming a significant problem. Here steel cases containing dangerously large amounts of radioactive wastes from nuclear reactors are being buried.

To p. #26

ACTIVITIES

MAGNETIC DEFLECTION OF β RAYS

Clamp a radioactive β source securely a distance of about a foot from a Geiger tube. Place a sheet of lead at least 1 mm thick between source and counter to reduce the count to background level. Hold one end (pole) of a strong magnet above or to the side of the sheet, and change its position until the count rate increases appreciably. By what path do the β rays reach the counter? Try keeping the magnet in the same position but reversing the two poles; does the radiation still reach the counter? Determine the polarity of the magnet by using a compass needle. If β rays are particles, what is the sign of their charge? (See Experiment 37 for hints.)

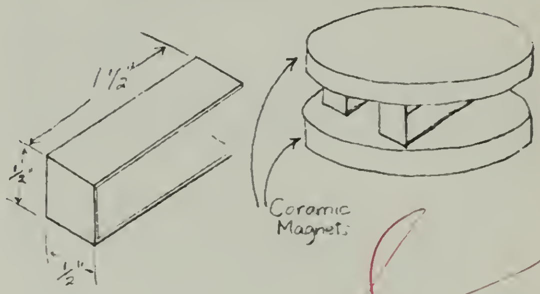


Omit

MEASURING THE ENERGY OF β RADIATION

With a device called a β-ray spectrometer, you can sort out the β particles emitted by a radioactive source according to their energy just as a grating or prism spectroscope spreads out the colors of the visible spectrum. You can make a simple β-ray spectrometer with two disk magnets and a packet of 4″ × 5″ Polaroid film. With it you can make a fairly good estimate of the average energy of the β particles emitted from various sources by observing how much they are deflected by a magnetic field of known intensity.

Mount two disk magnets as shown in the Activity, "Measuring Magnetic Field Intensity," in the Unit 4 *Handbook*, Chapter 14. Be sure the faces of the magnets are parallel and opposite poles are facing each other.



Bend a piece of sheet metal into a curve so that it will hold a Polaroid film packet snugly around the magnets. Place a β source behind a barrier made of thin sheet lead with two narrow slits that will allow a beam of β particles to enter the magnetic field as shown in Fig. 21-16. Expose the film to the β radiation for two days. Then carefully remove the magnets without changing the relative positions of the film and β source. Expose the film for two more days. The long exposure is necessary because the collimated beam contains only a small fraction of the β given off by the source, and because Polaroid film is not very sensitive to β radiation. (You can shorten the exposure time to a few hours if you use x-ray film.)

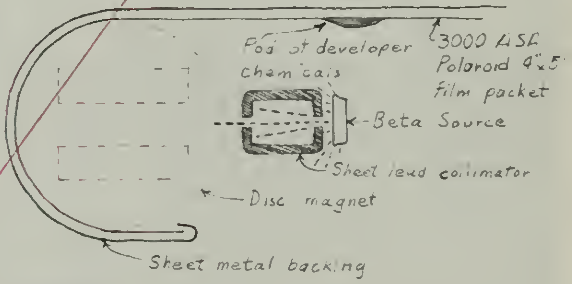


Fig. 21-16

When developed, your film will have two blurred spots on it; the distance between their centers will be the arc length *a* in Fig. 21-17.

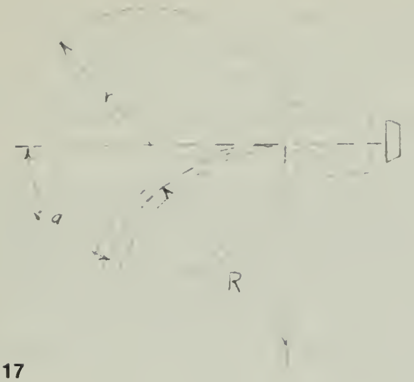


Fig. 21-17

An interesting mathematical problem is to find a relationship between the angle of deflection, as indicated by *a*, and the average energy of the particles. It turns out that you can calculate the *momentum* of the particle fairly easily. Unfortunately, since the β particles from radioactive sources are traveling at nearly the speed of light, the simple relationships between momentum, velocity, and kinetic energy (which you learned about in Unit 3) cannot be used. Instead, you would need to use equations derived from the special theory of relativity which, although not at all mysterious, are a little beyond the scope of this course. (The necessary relations are developed in the supplemental unit, "Elementary Particles.") A graph (Fig. 21-19) that gives the values of kinetic energy for various values of momentum is provided.

First, you need an expression which will relate the deflection to the momentum of the particle. The relationship between the force on a charged particle in a magnetic field and the radius of the circular path is derived in Sec. 18.2 of Unit 5 *Text*. Setting the magnetic force equal to the centripetal force gives

$$Bqv = \frac{mv^2}{R}$$

which simplifies to

$$mv = BqR$$

If you know the magnetic field intensity B (measured with the current balance as described in the Unit 4 *Handbook*), and the charge on the electron, and can find R, you can compute the momentum. A little geometry will enable you to calculate R from a, the arc length, and r, the radius of the magnets. A detailed solution will not be given here, but a hint is shown in Fig. 21-18.

Fig. 21-18

The angle θ is equal to $\frac{a}{2\pi r} \times 360°$, and you should be able to prove that if tangents are drawn from the center of curvature 0 to the points where the particles enter and leave the field, the angle between the tangents at 0 is also θ. With this as a start, see if you can calculate R.

The relationship between momentum and kinetic energy for objects traveling at nearly the speed of light

$$E = \sqrt{p^2c^2 + m_0{}^2c^4}$$

is discussed in most college physics texts. The graph in Fig. 21-19 was plotted using data calculated from this relationship.

From the graph, find the average kinetic energy of the β particles whose momentum you have measured. Compare this with values given in the *Handbook of Chemistry and Physics*, or another reference book, for the particles emitted by the source you used.

You will probably find a value listed which is two to three times higher than the value you found. The value in the reference book is

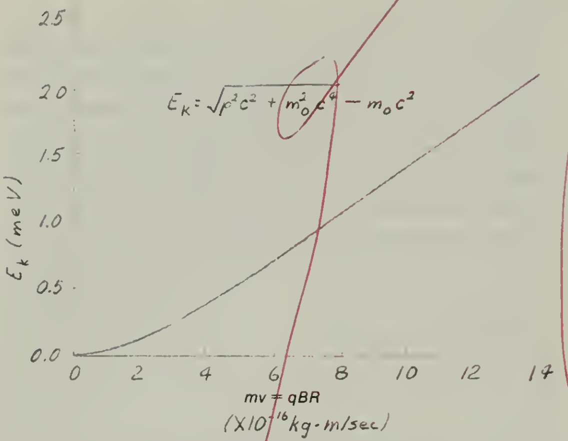


Fig. 21-19 Kinetic energy versus momentum for electrons ($m_0c^2 = 0.511$ meV).

the *maximum* energy that any one β particle from the source can have, whereas the value you found was the *average* of all the β's reaching the film. This discrepancy between the maximum energy (which all the β's should theoretically have) and the average energy puzzled physicists for a long time. The explanation, suggested by Enrico Fermi in the mid-1930's, led to the discovery of a strange new particle called the neutrino which you will want to find out about.

A SWEET DEMONSTRATION

In Experiment 46, "Half-Life I," it is difficult to show that the number of dice "decaying" is directly proportional to the initial number of dice, because statistical fluctuations are fairly large with only 120 dice. An inexpensive way to show that ΔN is directly proportional to N is to use at least 400 sugar cubes (there are 198 in the commonly available 1 pound packages). Mark one face with edible food coloring. Then shake them and record how many decayed as described in Experiment 46.

IONIZATION BY RADIOACTIVITY

Place a different radioactive sample inside each of several identical electroscopes. Charge the electroscopes negatively (as by rubbing a hard, rubber comb on wool and touching the comb to the electroscope knob). Compare the times taken for the electroscopes to completely lose their charges, and interpret your observations.

Place no sample in one electroscope so that you can check how fast it discharges without a sample present. What causes this type of discharge?

EXPONENTIAL DECAY IN CONCENTRATION

Stir 10 drops of food coloring into 1000 cc of water. Pour off 100 cc into a beaker. Add 100 cc of water, stir up the mixture, and pour off a second 100-cc sample. Keep repeating until you have collected 10 to 15 samples.

Questions:

The original concentration was 10 drops/1000 cc or 1 drop/100 cc. What is the concentration after one removal and the addition of pure water (one dilution cycle)? What is the concentration after two cycles? after three cycles? and after n cycles? [Answer: $(0.9)^n$ drops/100 cc.]

What is the number of cycles required to reduce the concentration to approximately $\frac{1}{2}$ of its original concentration?

How many times would you have to repeat the process to get rid of the dye completely?

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To p. 73

Chapter 23 The Nucleus

ACTIVITY

NEUTRON DETECTION PROBLEM ANALOGUE (CHADWICK'S PROBLEM)

It is impossible to determine both the mass and the velocity of a neutron from measurements of the mass and the final velocity of a target particle which the neutron has hit. To help you understand this, try the following:

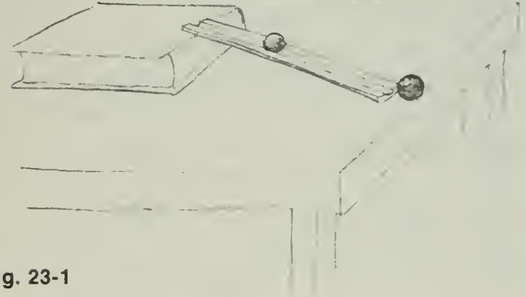

Fig. 23-1

Set up an inclined groove on a table as shown in Fig. 23-1. Let a small ball bearing roll part way down the groove, hitting the larger target ball and knocking it off the table. Note the point where the target ball strikes the floor. Now use another smaller ball as the projectile. Can you adjust the point of release until the target ball strikes the *same spot* on the floor as it did when you used the large projectile? If so, then two different combinations of mass and velocity for the projectile cause the same velocity of the target ball. Are there more combinations of mass and velocity of the target ball. Are there more combinations of mass and velocity of the "neutron" that will give the same result?

Now repeat the experiment, but this time have the same projectile collide in turn with two different target balls of different masses, and measure the velocities of the targets.

Use these velocity values to calculate the mass of the incoming neutron. (Hint: Refer to Sec. 23.4, *Text*. You need only the ratio of the final velocities achieved by the different targets; therefore, you can use the ratio of the two distances measured along the floor from directly below the edge of the table, since they are directly proportional to the velocities.) See also *Film Loop 49*.

"Incredible as it may seem to those of us who live in the world of anti-matter, a mirror image exists—the reverse of ourselves—which we can only call the world of matter."

Drawing by Alan Dunn, © 1965 The New Yorker Magazine, Inc.

FILM LOOP

FILM LOOP 49: COLLISIONS WITH AN OBJECT OF UNKNOWN MASS

In 1932, Chadwick discovered the neutron by analyzing collision experiments. This film allows a measurement similar to Chadwick's, using the laws of motion to deduce the mass of an unknown object. The film uses balls rather than elementary particles and nuclei, but the analysis, based on conservation laws, is remarkably similar.

The first scene shows collisions of a small ball with stationary target balls, one of similar mass and one a larger ball. The incoming ball always has the same velocity, as you can see.

The slow-motion scenes allow you to measure the velocity acquired by the targets. The problem is to find the mass and velocity of the incoming ball without measuring it directly. The masses of the targets are $M_1 = 352$ grams, $M_2 = 4260$ grams.

Chadwick used hydrogen and nitrogen nuclei as targets and measured their recoil velocities. The target balls in the film do not have the same mass ratio, but the idea is the same.

The analysis is shown in detail on a grey page in Chapter 23 of the *Text*. For each of the two collisions, equations can be written expressing conservation of energy and conservation of momentum. These four equations contain three quantities which Chadwick could not measure, the initial neutron velocity and the two final neutron velocities. Some algebraic manipulation allows us to eliminate these quantities, obtaining a single equation which can be solved for the neutron mass. If v_1' and v_2' are the speeds of targets 1 and 2 after collision, and M_1 and M_2 the masses, the neutron mass m can be found from

$$m(v_1' - v_2') = M_2v_2' - M_1v_1'$$

or

$$m = \frac{M_2v_2' - M_1v_1'}{v_1' - v_2'}$$

Make measurements only on the targets, as the incoming ball (representing the neutron) is supposed to be unobservable both before and after the collisions. Measure v_1' and v_2' in any convenient unit, such as divisions per second. (Why is the choice of units not important here?) Calculate the mass m of the invisible, unknown particle. In what ways might your result differ from Chadwick's?

Ck print of Effects"

Chapter 24 Nuclear Energy; Nuclear Forces

To p. 109

ACTIVITIES

TWO MODELS OF A CHAIN REACTION

Mousetraps

Carefully put six or more set mousetraps in a large cardboard box. Place two small corks on each trap in such a position that they will be thrown about violently when the trap is sprung. Place a sheet of clear plastic over the top. Then drop one cork in through the corner before you slide the cover completely on. Can you imagine the situation with trillions of tiny mousetraps and corks in a much smaller space?

Questions: What in the nucleus is represented by the potential energy of the mousetrap spring? What do the corks represent? Does the model have a critical size? How might you control the reaction? Describe the effect of the box cover.

Match Heads

Break off the heads of a dozen wooden matches about $\frac{1}{8}$ inch below the match head. Arrange the match heads as shown in the drawing. Place wads of wet paper at certain points. Light a match and place it at point A.

Observe what happens to the right and left sides of the arrangement. What component of a nuclear reactor is represented by the wet paper? How could you modify this model to demonstrate the function of a moderator?

Comment on how good an analogue this is of a nuclear chain reaction. (Adapted from *A Physics Lab of Your Own*, Steven L. Mark, Houghton Mifflin Co., Boston, 1964.)

MORE INFORMATION ON NUCLEAR FISSION AND FUSION

The U.S. Atomic Energy Commission has issued the following booklets on the practical applications of nuclear fission and fusion:

- "Nuclear Reactors"
- "Power Reactors in Small Packages"
- "Nuclear Power and Merchant Shipping"
- "Atomic Fuel"
- "Direct Conversion of Energy"
- "Power from Radioisotopes"
- "Atomic Power Safety"
- "Controlled Nuclear Fusion"

All are available free by writing USAEC, P.O. Box 62, Oak Ridge, Tenn. 37831.

PEACEFUL USES OF RADIOACTIVITY

Some of the uses of radioactive isotopes in medicine or in biology can be studied with the help of simple available equipment. See Experiment 48, "Radioactive Tracers," in Chapter 21 of this *Handbook*.

A few USAEC booklets that may provide useful information are:

- "Food Preservation by Irradiation"
- "Whole Body Counters"
- "Fallout from Nuclear Tests"
- "Neutron Activation Analysis"
- "Plowshare"
- "Atoms, Nature and Man"
- "Radioisotopes in Industry"
- "Nuclear Energy for Desalting"
- "Nondestructive Testing"

For experiments see: "Laboratory Experiments with Radioisotopes," U.S. Government Printing Office, Washington, D.C. twenty-five cents.

For necessary safety precautions to be taken in working with radioactive materials, see "Radiation Protection in Educational Institutions," NCRP Publication, P.O. Box 4867, Washington, D.C. 20008. Seventy-five cents.

Additional Books and Articles

On the following pages are three separate bibliographies:

Science and Literature —2
Collateral Reading for Physics Courses —1
Technology, Literature and Art since World War II —3

See Davenport
Part II

Skim through them to see the variety of kinds of books and articles that have been written on these topics. If you find an item that looks particularly interesting, see if you can find it in the library—or if you can get the library to order it.

Table of Some "Elementary" Particles

Family name	Particle name	Symbol	Rest mass*	Electric charge	Antiparticle	Average lifetime (seconds)
Photon	photon	γ (gamma ray)	0	neutral	same particle	infinite
Leptons	neutrino	ν, ν_μ	0	neutral	ν, ν_μ	infinite
	electron	e^-	1	negative	e^+ (positron)	infinite
	μ-meson (muon)	μ^-	207	negative	μ^+	10^{-6}
Mesons	π-mesons (pions)	π^+	273	positive	π^- same as	10^{-8}
		π^-	273	negative	π^+ the	10^{-8}
		π°	264	neutral	π° particles	10^{-16}
	K-mesons (Kaons)	K^+	966	positive	K^- (negative)	
		K°	974	neutral	K°	10^{-10} and 10^{-7}
	η-meson (eta)	η°	1073	neutral	η°	10^{-18}
Baryons	proton	p	1836	positive	p (antiproton)	infinite
	neutron	n	1839	neutral	n (antineutron)	10^3
	lambda	Λ°	2182	neutral	Λ°	10^{-10}
	sigma	Σ^+	2328	positive	Σ^- (negative)	10^{-10}
		Σ^-	2341	negative	Σ^+ (positive)	10^{-10}
		Σ°	2332	neutral	Σ°	10^{-20}
	xi	Ξ^-	2580	negative	Ξ^+ (positive)	10^{-10}
		Ξ^+	2570	neutral	Ξ°	10^{-10}
	omega	Ω^-	3290	negative	Ω^+	10^{-10}

* Mass of electron is 1 unit on this scale

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Answers to End-of-Section Questions

Chapter 21

Q1 It was phosphorescent. Becquerel wrapped a photographic plate in thick black paper to keep light out. Then he placed a small piece of the uranium compound on top of the black paper and allowed sunlight to fall on it. Upon developing the plate he found the silhouette of the mineral sample recorded on the plate. When he tried putting metallic objects between the sample and the plate he found their outlines recorded even when a layer of glass was also introduced to eliminate possible chemical action.

Q2 No treatment was needed—the emission was spontaneous.

Q3 They were puzzling because they needed nothing to start them, and there was nothing that could stop them. They were similar to X rays in that both were very penetrating radiations, and both could ionize.

Q4 It isn't—although slight differences might be observed because of the other element *absorbing* some of the radiation.

Q5 The radioactivity was much greater than expected for the amount of uranium in the ore.

Q6 Separating it from barium, which is almost identical chemically.

Q7 From most to least penetrating: γ, β, α. Penetrating power is inversely related to ionizing power because rays which are easily stopped (have low penetrating power) do so because they are expending their energy ionizing many atoms of the stopping material (high ionizing power), and vice-versa.

Q8 β particles were found to have the same q/m ratio as electrons.

Q9 α rays were deflected much less than β rays by a magnetic field.

Q10 Its emission spectrum, when caused to glow by an electric discharge, was the same as helium's.

Q11 It occurs when only a single pure element is present, and isn't affected by chemical combinations of that element.

Q12 An example would be the decay of radon into polonium with the emission of an alpha particle ($\mathrm{Rn} \rightarrow \mathrm{Po} + \mathrm{He}$). It was contrary to the ideas of indivisibility of atoms held by 19th century chemists.

Q13
(1) Many of the substances in a series have similar chemical properties.
(2) There are only small percentage differences in atomic mass.
(3) Many of the substances decayed very rapidly into something else; all three kinds of rays are given off by the mixture.

Q14 At the start, the emission will be relatively slow and will consist entirely of alpha particles. Later, the emission will be greater and will contain, besides alpha particles, beta and gamma rays.

Q15 The law of radioactive decay is a statistical law; it says nothing about how long it will take any given atom to decay. To specify a "life time" would be to predict when the last atom would decay. We do not know any way of doing that.

Q16 1/16 of it.

Q17 We do not know. The statistical half-life laws do not apply to small numbers of atoms, and we do not have any other laws which make predictions about individual atoms, or even about small numbers of atoms.

Chapter 22

Q1 They were *chemically* the same as previously known elements.

Q2 The atomic mass equals 12 amu. It occupies position 6 in the list of elements.

Q3 Decreases 4 units; stays essentially the same.

Q4 Decreases by 2 + charges; increases by 1 + charge.

Q5 The rules are:
(1) In alpha decay, the mass number decreases by 4, and the atomic number decreases by 2.
(2) In beta decay, the mass number remains the same, and the atomic number increases by 1.
(3) In gamma decay, both the mass number and the atomic number remain the same.

Example: ${}_{92}\mathrm{U}^{238} \rightarrow {}_{90}\mathrm{U}^{234} + \alpha$

In the Rutherford-Bohr model of the atom, the entire positive charge and almost the entire mass are contained in the nucleus. Since alpha, beta, and gamma rays are ejected from the nucleus they will carry away from it both mass and charge. The alpha particle carries 2 positive charges and 4 amu; hence rule (1). The beta particle carries 1 negative charge and negligible mass; hence rule (2). The gamma ray has no mass and is uncharged; hence rule (3).

Q6 By subtracting α particle masses from the mass of the parent of the decay series.

Q7 It must have a "velocity selector" which will allow only ions of a single speed to enter the magnetic field. This can be done with crossed electric and magnetic fields.

Q8
(1) Faint second line in mass spectrum of pure neon.
(2) Different atomic masses of samples of neon separated by diffusion.
(3) More intense second line in mass spectrum of one of the samples separated by diffusion.

Q9 More massive atoms have a lower average speed and so diffuse more slowly than the less massive ones.

Q10 ${}_{78}\mathrm{Pt}^{194}$; platinum.

Q11 (A − 4). The rule is: emission of an alpha particle results in a decrease in A of 4 units.

Q12 (Z + 1). The rule is: emission of a negative β particle results in an increase in Z of 1 unit.

Q13 An isotope of hydrogen with twice the atomic mass of ordinary hydrogen.

Q14 Heavy water is the compound D_2O. In other words, it is made with heavy hydrogen (= deuterium) rather than ordinary hydrogen.

Q15 The third isotope has a *very* low abundance.

Q16 $_6C^{12}$ is the current standard. It was chosen mainly because it readily forms many compounds and so is available for measuring other masses by mass spectrograph techniques which are much more accurate than chemical methods.

Chapter 23

Q1 Several atomic masses (which were not recognized as the average of several isotopes) were not close to whole multiples of the atomic mass of hydrogen.

Q2 12 protons and 6 electrons.

Q3 Yes, roughly. $_2He^4$ would contain 4 protons and 2 electrons inside the nucleus. (It does *not* work out, however, when very careful mass measurements are made.)

Q4 The number of tracks observed in a cloud chamber did not include any that would correspond to the original α particle breaking up into fragments.

Q5 The way it knocked protons out of paraffin would be for γ rays a violation of the principles of energy and momentum conservation.

Q6 A neutron has no charge, and so isn't deflected by magnetic or electric fields, nor does it leave a track in a cloud chamber.

Q7 The laws of conservation of momentum and kinetic energy were applied to neutron-proton and neutron-nitrogen head-on collisions. This yielded four equations in the four variables: m_n, v_n, v_n' (proton collision), and v_n' (nitrogen collision). The latter three were eliminated, and m_n found.

Q8 7 protons and 7 neutrons.

Q9 A nucleus of 2 protons and 2 neutrons, surrounded by 2 electrons.

Q10 A neutron in the nucleus changes into a proton and a β particle, which immediately escapes.

Q11 Without the extra particle, there was no way to explain the disappearance of energy in β-decay.

Q12 The repulsive electric force exerted by the large charge of the heavy nucleus on an α particle prevents it from reaching the nucleus.

Q13 Protons have only a single charge.

Q14 Some devices for producing projectiles are: Van deGraaff generators, linear accelerators, cyclotrons, synchrotrons, etc. Devices which detect nuclear reactions are: cloud chambers, spark chambers, photographic emulsions, and bubble chambers.

Q15 They have no electric charge and so are not repelled by nuclei.

Q16 $_{14}Si^{28}$

Q17 $_6C^{13}$. 7 protons, 6 neutrons before; 6 protons, 7 neutrons after.

Chapter 24

Q1 No, in some nuclear reactions energy is absorbed.

Q2 It can go off as γ rays or as the *KE* of the product particles.

Q3 The binding energy of the deuteron nucleus is the energy that would be required to break up the nucleus into its constituent particles: a proton and a neutron.

Q4 A nuclide with a high *average* binding energy is more stable.

Q5 No. Light nuclei are lower on the curve than heavy nuclei.

Q6 Capture of a neutron by a uranium nucleus, then the β decay of the new nucleus.

Q7 Neutrons.

Q8 A substance which slows down neutrons.

Q9 It slows down neutrons well (because of the abundance of H atoms), but it also absorbs many (to form "heavy" water).

Q10 By "control rods," made of a material which absorbs neutrons. The farther in the rods, the slower the reaction.

Q11 The positively charged nuclei repel each other and high speeds are necessary for the nuclei to come near enough in collisions to fuse.

Q12 Since at very high temperatures the gas is ionized, a properly shaped magnetic field could deflect the charged particles away from the walls.

Q13 Decreasing.

Q14 The protons in a nucleus repel each other with intense electric forces.

Q15 The average binding energy curve suggests that each particle in the nucleus is bound only by its immediate neighbors.

Q16 An excited nucleus becomes distorted in shape; electric repulsion between bulges then forces them apart.

Q17 In the case of U^{238}, the excitation energy due to neutron capture alone is less than the activation energy required for fission. For U^{235}, the excitation energy is greater than the activation energy.

Q18 They correspond to completed shells (or sets of energy states) of protons and neutrons in the nucleus.

Q19 Neither; they each have different strengths and weaknesses.

Brief Answers to Study Guide Questions

Chapter 21

21.1 Information
21.2 Discussion
21.3 (a) 1.2×10^{-13} joule
(b) 0.75 MeV
21.4 (a) 5.7×10^{-2} m
(b) 210 m
(c) $R_\alpha = 3700R_e$
21.5 Charges are positive; field is into the page.
21.6 (a) 1.8×10^{4} newtons/coul
(b) 1.8×10^{3} volts
(c) undeflected
21.7 (a) γ (b) α (c) α (d) γ (e) γ
(f) α or γ (g) β (h) α (i) α (j) β
21.8 Discussion
21.9 (a) one-half
(b) three-quarters
(c) discussion
21.10 10%
21.11 (a) graph
(b) proof
(c) 5.0×10^{20} atoms
21.12 (a) 5.7×10^{-13} joules/disintegration
(b) 45 watts
21.13 3.70×10^{5} disintegration/sec
21.14 The number remains constant.
21.15 (a) about 4 days
(b) discussion

Chapter 22

22.1 Information
22.2 Discussion
22.3 Discussion
22.4 (a) Discussion
(b) Discussion
22.5 (a) 5.4 cm
(b) 5.640 m
(c) 0.0048 m
22.6 Equations
22.7 Chart
22.8 Diagram
22.9 Diagram
22.10 4,000 years; 23,000 years
22.11 (a) 12.011 amu
(b) 6.941 amu
(c) 207.2 amu
22.12 4.0015 amu
22.13 (a) ¼
(b) about ½
(c) about 2.25×10^{9} years
(d) yes

Chapter 23

23.1 Information
23.2 Discussion
23.3 235 protons; 143 electrons
23.4 Equations
23.5 Equations
23.6 (a) γ (b) Al^{28} (c) Mg^{24} (d) Mg^{25}
23.7 (a) Discussion
(b) In Unit 3 under conservation laws.
23.8 1.10 amu, 5.2%
23.9 Table
23.10 (a) 78
(b) 79
(c) 80
(d) 80
23.11 (a) $_{11}\text{Na}^{24}$
(b) $_{11}\text{Na}^{24}$
(c) $_{11}\text{Na}^{24}$
(d) $_{11}\text{Na}^{24}$
23.12 Discussion
23.13 Discussion
23.14 Discussion
23.15 Discussion
23.16 Less by 0.02758 amu

Chapter 24

24.1 Information
24.2 4.95 MeV
24.3 7.07 MeV/nucleon
24.4 Opposite directions, each 8.65 MeV
24.5 Absorbed, 1.19 MeV
24.6 0.56 MeV
24.7 8.61 MeV
24.8 Neutron capture, β-decay, β-decay
24.9 Ba^{141} is 1180 MeV; Kr^{92} is 800 MeV;
U^{235} is 1790 MeV. Discussion
24.10 208 MeV
24.11 Diagram
24.12 Discussion
24.13 Discussion
24.14 Discussion
24.15 26.7 MeV
24.16 (a) 4.33×10^{9} kg/sec
(b) 5.23×10^{23} horsepower
24.17 Equations
24.18 1.59 MeV released
24.19 U^{233} is fissionable
24.20 Pu^{241} is fissionable
24.21 Discussion

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