

# *Physics*

## Students' book **Unit 5** **Atomic structure**



**Nuffield**Advanced**S**cience

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**Physics Students' book Unit 5**

**Atomic structure**

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Advanced Science

Science Learning Centres



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Physics Students' book **Unit 5**  
**Atomic structure**

**Nuffield Advanced Science**

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# Foreword

It is almost a decade since the Trustees of the Nuffield Foundation decided to sponsor curriculum development programmes in science. Over the past few years a succession of materials and aids appropriate to teaching and learning over a wide variety of age and ability ranges has been published. We hope that they may have made a small contribution to the renewal of the science curriculum which is currently so evident in the schools.

The strength of the development has unquestionably lain in the most valuable part that has been played in the work by practising teachers and the guidance and help that have been received from the consultative committees to each Project.

The stage has now been reached for the publication of materials suitable for Advanced courses in the sciences. In many ways the task has been a more difficult one to accomplish. The sixth form has received more than its fair share of study in recent years and there is now an increasing acceptance that an attempt should be made to preserve breadth in studies in the 16–19 year age range. This is no easy task in a system which by virtue of its pattern of tertiary education requires standards for the sixth form which in many other countries might well be found in first year university courses.

Advanced courses are therefore at once both a difficult and an interesting venture. They have been designed to be of value to teacher and student, be they in sixth forms or other forms of education in a similar age range. Furthermore, it is expected that teachers in universities, polytechnics, and colleges of education may find some of the ideas of value in their own work.

If the Advanced Physics course meets with the success and appreciation I believe it deserves, it will be in no small measure due to a very large number of people, in the team so ably led by Jon Ogborn and Dr Paul Black, in the

consultative committee, and in the schools in which trials have been held. The programme could not have been brought to a successful conclusion without their help and that of the examination boards, local authorities, the universities, and the professional associations of science teachers.

Finally, the Project materials could not have reached successful publication without the expert assistance that has been received from William Anderson and his editorial staff in the Nuffield Science Publications Unit and from the editorial and production teams of Penguin Education.

K. W. Keohane

*Co-ordinator*

*of the Nuffield Foundation Science Teaching Project*

# To the student

This book contains some of the things you need to help you to understand the work of this Unit, and some reading which we hope will help you to see how the work is relevant to the practical, everyday world. It does not contain all you need: you will have to consult textbooks and other more general books as well, working through theoretical arguments, reading about experiments, and finding out more about how the ideas can be put to practical use.

This book contains many questions; more than you will be able to do while working on this Unit. Later on, you may wish to use some of them for revision. You will find questions which take you step by step through the theoretical arguments in the course; students who took part in the trials have said that these questions are a good way to understand a piece of theory. You will have to pick and choose, according to your needs and tastes, amongst the other questions. A few give you simple practice in calculation. More invite you to argue about or discuss a problem, and some of these – usually marked '*For discussion*' – are not suited to formal written answers. They are meant to start off a discussion, which may then wander far from the question.

There are a few harder questions to challenge the clever, and you should not expect to be able to tackle every question easily. But most are meant for ordinary human beings, not for budding geniuses. If in doubt, try the obvious answer: usually there is no catch! Most questions have some kind of answer in the section headed 'Answers', though some of these suggest where you might find the needed information, instead of giving it. We have tried hard not to give wrong answers, but, being fallible like yourselves, may not have succeeded.

Some questions ask you to guess, speculate, or give your private opinion: obviously they have no one right answer.

## **What you are being asked to learn to do**

This course aims to help you to become more like a physicist. Most of you will not become physicists, but will use physics or learn more of it in one of a variety of scientific jobs or in further education. Physics, and the world with it, are changing so fast that no one can tell what bits of physics you will use in, say, ten years' time; however, one can be pretty sure that there are some basic ideas that will be relevant to the new problems of tomorrow. We have tried to build the course around what we believe to be these basic ideas.

So one thing the course aims at is helping you to become able to learn, in the future, the new ideas in physics you may meet, and helping you to become able to use the physics you have learned. It does that because these are the tasks that will face you.

In the future, you will need to be able to learn from books and articles; that is why the course contains a good deal of reading (at the end, you will find details of books referred to in the text). To use the physics you have met, you need to understand it – that is, to be able to use it in new kinds of problems. That is why so many questions in this book ask you to make up arguments about new problems, using what you know.

What is 'understanding'? That is, how does one recognize that someone understands a piece of physics? We think it is something like this. Suppose a group of people are talking about a problem in physics. Very rarely, even among research workers, will anyone immediately see an answer. More often, they each have some ideas which they try out in discussion with colleagues. Those who 'understand' their physics are the ones who can offer sensible, relevant ideas that would help towards clearing up the problem. A reasonably competent physicist expects himself and others to be able to draw on their knowledge and use it to make sensible contributions to the discussion of problems.

So to test whether you understand a piece of physics, it is asking too much to expect you to solve a new problem completely and correctly; few – if any – experts can do that. The test should be that of physicists talking together: can you produce sensible ideas that are relevant and would help a bit towards clearing up a problem? This is the test that will be used in the examination, and is the way to decide how well you have managed a question or problem in the work of the course.

The course also aims to show you what doing physics is like, and this is another reason for encouraging plenty of discussion of problems, for that is the way physicists work. It tries to show what kinds of questions physicists ask themselves and what sorts of ways they use to tackle them. We think this is important because to use physics successfully and to judge its claims and achievements you need to understand what it can, and what it cannot do. That is why several questions ask you about such things as how theories, models, experiments, and facts fit together. Physicists also guess, estimate, and speculate, so other questions ask you to do these things too, to find out what doing them is like and to become better at doing them.

There are a lot of misunderstandings about what physics is like. Some say it is all facts; others that it is all theory, having little to do with what happens in practice. Many are puzzled; asking whether what physics says is true or not, or how physicists arrive at their ideas. We hope you will find chances in this course to think about such matters, and that you will form your own views.

Some of the questions ask about how physics can be used in engineering and technology, and the articles in this book are also about that, because we think that you will rightly want to know when what you learn is of practical value.

Finally, one of the main reasons we want to offer you some physics is that we like the subject and get excited about it. So we hope you enjoy it too.



# Summary of Unit 5

## Atomic structure

The work of this Unit (and the *Teachers' guide*) is divided into four Parts, as below. This book itself, and the questions in particular, are however *not* divided into these Parts. This is because the work of Part One covers the whole subject matter of the Unit. The other Parts are intended to focus attention on some essential features of the work.

### Part One

#### **Radioactivity and the nature of atoms**

This Part concerns the discovery of radioactivity and the identification and properties of alpha, beta, and gamma rays, and gives an introduction to the discovery of the nucleus and the decay of radioactive elements. So it contains some history, some experiments, and some problems to try.

It happens that some of the more interesting experiments are too difficult or too dangerous for a school laboratory, so you will have to read or hear about them. Clearly you can only read or hear about the history. But reading about something, extracting the information you want, and learning from it is a valuable thing to be able to do: indeed it is the only way there is to learn outside schools and colleges or universities, and is an important way of learning inside them. So Part One is planned around individual reading and experiment. We hope you will treat this as a way of learning to read more effectively in general as much as a way of studying the particular topics suggested.

So that you can find out how well you have managed, and practise expressing yourself clearly and to the point, we are suggesting that groups of students take on particular tasks and tell the others what they have learned or found out. This has the advantage that a class as a whole can cover a wider range of material, and that each group can concentrate on the difficulties of its own task.

*Experiments.* Each task will probably contain an experiment. Some of you will study the different sorts of radiation, others the collisions of nuclear particles, and others will look at radioactive decay. There are notes about each of the experiments, numbers 5.1 to 5.12, in the *Students' laboratory book*, to help you to manage on your own.

*Reading.* On page 128 in this *Students' book* there is a long list of reading references. Each reference has some notes with it about what to look for, what to skip, and troubles you may meet with unfamiliar units or strange ideas. Each task will probably contain some reading.

Some references are from textbooks. Some are from collections of the original writings of Becquerel, Rutherford, and other people. Some are from more general books which discuss the discovery of radioactivity and the nucleus, and tell you about the people involved.

You will probably be assigned one particular piece of reading. To make this easy, each reference has a number. You do not have to read all the references; indeed, many of them cover the same ground. If you find that a piece of reading you start is too easy, or is too hard for you, it should be possible to use the notes given with the references to find another covering similar material, which may suit you better.

## Part Two

### **The Rutherford model of the atom**

This Part looks more closely at one of the issues studied in Part One. It is the invention by Rutherford of the idea that an atom has a small, charged, massive nucleus, and how that idea was tested by experiment.

#### *Facts and evidence*

What alpha particles probably are. The energy they probably have. The startling fact that some alpha particles bounce back when fired at atoms in a metal foil.

### *Guessing a model*

Rutherford's suggested picture of what atoms are like, to explain the bouncing back of alpha particles. Rough estimate of the size of a nucleus.

### *Test of the model*

Finding out how alpha particles would be scattered, if Rutherford was right to think of them being deflected by an electrically charged nucleus. Use of a gravitational analogue for a  $1/r^2$  force and  $1/r$  potential. (Ideas from Unit 3 are needed here.)

Comparison of the scattering of ball bearings by the analogue hill with that of alpha particles by nuclei. The 'truth' of the model.

## Part Three

### **Exponential decay**

This Part has a lot of mathematics in it, but it is, we hope, useful, to be learned and understood as a part of becoming a more skilful user of mathematics in physics, biology, chemistry, or engineering.

### *Radioactivity and chance*

The decay of a radioactive substance, and the chancy, random nature of this process.

### *The equation $N/N_0 = e^{kt}$*

Graphical study of the rate of change of numbers of atoms, cars, bacteria, people, power stations, and so on, illustrating exponential change. The section 'Exponential changes', page 52, may help you to study this by yourself.

## Part Four

### **New ideas and problems about atoms**

This Part tries to tie earlier ideas together, and then to look ahead to later problems in the course.

#### *Physics and the chemical Periodic Table*

Atomic number and the charge on a nucleus.

The nucleus and neutrons.

#### *Uses of radioactivity*

Transmutation and isotopes.

#### *Link with ideas about energy levels from Unit 2*

Ionization energies and the nuclear charge

#### *A new problem*

Light seems to deliver energy in lumps, or quanta. The photo-electric effect. The link between quanta and energy levels.

# Questions

## Questions 1 to 8 Radioactive radiations and their energy

**1** You will have noticed the following precautions being observed when radioactive sources are being handled in school.

**a** The sources are handled only with tongs.

**b** The sources are handled so that the radiation is never directed towards people.

**c** Whenever not in use, sources are put in a box with lead shielding and kept in a locked cupboard which has a warning notice on it.

Suppose your aunt has heard that you are doing radioactivity and is worried lest you be exposed to any radiation. Write her a letter explaining the reasons for the precautions taken. (She probably does not realize the existence of 'background' radiation.)

**2** Things are not always what they seem. A light-year is not a unit of light, nor of time, but a unit of distance.

What is an electronvolt a unit of? Explain.

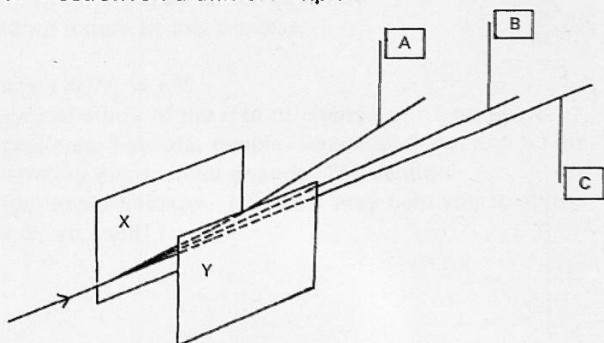


Figure 1

**3** Figure 1 roughly shows paths of alpha, beta, and gamma rays sent between plates X and Y between which there is a large potential difference. See question 8 to get an idea of whether figure 1 is realistic or not.

Which is the path marked by box A, alpha, beta, or gamma? What about boxes B and C? Which plate is positively charged?

**4** The Avogadro constant  $L$  is chosen (defined) to be the number of  $^{12}\text{C}$  atoms in a sample of that isotope with a mass of exactly 12 grammes.

**a** What, approximately, is the mass of an alpha particle?

$$L = 6.02 \times 10^{23} \text{ mol}^{-1}$$

**b** What velocity has an alpha particle which has a kinetic energy of one million electronvolts?

$$\text{Charge on electron, } e = 1.6 \times 10^{-19} \text{ C.}$$

**5** This question follows through an argument set out by Rutherford and Soddy in their paper 'Radioactive change', 1903. See the extract on pages 78 to 82.

The estimates are similar to those of Rutherford and Soddy, converted to SI units.

**a** If each alpha particle from radium has energy  $10^{-12} \text{ J}$ , and there are  $10^{21}$  radium atoms in a gramme of radium, what total energy is emitted if each atom emits one ray?

**b** Each atom emits at least five rays. How does that alter the answer to **a**?

**c** Is the answer to **b** a minimum estimate of the energy emitted or a maximum estimate?

**d** The total electric current from ions produced by alpha particles emitted from one gramme of pure radium in air is about  $10^{-3} \text{ A}$ . Each ion has a charge of about  $10^{-19} \text{ C}$ . How many ions are being produced each second?

**e** The least energy needed to produce an ion in air is about  $10^{-18} \text{ J}$ . How much energy is emitted in one second by one gramme of radium?

- f In one second, what fraction is emitted out of the total energy that will be given out ultimately by the radium?
- g Make a rough estimate of the lifetime of a sample of radium.

**6** A lump of radium-containing material is always slightly hotter than its surroundings. (See Romer, *The discovery of radioactivity and transmutation*, page 167, for a paper by P. Curie and A. Laborde reporting some measurements; reading reference 3D.)

1 mole of radium, burning to radium oxide, releases  $525 \times 10^3$  joules.

a How much energy is that, *per atom of radium*?

When radium atoms disintegrate, each emits about five alpha particles each of energy about 5 MeV.

b How much energy, in joules, is 5 MeV?

c How much energy is emitted when one mole of atoms disintegrates?

d How does the energy released in the radioactive decay of radium compare with the energy released on oxidation?

e Why are radium-containing materials not very hot indeed?

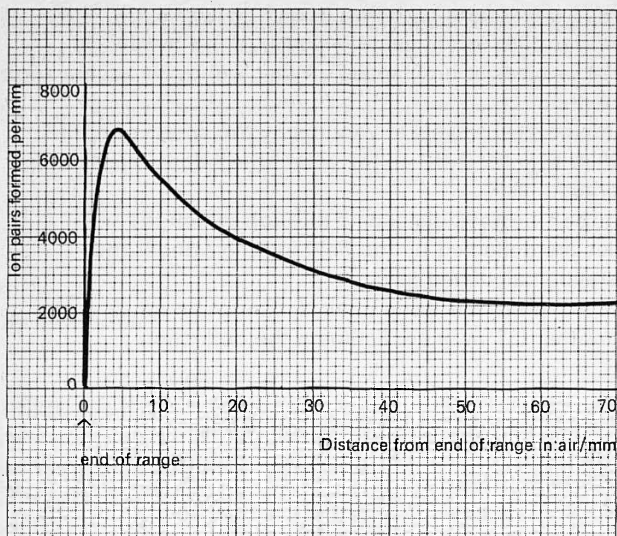
$$L = 6 \times 10^{23} \text{ mol}^{-1}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

$$\text{half-life of } ^{226}\text{Ra} = 1600 \text{ years}$$

**7** The graph in figure 2 shows how many ion pairs per mm are formed by an alpha particle at each point in its track. Use this graph to estimate the total number of ion pairs formed by a single track 50 mm long. If 30 electronvolts is the average energy required to produce one ion pair, what is the total energy of a single alpha particle?

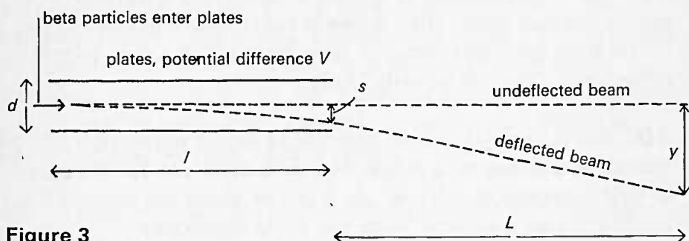
**8** Figure 3 is a sketch being made by someone trying to design an arrangement that will detect the deflection of beta particles by an electric field. The idea is to have parallel plates, length  $l$ , spacing  $d$ , down the centre of which the beta particles travel. After travelling the distance  $l$  they have been



**Figure 2**

Number of ion pairs per mm of track versus range for an alpha particle in air.

After Gentner, W., Maier-Leibnitz, H., and Bothe, W. (1954) An atlas of typical expansion chamber photographs. Pergamon.



**Figure 3**

deflected sideways by a distance  $s$ . From there on, they travel more or less in a straight line, and have been deflected by a distance  $y$  after going a further distance  $L$  to a detector.

**a** What is the electric field  $E$  between the plates if  $V = 2\text{ kV}$  and  $d = 2\text{ mm}$ ?

**b** What is the sideways force  $F$  on an electron, charge  $e = 1.6 \times 10^{-19}\text{ C}$ , between the plates?



**c** A fast moving beta particle's mass  $m$  is about  $10^{-29}$  kg (larger than the 'usual' value because of the relativistic increase of mass at high speed). What will be its acceleration  $a$  in the field?

**d** A beta particle travels at very nearly the speed of light,  $3 \times 10^8$  m s $^{-1}$ . If  $l$  is 0.1 m for what time  $t$  does this sideways acceleration last?

**e** Find the sideways distance  $s$  through which the beta particles are deflected by the field in time  $t$  under the acceleration calculated in **c**.

**f** If the experiment is done in air,  $L$  cannot be much more than another 0.1 m or so. Estimate the deflection  $y$ .

## Questions 9 to 18 . Radioactive decay

### 9 *For discussion*

The arrival of particles at a Geiger counter from a radioactive substance is said to be 'random'. Do you think that the following are sensible descriptions of what 'random' means in this context?

**a** The particles arrive at a basically steady rate, which is disturbed by small variations.

**b** In each second there is a fixed chance that a particle will arrive, but just when they arrive is quite unpredictable.

**c** The time between particles may be 0.1 s, 1 s, 5 s, or any other value: each is equally likely.

**10** Bill is using a Geiger counter to count particles from the radioactive decay of a substance, and observes 1500 counts in half a minute at 2.0 p.m. At 3.0 p.m. there are only 760 counts in half a minute, with the same apparatus.

Bill says, 'Even though I cannot count the radioactive atoms in the substance, I know that there were only approximately half as many at 3 o'clock as there were at 2 o'clock.' Is he right? Explain.

Does he say 'approximately' only because 760 is not quite half of 1500?

**11 a** The half-life of  $^{90}\text{Sr}$  is 27 years. The half-life of  $^{24}\text{Na}$  is 15 hours. Which of two samples, one containing  $10^{20}$  atoms of  $^{90}\text{Sr}$ , and the other containing  $10^{20}$  atoms of  $^{24}\text{Na}$ , would have the highest activity?

**b** Sketch rough graphs showing how the number of atoms of  $^{90}\text{Sr}$  and of  $^{24}\text{Na}$  changes with time.

**c (Harder)** After roughly how long would the activities become equal?

## **12** *For discussion*

**a** Suppose half the human beings in Western Europe who have survived childhood, die before they are 70 years old, and half die at a greater age.

The half-life of the atoms in a sample of a radioactive element (of one sort only, not a mixture) might also be 70 years. If you heard of a person living to 140 years you would be surprised; if you heard of a person living to 210 years you wouldn't believe it.

Could one of the atoms in the sample of half-life 70 years live for 210 years?

**b** In exponential decay, after a given interval of time, the number of atoms remaining is always the same fraction of the number there was at the beginning of that time interval.

Therefore, someone might say, however long you wait there will always be some left. A sample of radioactive atoms will last for an infinite time. Is this sense?

**13** A radioactive substance is set up in front of a GM tube connected to a scaler. The scaler is set counting at the same moment that a stopwatch is started. Every time the second hand reaches a minute, a boy records the reading of the scaler without stopping it counting. He tabulates the readings as shown in table 1.

Time	Scaler reading
0	0000
1	6015
2	8026
3	9016
4	9401
5	9541
6	9802
7	9636
8	9673

**Table 1**

- a** One of the readings is suspect. Which one? What did the boy probably mean to record?
- b** Having made this correction, work out from the readings what was the count-rate in each successive minute, giving your answers in number of counts per minute.
- c** What do these readings suggest is happening?
- d** Plot the count-rates on a suitable graph and deduce a value for the half-life of the radioactive substance. (The mean of at least two values is required.)
- e** Jill says that a better result would be obtained if the readings were extended over a further eight minutes and that the boy stopped too soon. Is this a good or a bad idea? Give reasons.
- f** Jack knows that there are random fluctuations in radioactive experiments. He says a better result would be obtained if more counts were taken and that it would be better to count for five-minute intervals, not one-minute intervals. Give your reasons why you think this is a good or a bad idea.
- g** There is a slight increase in count-rate during the eighth minute. Is this significant? Give the reason for your answer.
- h** Suggest any way in which you think the experiment might be improved.
- (From Nuffield O-level examination. Reproduced by permission of the Oxford and Cambridge Schools Examination Board.)*

**14** The Avogadro constant  $L = 6.02 \times 10^{23}$  individuals per mole. Radium of atomic mass 226 has a half-life of 1600 years.

**a** Show that a 1.00 g sample of  $^{226}\text{Ra}$  contains  $2.66 \times 10^{21}$  atoms.

**b** How many of the original atoms remain out of this sample after 3200 years?

**c** Make a graph showing the number remaining at times up to about 8000 years from the moment when there was exactly 1.00 g of radium.

**d** Estimate how many atoms will decay *during* the 4000th year.

**e** The activity of 1 gramme of  $^{226}\text{Ra}$  is  $3.7 \times 10^{10}$  disintegrations per second. This activity is called 1 curie (symbol Ci). How many grammes of  $^{226}\text{Ra}$  are there in a radium source of strength  $10 \mu\text{Ci}$ ?

**f** What is the chance that any one radium atom in a sample will disintegrate in the next ten seconds? (The 'chance' that any one atom will decay is equal to the fraction which will disintegrate out of any large number of atoms.)

### **15** *For discussion*

Three tanks of water are arranged as shown in figure 4. Each has the same cross-section. They are intended to represent the changes when atoms of an element A decay into atoms of an element B, which then decay into stable atoms of an element C. The rate of flow through each outlet is proportional to the water depth in that tank.

**a** Why has C no outlet?

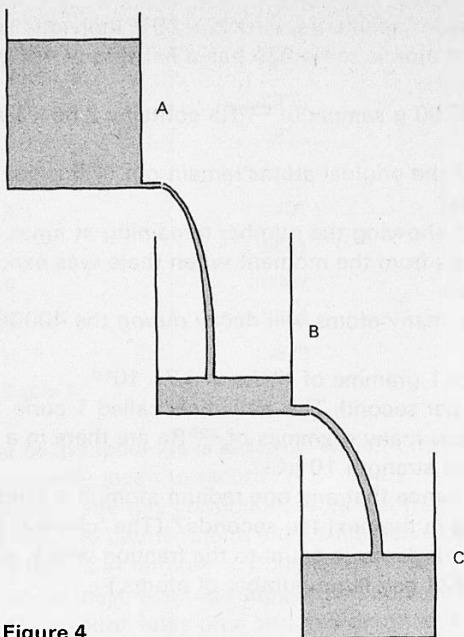
**b** Starting with A full, and B and C empty, what happens first to the water level in B?

**c** Could the level in B become steady at any stage?

**d** Will the level in C become steady at any stage?

**e** In terms of radioactive materials, what do the levels in the tanks represent?

**f** What do the sizes of the outlets represent?



**Figure 4**

**g** Suppose that tank A is now made of very large area without altering the size of the hole (so that it supplies water to B at a steady rate) and the hole in B is made smaller. How does the behaviour of the water level in B differ from its behaviour before these changes were made?

**h** In an experiment with protactinium, an organic liquid is used to extract the protactinium (half-life about 1 minute) from a mixture containing another radioactive element which decays into protactinium.

How would you alter the water model, using another tank, to make a model of this experiment?

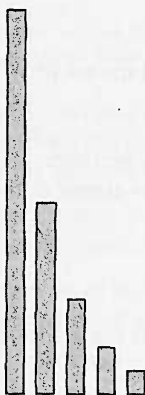
## **16** *For discussion*

Suppose that under conditions of primitive life, *Homo sapiens* has a death rate of about 40 per thousand each year, and there are about 40 births per thousand of the population, per

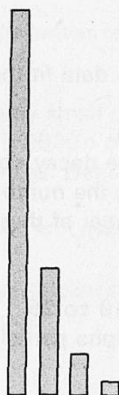
year. What will be the effect on the total population in the short run, if the death rate is reduced (perhaps by improved medical methods) while the birth rate remains steady?

What complications might arise in the long run?

**17** Ann says she knows what an exponential curve is and offers to illustrate it by taking some drinking straws, cutting one in half, then one of the halves into half again, then one of the quarters into half again and so on. She then places the straws together, a full sized one, a half one, a half of a half one, a half of a half of a half, etc. (figure 5a).



a



b

**Figure 5**

Mary says she had thought of a similar method but instead of using halves each time she had cut thirds (figure 5b).

- a Are both producing exponential models? Explain.  
b How could you check to see if a graph is 'exponential'?

**18** Table 2 gives the number of counts recorded in one minute (the counting rate) at intervals of  $\frac{1}{2}$  hour or 1 hour, when a radioactive substance was placed near a counter.

Time in hours	Counting rate in counts per minute	Time in hours	Counting rate in counts per minute
0.0	11 089	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		

**Table 2**

**a** Test whether the data fit the mathematical model of exponential decay.

**b** Find the half-life.

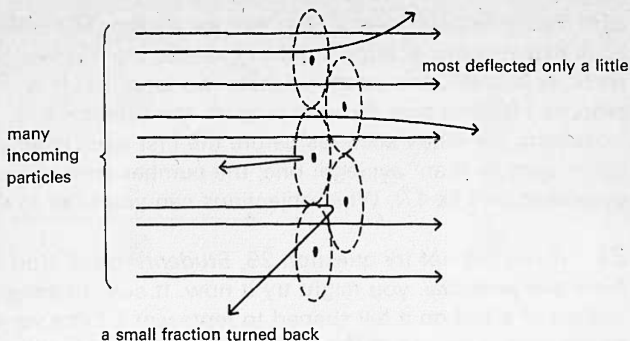
**c (Harder)** Find the decay constant  $k$ , in the equation  $N = N_0 e^{-kt}$ .  $N_0$  is the number of radioactive atoms at the start,  $N$  is the number of these left at time  $t$ .

### Questions 19 to 25

These are about alpha particle scattering and the evidence for the nucleus.

**19** In this question, you will be asked to estimate the size of an atomic nucleus. Geiger and Marsden did experiments on the number of alpha particles scattered through large angles by gold and by platinum. Taken together, these suggest that about 1 in 8000 alpha particles is turned back through a large angle by a gold foil  $6 \times 10^{-7}$  m thick. If such a foil has  $n$  layers of atoms then  $1/n$  of this number of particles would be turned back by one layer; that is,  $1/8000n$  of the particles is turned back.

All the alpha particles would be turned back if the cross-sectional area of the layer were filled with nuclei. Half the alpha particles would be turned back if the layer were 'half-filled' with nuclei. Since  $1/8000n$  is turned back then only  $1/8000n$  of the layer is filled with nuclei. See figure 6.



**Figure 6**

The 'target' area of the nuclei decides the fraction of alpha particles turned through a large angle.

If we can assume that there are only small gaps between atoms, then the nuclei represent  $1/8000n$  of the total area 'seen' by approaching alpha particles. Hence

$$\frac{\text{target area of nucleus}}{\text{cross-sectional area of atoms}} \approx 1/8000n.$$

The number of layers,  $n$ , in a given thickness of the foil will depend on the diameter of the atoms.

$$n \approx \frac{\text{thickness of foil}}{\text{diameter of atom}}$$

So the whole calculation now depends upon being able to calculate the size of an atom of gold. A similar calculation was done for copper in Unit 1. You need to know that the density of gold is  $19.3 \times 10^3 \text{ kg m}^{-3}$ , its atomic mass is 197, and the Avogadro constant is  $6 \times 10^{23} \text{ mol}^{-1}$ .

Make a rough estimate of the diameter of a nucleus.



**20** You may have seen a film of alpha particle scattering. In such experiments, at large angles of scatter the number of particles is small, and counting them is a long job. It is proposed to save time by switching on the detector and measuring the time  $t$  seconds before the first particle arrives. If this particle is an 'average' one, the number arriving each second should be  $1/t$ . What objections can you offer to this?

**21** If you did not try question 29, *Students' book* Unit 3, *Field and potential*, you might try it now. It concerns the motion of a ball on a hill shaped to represent a force varying as the inverse square of the distance from a fixed point; a situation encountered by an alpha particle moving near the nucleus of an atom.

**22** a Suppose an alpha particle travelling at  $10^6 \text{ m s}^{-1}$  happens to hit another stationary helium nucleus 'head on'.



Figure 7

How will each particle be moving after the collision?

**b** Now suppose the stationary target is a proton (hydrogen nucleus) also hit 'head on'.

At what velocity will each particle be travelling after the collision? Assume that no kinetic energy vanishes overall. What else must you assume?

**c** In collisions of alpha particles with, say, gold nuclei, it is usually assumed for simplicity that the gold nucleus is not moving after the collision. Is this a fair assumption to make?

**23** Describe the forces between the object A (at rest) and the bombarding particle P, that would explain the paths shown in figure 8.

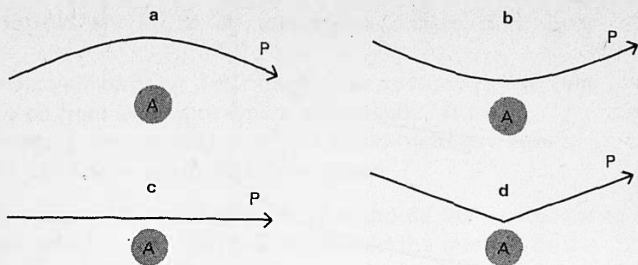


Figure 8

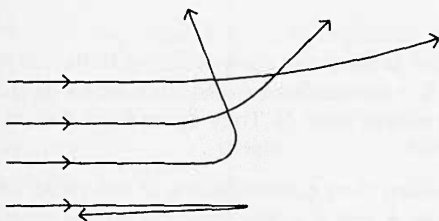


Figure 9

**24** Figure 9 shows paths of four alpha particles deflected (at different times) by one fixed charged nucleus.

Copy the sketch and mark in a likely position for the scattering nucleus. How did you choose this position? The sketch is very much scaled up. On this scale, about how far from the nucleus is the 'edge' of the atom it belongs to? There is more than one way of making this estimate, using parts of the data below. Find one.

Kinetic energy of alpha particle is about  $5 \times 10^6$  electronvolts.

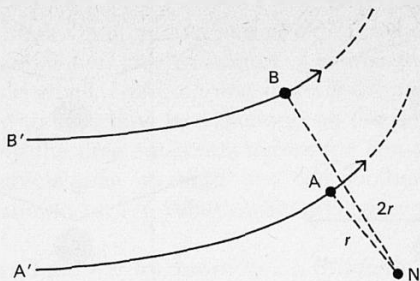
Potential energy of alpha particle near the 'edge' of a gold atom is about 1000 electronvolts.

Radius of a gold atom is about  $3 \times 10^{-10}$  m.

Radius of a gold nucleus is about  $10^{-14}$  m.

Atomic number of gold = 79,  $e = 1.6 \times 10^{-19}$  C.

$$1/4\pi\epsilon_0 = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2}.$$



**Figure 10**

**25** In figure 10, A is an alpha particle being deflected by a charged nucleus N,  $r$  metres from A. Another alpha particle B happens to be  $2r$  metres from N. They come from distant points A', B'.

**a** Why do the (broken line) continuations of the paths of the alpha particles from A and B curve upwards on the sketch?

**b** If the forces on A and B from N are electrical, how does the force on A compare in size with that on B? (Ignore forces between A and B.)

**c** In what direction (or directions) are the forces on A and B?

**d** Add to the sketch arrowed lines (vectors) at A and B representing the direction of *velocity* of each particle.

**e** In **d** you will not have been able to know for certain how big the velocities are. But is the velocity at A larger, smaller, or the same size as the velocity at A'?

**f** Sketch the path of an alpha particle deflected through about  $90^\circ$  by a nucleus. Mark in the position of the nucleus. Mark the point where the speed of the alpha particle would be least. Explain. If the velocities are equal at A' and B', how do the velocities at A and B compare?

**g** Suppose you could lay down a flat surface (like a very thin sheet of paper) so that incoming alpha particles travelled along the flat surface, and the scattering nucleus also lay on the surface. Would the alpha particles leave the surface as they were deflected by the nucleus? (Try a guess. Harder – explain.)

**26** Heavy hydrogen,  $^2\text{H}$ , often called deuterium, was first separated from a mixture which was mostly  $^1\text{H}$  by evaporating several litres ( $\text{dm}^3$ ) of liquid hydrogen very slowly, until only about  $1 \text{ cm}^3$  remained.

In this residue  $^2\text{H}$  was detected. Why should this process tend to concentrate  $^2\text{H}$  in the residue? Would the method be as effective with liquid neon, containing mostly  $^{20}\text{Ne}$  and a little  $^{22}\text{Ne}$ , to separate the two?

**27** The atomic mass of lead, as tabulated in data books, is  $207.21 \text{ g mol}^{-1}$ . Table 3 gives the atomic masses of lead taken from several different minerals.

Mineral	Origin	Atomic mass/ $\text{g mol}^{-1}$
Cleveite	Norway	206.08
Bröggerite	Norway	206.01
Pitchblende	W. Africa	206.05
Kolm	Sweden	206.01
Thorite	Ceylon	207.8
Thorite	Norway	207.9

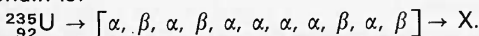
**Table 3**

What do these values suggest to you?

**28** The isotope  $^{235}\text{U}$  decays into another element, emitting an alpha particle.

What is that element? (Use a Periodic Table.)

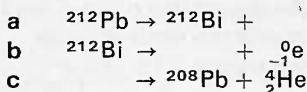
This element decays, and the next, and so on until a stable element is reached. The complete list of particles emitted in this chain is:



What is the stable element X? (You could write down each element in the series, but there is a quicker way.)

**29** Use tables of atomic mass numbers and atomic numbers to complete reactions **a**, **b**, and **c**.

Each item should have the mass number at the top left (superscript) and the atomic number at the lower left (subscript). For example, for uranium of mass number 238 write  ${}^{238}_{92}\text{U}$ ; for an electron, write  ${}^0_{-1}\text{e}$ .



**30** The radioactive isotope of carbon,  ${}^{14}\text{C}$ , is used for the dating of some archaeological finds.  ${}^{14}\text{C}$  emits beta particles, and has a half-life of 5570 years. This isotope is present in small amounts in the carbon present as carbon dioxide in the atmosphere have remained fairly steady for at least the last content of radioactive carbon when they are alive.

The  ${}^{14}\text{C}$  is made continually by the interaction of cosmic rays with the nitrogen in the upper atmosphere. There is evidence that the rate of production of  ${}^{14}\text{C}$  and its concentration in the atmosphere have remained fairly steady for at least the last 10 000 years.

When an animal or plant dies, it stops exchanging carbon dioxide with the atmosphere. The  ${}^{14}\text{C}$  in wood or bones then decays, reducing in amount and activity year by year.

**a** When an organism is alive, it contains about one atom of  ${}^{14}\text{C}$  to every  $10^{10}$  atoms of ordinary  ${}^{12}\text{C}$ . In one second, a fraction  $4 \times 10^{-12}$  of the atoms of  ${}^{14}\text{C}$  present may be expected to decay. Estimate the activity in decays per second of one gramme of carbon from a living organism.

The Avogadro constant =  $6 \times 10^{23} \text{ mol}^{-1}$ .

**b** What activity would you expect from one gramme of carbon taken from the bones of a bison eaten by men some 11 000 years ago, when the great ice sheets covered much of Europe and North America?

**c** About how far back in time do you think the  ${}^{14}\text{C}$  clock might be of use to archaeologists?

**31** Radioactivity finds many uses. Choose one or more of the following and outline how the problem might be solved. If you can think of a better method that does not use radioactivity, mention it.

**a** Carbon dioxide is assimilated by plants and it is customary to think of this taking place through the leaves. It is suggested that there could be some carbon dioxide assimilated through the roots. How might you determine whether this were so?

**b** In ham the fat contains no potassium, but the meat does. How might this fact be used to give a quick measurement of the fat content in ham? (Natural potassium contains a small amount of an isotope which is  $\beta$ ,  $\gamma$  active, but the activity is very low.)

**c** How might you determine the fraction of the total phosphorus intake of a plant that comes from phosphorus that is present naturally in the soil, and the fraction from a dressing of phosphorus fertilizer?

**d** The life-time of a car tyre at  $100 \text{ km h}^{-1}$  has been found to be only 60 per cent of that at  $50 \text{ km h}^{-1}$ . How do you think the wear of tyres might be measured?

**e** In an experiment water was in contact with mercury. The results from the experiment were not what were expected and there seemed to be the possibility that mercury is very slightly soluble in water. How might this be checked?

**f** How could the thickness of steel strip from a rolling mill be measured continuously, as it emerges from the rollers? What might be the advantage of finding a way of controlling the roller spacing directly, using an (amplified) electric current from the measuring device?

**g** How might an automatic alarm be made to indicate when the water in a  $0.20 \text{ m}$  diameter iron pipe with walls  $5 \text{ mm}$  thick rose to a particular level?

**h** How might a monitoring device be made which would check whether the tobacco in cigarettes was being packed at the right density by a machine?

**i** How might the thickness of paint sprayed on a car body be monitored?

**j** How might the thickness of the very thin sort of paper used to make capacitors be monitored as the paper is produced?

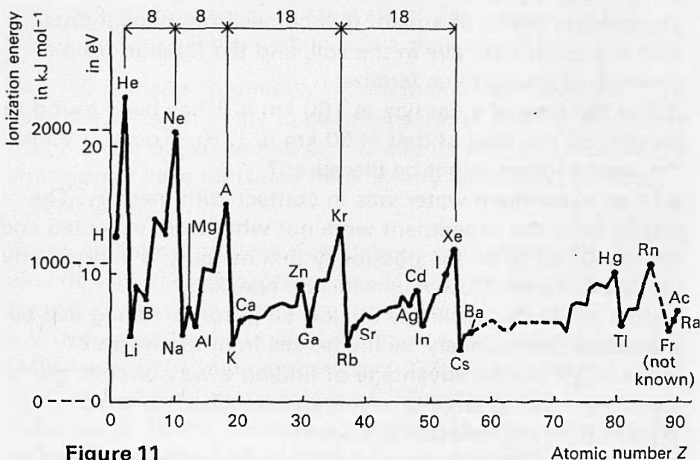
## Questions 32 and 33

These questions are about how the ionization energy and the size of an atom vary from element to element.

**32** Figure 11 shows the energy needed to remove one electron from an atom, leaving it ionized, for atoms up to atomic number about 90. The energies are given in electronvolts, and, for comparison, in  $\text{kJ mol}^{-1}$ .

**a** The elements helium, neon, argon, krypton, and xenon come at peaks in figure 11. What chemical properties do these elements share?

**b** The elements lithium, sodium, potassium, rubidium, caesium, come at the lowest points of figure 11. What kind of chemical properties do these elements share?



**Figure 11**

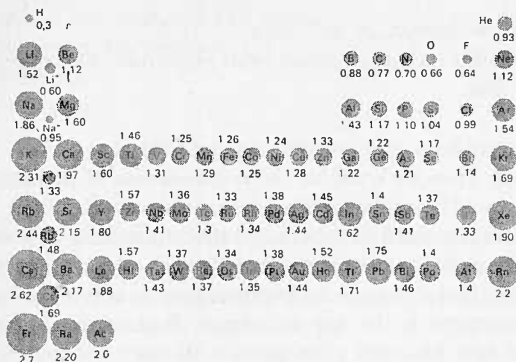
Ionization energies of the elements.

**c** Look where sodium, Na, comes in figure 11. Now find the element neon, Ne, which differs from sodium only in having one electron less. Do you think a sodium atom's 'last' electron is tightly held to the atom?

Can you find a similar pair of elements about which similar remarks might be made?

**d** Would you say that calcium, strontium, and barium occupy similar positions on the graph? Are they chemically similar?

**e** Radium belongs to the same chemical family as calcium, strontium, and barium. The ionization energy of francium, the element one before radium, is not known. Predict the value, from the overall shape of the graph.



(Atomic radii determined from covalent bond distances)

**Figure 12**

The Periodic Table showing atomic, and some ionic, radii/ $10^{-10}$  m  
*After Campbell, J. A. (1946) 'Atomic size and the Periodic Table.'*  
 J. Chem. Educ. 23, 525.

**33** Figure 12 shows the radii of atoms of most elements, and the radii of the ions of a few.

**a** The atoms of Na, K, Rb, Cs, Fr are large. They all have small ionization energies. Suggest a link between these two facts.

**b** The ions of Na, K, Rb, Cs, are a good deal smaller than the atoms of each element. Suggest a reason, based on the answer to a.

**c** The Li atom has a nucleus with three charged protons, and contains three electrons within a radius of  $1.52 \times 10^{-10}$  m. The gold atom has a nucleus with 79 protons, and contains



79 electrons within a radius of  $1.44 \times 10^{-10}$  m. What general, rough rule can you give for the order of magnitude of the radius of atoms of an element with  $Z$  protons and  $Z$  electrons? Is it a surprising rule?

### Questions 34 and 35    Laws and theories

#### **34**    *For discussion, or an essay*

The following passage comes from Feynman, *The character of physical law*.

In general we look for a new law by the following process. First we guess it. Then we compute the consequences of that guess to see what would be implied if this law that we guessed is right. Then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works. If it disagrees with experiment it is wrong. In that simple statement is the key to science. It does not make any difference how beautiful your guess is. It does not matter how smart you are, who made the guess, or what his name is – if it disagrees with experiment it is wrong. That is all there is to it.

It is true that one has to check a little to make sure that it is wrong, because whoever did the experiment may have reported incorrectly, or there may have been some feature in the experiment that was not noticed, some dirt or something; or the man who computed the consequences, even though it may have been the one who made the guesses, could have made some mistake in the analysis. . . .

This will give you a somewhat wrong impression of science. It suggests that we keep on guessing possibilities and comparing them with experiment, and this is to put experiment into a rather weak position. In fact experimenters have a certain individual character. They like to do experiments even if nobody has guessed yet, and they very often do their experiments in a region in which people know the theorist has not made any guesses. . . . In this way experiment can produce unexpected results, and that starts us guessing again.

Try to think of two or three definite examples of theories or laws in physics, and discuss whether they do, or do not, seem to fit into the pattern Feynman describes. Can you think of any instances where experiments gave an unexpected result, and suggested a new theory or law?

### **35** *For discussion, or an essay*

Mr Turnbull had predicted evil consequences, . . . and was now doing the best in his power to bring about the verification of his own prophecies.

*(Anthony Trollope)*

Experience is the name everyone gives to their mistakes.

*(Oscar Wilde)*

The passage from Feynman in question 34 says that a proposed law or theory can be shown by experiment to be wrong, but Feynman says nothing about showing it to be true. Later on he writes:

Suppose you invent a good guess, calculate the consequences, and discover every time that the consequences you have calculated agree with experiment. The theory is then right? No, it is simply not proved wrong.

(This view about the possibility of showing theories to be wrong but not of showing them to be right was put forward by the philosopher Karl Popper.)

**a** Think of a theory, and see if you agree or not with Feynman and Popper about whether it can be *known* to be true. If possible, think of one, maybe not in physics at all, but perhaps in biology or geology, which was once generally accepted, but is now rejected.

**b** The physicist Fermi guessed that there might be particles with zero mass and zero charge, which he called neutrinos, emitted by beta active isotopes like  $^{90}\text{Sr}$ , and in many other nuclear reactions, including those inside nuclear reactors. People set out to make and detect them, and succeeded. Others have predicted the existence of particles called

quarks, with peculiar charges like one-third of an electron charge. People have tried to make and detect them: at the time of writing they have not succeeded. Were all these people behaving like Trollope's Mr Turnbull?

### Questions 36 to 39

Questions about quanta of light energy; the grainy nature of electromagnetic waves.

**36** Einstein, in a paper to the journal *Annalen der physik* in 1905, suggested a model for the microscopic nature of light and applied that model to explain the photo-electric effect. Here is a translated quotation from the paper.

According to the concept that the incident light consists of energy quanta of magnitude  $hf$ , however, one can conceive of the ejection of electrons by light in the following way. Energy quanta (photons) penetrate into the surface layer of the body, and their energy is transformed, at least in part, into kinetic energy of electrons. The simplest way to imagine this is that a light quantum delivers its entire energy to a single electron; we shall assume that this is what happens. . . . An electron to which kinetic energy has been imparted within the body will have lost some of this energy by the time it reaches the surface. Furthermore, we shall assume that in leaving the surface of the body each electron must perform an amount of work  $W_0$ , characteristic of the substance of which the body is composed. The ejected electrons leaving the body with the largest normal velocity will be those that were directly at the surface. The kinetic energy of such electrons is given by  $KE_{\max} = hf - W_0$ .

If the emitting body is charged to a positive potential difference relative to a neighbouring conductor, and if  $V$  represents the potential difference which just stops the photoelectric current . . . [then]

$$eV = hf - W_0$$

where  $e$  denotes the electronic charge.

If the deduced formula is correct, a graph of  $V$  versus the frequency of the incident light must be a straight line with a slope that is independent of the nature of the emitting substance. . . .

(From Einstein, A., *Annalen der Physik*, 1905, 17, 132, as reproduced, in translation, in Arons, *Development of concepts of physics*. Einstein's symbols have been modified.)

- a What does Einstein suppose is the greatest amount of energy an electron can acquire from light of frequency  $f$ , before it leaves the metal?
- b Will electrons be emitted if  $hf$  is equal to, or less than,  $W_0$ ?
- c Why is the emitting body to be 'charged to a positive potential difference relative to a neighbouring conductor'?
- d Blue light ejects electrons from sodium, but not from platinum. What difference between sodium and platinum would Einstein suggest as an explanation of this?

### Questions 37 to 39

In answering these questions you will need to know that:

The charge on the electron is  $1.6 \times 10^{-19}$  C.

Planck's constant is  $6.6 \times 10^{-34}$  J s.

Velocity of electromagnetic radiation is  $3 \times 10^8$  m s $^{-1}$ .

A radioactive source of strength 1 curie undergoes

$3.7 \times 10^{10}$  disintegrations per second.

**37** The Brookmans Park (London) Radio 4 transmitter transmits on a wavelength of 330 m at a power of 140 kW. Estimate:

- a The energy of one photon of this radiation.
- b The number of photons emitted per second.

A 15 W sodium lamp emits light mainly of wavelength about  $6 \times 10^{-7}$  m. Estimate:

- c The energy of one photon of this radiation.
- d The number of photons emitted per second.

**38** a One electronvolt is the energy transformed when an electron moves between points whose p.d. is 1 V. How many joules of energy are equal to 1 eV?

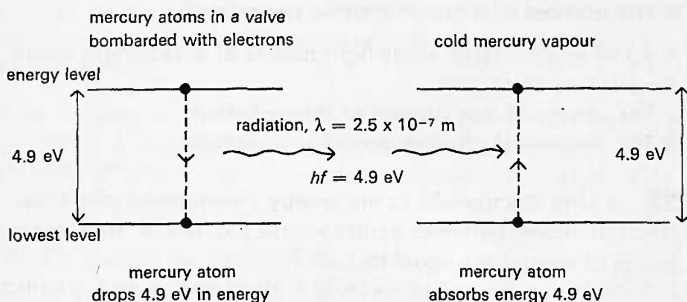
b Suppose an excited atom loses 1 eV of energy as a quantum of radiation. What wavelength does the radiation have and in which part of the electromagnetic spectrum does it lie?

c The wavelength of Radio 2 is 1500 m and the station radiates 400 kW of power. How many quanta are emitted in 1 second?

d Suppose a source of  $^{60}\text{Co}$  has a strength of 100 curies. Each disintegration causes the emission of a  $\beta$  particle of negligible energy and two quanta of  $\gamma$  radiation, of energies 1.35 MeV and 1.5 MeV. How many quanta are emitted in 1 second? Express the power of the source in watts.

**39** In a valve containing mercury vapour it is found that there is a marked change in the resistance between its electrodes when the p.d. between them is raised to 4.9 volts. A valve which is similar but contains no mercury does not show this change. A possible deduction is that mercury atoms are prone to absorb energy in amounts equal to that of an electron which has been accelerated by a p.d. of 4.9 volts, that is  $4.9 \times 1.6 \times 10^{-19}$  joule. If, shortly after receiving the energy, a mercury atom gives it out again as a quantum of radiation, the energy of the quantum would be  $hf$  where  $h$  is Planck's constant,  $6.6 \times 10^{-34}$  J s, and  $f$  is the frequency. So the frequency of the radiation would be  $4.9 \times 1.6 \times 10^{-19} / 6.6 \times 10^{-34}$  Hz. Electromagnetic radiation travels at  $3 \times 10^8$  m s $^{-1}$ , so the wavelength of the radiation would be  $3 \times 10^8 \times 6.6 \times 10^{-34} / 4.9 \times 1.6 \times 10^{-19}$  metre, or  $2.5 \times 10^{-7}$  metre.

a How could you detect such radiation coming from the valve?



**Figure 13**

**b** If you tried to shine the radiation through mercury vapour and you found the mercury vapour to be nearly opaque, where do you think the energy of the radiation would eventually go?

**Question 40 (optional)**

This is about how the wavelengths of X-ray quanta can be used to give evidence about the atomic numbers of elements.

**40** Soon after the diffraction of X-rays was discovered, and at a time (1913) when models of the atom were a real problem, a young physicist at Cambridge produced some remarkable evidence that the chemists' list of elements in serial order had a physical basis. He – Moseley – measured the wavelengths of the short wavelength X-rays produced when a whole series of elements were used as the targets in an X-ray tube. You can find one of his papers reprinted on page 186 of *Classical scientific papers (physics)* (reference 1).

Here are some of his results.

	Atomic mass	Wavelength $\lambda/10^{-10} \text{ m}$
calcium	40.09	3.357
titanium	48.1	2.766
vanadium	51.06	2.521
chromium	52.0	2.295
manganese	54.93	2.117
iron	55.85	1.945
cobalt	58.97	1.794
nickel	58.68	1.664
copper	63.57	1.548
zinc	65.37	1.446

**Table 4**

**a** Plot a graph of wavelength  $\lambda$  against atomic mass. Is the graph smooth?

**b** Plot a graph of wavelength against the *serial order* in the list. That is, call calcium 1, titanium 2, etc.

Is this graph more or less smooth than the first? The elements are listed in the order in which chemists place them in the Periodic Table, but there is one element now known to us which is missing from the list. (Moseley was unable to obtain an X-ray wavelength measurement for it.) Can you find, from the graph, the place where the missing element should come in the list, and predict the wavelength of X-rays associated with it?

**c** What reason can you offer for thinking that, with the addition of this one new element, the list now contains *all* the elements from Ca to Zn?

# Answers

**1** The notes in the *Students' laboratory book* about experiments 5.1 to 5.12 are prefaced by a note about precautions which you should observe when handling radioactive substances; you ought to read this.

The radiation from a radioactive substance can harm you in several ways if it is absorbed by part of your body. Because one kind of change it can produce is a change of the genetic information stored in the genes in cells, it is especially important to keep such radiation away from the reproductive organs. That does not mean that it is safe to allow the radiation to reach other parts of the body: it is not.

The simplest precaution, and perhaps the most effective, is to keep the source at a distance. Few alpha particles travel more than 50 mm or so in air, so an alpha source held in tongs is pretty safe, as long as the source itself is sealed and you cannot breathe or ingest any of the radioactive substance. Gamma rays spread out so that their intensity falls off as the inverse square of the distance, so again distance helps, though it does not reduce the radiation received to zero. Lead blocks are used to absorb gamma rays from sources stronger than those in schools.

The only radioactive substances you are allowed to handle which are not in a sealed form are the naturally occurring salts of uranium, thorium, and potassium. These have long half-lives, and the radiation from them is small. The strength of the sealed sources you may use is also limited.

Everybody is continually exposed to radiation from both cosmic rays and the radioactive minerals in the Earth. The various regulations aim to make sure that you and your teacher cannot receive in a year more than a very small extra fraction of the dose you will in any case receive from this natural background. It is possible that some luminous wrist watches could deliver a dose greater than the sources you may handle in school.



Despite such assurances, an aunt of yours would be right to express some concern. Too little is known about the effect of low doses of radiation. It is very important that rules and precautions to protect people handling radioactive sources should be framed with care, revised from time to time, and, above all, obeyed.

**2** An electronvolt is a unit of energy. It is the energy transformed when one electron, or when an object carrying the same charge as an electron, moves through a potential difference of one volt.

$$1 \text{ electronvolt} = 1.6 \times 10^{-19} \text{ joule.}$$

The electronvolt is a useful unit, but energies in electronvolts must be converted into joules if they are to be used together with other quantities to make calculations. See question 4, for example.

**3** Box B, marking the undeflected middle beam, must be the gamma rays. Box A marks a beam which is much more deflected than that marked by box C, so box A is presumably the beta particles and box C the more massive alpha particles (ignoring speed differences). That would make plate X positive.

**4** Mass of alpha particle  $\approx 7 \times 10^{-27} \text{ kg}$ .  
Velocity  $\approx 7 \times 10^6 \text{ m s}^{-1}$ . Note that to use the equation, kinetic energy  $= \frac{1}{2}mv^2$ , with  $m$  in kilogrammes, the energy must be in joules, not electronvolts.

**5** a  $10^9 \text{ J}$ .

b The total energy is larger,  $5 \times 10^9 \text{ J}$ .

c A minimum estimate.

d  $10^{16} \text{ s}^{-1}$ .

e  $10^{-2} \text{ J s}^{-1}$ .

f About  $2 \times 10^{-12} \text{ s}^{-1}$ .

g Of the order  $5 \times 10^{11} \text{ s}$ . Note that this is something of an overestimate, the half-life being 1600 years, or  $5 \times 10^{10} \text{ s}$ . But the errors involved in the approximations made could easily amount to a factor of ten.

**6 a**  $8.8 \times 10^{-19} \text{ J}$ .

**b**  $8 \times 10^{-13} \text{ J}$ .

**c**  $2.4 \times 10^{12} \text{ J}$ .

**d** The energy released in the radioactive decay of radium is greater than that released on oxidation by a factor of over a million.

**e** Even with 1 mole of radium (226 g — a very large sample), the energy is dissipated over thousands of years. In the first 1600 years 0.5 mole will have decayed and dissipated.

**7** The graph is not too easy to read. You have to start at the righthand end, at whatever distance the particle will ultimately travel before it stops. The number of ion pairs is the area below the graph from the distance 50 mm back to the origin. One rough estimate of ours from the graph put the number of ion pairs at about 200 000.

The total energy of an alpha particle of that range then comes to 6 MeV.

**8 a**  $E = 2000/2 \times 10^{-3} = 10^6 \text{ V m}^{-1}$ .

**b**  $F = 1.6 \times 10^{-13} \text{ N}$ .

**c**  $a = F/m = 1.6 \times 10^{16} \text{ m s}^{-2}$ .

**d**  $t = 3.3 \times 10^{-10} \text{ s}$ .

**e**  $s = \frac{1}{2}at^2 = 9 \times 10^{-4} \text{ m} \approx 1 \text{ mm}$ .

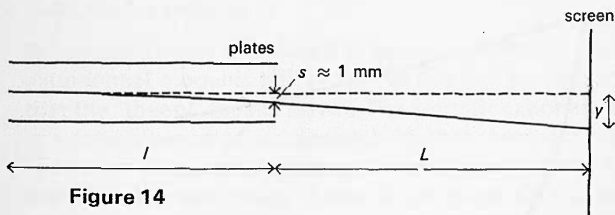


Figure 14

**f** If  $L = l$ , the deflection  $y$  will be more than twice as big as  $s$ , because the straight path from the edge of the plates to the screen cuts the undeflected path through the plates (if projected back somewhere between the plates, not at the far end of the plates. An estimate of 3 or 4 mm for  $y$  might be fair.

**9 a** Not very good. It describes roughly what happens, but may give the wrong impression about why. The particles come in by chance, and if the chance of arrival stays the same, over a long time there will be a steady average rate. (Unlike water running out of a bath, occasionally disturbed by a toe in the plug hole.)

**b** We tried to make this a correct description.

**c** Wrong. The time between arrivals may have any value, but not all intervals are equally likely. The average interval is very likely; much longer or shorter intervals are less likely.

**10** If this is the decay of a radioactive substance into a stable substance, then Bill is correct. The rate of decay is proportional to the number of original atoms left. The word 'approximately' is used because of the random nature of emission from radioactive substances. If Bill had measured the counts in half a minute at 1 minute after 3.0 p.m. he could easily have recorded 759, or 780, or 740, or 770, or some similar number of counts.

**11 a** In the same short time, say one second, more sodium atoms than strontium atoms will disintegrate, because the sodium has the shorter half-life.

**b** See figure 15.

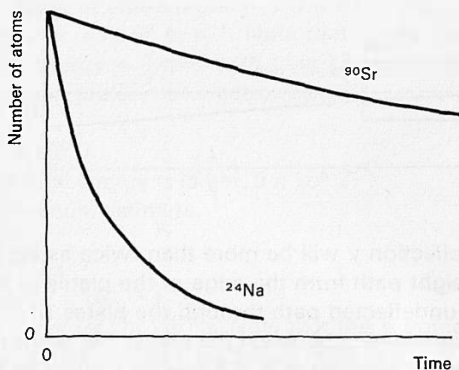


Figure 15

c 27 years is about  $1.6 \times 10^4$  times longer than 15 hours, so the sodium will initially be about this many times more active than the strontium. In 15 hours the activity of the sodium will fall to one half; in twice as long to one quarter, and so on. It will have fallen by a factor  $1.6 \times 10^4$  after  $n$  periods of 15 hours, where

$$2^n = 1.6 \times 10^4, \text{ and therefore}$$

$$n \approx 14$$

Fourteen times fifteen hours is about 9 days; much less than the 27 year half-life of the strontium, so the strontium activity will not have diminished very much at all. So 9 days may be a fair estimate of the time taken for the two activities to become equal.

- 12** a Yes. One half will survive more than 70 years; one quarter more than 140 years; one eighth more than 210 years.  
 b A common answer is that a radioactive sample has an infinite lifetime 'in theory but not in practice'. This seems to us a bit feeble, though not absolutely wrong.

The smooth mathematical model of exponential decay does not exactly fit the behaviour of radioactive atoms. As you may have found by experiment, the rate of decay of a sample fluctuates considerably. The average rate of decay is close to the value to be expected from the mathematical model, but need not be equal to it.

When the sample is reduced to only a few atoms, the smooth exponential model is a poor fit. Yet it is not enough to say that the 'theory' breaks down. The smooth exponential decay is a consequence of supposing both that there is a constant chance of decay for each atom in each time interval, and also that there are very many atoms. When there are not very many atoms, the smooth decay is no longer a consequence to be expected. But so far as is known, it remains true that the chance of decay is constant. When one atom remains, that atom may decay in the next second, or in the next hundred years. It is possible to say how long it will last on average: that is, how long one atom will last in many trials. But it is not possible to say how long one particular atom will last.

**13 a** 9802 — probably should have been 9602.

**b** 6015, 2011, 990, 385, 140, 64, 35, 37.

**c** Decay. After about 7 minutes the count is mainly due to the background.

**d** Half-life approximately 50 to 60 s.

**e** The count-rate would not significantly change if the counting were continued for a longer period.

**f** Very little of the radioactive substance is left after 7 minutes and thus only 2 useful readings would be possible for five-minute intervals. This would not be enough to enable the half-life to be determined.

**g** Random fluctuations in the background count are probably responsible for the increase.

**h** The experiment could be repeated to give a better value for the half-life. Readings could be taken at intervals closer than 1 minute during the first few minutes.

**14 a** 226 g of  $^{226}\text{Ra}$  contains  $6.02 \times 10^{23}$  atoms.

Hence 1 g contains  $\frac{6.02 \times 10^{23}}{226} = 2.66 \times 10^{21}$  atoms

**b**  $\frac{2.66 \times 10^{21}}{2 \times 2} = 6.65 \times 10^{20}$  atoms.

**d** Of the order  $10^{17}$  atoms.

**e**  $10^{-5}$  g.

**f**  $\frac{3.7 \times 10^{10}}{2.66 \times 10^{21}} \times 10 = 1.4 \times 10^{-10}$ .

**15 a** There is no decay of C as it is stable.

**b** Level increases. The rate of flow from B to C is proportional to the depth of water in B and thus initially the flow rate into B must be greater than the flow rate out of B.

**c** Yes, at times when the flow rate into B equals the flow rate out of B.

**d** When all the water is in C.

**e** The amount of radioactive substance.

**f** The chance of atoms decaying.

**g** The water level in B when it becomes steady will be higher than before. If A is large this steady level will last for a long time.

**h** Quickly empty B (when steady) into another tank like it, which also drains into C.

**16** The population, previously steady, will grow. If food supplies are insufficient, or overcrowding produces disease, the death rate may rise and slow down or stop the growth. Many other factors may also be involved.

**17 a** Both are exponential. The lengths of straws decrease in a fixed proportion.

**b** Plot the logarithm of the exponentially varying quantity against the other variable, or check whether the change is by a constant factor in equal steps of time (or other variable).

**18 a** The mathematical model of exponential decay is a good fit. This can be tested either by plotting the count-rate against time and seeing whether the time for it to be halved is constant, or by plotting the logarithm of the count-rate against time and seeing whether it is a straight line. The latter is the better method.

**b** 2.3 hours.

**c** 0.03 per hour.

**19** There are  $6 \times 10^{23}$  atoms in a mass of 197 g of gold, and this mass fills a volume of  $\frac{197 \times 10^{-3}}{19.3 \times 10^3} \text{ m}^3$ .

The volume occupied by one atom comes to  $17 \times 10^{-30} \text{ m}^3$ ; the cube root of this gives an estimate of the diameter of one atom.

Diameter of a gold atom  $\approx 2.6 \times 10^{-10} \text{ m}$ .

Number of layers  $n$  in a foil  $6 \times 10^{-7} \text{ m}$  thick  $\approx 2.3 \times 10^3$  layers, dividing the thickness of the foil by the diameter of an atom.

If  $d$  is the diameter of a nucleus, then

$$\frac{d^2}{(2.6 \times 10^{-10})^2} \approx \frac{1}{8000n}$$

$$d \approx 6 \times 10^{-14} \text{ m}.$$

The roughness of the data does not justify an accurate calculation, including factors like  $\pi$ , or allowing for the way gold atoms pack together. The important thing is the order of magnitude of the answer, some  $10^4$  times smaller than the diameter of an atom.

**20** The particles do not arrive regularly, but at random. It is impossible to tell if the one counted is an 'average' particle. In order to find the average a number of measurements have to be made. The method is as bad as counting long enough only to get 1 count.

**21** See *Students' book*, Unit 3, answer 29.

**22 a** The incident particle will stop. The other particle moves on in the same direction at  $10^6 \text{ m s}^{-1}$ .

**b** Conservation of momentum is needed.

After the collision:

Alpha particle, velocity (in the original direction) =  $0.6 \times 10^6 \text{ m s}^{-1}$ .

Proton, velocity (in the original direction) =  $1.6 \times 10^6 \text{ m s}^{-1}$ .

The mathematics produces another solution, in which the alpha particle goes straight on at the same speed, and the proton stays at rest. That is, the alpha particle misses the proton! The mathematics wasn't told that they must collide!

**c** The gold nucleus, atomic mass 197, is much more massive than the alpha particle and its velocity after the impact can only be very small. Even if the momentum change of the alpha particle and of the nucleus is as large as possible ( $2mv$ ) the *velocity* of the nucleus is still small.

**23** Figure 8a: An attractive force which decreased with distance from A.

**b** A repulsive force which decreased with distance from A.

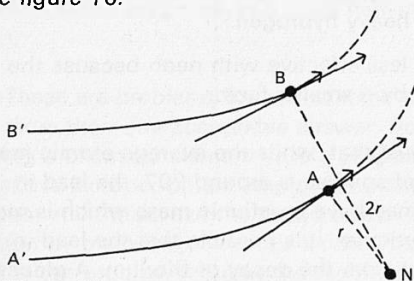
**c** No significant force at the distances shown.

**d** A repulsive force which suddenly affects P at a small distance from A.

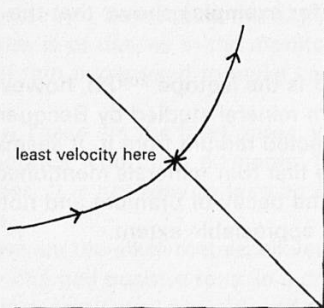
**24** The position of the nucleus must be along a line bisecting the incoming and return paths of an alpha particle. (It is assumed that no significant velocity is transferred to the nucleus.)

One way to find the scale of the drawing is to say that the potential energy where the head-on collision 'turns round' is equal to the initial kinetic energy,  $5 \times 10^6$  eV. As the potential energy at the 'edge' is 1000 eV (this figure neglects the effect of other electrons) and the potential energy varies as  $1/r$ , the 'edge' of the atom is 5000 times further away from the nucleus than the turn-around point of the head-on collision.

- 25** a The alpha particles are being repelled by the nucleus.  
 b The force on B will be one quarter of that on A.  
 c The forces are along the lines NA and NB.  
 d See figure 16.



**Figure 16**



**Figure 17**



e The velocity at A will be less than that at A' as some of the kinetic energy of the alpha particle has been converted into potential energy.

f See figure 17. At X the potential energy will be a maximum.

The potential energy at B is half of that at A so that velocity at B will be greater than that at A. Less kinetic energy has been changed to potential energy.

g No. The force between the particles is always along the line joining them, and so there is no force deflecting the alpha particles out of the original plane surface.

**26** The mass of heavy hydrogen is twice that of 'normal' hydrogen. As the two, in a mixture, are at the same temperature they should have the same average kinetic energy, according to the kinetic theory of gases. The average velocity of heavy hydrogen molecules will therefore be less than that of normal hydrogen. Thus, more normal hydrogen will evaporate than heavy hydrogen.

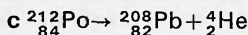
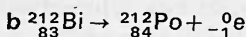
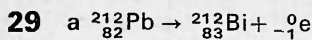
The method will be less effective with neon because the velocities will differ by a smaller factor.

**27** The data suggest that, while the average atomic mass of lead from a variety of sources is around 207, the lead in particular minerals may have an atomic mass which is more or less than this. In particular, it is possible that the lead in thorite comes in part from the decay of thorium. A glance at the decay series of  $^{232}\text{Th}$  (see Caro, McDonell, and Spicer, *Modern physics*, page 213, for example) shows that the series ends with  $^{208}\text{Pb}$ .

Lead from the decay of  $^{238}\text{U}$  is the isotope  $^{206}\text{Pb}$ , however. Pitchblende was the uranium mineral studied by Becquerel and by the Curies, who extracted radium from it. It seems probable that the lead in the first four minerals mentioned comes at least in part from the decay of uranium and not from the decay of thorium to any appreciable extent.

**28**  $^{235}\text{U} \rightarrow ^4\text{He} + ^{231}\text{Th}$ .

The element X is  $^{207}\text{Pb}$ .



**30 a** One gramme of carbon contains  $0.5 \times 10^{23}$  atoms, since 12 g contain  $6 \times 10^{23}$  atoms. Of these, about  $0.5 \times 10^{13}$  atoms are the isotope  ${}^{14}\text{C}$ . In one second,  $4 \times 10^{-12}$  of the  ${}^{14}\text{C}$  atoms will decay, so one may expect around 20 decays per second.

**b** 11 000 years is close to two half-lives, so the activity might be around 5 decays per second from one gramme.

**c** The rate of decay is small, and the smaller it is, the harder it will be to measure the rate accurately unless one is prepared to measure it over a very long period. Even with counting times of about a day, the  ${}^{14}\text{C}$  method is subject to pretty large errors for times above about two half-lives, and is not of great assistance much beyond three half-lives, say 20 000 years.

**31** These are problems for you to think about, and several have more than one acceptable answer. Some involve labelling a chemical element with a proportion of a radioactive isotope; others employ naturally occurring isotopes; still others use the absorption of different sorts of radiation by materials of various kinds. You should consider whether the problem requires the radiation involved to be very penetrating, like gamma rays, or moderately penetrating, like beta rays. Sometimes the high absorption of alpha particles is of use, as in the monitoring of the thickness of the sort of thin paper used to make capacitors.

**32 a** These are the inert gases, which rarely form compounds with other elements. They have high ionization energies. It is not easy to take an electron from one of these atoms.

**b** These are the alkali metals, all very reactive, readily forming singly charged positive ions. In a crystal of sodium chloride, the sodium atoms are all ionized, and the crystal is a vast assembly

- of  $\text{Na}^+$  and  $\text{Cl}^-$  ions. All have low ionization energies, indicating the ease with which an atom loses an electron.
- c** Neon has a large ionization energy; sodium, with one more electron, has a low ionization energy. It looks as if the 'last' electron in a sodium atom is rather loosely held. (In fact, it takes 47 eV to remove a *second* electron from sodium, so it is only the 'last' one which is nearly free.)
- d** Yes, each comes first on the rise following a trough. They are another chemically similar family.
- e** If francium comes one before radium, it must be an alkali metal, like Li, Na, K, Rb, Cs. Looking at these, their ionization energies are all seen to be low, from 3 to 5 eV. The value drops slowly as one goes along the list, so francium will probably have an ionization energy nearer the lower end of this range.

**33 a** An electron a long way from a nucleus will be weakly bound to it, as electrical forces diminish with distance. If at least one electron is a long way out from the nucleus, the atom will be big, and will have a low ionization energy. (The fact that the energy needed to remove a second electron from Na is 47.3 eV, while that to remove the first is only 5.1 eV, suggests that only one electron is a long way out in Na. These data appeared in question 32.)

**b** The ion  $\text{Na}^+$  is a good deal smaller than the atom Na, suggesting that just one electron in Na, and in other similar elements, is a long way out. If so, the energy needed to remove this electron will be small, as the data in figure 11 show it to be.

**c** The simple general rule is that all atoms are about the same size, whatever the number  $Z$  of electrons bound to a nucleus of charge  $Z$ . While  $Z$  varies from 1 to 90, the radius goes up and down around  $1.5 \times 10^{-10}$  m. The smallest radius is  $0.3 \times 10^{-10}$  m; the largest shown is  $2.7 \times 10^{-10}$  m, a factor of only 9. It is probably a surprising rule. Despite the extra attraction of a strongly charged nucleus, the electrons of a heavy element occupy much the same space as those of a light element. Or, one might be surprised at the opposite side of the same coin; that ninety electrons pack into the same space as three.

**34** The important thing in questions like these is not to  
**35** reach a 'right' answer — there probably isn't one. You should try to give as many examples as possible, and support them with clear arguments if you can. You do not need to agree with Feynman, or with anybody else, for that matter. But for your views to command respect, they must be clear, reasoned, and illustrated with examples.

For instance, in question 34, you might argue that Rutherford's idea that an atom contains a small charged nucleus seems like the kind of guess Feynman mentions. You could suggest that it is certainly true that, having made the guess, some hard computation had to be done to find out what the consequences of the guess would be for alpha particle scattering. And you could argue that Geiger's and Marsden's experiments are a good example of the careful testing of these consequences.

But you might also point out that Rutherford did not have his idea 'out of the blue'. It seems to have come out of his surprise at finding any alpha particles at all scattered at large angles. You might discuss why he might have been surprised: it was probably because the ideas then current about what atoms were like (the Thomson model) strongly suggested that there would be no large angle scattering. This is an aspect of the matter that Feynman only hints at.

You may find some help in these books:

Rothman, *The laws of physics*

Feynman, *The character of physical law*

Bronowski, *The common sense of science*

or the *Scientific American* Offprint,

Dirac, 'The evolution of the physicist's picture of nature.'

**36** a *hf*.

b No.

c To provide a means of measuring the maximum kinetic energy  $hf - W_0$  of the electrons, by requiring them to transform this energy into potential energy  $eV$ , and finding what value of  $V$  just prevents electrons from reaching the neighbouring conductor.

**d** For sodium  $hf$  must be bigger than  $W_0$ ; for platinum it must be smaller. As  $f$  is the same for the same colour,  $W_0$  for platinum must be bigger than  $W_0$  for sodium.

**37 a**  $6 \times 10^{-28}$  J.

**b**  $2.3 \times 10^{32}$  photons per second.

**c**  $3.3 \times 10^{-19}$  J.

**d**  $4.5 \times 10^{19}$  photons per second.

**38 a**  $1.6 \times 10^{-19}$  J.

**b**  $1.24 \times 10^{-6}$  m, or 1240 nm. This is an infra-red wavelength.

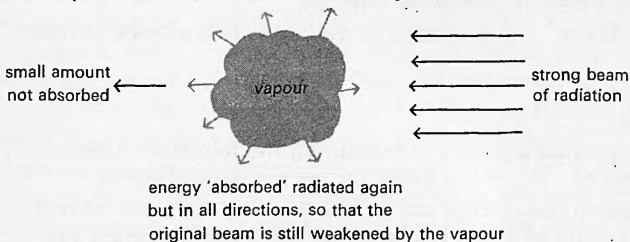
**c**  $3 \times 10^{33}$  photons per second.

**d**  $7.4 \times 10^{12}$  photons per second. The power is about 1 W.

**39 a** The radiation would be in the ultra-violet part of the spectrum. If the valve were made of glass, little, if any, would emerge, but some would emerge if the valve were made, say, of quartz. It could be detected photographically, or by the fluorescence it produces in suitable paints, or by its photo-electric effect.

**b** The mercury vapour would be absorbing the radiation, with mercury atoms initially in the lowest energy level jumping up to the excited level 4.9 electronvolts above the lowest level. These atoms, or some of them, would radiate the energy again later on, as they returned to the lowest energy level. But they would radiate in all directions, not just in the direction of the original beam. So the vapour would seem opaque, even if it radiated as much energy as it received. See figure 18.

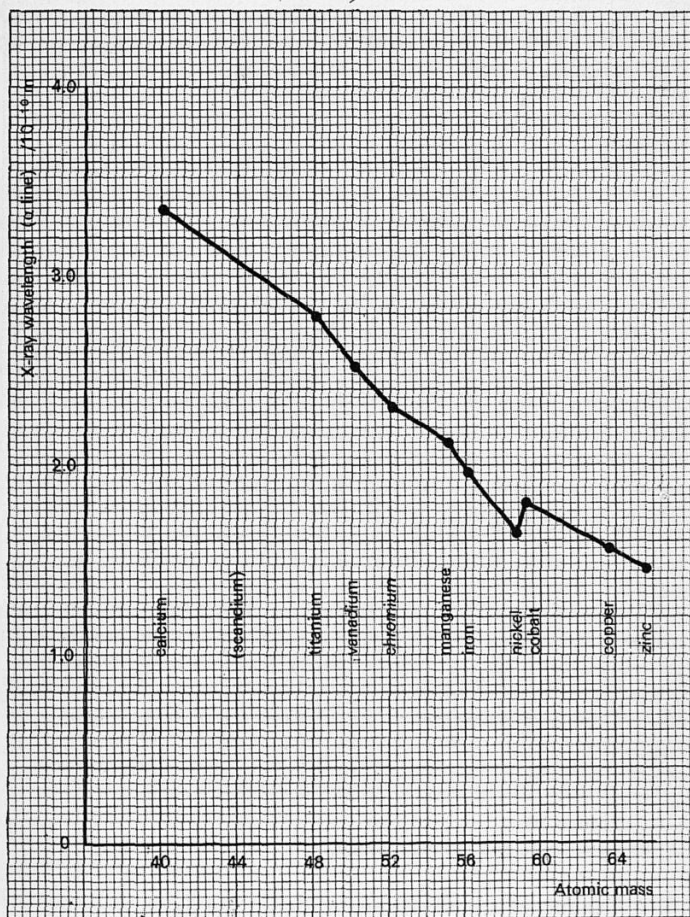
Ultimately, the radiation would be absorbed by matter around the experiment, which would be slightly warmer as a result.



**Figure 18**

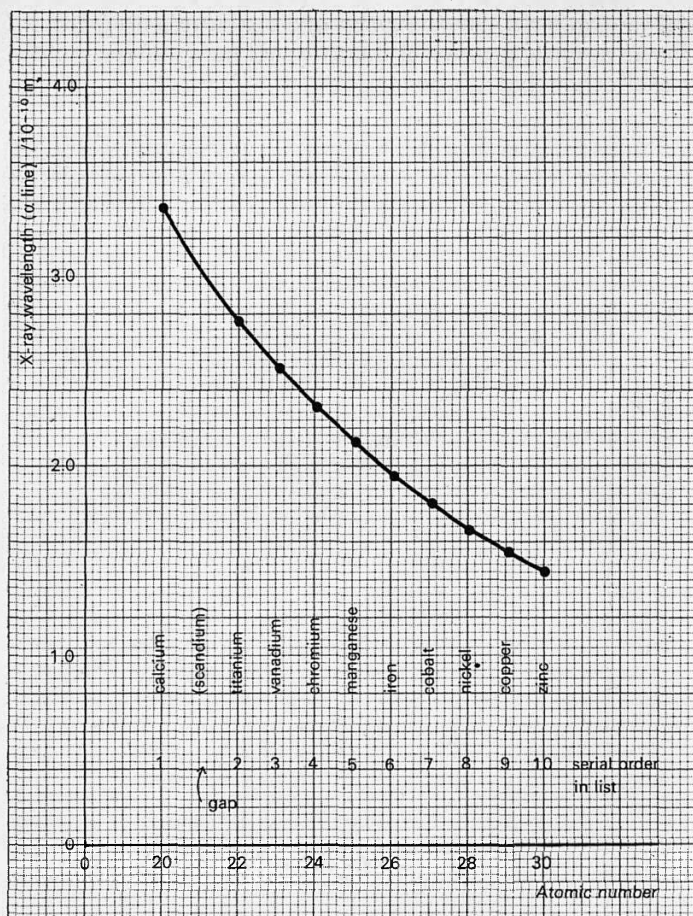
Absorption of radiation by mercury vapour.

**40** a Figure 19 shows a graph of  $\lambda$  against atomic mass. It shows a steady downward trend, except for a bump around nickel-cobalt, but it is not smooth.



**Figure 19**

X-ray wavelength and atomic mass.



**Figure 20**

X-ray wavelength and atomic number.

**b, c** A graph of  $\lambda$  against serial order in the list is smooth, except for too sharp a drop from calcium to titanium. If a new element is supposed to come after calcium but before titanium, occupying place number 2, the curve is quite smooth. The missing element is called scandium. Its atomic

number — that is, its place in the serial order of the elements, with hydrogen as number 1 — is 21, calcium being 20 and titanium 22.

Figure 20 shows the plot of  $\lambda$  against atomic number, a place having been made for scandium. The wavelength of X-rays from scandium would be about  $3.05 \times 10^{-10}$  m. The smoothness of the curve suggests that no other elements are missing.

*Additional note.* When Moseley did this work, there was a theory which said what the frequencies of the X-rays should be. This was Bohr's atomic theory, which gave the energies of the energy levels within the atoms, and so the energy  $hf$  of the radiation, and its frequency  $f$  could be found using the value of Planck's constant  $h$ .

Bohr's theory said that the frequency  $f$  should be proportional to  $(Z-1)^2$ , where  $Z$  is the atomic number. You could test this using the data given in the question, if you like.



# Exponential changes

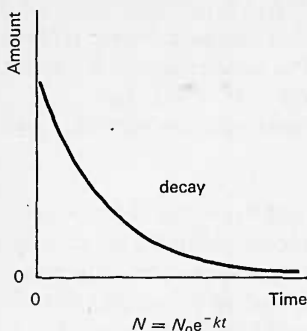


Figure 21

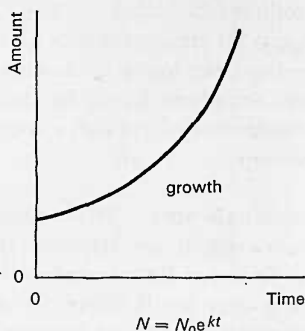


Figure 22

Exponential changes occur when something changes by an amount that is proportional to how much of that something there already is. One such change is the adding of interest to capital, and later, the adding of new interest paid on the now larger capital. Examples in physics include decay of charge on a capacitor, and decay of radioactive materials, as well as some changes of current in wire coils. Sometimes oscillations diminish exponentially (see 'The Severn Bridge', *Students' book*, Unit 4).

Chemical reactions sometimes behave exponentially. In an explosion, it may be that the amount of material reacting in the next microsecond is, say, proportional to the temperature. If the temperature were proportional to the amount already reacted, which it might be if heat losses were small, the explosion would grow exponentially (until it ran out of reactants). Naturally, most real explosions are more complex.

The bacterium *Lactobacillus bulgaricus*, which turns milk into yoghurt, grows in number because each bacterium can divide into two, grow, divide again, and so on. If there is enough food (milk), and the time between divisions is steady, the number of new bacteria produced every hour is proportional to the number already present. Until the food starts to run out, the growth can be exponential.

This section of the *Students' book* tries to show you why exponential changes are important in science, how to test whether a change is exponential, and why the strange looking mathematical form  $e^{kt}$  appears in the mathematical representation of exponential change. It will show you how to calculate the number  $e$  (roughly, at least), whose value is the never ending decimal that begins 2.718 . . . .

### Logarithmic graphs

An exponential curve grows so that the amount present is *multiplied* by a steady factor in successive equal time intervals. If a graph of the *logarithm* of the amount is plotted against time, it is a straight line if the amount grows (or decreases) exponentially, for when the amount is multiplied by a factor  $f$ , the logarithm has a constant quantity  $\lg f$  added. So  $\lg(\text{amount})$  goes up in equal steps as time changes in equal steps.

It is quick and convenient when testing for exponentials to use log-linear graph paper, on which the ordinate ( $y$  axis) grid is already printed logarithmically.

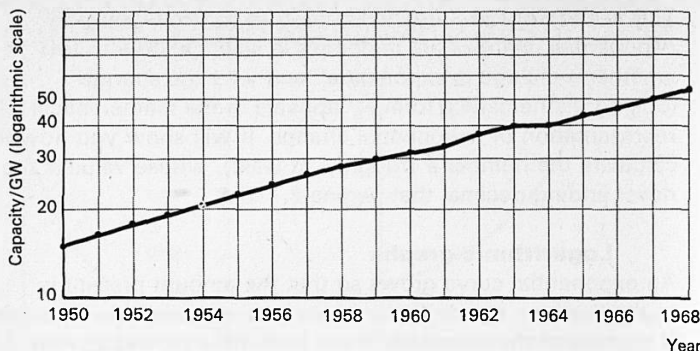
Table 5 gives data for the capacity of the electrical generating plant installed in Great Britain for each year from 1950 to 1969, from *Annual abstract of statistics* (H.M.S.O.).

Capacity of UK electrical generating plant, 1950–1969

Year	50	51	52	53	54	55	56
Capacity/GW	15.0	16.2	17.7	19.2	20.6	22.5	24.6
Year	57	58	59	60	61	62	63
Capacity/GW	26.6	28.0	30.0	31.9	33.9	37.2	39.3
Year	64	65	66	67	68	69	
Capacity/GW	40.0	43.9	46.2	50.0	53.6	55.1	

Table 5

The graph in figure 23 shows that although the logarithm of the capacity does not exactly follow a straight line, there are periods when it does do so to a good accuracy. Overall, it is roughly, but not exactly, true that the growth is exponential. From 1950 to 1958 it was very nearly



**Figure 23**

Growth of capacity of electrical generating plant in the United Kingdom. Data from Central Statistical Office (1970) Annual abstract of statistics. By permission of the Controller, H.M.S.O.

exponential, and also from 1964 to 1968. The economic recession in the early 1960s might account for the pause at about 1963. You may be able to find out how the graph has gone between 1968 and the year in which you read this.

You may like to speculate why the capacity of power stations in an industrial country tends to increase by a roughly constant factor each year (doubling about every decade, as you can see from the graph). Such growth, at a similar rate, is common to nearly all industrial countries during the middle of this century.

### Epidemics

The wider the spread of influenza, the greater the number of people liable to infection. So epidemics grow, until the supply of people runs out, or the people become resistant or are put in isolation. Near the beginning of an epidemic, the growth is often exponential. One of the best known epidemics is the Great Plague of 1665. Readers of Pepys's Diary can get a good impression of what an exponential growth feels like when it is going on around you.

The data in table 6 give the weekly death toll in the Great Plague of 1665.

Week ending	Plague deaths	Week ending	Plague deaths
April 25	0	August 29	6102
May 2	0	September 5	6988
9	9	12	6544
16	3	19	7165
23	14	26	5533
30	17	October 3	4929
June 6	43	10	4327
13	112	17	2665
20	168	24	1421
27	267	31	1031
July 4	470	November 7	1414
11	725	14	1050
18	1089	21	652
25	1843	28	333
August 1	2010	December 5	210
8	2817	12	243
15	3880	19	281
22	4237		

**Table 6**

Bill of mortality of the Plague year 1665 in London.

*From Creighton, C. (1965) A history of epidemics in Britain, Vol. I, Cass.*

## Questions on exponential changes

**1** Show that the number of deaths per week grew exponentially until late July. Show that if this exponential growth had continued after July, the rise would have been greater than it actually was.

**2** Table 7 shows the number of cars in private ownership in Britain from 1950 to 1968. Find out if the number rose exponentially. (Some people regard cars as being like an epidemic, though most find them very useful. If they are a disease, they are one which most of us try to catch.)

Year	Cars in millions	Year	Cars in millions
1950	2.26	1960	5.53
1951	2.38	1961	5.98
1952	2.51	1962	6.56
1953	2.76	1963	7.37
1954	3.10	1964	8.25
1955	3.52	1965	8.92
1956	3.89	1966	9.51
1957	4.19	1967	10.3
1958	4.55	1968	10.8
1959	4.97	1969	11.2

**Table 7**

The number of cars in private ownership in Britain.

*From Central Statistical Office (1970) Annual abstract of statistics.*

*By permission of the Controller, H.M.S.O.*

Year	Estimate 1 Willcox	Estimate 2 Carr-Saunders	U.N.O. data
1650	$0.47 \times 10^9$	$0.55 \times 10^9$	
1750	$0.69 \times 10^9$	$0.73 \times 10^9$	
1800	$0.92 \times 10^9$	$0.91 \times 10^9$	
1850	$1.09 \times 10^9$	$1.17 \times 10^9$	
1900	$1.57 \times 10^9$	$1.61 \times 10^9$	
1920			$1.81 \times 10^9$
1930			$2.01 \times 10^9$
1940			$2.25 \times 10^9$
1950			$2.51 \times 10^9$
1960			$2.99 \times 10^9$

**Table 8**

Estimates of the world's population.

*From Thompson, W. S., 5th revised edition (1965) Population problems, McGraw-Hill.*

**3** Many estimates have been made of the growth of the world's population. Show that the growth suggested by the data in table 8 indicates a rise even 'faster' than an exponential.

As you will know, there are conflicting views as to what can, or should, be done about the population problem. But it is widely accepted as being perhaps the most serious facing mankind today.

### **The mathematical form of an exponential change**

The questions that follow are about the shape and meaning of the mathematical equations that describe exponential changes. You will need to understand these things before you start:

*Logarithms.* The logarithms of two numbers are added to find the logarithm of their product.  $\lg AB = \lg A + \lg B$ .

*Powers.* Powers add when numbers expressed as powers multiply. That is,

$$10^2 \times 10^5 = 10^7; 2^3 \times 2^{0.2} = 2^{3+0.2} = 2^{3.2}.$$

In  $10^2$ ,  $2^3$ ,  $a^t$ , the quantities 2, 3,  $t$  are called *exponents* as well as 'powers' or 'indices'. That is where the word *exponential* comes from.

**4** This question is about how to express in a mathematical form the idea this section began with, that exponential changes occur when the rate of change of something is in proportion to the quantity of that thing already present.

Consider an equation of the form:

$$\frac{\Delta N}{\Delta t} = kN \text{ where } t \text{ is time and } k \text{ is a constant.}$$

The symbol  $\Delta$  means 'change of'. Suppose  $N$  stands for the number of families which have central heating in their homes.

**a** What does  $\Delta N$  mean?

**b** What does  $\frac{\Delta N}{\Delta t}$  mean?

It might be plausible to think that a family would not consider installing central heating unless they knew of other families like themselves who had done so, and who recommended it.

- c Taking this view, can you suggest why a mathematical model like  $\frac{\Delta N}{\Delta t} = kN$  might be appropriate for the way in which the number of families having central heating changes?
- d If 'keeping up with the Joneses' were the only factor, the simple mathematical model might be appropriate. Can you think of any complications which would make it less apt?
- e Think now about the spread of a fashion in, say, clothes. If such a model were appropriate for the period when a fashion was spreading, how might the existence of television in a society alter the value of  $k$ ?
- f Fashions never go on and on spreading. Sketch a rough graph of the change in time of the number of people following a fashion which starts with only a few people if  
 1 the fashion becomes orthodox, and pretty well everyone adopts it,  
 2 the fashion becomes unfashionable, and more and more people reject it.
- Mark on your sketch graphs the points beyond which the model  $\frac{\Delta N}{\Delta t} = kN$  is no longer at all appropriate, supposing that it serves reasonably well for the initial spreading period.

To summarize,  $\Delta N/\Delta t = kN$  is a simple, definite recipe for how  $N$  will next change, in the following time interval  $\Delta t$ .

Although it might be an exact recipe for some problems, for others it may be just nearly right or perhaps only roughly right.

To be interesting, a simple recipe like this must apply at least in part to a wide variety of situations.

### A solution to a differential equation

An equation like  $s = \frac{1}{2}at^2$  tells you what the distance  $s$  will be at some time  $t$ . An equation like  $\Delta N/\Delta t = kN$  does not do that. It says that if  $N$  has *this* value *now*, in a moment or two it will differ from that value by  $\Delta N$ , and it gives a recipe for working out  $\Delta N$ . Such equations are called 'differential'.

But one still needs to know what  $N$  will be at some time  $t$ . If  $N$  is the number of yeast cells in a culture of yeast, or maybe in a brewer's vat, the number to be expected after several hours may be needed. Sometimes, an equation (like  $s = \frac{1}{2}at^2$ )

can be found, sometimes not. If it can, it is called a solution of the differential equation. It is *a* solution, not *the* solution, because it will differ according to where one started off. The recipe for change doesn't say how many yeast cells there are to start with, for example, but the number of cells at time  $t$  depends on how many there originally were.

*The equation  $N = a^t$*

It is not too hard to think of the right kind of shape of equation to suggest for a solution of the recipe  $\frac{\Delta N}{\Delta t} = kN$ , though it looks a bit strange until you get used to it. The next question shows you why  $N = a^t$ , where  $a$  is just some number, makes a reasonable choice.

**5** a If  $N = 2^t$  how would you use *logarithm tables* to find  $N$  when  $t = 7$ ? (We know you could do it without, of course.)

b Use logarithms to find the value of  $N = 2^{0.5}$ .

c Plot a graph of  $N = 2^t$  from  $t = 0$  to  $t = 1.0$ . Why does the graph start at  $N = 1.0$ ? Use axes which allow  $N$  to go from 1.0 to at least 3.0.

d Sketch the graph of  $N = 1^t$ . Also, *either, if you can, sketch roughly the graph of  $N = 3^t$  on the same axes, getting the values at  $t = 0$  and  $t = 1.0$  exactly; or plot a graph of  $N = 3^t$  using logarithms.*

e Consider the graph of  $N = 2^t$ . When  $t$  goes up in equal steps from 0 to 0.2, then to 0.4, to 0.6, and so on, the same thing happens each time to the value of  $N$ . Say carefully what that same thing is, perhaps by inspecting your graph.

f Find  $N = 2^{0.2}$  from your graph. Knowing that  $2^3$  is equal to 8.0, what is  $2^{3.2}$ ? (Remember,  $2^{a+b}$  means  $2^a \times 2^b$ .)

g Inspect table 9. Use it to explain why, when  $t$  increases in equal steps,  $a^t$  is multiplied by a constant factor.

$$a^t$$

$$a^t \times a^t = a^{2t}$$

$$a^t \times a^t \times a^t = a^{3t}$$

$$a^t \times a^t \times a^t \times a^t = a^{4t}$$

Table 9



Exponential changes, whether they are the fall of charge on a capacitor or the growth of generating power have the 'equal ratio' property in common. The changing quantity alters by a constant *factor* when time (or another variable) increases in equal steps. The equation  $N = a^t$  shares this property.

The next question is about the problem, what value of  $a$  goes with a particular value of  $k$  in  $\Delta N = kN$ ? In particular, what value of  $a$  fits the case when  $k = 1$ ?

**6 a** Using the same scale as for question 5 plot out step by step the growth of  $N$ , starting at  $N = 1.0$  when  $t = 0$  if

$$\frac{\Delta N}{\Delta t} = +1.0N$$

$N$  might be the number of bacteria in a colony, for example.

To start you off, when  $N = 1.0$ ,  $\Delta N = 1.0 \times \Delta t$ .

Taking time intervals  $\Delta t$  as 0.1 second,  $\Delta N$  begins by being 0.1. See figure 24.

After 0.1 second,  $N$  has become 1.1. In the *next* 0.1 second,  $\Delta N$  is a little larger than 0.1. Why?

After ten steps you reach  $t = 1.0$ , when  $N$  will have risen to about 2.6 or 2.7. Stop at  $t = 1.0$ .

**b** Repeat the curve drawing for the growth represented by

$$\frac{\Delta N}{\Delta t} = 0.7N \text{ starting with } N = 1.0 \text{ at } t = 0.$$

Why is this growth slower?

Now compare these curves with those from question 5.

**c** What value will  $N$  reach at  $t = 1$  if  $N = 2^t$ ?

**d** What will  $N$  be at  $t = 1$  if  $N = a^t$ ?

**e** If the curves drawn in **a** and **b** above can be represented by equations like  $N = a^t$ , what values of  $a$  would be suitable for each curve (approximately)?

### A value for $a$ in $N = a^t$

You have reason to think that the curve you have drawn in the answer to question 6, part **a** has the form  $N = a^t$ , because this equation has the proper 'constant ratio' property. You can check that your curve has this property

too, by looking at it.  $\frac{\Delta N}{\Delta t} = 1.0N$  is a recipe for growth with

'constant ratio'. But what value has  $a$ ?

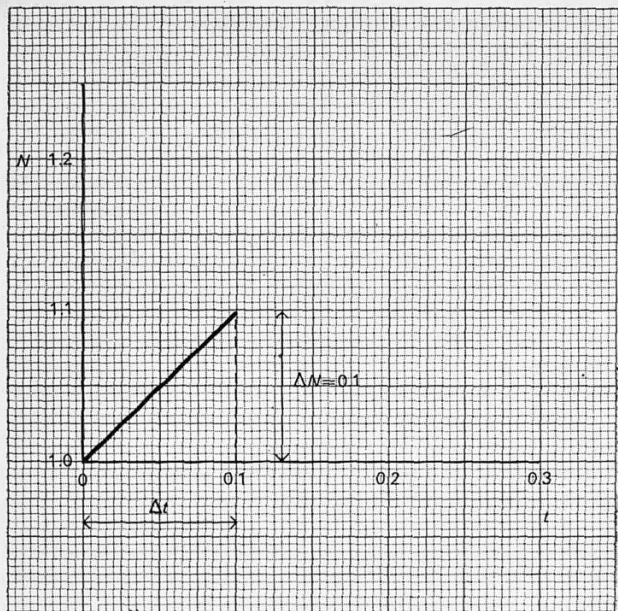


Figure 24

Whatever the value of  $a$  is, it is bigger than 2, because your curve lies above the graph of  $N = 2^t$ . However,  $a$  is less than 3, because your curve lies below  $N = 3^t$ . Your curve, drawn from the recipe  $\Delta N/\Delta t = 1.0N$ , could be represented by the equation  $N = a^t$ , if  $a$  were between 2 and 3. Your graph may give a value around 2.6; more accurate calculations give 2.718. They also show that this number is a never-ending decimal, like  $\pi$  or  $\sqrt{2}$ , so one should write 2.718 . . . . This number has a mathematical symbol,  $e$ . So the solution to the recipe  $\Delta N/\Delta t = 1.0N$  if  $N$  starts at 1.0 when  $t = 0$ , is  $N = e^t$ .

### A not so special case

The recipe  $\Delta N/\Delta t = 1.0N$  is a very special case; what about  $\Delta N/\Delta t = kN$  with  $k$  not equal to one? The next question uses the graph drawn in question 6b for which  $k$  was 0.7, to find out how to cope with the more general problem.

**7** Question 6e suggests that the solution to  $\frac{\Delta N}{\Delta t} = 1.0N$  (the first curve) can be written as  $N = e^t$ , where  $e$  is written for the number 2.7 (more accurately, 2.718 ...).

Use logarithms to find  $e^{0.7}$ , or read the value at  $t = 0.7$  from the first curve  $\frac{\Delta N}{\Delta t} = N$ .

The value of  $e^{0.7}$  should be nearly 2.0, and in question 6b you should have seen that the solution to  $\frac{\Delta N}{\Delta t} = 0.7t$  is approximately  $N = 2.0^t$ .

Instead of writing

$$N = 2.0^t$$

we can write

$$N = (e^{0.7})^t \text{ since } e^{0.7} \approx 2.0$$

So a solution to  $\Delta N/\Delta t = 0.7t$  is  $N = e^{0.7t}$ .

Now make a speculation. If the equation  $\frac{\Delta N}{\Delta t} = kN$  has a solution  $N = a^t$ , is the value of ' $a$ ' likely to be

$$a = e^k?$$

$$\text{or } a = ke?$$

$$\text{or } a = e/k?$$

### A solution in general

The lesson from question 7 is that if we have to solve

$\frac{\Delta N}{\Delta t} = kN$ , the solution is like that for  $\frac{\Delta N}{\Delta t} = 1.0N$ , which is  $N = e^t$ , except that the constant  $k$  appears, multiplying  $t$ .

When  $N = 1.0$  at  $t = 0$ , the equation that tells us the value of  $N$  at time  $t$ , if  $\frac{\Delta N}{\Delta t} = kN$ , is

$$N = e^{kt}.$$

We have been thinking about growth only, as that is easier. But this result can cope with decay, too. The recipe for change, when  $N$  *decreases*, as in radioactive decay, is just

$$\frac{\Delta N}{\Delta t} = -kN.$$

The minus sign arranges that the changes  $\Delta N$  are all *subtracted* from the previous value of  $N$ . But this is like the growth version, with a negative value of  $k$ . Following the same rule ( $N$  is  $e$  to the power  $t$  times  $k$ ) gives

$$N = e^{-kt}.$$

Is this sensible? Yes, because, just as  $10^{-2}$  means  $1/10^2$ , so  $e^{-kt}$  means  $\frac{1}{e^{kt}}$ .

We have seen that  $e^{kt}$  is multiplied by a constant factor when  $t$  rises in equal steps. So  $\frac{1}{e^{kt}}$  is *diminished* by a constant factor when  $t$  rises in equal steps. And that is just what an exponential decay curve that obeys the recipe  $\frac{\Delta N}{\Delta t} = -kN$  does do.

Finally, what about not requiring  $N$  to be 1 when  $t = 0$ , which is, after all, not very realistic? This turns out to be easy.

Suppose there are 10 000 radioactive nuclei in a sample at some moment,  $t = 0$ . All of them, 10 000 out of 10 000, are there to start with. If 2000 decay in the first two seconds, say, then 2000/10 000 have gone. Both the number of nuclei, and the fraction of them remaining, diminish by the *same* proportion of themselves. But the fraction remaining, which we might write as  $N/N_0$ , if there were  $N_0$  to start with, must be equal to one, at the start.  $N/N_0$  is equal to one at  $t = 0$ , and obeys the same recipe for change as does  $N$ . So the solution is simply  $N/N_0 = e^{-kt}$ .

In general, if  $\frac{\Delta N}{\Delta t} = kN$ , and  $N = N_0$  at  $t = 0$ , then

$$N = N_0 e^{kt}.$$

**Postscript:**  $N = N_0 e^{kt}$

This is the exponential equation. It gives the number of atoms left in a sample of radioactive material after any time, or the number of bacteria in a growing colony. It has uses, often as an approximation, in studying the growth and decay of many things in many sciences.

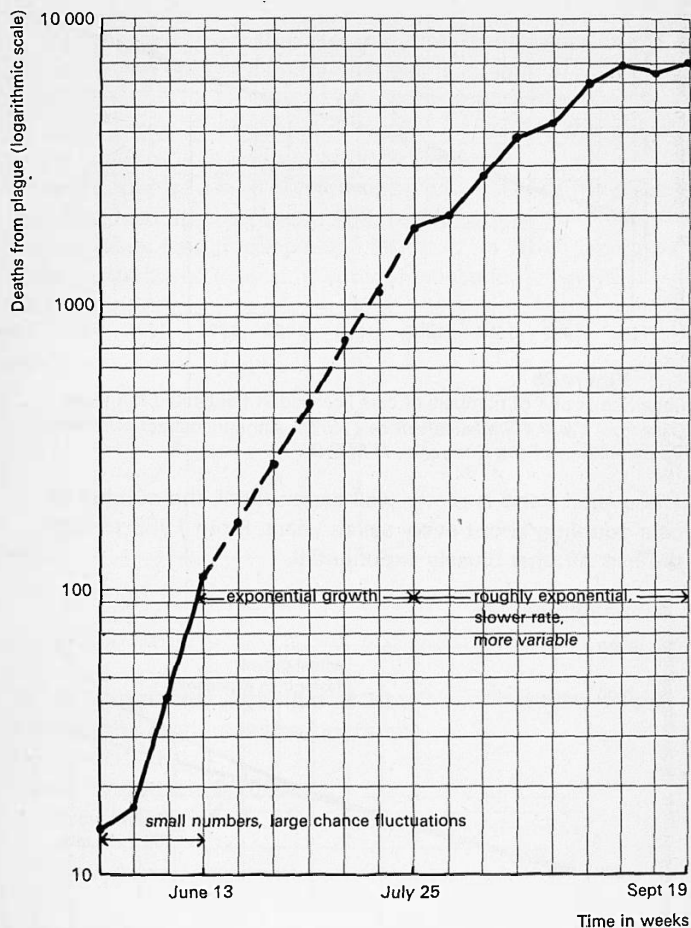
Later on, you may find that it has use and interest beyond growth and decay. One interesting use comes out of supposing that  $k$  might contain the strange quantity  $\sqrt{-1}$ . Then it turns out that the solutions of the equation behave like the oscillating quantities studied in Unit 4, *Waves and oscillations*. But that is for the future.

In this course, exponentials turn up from time to time, and Unit 9, *Change and chance*, is one example. There the use of exponentials has nothing to do with time at all. It turns out that an exponential equation gives the chance that a molecule will acquire a lot more energy than, on average, is its fair share. Such molecules do interesting things. They are the ones that evaporate from the wet washing, they are the ones which join others in chemical reactions, and they are the ones which can emit light or become ionized.

Perhaps the method is even more important than the answer. Here, and in Units 2, *Electricity, electrons, and energy levels*, and 4, *Waves and oscillations*, you have been solving *differential equations*, recipes for change. Often in physics, chemistry, or all sorts of engineering, a problem starts out as a differential equation. This is because many of the basic laws of physics say, not necessarily how things are (though some, like the law of gravitation, do this), but how things will change. To find out how things will change, it is necessary to solve the recipe for change. Sometimes equations exist to do the job. At other times they do not, and graphical or numerical methods, like those you have used, come into their own. Indeed, with the advent of computers, which are rather good at tedious repetitive arithmetic following simple rules, such methods are now widely used. It is a fair bet that, as you read this, someone, somewhere, is solving a differential equation on a computer.

# Answers to questions on exponential changes

1 See figure 25.

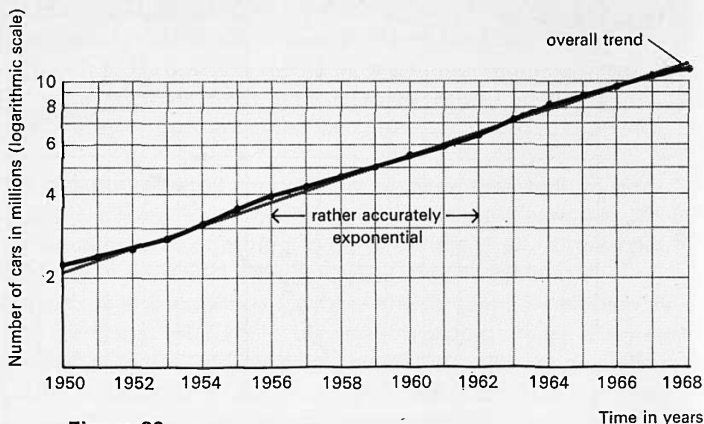


**Figure 25**

Logarithmic plot of deaths in the Great Plague, 1665.

Data from Creighton, C. (1965) *A history of epidemics in Britain, Volume I, Cass.*

## 2 See figure 26.

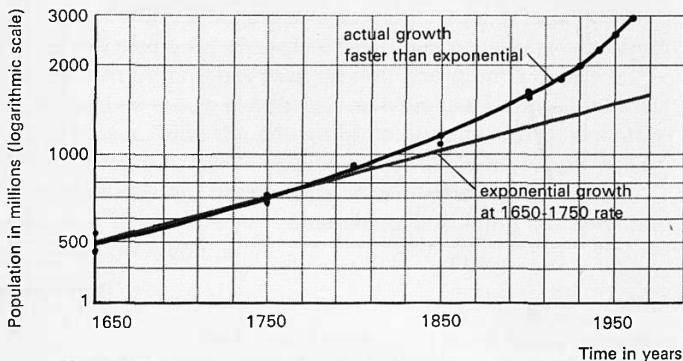


**Figure 26**

Logarithmic plot of numbers of cars licensed in the United Kingdom.  
*Data from Central Statistical Office (1970) Annual abstract of statistics.*  
*By permission of the Controller, H.M.S.O.*

The overall trend is pretty well exponential, the number of cars doubling about every seven years. From 1956 to 1962 the rise is rather closely exponential.

## 3 See figure 27.



**Figure 27**

Logarithmic plot of the population of the world.  
*Data from Thompson, W. S. (1965) Population problems. McGraw-Hill.*  
*Used with the permission of McGraw-Hill Book Company.*

**4 a** The change in the number of families which have central heating.

**b** The rate at which the number of families with central heating changes.

**c** This model suggests that the rate at which the number of people having central heating changes is directly proportional to the number of people having central heating. This would give an exponential growth. In real life this could be the result of 'keeping up with the Joneses'.

**d** There could be a limit on the supply of money or the supply of central heating equipment. This would reduce the value of  $k$  after a time. Not all people can afford to do what they want.

**e** The existence of television could increase the value of  $k$ .

**f** See figure 28.

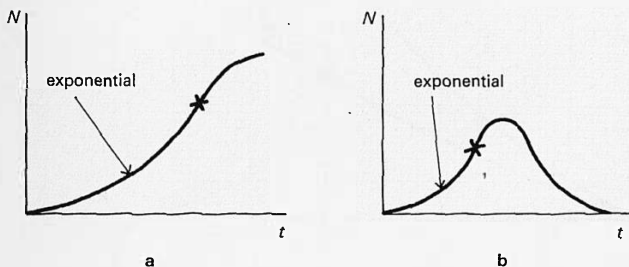


Figure 28

**5 a** Multiply the logarithm of 2 by 7 and find the number of which the product is the logarithm.

**b**  $\lg 2 = 0.3010$

$$\lg N = 0.5 \lg 2 = 0.1505$$

$$N = 1.415$$

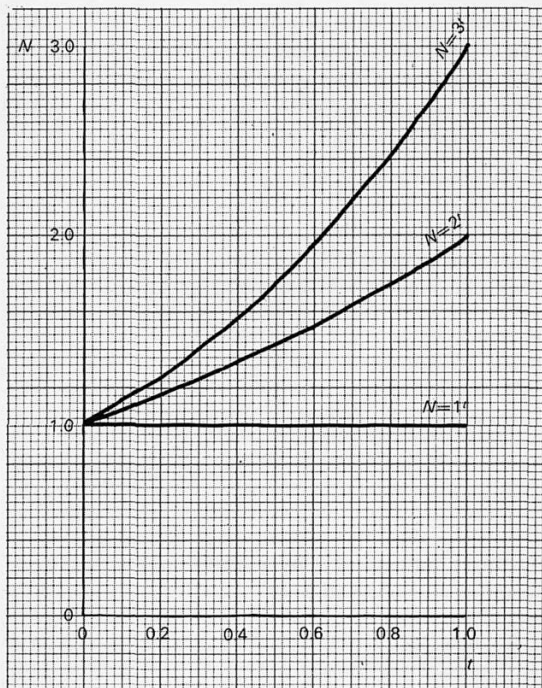


c, d See figure 29.

e At each step of 0.2 in  $t$ , the value of  $N$  is multiplied by the same factor, which is  $2^{0.2}$ , or 1.15.

f  $2^{0.2} = 1.15$ ,  $2^{3.2} = 9.20$ .

g In the series  $a^t$ ,  $a^{2t}$ ,  $a^{3t}$ ,  $a^{4t}$ , each exponent is equal to the previous one with  $t$  added to it. But adding  $t$  to the exponent of  $a$  means multiplying by  $a^t$ .



**Figure 29**

Plots of  $N = 1^t$ ,  $N = 2^t$ ,  $N = 3^t$ .

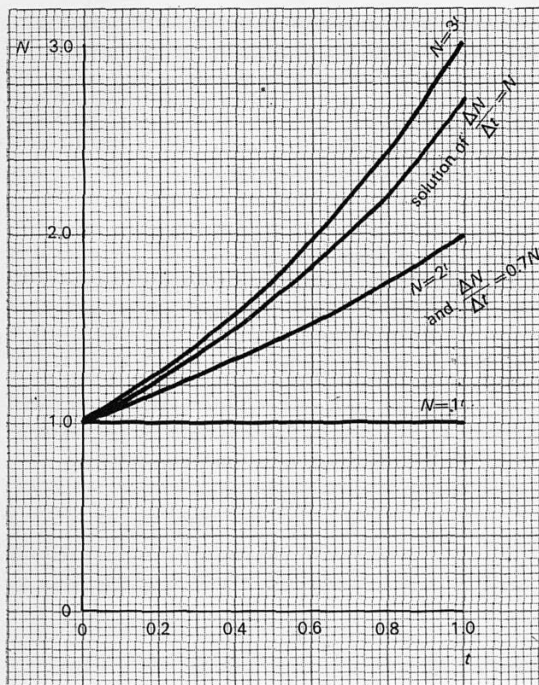
**6 a, b** See figure 30.

**c** If  $N = 2^t$ , at  $t = 1$ ,  $N = 2$ .

**d**  $N = a$  at  $t = 1$ .

**e** For  $\frac{\Delta N}{\Delta t} = (1.0)N$ ,  $N \approx 2.7$  at  $t = 1$ .

For  $\frac{\Delta N}{\Delta t} = (0.7)N$ ,  $N \approx 2.0$  at  $t = 1$ .



**Figure 30**

Plots of  $N = 1^t$ ,  $N = 2^t$ ,  $N = 3^t$  and solution of  $\frac{dN}{dt} = +(1.0)N$ .

**7**  $e^{0.7} = 2.01 \approx 2.0$ .

Since  $(e^{0.7})^t = e^{0.7t}$ , the best speculation is  $a = e^k$ .

# Radioactivity and the nuclear atom

Everybody knows, nowadays, that physicists think of atoms as having a very small, massive, positively charged core or nucleus, surrounded by light, negatively charged electrons. Energy from atomic nuclei looks like being of increasing importance to our civilization. The radiations from nuclei are used in industry and in medicine and we are all very much aware of the importance of controlling man's ability to tap this source of power. This chapter is concerned with the birth of the idea of the nucleus, over the few years from 1896 to 1915. (Notes on the extracts quoted are collected at the end of each extract.)

## **The birth of the nuclear atom**

The modern picture of the atom has two birthdays close together, one in 1896 and the other in 1897, although the picture remained unclear for another twenty years. The first discovery, by Becquerel, was of the radiation from materials like uranium; the effect we now call radioactivity. From this work came, ultimately, the idea of the nucleus. A year later, J. J. Thomson, at the culmination of a long series of experiments on electrical discharges in gases, found evidence of the nature of the rest of the atom. His work suggested that all atoms, no matter of what chemical element, contained the same light, negatively charged particle which we now call the electron.

## **Becquerel's discovery – the 'inside' of atoms**

In 1896, Henri Becquerel was trying to see whether phosphorescent materials that glowed when light had shone on them emitted any penetrating rays like the X-rays Röntgen had recently discovered coming from the glowing glass walls of his electrical discharge tubes. His reports of this discovery are to be found in Romer, *The discovery of radioactivity and transmutation* (reference 3) and are described in Romer, *The restless atom* (reference 18).

In February 1896 Becquerel reported in the journal *Comptes rendus de l'Académie des Sciences* 122, 742\*.

One of Lumière's gelatine bromide photographic plates<sup>(1)</sup> is wrapped in two sheets of very heavy black paper so that the plate does not fog on a day's exposure to sunlight.

A plate of the phosphorescent substance<sup>(2)</sup> is laid above the paper on the outside and the whole exposed to the sun for several hours. When later the photographic plate is developed, the silhouette of the phosphorescent substance is discovered, appearing in black on the negative.

A little later, in the same volume of *Comptes rendus de l'Académie des Sciences*, Paris, Becquerel wrote:

Among the preceding experiments<sup>(3)</sup> some were prepared on Wednesday the 26 and Thursday the 27 of February, and, as on those days the sun appeared only intermittently, I held back the experiments that had been prepared, and returned the plate holders to darkness in a drawer, leaving the lamellas<sup>(4)</sup> of the uranium salt in place. As the sun still did not appear during the following days, I developed the photographic plates on the first of March, expecting to find very weak images. To the contrary, the silhouettes appeared with great intensity. I thought at once that the action must have been going on in darkness. . . .

### Notes

*Henri Becquerel* (1852–1908) belonged to a family of scientists. His father and grandfather were professors of physics too, and his father had had an interest in phosphorescence.

<sup>1</sup> Notice how physicists were quick to take up new ideas, using the recently developed photographic plate as a tool.

<sup>2</sup> He used uranium potassium sulphate, laid down in a thin crust on a plate.

<sup>3</sup> Becquerel was continuing tests with uranium salts laid over shielded photographic plates.

<sup>4</sup> Lamellas are thin layers or crusts.

\* As translated in Romer, A. (ed.) (1964) *The discovery of radioactivity and transmutation*. Dover.

More tests soon showed that Becquerel was right: the uranium salts were emitting some invisible, penetrating radiation. Before long, by trying other substances, the tests identified uranium as the culprit. You could easily repeat some of Becquerel's experiments.

Becquerel's experiments were the first whose effects were directly due to changes in what later became called the nucleus of an atom. And radioactivity, which he discovered, was the tool that suggested the existence of the nucleus.

### **J. J. Thomson and electrons – the 'outside' of atoms**

In October 1897, the *Philosophical magazine* (5) 44, (page 293) published a paper by Thomson describing his experiments on cathode rays. The paper is reprinted in *Classical scientific papers (physics)*.

As you already know, electrons can be produced in many ways; from heated filaments, by shining light on some metals, and by making an electrical discharge in a gas at low pressure. Thomson and others studied the rays they called cathode rays, which came from the cathode of an electrical discharge tube. The paper reports evidence that the cathode rays are streams of negatively charged particles or 'corpuscles' and that the properties of the particles, especially their mass, are just the same whatever gas is used in the tube or whatever metal is used for the cathode. We now call Thomson's 'corpuscles' electrons.

In a series of lectures in 1903, Thomson looked back to this earlier work, and tried to suggest ways in which it might throw light on the structure of atoms, and especially on the perplexing problem of the regularities of the Periodic Table of the elements. He tried to find ways to explain how elements might come to be arranged in groups containing 2-8-8- etc. elements, with properties repeating from group to group.

The next quotation is from the book of those lectures, *Electricity and matter* (Constable, 1904).

## Chapter V

### Constitution of the atom

We have seen that whether we produce the corpuscles<sup>(1)</sup> by cathode rays, by ultra-violet light, or from incandescent metals, and whatever may be the metals or gases present we always get the same kind of corpuscles. Since corpuscles similar in all respects may be obtained from very different agents and materials, and since the mass of the corpuscles is less than that of any known atom, we see that the corpuscle must be a constituent of the atom of many different substances. That in fact the atoms of these substances have something in common.

We are thus confronted with the idea that the atoms of the chemical elements are built up of simpler systems; an idea which in various forms has been advanced by more than one chemist. Thus Prout, in 1815, put forward the view that the atoms of all the chemical elements are built up of atoms of hydrogen; if this were so the combining weights of all the elements would, on the assumption that there was no loss of weight when the atoms of hydrogen combined to form the atom of some other element, be integers; a result not in accordance with observation<sup>(2)</sup>. To avoid this discrepancy Dumas suggested that the primordial atom might not be the hydrogen atom, but a smaller atom having only one-half or one-quarter of the mass of the hydrogen atom. Further support was given to the idea of the complex nature of the atom by the discovery by Newlands and Mendeleeff of what is known as the Periodic Law, which shows that there is a periodicity in the properties of the elements when they are arranged in the order of increasing atomic weights.

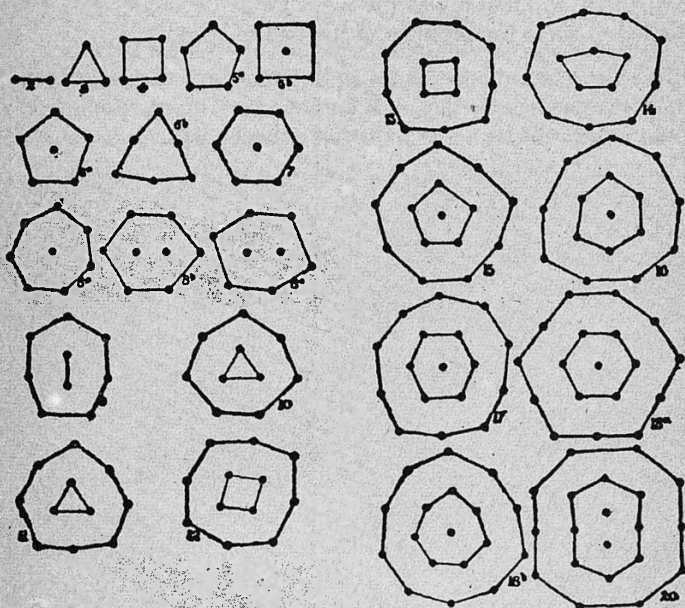
It may thus not be superfluous to consider the bearing of the existence of corpuscles on the problem of the constitution of the atom,<sup>(3)</sup> and although the model of the atom to which we are led by these considerations is very crude and imperfect, it may perhaps be of service by suggesting lines of investigation likely to furnish us with further information about the constitution of the atom. . . .

With any considerable number of corpuscles the problem of finding the distribution when in equilibrium becomes too complex for calculation; and we have to turn to experiment and see if we can make a model in which the forces producing equilibrium are similar to those we have supposed to be at work in the corpuscle. Such a model is afforded by a very simple and beautiful experiment first made, I think, by Professor Mayer.<sup>(4)</sup> In this experiment a number of little magnets are floated in a vessel of water. The magnets are steel needles magnetized to equal strengths and are floated by being thrust through small disks of cork. The magnets are placed so that the positive poles are either all above or all below the surface of the water. These positive poles, like the corpuscles, repel each other with forces varying inversely as the distance between them. The attractive force is provided by a negative pole (if the little magnets have their positive poles above the water) suspended some distance above the surface of the water.

The configurations which the floating magnets assume as the number of magnets increases from two up to nineteen is shown in Fig. 17 [figure 31], which was given by Mayer.<sup>(5)</sup>

I think this table<sup>(6)</sup> affords many suggestions toward the explanation of some of the properties possessed by atoms. Let us take, for example, the chemical law called the Periodic Law; according to this law if we arrange the elements in order of increasing atomic weights, then taking an element of low atomic weight, say lithium, we find certain properties associated with it. These properties are not possessed by the elements immediately following it in the series of increasing atomic weight; but they appear again when we come to sodium, then they disappear again for a time,

but reappear when we reach potassium, and so on. Let us now consider the arrangements of the floating magnets, and suppose that the number of magnets is proportional to the combining weight of an element. Then, if any property were associated with the triangular arrangement of magnets, it would be possessed by the elements whose combining weight was on this scale three, but would not appear again until we reached the combining weight ten, when it reappears, as for ten magnets we have the triangular arrangement in the middle and a ring of seven magnets outside. When the number of magnets is increased the triangular arrangement disappears for a time, but reappears with twenty magnets, and again with thirty-five, the triangular arrangement appearing and disappearing in a way analogous to the behaviour of the properties of the elements in the Periodic Law.



**Figure 31**

*From Thomson, J. J. (1904) Electricity and matter. Constable.*



## Notes

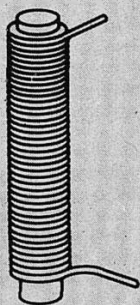
*J. J. Thomson* (1856–1940) was born in Manchester. His father intended to apprentice him to a locomotive builder, but the waiting list was long. To fill in time, Thomson went to Owens College, Manchester, and then, on a scholarship, to Cambridge; at 28, he was Cavendish Professor of Physics. In later life, he said of the work reported here: 'At first there were very few who believed in the existence of these bodies smaller than atoms. . . . I had myself come to this explanation of my experiments with great reluctance.'

<sup>1</sup> Corpuscles – electrons.

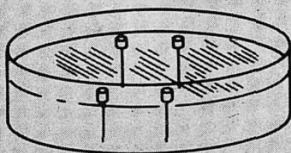
<sup>2</sup> For example  $H = 1$ , but  $Cl = 35.5$ .

<sup>3</sup> It is interesting that Thomson's son, George, shared a Nobel prize for showing that these same electrons had wave-like properties, and that it was the wave properties which finally helped to solve the problem of the nature of atoms.

<sup>4</sup> The diagram in figure 32 gives a picture of the experimental model suggested by Mayer. It comes from Thomson's *The corpuscular theory of matter* (Scribner's, 1907).



**Figure 32**  
From *Thomson, J. J. (1907)*  
*The corpuscular theory of matter.*  
Scribner's.



<sup>5</sup> Don't worry about the details. The idea turned out not to work very well. But see how the floating magnets produce number patterns like those of the Periodic Table. Thomson had in mind a model in which electrons (corpuscles – represented by the floating magnets) were embedded in a cloud of positive charge, rather like currants in a bun.

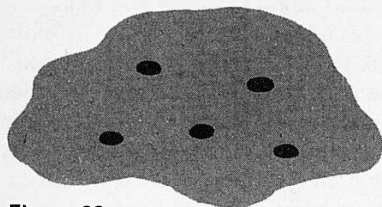


Figure 33

The attractive effect of the positive charge cloud was represented by the large magnet suspended over the small floating magnets.

<sup>6</sup> Thomson went on to tabulate the numbers of magnets in each stable pattern, going on to larger numbers than are in the diagram in figure 31. He refers here to this table, which for brevity is not reproduced. There is a version of the table in his 1897 paper reprinted in *Classical scientific papers (physics)* (page 98).

### Rutherford and alpha particles

We now return to the other side of the story – radioactivity. Soon after Becquerel's discovery, it was found that there were three different kinds of radiation from uranium and other radioactive substances. They were called alpha, beta, and gamma radiations.

It was the alpha particles that happened to be the tool which, almost by accident, gave Rutherford the clue which led him to his nuclear model for an atom. Before this could happen, Rutherford had found out a good deal about alpha particles. You can read some of his reports in *Classical scientific papers (physics)*. In 1902 he discussed the causes of radioactivity. In 1903, he reported the deflection of alpha particles by electric and magnetic fields. In 1909, Rutherford

and Royds collected the gas formed when alpha particles were trapped in a tube, and showed that it was helium, indicating that alpha particles were charged helium atoms. These papers, especially the last two, are well worth looking through.

But Rutherford thought that alpha particles and helium were connected, long before his experiment in 1909. The extract which follows goes back to 1903, when Rutherford and Soddy published a general review of the state of knowledge at that time. In it, they make a number of rough (but quite good) estimates of the charge, mass, energy, and velocity of alpha particles. Without such estimates, the behaviour of alpha particles would have been much harder to understand and the alpha particle scattering experiment which gave the clue to the nucleus would have been unintelligible.

The extract that follows is taken from 'Radioactive change' by E. Rutherford and F. Soddy, *Philosophical magazine* 1903, (6), 5, 576–591. This paper is reprinted in *The discovery of radioactivity and transmutation*, edited by A. Romer.

#### 7. The energy of radioactive change, and the internal energy of the chemical atom.

The position of the chemical atom as a very definite stage in the complexity of matter, although not the lowest of which it is now possible to obtain experimental knowledge, is brought out most clearly by a comparison of the respective energy relations of radioactive and chemical change. It is possible to calculate the order of the quantity of energy radiated from a given quantity of radio-element during its complete change, by several independent methods, the conclusions of which agree very well among themselves. The most direct way is from the energy of the particle projected, and the total number of atoms. For each atom cannot produce less than one 'ray' for each change it undergoes, and we therefore arrive in this manner at a minimum estimate of the total energy radiated. On the other hand, one atom of a radio-element, if completely resolved into projected particles, could not produce more than about 200 such particles at most,

assuming that the mass of the products is equal to the mass of the atom. This consideration enables us to set a maximum limit to the estimate. The rays represent so large a proportion of the total energy of radiation that they alone need be considered.

Let  $m$  = mass of the projected particle,  
 $v$  = the velocity,  
 $e$  = charge.

Now for the  $\alpha$  ray of radium

$$v = 2.5 \times 10^9, ^{(1)}$$

$$\frac{e}{m} = 6 \times 10^3. ^{(2)}$$

The kinetic energy of each particle

$$\frac{1}{2}mv^2 = \frac{1}{2} \frac{m}{e} v^2 e = 5 \times 10^{14} e.$$

J. J. Thomson has shown that

$$e = 6 \times 10^{-10} \text{ E.S. Units} = 2 \times 10^{-20} \text{ electromagnetic units.} ^{(3)}$$

Therefore the kinetic energy of each projected particle =  $10^{-5}$  erg<sup>(4)</sup>. Taking  $10^{20}$  as the probable number of atoms in one gram of radium, the total energy of the rays from the latter =  $10^{15}$  ergs<sup>(5)</sup> =  $2.4 \times 10^7$  gram-calories<sup>(6)</sup>, on the assumption that each atom projects one ray. Five successive stages in the disintegration are known, and each stage corresponds to the projection of at least one ray. It may therefore be stated that the total energy of radiation during the disintegration of one gram of radium cannot be less than  $10^8$  gram-calories, and may be between  $10^9$  and  $10^{10}$  gram-calories. The energy radiated does not necessarily involve the whole of the energy of disintegration and may be only a small part of it.  $10^8$  gram-calories per gram may therefore be safely accepted as the least possible estimate of the energy of radioactive change in radium. The union of hydrogen and oxygen liberates approximately  $4 \times 10^3$  gram-calories per gram of water produced, and this reaction sets free more energy for a given weight than any other chemical change known. The energy of radioactive change must therefore be at least twenty-thousand times, and may be a million times, as great as the energy of any molecular change.

The rate at which this store of energy is radiated, and in consequence the life of a radio-element, can now be considered. The order of the total quantity of energy liberated per second in the form of rays from 1 gram of radium may be calculated from the total number of ions produced and the energy required to produce an ion. In the solid salt a great proportion of the radiation is absorbed in the material, but the difficulty may be to a large extent avoided by determining the number of ions produced by the radiation of the emanation, and the proportionate amount of the total radiation of radium due to the emanation. In this case most of the rays are absorbed in producing ions from the air. It was experimentally found that the maximum current due to the emanation from 1 gram of radium, of activity 1000 compared with uranium, in a large cylinder filled with air, was  $1.65 \cdot 10^{-8}$  electromagnetic units.<sup>(7)</sup> Taking  $e = 2 \cdot 10^{-20}$ , the number of ions produced per second  $= 8.2 \cdot 10^{11}$ . These ions result from the collision of the projected particles with the gas in their path. Townsend (*Phil. Mag.* 1901, vol. i.), from experiments on the production of ions by collision, has found that the minimum energy required to produce an ion is  $10^{-11}$  ergs<sup>(8)</sup>. Taking the activity of pure radium as a million times that of uranium, the total energy radiated per second by the emanation from 1 gram of pure radium  $= 8200$  ergs. In radium compounds in the solid state, this amount is about 0.4 of the total energy of radiation, which therefore is about

$2 \cdot 10^4$  ergs per second,<sup>(9)</sup>

$6.3 \cdot 10^{11}$  ergs per year,

15,000 gram-calories per year.

This again is an under-estimate, for only the energy employed in producing ions has been considered, and this may be only a small fraction of the total energy of the rays.

Since the  $\alpha$  radiation of all the radio-elements is extremely similar in character, it appears reasonable to assume that the feebler radiations of thorium and uranium are due to these elements disintegrating less rapidly than radium. The energy radiated in these cases is about  $10^{-6}$  that from radium, and is therefore about 0.015 gram-calorie per year. Dividing this quantity by the total

energy of radiation,  $2.4 \cdot 10^7$  gram-calories, we obtain the number  $6 \cdot 10^{-10}$  as a maximum estimate for the proportionate amount of uranium or thorium undergoing change per year. Hence in one gram of these elements less than a milligram would change in a million years. In the case of radium, however, the same amount must be changing per gram *per year*. The 'life' of the radium cannot be in consequence more than a few thousand years on this minimum estimate, based on the assumption that each particle produces one ray at each change. If more are produced the life becomes correspondingly longer, but as a maximum the estimate can hardly be increased more than 50 times. So that it appears certain that the radium present in a mineral has not been in existence as long as the mineral itself, but is being continually produced by radioactive change.

Lastly, the number of 'rays' produced per second from 1 gram of a radio-element may be estimated. Since the energy of each 'ray' =  $10^{-5}$  ergs =  $2.4 \cdot 10^{-13}$  gram-calories,  $6 \cdot 10^{10}$  rays are projected every year from 1 gram of uranium. This is approximately 2000 per second. The radiation of 1 milligram of uranium in one second is probably within the range of detection by the electrical method. The methods of experiment are therefore almost equal to the investigation of a single atom disintegrating, whereas not less than  $10^4$  atoms of uranium could be detected by the balance.

It has been pointed out that these estimates are concerned with the energy of radiation, and not with the total energy of radioactive change. The latter, in turn, can only be a portion of the internal energy of the atom, for the internal energy of the resulting products remains unknown. All these considerations point to the conclusion that the energy latent in the atom must be enormous compared with that rendered free in ordinary chemical change. Now the radio-elements differ in no way from the other elements in their chemical and physical behaviour. On the one hand they resemble chemically their inactive prototypes in the periodic system very closely, and on the other they possess no common chemical characteristic which could be associated with their radioactivity. Hence there is no reason to assume that this enormous store of energy is possessed by the radio-elements alone.

It seems probable that atomic energy in general is of a similar, high order of magnitude, although the absence of change prevents its existence being manifested. The existence of this energy accounts for the stability of the chemical elements as well as for the conservation of radioactivity under the influence of the most varied conditions. It must be taken into account in cosmical physics. The maintenance of solar energy, for example, no longer presents any fundamental difficulty if the internal energy of the component elements is considered to be available, i.e. if processes of sub-atomic change are going on. It is interesting to note that Sir Norman Lockyer has interpreted the results of his spectroscopic researches on the latter view (*Inorganic Evolution*, 1900) although he regards the temperature as the cause rather than the effect of the process.

*McGill University, Montreal.*

### *Notes*

*Ernest Rutherford* (1871–1937) came from New Zealand to Cambridge to work under J. J. Thomson. In 1898 he moved to Canada, to McGill University. There he was joined by Frederick Soddy, a young chemist, and for several years they studied radioactivity together. In 1907, Rutherford returned to England as professor at Manchester. It was there that his great work on the nature of the atom was done.

Then in 1919, J. J. Thomson retired as Cavendish Professor at Cambridge, and Rutherford succeeded him. At the Cavendish he trained and stimulated many of the men — Cockcroft, Chadwick, and others — who went on to discover yet more about the structure of nuclei.

Rutherford and Soddy did not use SI units, which are a recent innovation. The units translate as follows:

$$^1 v = 2.5 \times 10^7 \text{ m s}^{-1}.$$

$$^2 e/m = 6 \times 10^7 \text{ C kg}^{-1}.$$

$$^3 e = 2 \times 10^{-19} \text{ C}.$$

$$^4 10^{-5} \text{ erg} = 10^{-12} \text{ joule}.$$

<sup>5</sup>  $10^{15}$  ergs =  $10^8$  joules.

<sup>6</sup> 1 gram-calorie = 4.2 joules.

<sup>7</sup>  $1.65 \times 10^{-8}$  electromagnetic unit =  $1.65 \times 10^{-7}$  A.

<sup>8</sup>  $10^{-11}$  erg =  $10^{-18}$  joule (i.e. about 10 eV).

<sup>9</sup>  $2 \times 10^4$  ergs per second =  $2 \times 10^{-3}$  watt.

### **The great scattering experiment**

One of the biggest surprises in this exciting era was the result of an experiment by Geiger and Marsden in which they bombarded a thin gold foil with alpha particles. Most of the particles passed straight through the foil as expected, but occasionally one would be 'scattered' through a large angle on passing through the foil, or even turned right back from the foil. Rutherford said, 'It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15 inch shell at a piece of tissue paper and it came back and hit you.'

For an early report on this remarkable phenomenon, by Geiger and Marsden in the *Proceedings of the Royal Society* (1909) A, **82**, 495–500, see page 143 of reference 1.

Rutherford proposed his nuclear atom to account for these results. If most of the mass of the atom is concentrated in a very small positively charged nucleus surrounded at a distance by a distribution of negative electrons, then most of the alpha particles would be expected to pass through the foil unaffected. Those few that came close enough to the nucleus would be deflected, the angle of deflection or scattering depending on how close to the nucleus the alpha particle passed. He assumed that the force between nucleus and alpha particle obeyed an inverse square law and calculated how the fraction of incident particles that are scattered through an angle  $\phi$  should depend on  $\phi$ .

The next extracts are from the paper by Geiger and Marsden which describes their tests of Rutherford's theory. The paper was called 'The laws of deflexion of  $\alpha$  particles through large



angles' and was published in the *Philosophical magazine*, 1913, (6) 27, 604. The extracts reprinted here merely reproduce their description of the experiment and some of their results. You will find much more information in the original paper which is on page 162 of reference 1.

In a former paper one of us has shown that in the passage of  $\alpha$  particles through matter the deflexions are, on the average, small and of the order of a few degrees only. In the experiments a narrow pencil of  $\alpha$  particles fell on a zinc-sulphide screen in vacuum, and the distribution of the scintillations on the screen was observed when different metal foils were placed in the path of the  $\alpha$  particles. From the distribution obtained, the most probable angle of scattering could be deduced, and it was shown that the results could be explained on the assumption that the deflexion of a single  $\alpha$  particle is the resultant of a large number of very small deflexions caused by the passage of the  $\alpha$  particle through the successive individual atoms of the scattering substance.

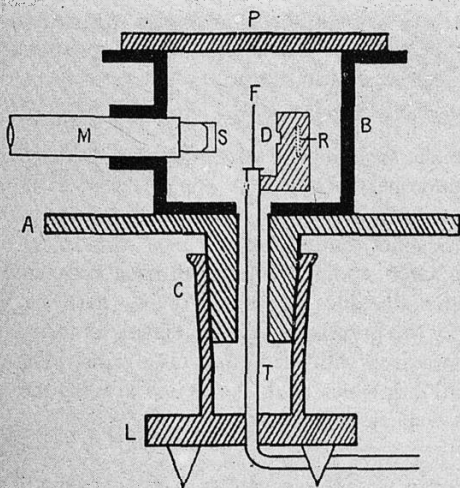
In an earlier paper, however, we pointed out that  $\alpha$  particles are sometimes turned through very large angles. This was made evident by the fact that when  $\alpha$  particles fall on a metal plate, a small fraction of them, about  $1/8000$  in the case of platinum, appears to be diffusely reflected. This amount of reflexion, although small, is, however, too large to be explained on the above simple theory of scattering. It is easy to calculate from the experimental data that the probability of a deflexion through an angle of  $90^\circ$  is vanishingly small, and of a different order to the value found experimentally.

Professor Rutherford has recently developed a theory to account for the scattering of  $\alpha$  particles through these large angles, the assumption being that the deflexions are the result of an intimate encounter of an  $\alpha$  particle with a single atom of the matter traversed. In this theory an atom is supposed to consist of a strong positive or negative central charge concentrated within a sphere of less than about  $3 \times 10^{-12}$  cm radius, and surrounded by electricity of the opposite sign distributed throughout the remainder of the atom of about  $10^{-8}$  cm radius. In considering the deflexion of an  $\alpha$  particle directed against such an atom, the main deflexion-effect can be supposed to be due to the central

concentrated charge which will cause the  $\alpha$  particle to describe an hyperbola with the centre of the atom as one focus.<sup>(1)</sup>...

### 1 *Variation of scattering with angle*

We have already pointed out that to obtain measurable effects an intense pencil of  $\alpha$  particles is required. It is further necessary that the path of the  $\alpha$  particles should be in an evacuated chamber to avoid complications due to the absorption and scattering of the air. The apparatus used is shown in figure 1 [figure 34] and mainly consisted of a strong cylindrical metal box B, which contained the source of  $\alpha$  particles R, the scattering foil F, and a microscope M to which the zinc-sulphide screen S was rigidly attached<sup>(2)</sup>. The box was fastened down to a graduated circular platform A, which could be rotated by means of a conical airtight joint C. By rotating the platform the box and microscope moved with it, whilst the scattering foil and radiating source remained in position, being attached to the tube T, which was fastened to the standard L. The box B was closed by the ground-glass plate P, and could be exhausted through the tube T.



**Figure 34**

From Geiger, H. and Marsden, E. (1913) 'The laws of deflexion of alpha particles through large angles.' *Phil. mag.* (6). 27, 604.

Table II<sup>(3)</sup>  
Variation of scattering with angle (collected results)

I	II	III	IV	V	VI
			Silver		Gold
Angle of deflexion $\phi$ , in degrees	$\frac{1}{\sin^4 \phi/2}$	Number of scintillations, $N$	$\frac{N}{\sin^4 \phi/2}$	Number of scintillations, $N$	$\frac{N}{\sin^4 \phi/2}$
°					
150	1.15	22.2	19.3	33.1	28.8
135	1.38	27.4	19.8	43.0	31.2
120	1.79	33.0	18.4	51.9	29.0
105	2.53	47.3	18.7	69.5	27.5
75	7.25	136	18.8	211	29.1
60	16.0	320	20.0	477	29.8
45	46.6	989	21.2	1435	30.8
37.5	93.7	1760	18.8	3300	35.3
30	223	5260	23.6	7800	35.0
22.5	690	20 300	29.4	27 300	39.6
15	3445	105 400	30.6	132 000	38.4
30	223	5.3	0.024	3.1	0.014
22.5	690	16.6	0.024	8.4	0.012
15	3445	93.0	0.027	48.2	0.014
10	17 330	508	0.029	200	0.0115
7.5	54 650	1710	0.031	607	0.011
5	276 300	...	...	3320	0.012

**Table 10**

*Variation of scattering with velocity<sup>(4)</sup>*

In order to determine the variation of scattering with velocity the apparatus was somewhat modified. A conical glass tube coated with active deposit was again used as source of radiation. This source was placed about 1 mm from the mica window, so that it was possible to insert additional sheets of mica between the source and the window to reduce the velocity of the  $\alpha$  particles. Mica sheets were used for this purpose on account of their uniformity of thickness in comparison with metal foils. The micas were attached to a cardboard disk which could be rotated to bring the different sheets successively in position.

Table VII  
Variation of scattering with velocity

I	II	III	IV	V
Number of sheets of mica	Range $R$ of $\alpha$ particles after leaving mica	Relative values of $1/v^4$	Number $N$ of scintillations per minute	$Nv^4$
0	5.5	1.0	24.7	25
1	4.76	1.21	29.0	24
2	4.05	1.50	33.4	22
3	3.32	1.91	44	23
4	2.51	2.84	81	28
5	1.84	4.32	101	23
6	1.04	9.22	255	28

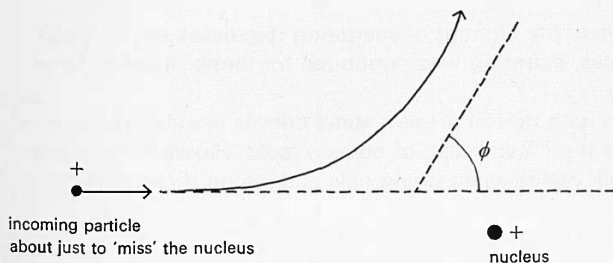
**Table 11**

### Notes

*Hans Geiger* (1882–1945) came to Manchester from Germany in 1906, and worked there with Rutherford. He and Müller later developed the well known Geiger-Müller tube.

*Ernest Marsden* (1889–1970) assisted Geiger when he was still an undergraduate and together they found the large angle scattering of alpha particles. Later he returned to Manchester to make the tests reported in this paper.

<sup>1</sup> Geiger and Marsden have in mind a picture of the kind illustrated in figure 35.



**Figure 35**

<sup>2</sup> The zinc sulphide screen S was used to detect the alpha particles. Each particle hitting it gave a faint flash of light visible in the microscope M. The experiment involved long periods of waiting until Geiger's or Marsden's eyes were adapted to the dark and could see the faint flashes.

<sup>3</sup> Rutherford's calculations showed that, if his picture was right, the number of alpha particles counted at an angle  $\phi$  should vary as  $1/\sin^4 (\phi/2)$ . This Geiger and Marsden set out to test. The table gives their results for silver and for gold foils. Columns III and V are the numbers of alpha particles arriving in a standard time. Column II is  $1/\sin^4 \phi/2$ . Columns IV and VI make the test: in each case, the number of particles at angle  $\phi$  is proportional to  $1/\sin^4 \phi/2$ , though the silver results are less good.

<sup>4</sup> They also compared the scattering of slow and fast alpha particles, as Rutherford had predicted that the number scattered would vary as  $1/(\text{velocity})^4$ . This was one of a whole series of detailed tests of a number of predictions made by Rutherford. Every prediction was confirmed. The extracts reproduced here are just a small part of a long paper.

#### *A filmed version of the scattering experiment*

You may have seen a film of a recent revival of the scattering experiment 'The Rutherford model of the atom', Rank-Mullard. Table 12 gives some of the results obtained in that filmed experiment. How well do they agree with the prediction?

Note that:

**a** because the amount of scattering decreases as the angle increases, counting was continued for longer times at larger angles.

**b** even with no foil present some counts are always recorded. Why is this? You must, of course, make allowances for this 'no-foil' count when doing calculations on these data.

$\phi$	$1/\sin^4 \phi/2$	Time of counting in minutes	Total counts	Counts with no foil
20	1101	0.5	530	76
30	222	2	395	28
40	72.7	5	334	36
50	31.5	10	281	20
60	16.0	10	144	9
70	9.17	20	180	10
80	5.92	40	224	20
90	4.00	50	175	15
135	1.38	100	133	40

Table 12

angle $\phi$	Number scattered at angle $\phi$ into fixed small area	Numbers proportional to number of alpha particles scattered at more than $\phi$
180	—	0
165	—	8
150	33.1	32
135	43.0	79
120	51.9	154
105	69.5	266
90		448
75	211	767
60	477	1384
45	1435	2811
37.5	3300	
30	7800	7725
22.5	27 300	
15	132 000	45 800

Table 13

Central column from Geiger, H. and Marsden, E. (1913).

### The number of alpha particles scattered at more than any angle $\phi$

You may have tried another model for the scattering of alpha particles – a curved cone-shaped hill to represent the inverse square law force between particle and nucleus. To compare the experimental results for the hill with those of an experiment on alpha particle scattering, it is useful to know how many particles are scattered at *more than* each angle  $\phi$ .

Table 13 on page 89 gives Geiger's and Marsden's results for gold, together with numbers calculated from these results which are proportional to the number scattered at *more than* each angle.

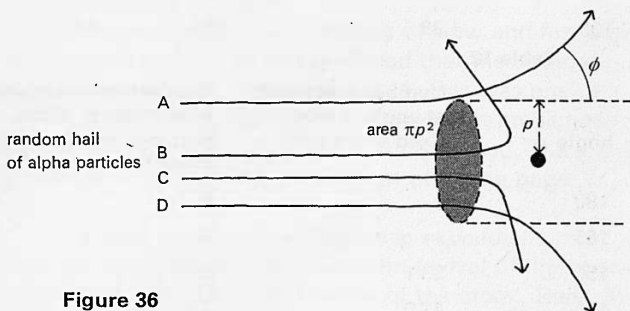


Figure 36

An alpha particle A aimed a distance  $p$  from the nucleus is scattered through some angle  $\phi$ . All particles like B, C, D, coming closer than  $p$ , going through an area  $\pi p^2$ , are scattered by *more than*  $\phi$ . So if the alpha particles come in a uniform random hail, the number coming closer than  $p$  will be proportional to the area  $\pi p^2$ , or proportional to  $p^2$ .

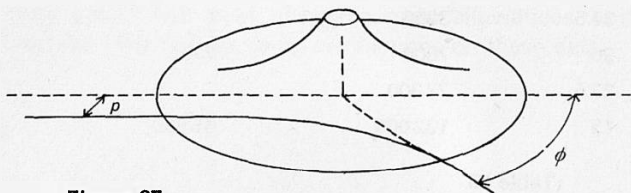


Figure 37

For the hill model, experiments give a relation between aiming error  $p$  and angle  $\phi$ . If the hill is a good model, the relation between  $p^2$  and the angle  $\phi$  for the hill should be the same as the relation between the number of alpha particles scattered through more than  $\phi$  and the angle  $\phi$ , in the real alpha particle experiment.

### The problem of the size of charge on the nucleus

The number of alpha particles scattered by a material depends on the charge on the nucleus, according to Rutherford's model. (The bigger the charge, the more particles are scattered.)

The calculation is rather involved, so in figure 38 we have drawn a diagram, like a sausage machine, showing what goes into and what comes out of the mathematics.

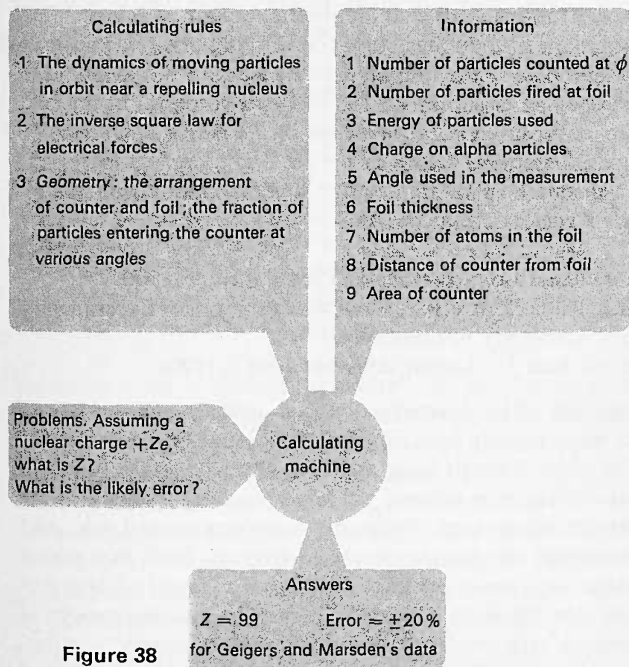


Figure 38



Chadwick later repeated the scattering experiment, to try to measure the nuclear charge of several elements. See table 14.

Element	Mass number	Atomic number	Z from scattering
Gold	197	79	$77.4 \pm 1.0$
Silver	108	47	$46.3 \pm 0.7$
Copper	63.5	29	$29.3 \pm 0.5$

**Table 14**

(Chadwick, J., 1920 Phil. mag. (6), 40.)

The answer is rather clear: the charges on these nuclei are not equal to the mass, but to the Periodic Table serial number.

### **The Rutherford model**

In 1920 Rutherford gave the Bakerian lecture to the Royal Society. At the start of that lecture he looked back over the development of the ideas surveyed in this book, and described briefly and clearly the model he invented and the evidence that suggested or supported it. The first two pages of the lecture, as reported in *Proceedings of the Royal Society, A* Volume 97, page 374, appear below. The complete lecture, which discusses early transmutation experiments, appears in *Classical scientific papers (physics)*.

#### **Bakerian Lecture: Nuclear Constitution of atoms**

By Sir E. Rutherford, F.R.S., Cavendish Professor of Experimental Physics, University of Cambridge.

(Received June 3, – Lecture delivered June 3, 1920).

*Introduction.* The conception of the nuclear constitution of atoms arose initially from attempts to account for the scattering of  $\alpha$  particles through large angles in traversing thin sheets of matter. Taking into account the large mass and velocity of the  $\alpha$  particles, these large deflexions were very remarkable, and indicated that very intense electric or magnetic fields exist within the atom. To account for these results, it was found necessary to assume that the atom consists of a charged massive nucleus of dimensions very small compared with the ordinarily accepted magnitude of the diameter of the atom. This positively charged

nucleus contains most of the mass of the atom, and is surrounded at a distance by a distribution of negative electrons equal in number to the resultant positive charge on the nucleus. Under these conditions, a very intense electric field exists close to the nucleus, and the large deflexion of the  $\alpha$  particle in an encounter with a single atom happens when the particle passes close to the nucleus. Assuming that the electric forces between the  $\alpha$  particle and the nucleus varied according to an inverse square law in the region close to the nucleus, the writer worked out the relations connecting the number of  $\alpha$  particles scattered through any angle with the charge on the nucleus and the energy of the  $\alpha$  particle. Under the central field of force, the  $\alpha$  particle describes a hyperbolic orbit round the nucleus, and the magnitude of the deflexion depends on the closeness of approach to the nucleus. From the data of scattering of  $\alpha$  particles then available, it was deduced that the resultant charge on the nucleus was about  $\frac{1}{2}Ae$ , where  $A$  is the atomic weight and  $e$  the fundamental unit of charge. Geiger and Marsden made an elaborate series of experiments to test the correctness of the theory, and confirmed the main conclusions. They found the nucleus charge was about  $\frac{1}{2}Ae$ , but, from the nature of the experiments, it was difficult to fix the actual value within about 20 per cent. C. G. Darwin worked out completely the deflexion of the  $\alpha$  particle and of the nucleus, taking into account the mass of the latter, and showed that the scattering experiments of Geiger and Marsden could not be reconciled with any law of central force, except the inverse square. The nuclear constitution of the atom was thus very strongly supported by the experiments on scattering of  $\alpha$ -rays.

Since the atom is electrically neutral, the number of external electrons surrounding the nucleus must be equal to the number of units of resultant charge on the nucleus. It should be noted that, from the consideration of the scattering of X-rays by light elements, Barkla had shown, in 1911, that the number of electrons was equal to about half the atomic weight. This was deduced from the theory of scattering of Sir J. J. Thomson, in which it was assumed that each of the external electrons in an atom acted as an independent scattering unit.

Two entirely different methods had thus given similar results with regard to the number of external electrons in the atom, but the scattering of  $\alpha$ -rays had shown in addition that the positive charge must be concentrated on a massive nucleus of small dimensions. It was suggested by Van den Broek that the scattering of  $\alpha$  particles by the atoms was not inconsistent with the possibility that the charge on the nucleus was equal to the atomic number of the atom, i.e. to the number of the atom when arranged in order of increasing atomic weight. The importance of the atomic number in fixing the properties of an atom was shown by the remarkable work of Moseley on the X-ray spectra of the elements. He showed that the frequency of vibration of corresponding lines in the X-ray spectra of the elements depended on the square of a number which varied by unity in successive elements. This relation received an interpretation by supposing that the nuclear charge varied by unity in passing from atom to atom, and was given numerically by the atomic number. I can only emphasize in passing the great importance of Moseley's work, not only in fixing the number of possible elements, and the position of undetermined elements, but in showing that the properties of an atom were defined by a number which varied by unity in successive atoms. This gives a new method of regarding the periodic classification of the elements, for the atomic number, or its equivalent the nuclear charge, is of more fundamental importance than its atomic weight. In Moseley's work, the frequency of vibration of the atom was not exactly proportional to  $N$ , where  $N$  is the atomic number, but to  $(N-a)^2$ , where  $a$  was a constant which had different values, depending on whether the K or L series of characteristic radiations were measured. It was supposed that this constant depended on the number and position of the electrons close to the nucleus.

### The neutron

At the end of the above lecture, Rutherford speculated about the possible existence of a new 'atom' or particle with the same mass as a proton but with zero charge. A decade later, Chadwick, working under Rutherford, found such particles. You may like to look at Chadwick's *Some personal notes on the search for the neutron*, reproduced in Project Physics, Reader, Unit 6 (reference 5).

## **Chance and randomness become part of physics**

We conclude with another aspect of the discovery of radioactivity – the introduction of chance and randomness at the heart of physics.

Rutherford and others naturally investigated whether the emission of radiation from radioactive substances was affected by heat, chemical state, and so on. They found that it was not; if it had been, the search would have started for rules about how it depended on such factors. But there were no rules.

In addition, the particles or gamma rays did not seem to be emitted at special times. It was not the case that the atoms all decayed together, or that the decay of one made any difference to the time of decay of another. Rather, the decaying atoms behaved just as if someone were throwing dice to decide the fate of each one. One might decay almost at once, while another could last out for a long time. No way could be found of predicting which atom would decay at any particular time.

You may be amused by the following piece from the memories of William Kay, who was Rutherford's laboratory technician in Manchester. He is talking about an idea Rutherford had for seeing if the radioactivity from radium 'emanation' (that is, a radioactive gas from radium) would be altered by making it very hot and putting it under high pressure inside a 'bomb' in which an explosive charge was placed. The extract comes from S. Devons's 'Recollections of Rutherford.'

*Kay*

He hadn't been here very long when he got going, you know. Well, he was working here then, and we had a thing for measuring the explosive power of cordite, or something, which was a great big iron bomb, and you got the pressure by the explosion in this 3-inch wall thickness – and the temperature by thermocouple.

Well, Rutherford hadn't been here, oh, a week or two, I think, perhaps a few weeks, and then he suddenly thought: 'To hell with our radioactive material. It's never been under pressure like that. – That will make it go up to about 1000 atmospheres and 1000 degrees Centigrade – what will emanation do in it?' And straight-away he fitted it up with no trouble at all. He fitted it up, and put the emanation in, and got his electroscopes up, and got the decay, and exploded it. . . . It was in one of the cellars. But no, no difference, you see, and he dropped it straight away. But it's so tricky, them kind of things.

*What was he looking for?*

*Kay*

Well, to see if pressure and temperature had any effect on it, you see. 'Cause you see, when the explosion occurred, you'd got 1000 atmospheres and 1000 degrees Centigrade.

*And he was looking for a change in activity?*

*Kay*

Yes, at those big pressures . . . you see.

*Quoted in Gershenson, D. E., and Greenberg, D. A. (1963) The natural philosopher, Volume I; Waltham, Massachusetts; Xerox College Publishing.*

### **Evidence that radioactive decay is governed by chance**

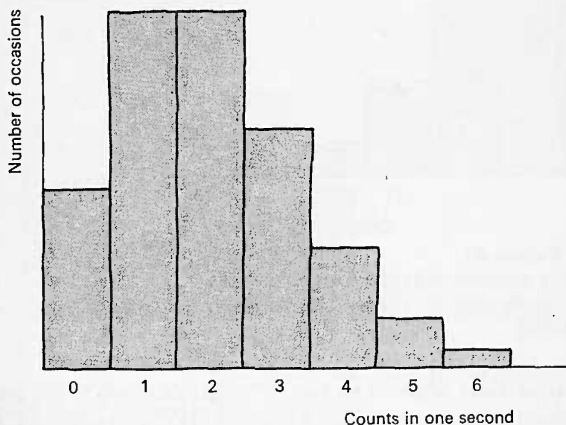
There are two sorts of evidence. First, the decay of a sample of material containing many atoms follows a simple exponential decay law, as you should have seen for yourself. Now, such a law could be the result of there being a steady, fixed, small chance that any one atom will decay in the next few seconds.

Suppose this chance is just one in a million. Then in the next few seconds, close to one atom in a million will decay. If there

are  $10^{20}$  atoms there,  $10^{14}$  will decay. Later there may be only  $10^{18}$  atoms left. Of those, if the chance of decay is still the same,  $10^{12}$  will decay. The number decaying will be proportional to the number there. If this is so, the decay will be exponential. The section 'Exponential changes' in this book has more to say about that.

But it is not obvious that the exponential decay that we do observe *must* be explained in this way. Decay of charge on a capacitor or the dripping of water out of a tube can both be exponential without there being an obvious chance-like behaviour in the background (though maybe there is).

The best evidence that chance is at work is that chance-like accidents happen. If you were spinning a coin which turned up heads and tails always in *exactly* equal numbers, you would suspect that something funny was going on. If chance is at work, the numbers ought to be about the same, but not always and not exactly.



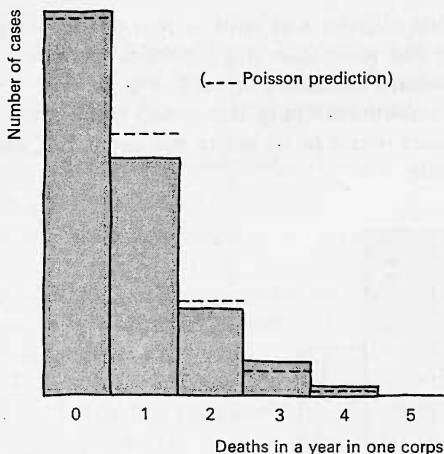
**Figure 39**

Differing numbers of counts in a second.

Suppose a radioactive sample gives, on average, two decays in a second. Then there ought to be one decay in a second

sometimes, balanced by other one-second intervals with three decays. There will even be one-second intervals with no decays at all, and others with four or five. A thousand in a second could happen, but is so rare (if the average is only two) as never to be observed. If you count up the occasions on which there are no decays, one decay, two, three, and so on and make a chart of them, it looks like figure 39.

Figure 39 shows what may be expected on many trials. The French mathematician Poisson worked out the shape of the chart for any average number of events observed, not just for the average 2. Radioactive decays fit this shape very well.



**Figure 40**

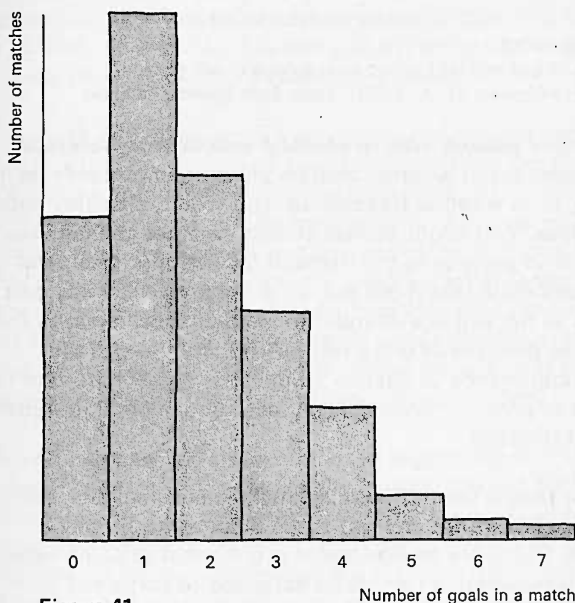
Differing numbers of deaths from horse kicks.

*Data from Weaver, W. (1964) Science Study Series No. 24, Lady Luck, Heinemann.*

A famous early attempt to see if Poisson's ideas fitted real situations was made by Bortkewitsch. His observations were macabre: the number of deaths from horse kicks a year in a Prussian cavalry corps over the years 1875 to 1894. It seems sensible to suppose that there is a small steady chance that a trooper will die in this way in a year. If so, the number of deaths should fit Poisson's prediction. Figure 40 is a chart of

the data. It also shows the number of times a corps *should*, according to Poisson, have suffered no deaths, one death, two deaths, and so on. The agreement is very good.

Figures 41 and 42 give other illustrations. Figure 41 shows the number of occasions on which a football team scored no goals, one goal, two goals, and so on, in a match. Footballers do not like to think this is a matter of chance, but the evidence is that it is, pretty much. Figure 42 shows the pattern for the number of lost articles handed in per day in a department store. Like these things, radioactive decays are governed by chance.



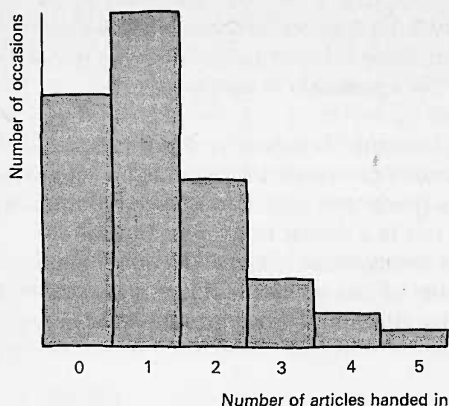
**Figure 41**

Numbers of goals scored in football matches.

Data from Moroney, M. J. (1956) *Facts from figures*, Penguin.

If you want to know more about chance, or the Poisson distribution, try Moroney, *Facts from figures*, or Weaver, *Lady Luck*, from both of which the data above were drawn. See page 139 for details.





**Figure 42**

Numbers of lost articles handed in at a department store.

*Data from Moroney, M. J. (1956) Facts from figures, Penguin.*

### **Other places where chance matters in science**

If you were asked whether chance plays an important role in farming, or in weather forecasting, you would probably agree that it does. You might be less certain whether chance was important in estimating the demand for petrol or steel, and might well think that it did not, or should not, play any part in physics. Is not physics devoted to mathematical laws; to being as sure as possible of one's results? Such a view of the relative importance of chance would miss some important features of physics. Chance is, in fact, fundamental to much physical thinking.

Firstly, a simple point. Physicists make measurements, and they sometimes (not always) make them as accurately as possible. But every measurement is uncertain to some extent: that is, if repeated, it cannot be expected to come out exactly the same each time. Accurate measurement is the art of making these variations as small as is practicable. The theory of chance provides ways of analysing the variations that are left over when as much as possible of the measuring process has not been left to chance. Using the theory, a physicist can say, not that he is certain the result is such and such, but how likely it is to lie within stated limits. Thus

Froome, who measured the velocity of microwaves in 1948, claims that they travel at  $299\,792.5 \pm 0.1 \text{ km s}^{-1}$ . This means that he thinks the chances are about 7 in 10 that the value lies within the stated limits, and better than 9 in 10 that it lies within twice these limits. These odds come from the theory of chance applied to measuring processes.

Chance pervades much of chemistry, and the processes of chemical industry. When, say, ammonia is made from nitrogen and hydrogen, the chemist or industrialist cannot take the individual molecules and hold a marriage service over them. The molecules move about at random, colliding and separating. All the chemists can do is to arrange matters, by heating, cooling, compressing, or using catalysts, so that it is as likely as possible that many of the molecules will by chance combine within a reasonable time.

The same principles apply even to the boiling of a kettle. If 'heat' is just the motion of atoms or molecules, the flow of heat into a kettle means that the molecules in the kettle are acquiring energy of motion from outside. Any one molecule may, or may not, happen to make collisions in such a way that it moves faster. The art of boiling kettles is to make sure that it is more likely that they do than that they do not, and the way to do it is to put the kettle onto something 'hotter' than itself. Ask a physicist what 'hotter' means, and in the end he will have to tell this kind of story about chance.

Indeed, we may have been unfair in suggesting that chance entered science with radioactivity. During the last part of the nineteenth century Boltzmann and others were busy trying to show that chemical reactions, the flow of heat, and other such changes could be explained as the result of chance exchanges of energy and position amongst atoms. Even this development was foreshadowed by the kinetic theory of gases, which, with its explanation of gas pressure as the result of random molecular bombardment, is perhaps the first occasion when chance entered physics.

Radioactive decay is not one regrettable exception to an otherwise tidy rule of certainty in physical laws. Our present understanding of atoms and the particles of which they are made suggests that *all* our knowledge of their behaviour can only be knowledge of the chance that this or that event will happen. There are no certainties among predictions of atomic behaviour.

An electron in an atom is not thought of as being definitely on one side of the atom at one moment and then, later, definitely round the other side, as if it had travelled round an orbit. We think that such descriptions cannot be given; that all that can be discovered is the chance that the electron will be in one place or another. Some physicists regret this uncertainty at the heart of physics; most accept it, though what the future holds is anybody's guess.

# Radioisotopes

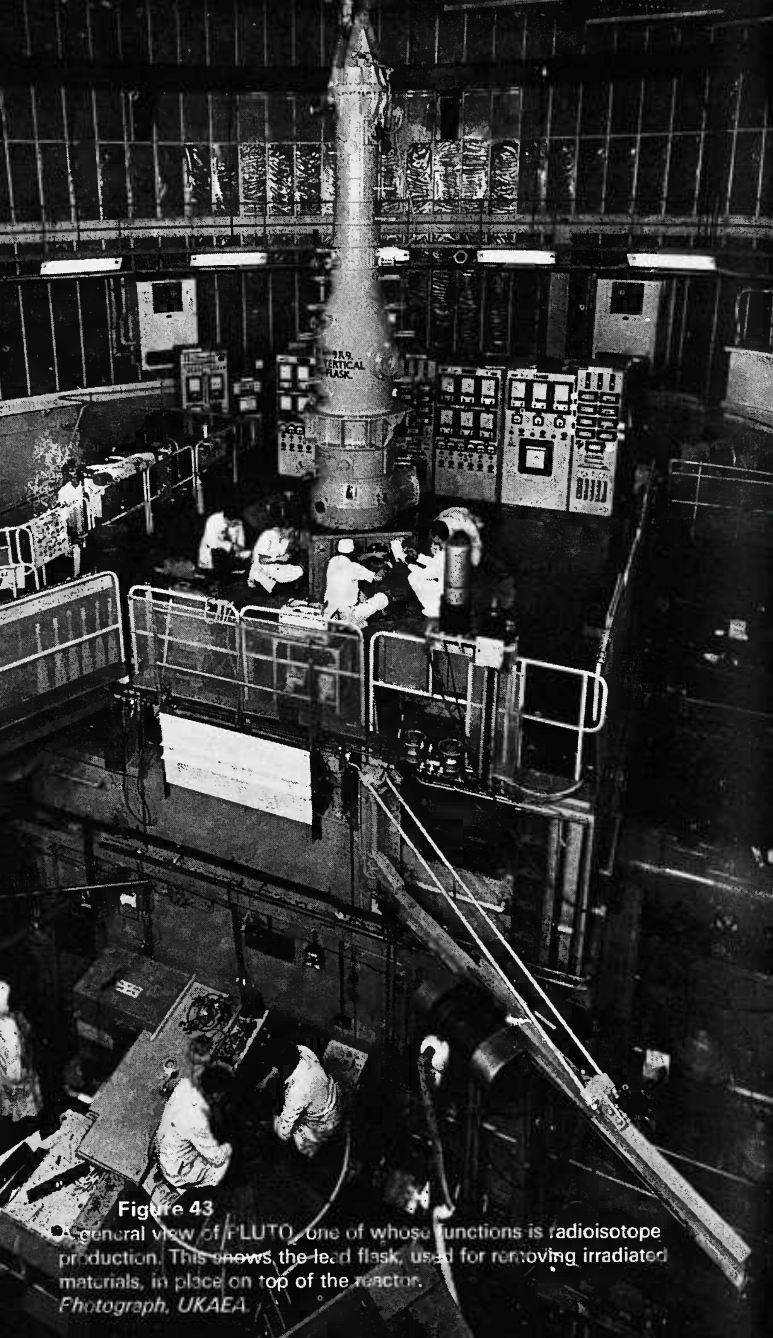
Suppose that you are an engineer studying the wear of piston rings in a high performance racing car engine. You could run the engine for several thousand miles, dismantle it, and measure the ring wear, then reassemble and repeat the test until you had all the data you needed. Taking an engine to pieces and putting it together again is a time-consuming business and you can never be absolutely sure that the reassembled engine is *exactly* the same in every detail as the one which started the test. How much better if the engine never had to be dismantled at all but, instead, you could simply change its oil at intervals and determine exactly how much of the metal particles in the oil came from the piston rings you were interested in.

Thanks to radioactive isotopes, engineers can now do just that. They can study wear in the most inaccessible places without dismantling machinery, and they can locate flaws in pipelines and welds thousands of miles from civilization where there are no sophisticated workshops, or even power supplies available to them. Thanks to radioactive isotopes, the neuro-surgeon can locate the exact position of a brain tumour before he opens his patient's skull; his colleagues can study the functioning of glands and other organs of the body and, in some cases, they can cure one of the most feared of all diseases, cancer.

This chapter is about radioactive isotopes and some of the uses to which they can be put.

## **How radioisotopes are used**

The uses of radioisotopes are of two main sorts. On the one hand, we can use a radioisotope as a miniature transmitting station, sending out radiation which, when suitably detected, reveals the whereabouts of the isotope. This is the basic idea behind 'tracer' techniques in which molecules are 'labelled' by having a radioisotope built in amongst their atoms, and are



**Figure 43**

● General view of PLUTO, one of whose functions is radioisotope production. This shows the lead flask, used for removing irradiated materials, in place on top of the reactor.

*Photograph, UKAEA.*

then sent off into inaccessible places, perhaps in the human body. The radiation which they emit tells us exactly where they are and enables us to follow their progress:

The second kind of use for radioisotopes exploits the properties of the radiations themselves. For example, the  $\gamma$ -radiation emitted by cobalt 60 is deadly to living organisms and can be used to kill them in sterilization plants. Also,  $\gamma$ -radiation is very penetrating and can pass through considerable thicknesses of steel or lead. This sort of property is useful, for example, in taking 'X-ray' photographs of metal articles. The less penetrating  $\beta$ -radiation can be used to measure the thickness of some materials, and even to determine whether a can of beer has been properly filled at the brewery! (See figure 53, page 119.)

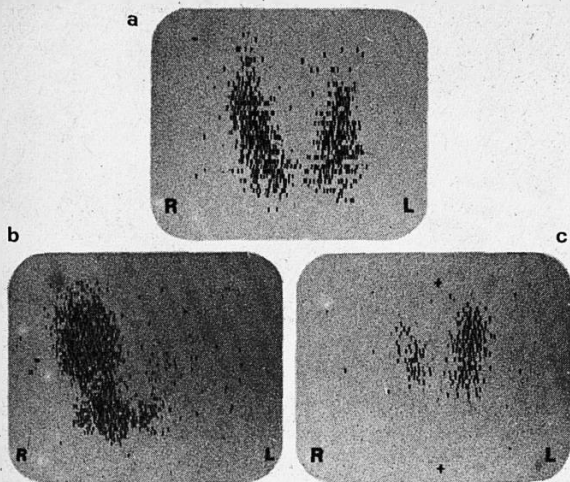
### **Labelled compounds**

Labelled compounds are used almost exclusively as tracers and many are valuable in biological, medical, and biochemical work. Molecules which play important roles in living organisms are compounds of carbon, hydrogen, nitrogen, oxygen, sulphur, phosphorus, and iodine. Thus it is the radioisotopes of these elements which are of particular interest; unfortunately, however, there are no radioisotopes of oxygen and nitrogen which have long enough half-lives for tracer studies. Carbon 14 and tritium (hydrogen 3) are undoubtedly the two most important radioisotopes for biological studies, since all biologically interesting molecules contain either carbon or hydrogen. Sometimes, a molecule can be labelled by biological methods of synthesis. A rather interesting example is called 'isotope farming'. A plant or micro-organism is fed on a diet which contains simple molecules labelled with radioisotopes. The plant or micro-organism then synthesizes complex molecules which have the radioisotope in them. Plants reared in an atmosphere containing  $\text{CO}_2$  labelled with carbon 14 have been used to synthesize cardiac glycosides, i.e. drugs which have an action on the heart. The same method has been employed to prepare labelled alkaloids, compounds of complex structure which find a variety of uses in medicine.

The thyroid gland, which is situated in the throat, secretes hormones, which are chemical substances that control some of the most important functions of the body. The hormone secreted by the thyroid gland is called thyroxine. Its functions are concerned with growth and mental development in childhood and with regulating the rate of metabolism in the adult. If the thyroid gland does not produce enough of its hormone in the child, he fails to develop properly and becomes what is known as a cretin. Cretins are stunted, mentally deficient people who had no future at all until the chemist succeeded in synthesizing thyroxine, which, when taken by mouth, cures the condition. In hitherto normal adults too, problems arise if the thyroid fails to function properly.

If it makes too little thyroxine the person becomes dull and lethargic as his bodily processes slow down. His face and hands become swollen and his condition is generally miserable. Once again, the administration of thyroxine can cure him. On the other hand, the thyroid gland may become overactive and produce too much thyroxine. When this occurs, the bodily mechanisms speed up, the person loses weight and is anxious and irritable, his eyeballs may begin to protrude, and he is in general far from well, and difficult to live with. The cure in such a case is often surgical, the output of the gland being reduced by taking some of its tissue away.

What has all this to do with radioisotopes? Simply that they have provided one of the most useful methods of assessing the level of activity of the thyroid gland and of examining it without operating on the patient. Thyroxine contains iodine atoms and if a person takes iodine by mouth, the element rapidly accumulates in the thyroid gland, where it is used to make thyroxine. In studying the thyroid the radioisotope iodine 131, a  $\beta$ ,  $\gamma$  emitter, is generally used, given as a dose of labelled sodium iodide. Some time later the amount of iodine 131 which has accumulated in the thyroid is estimated. This is done by detecting the radiation given off from the gland by means of a Geiger counter or a scintillation counter and comparing the result with those obtained from healthy glands. (Geiger counters are excellent



**Figure 44**

**a** A normal thyroid.

**b** One part of the thyroid has taken up nearly all the radioactivity. It is therefore overactive, a condition caused by a nodule in the gland.

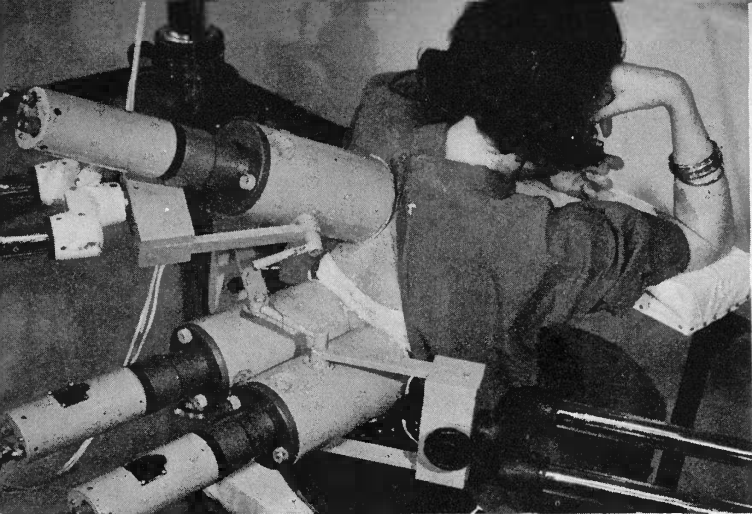
**c** An underactive thyroid condition.

*Photographs, UKAEA.*

for  $\beta$  particles, but scintillation counters are better for  $\gamma$ -rays.) In the technique known as 'scanning', a scintillation counter is moved over the patient's throat in a series of sweeps and its output depicted in black and white or colour by a suitable display system. This process builds up a picture of the gland showing where the iodine 131 has accumulated. Some tumours do not take up iodine and their presence is revealed on the scan by 'cold' areas, i.e. places in which no iodine 131 is present.

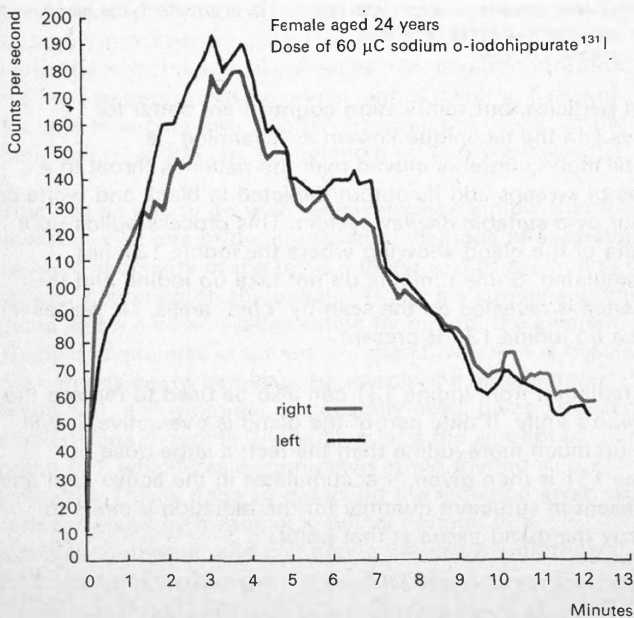
The radiation from iodine 131 can also be used to replace the surgeon's knife. If only part of the gland is overactive, it will take up much more iodine than the rest; a large dose of iodine 131 is then given. It accumulates in the active spot and is present in sufficient quantity for the radiation it emits to destroy the gland tissue at that point.

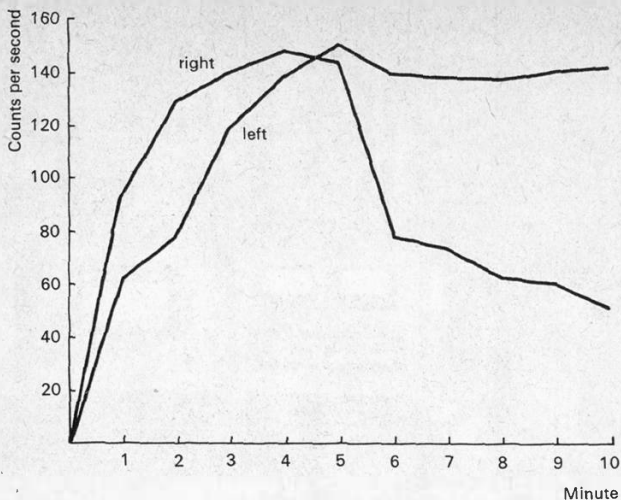




**Figure 45**

The counters in position, two over the kidneys and one over the heart.  
*Photograph, UKAEA.*





**Figure 47**

An abnormal renogram. Notice that the Hippuran is not dwindling away from the left kidney as it does from the right one. The kidney removes unwanted substances from the blood, forming urine which passes into the bladder via tubes called the ureters. This abnormal renogram indicates that urine is being dammed back into the left kidney and that the left ureter is blocked.

*By courtesy of the Director, The Radiochemical Centre, Amersham.*

Iodine 131, and also iodine 125, can be used to label molecules which pass through the kidneys. A substance known as Hippuran (sodium ortho-iodohippurate) is one such compound. To obtain information about renal (kidney) function, the patient is given an injection of labelled Hippuran directly into a vein. The passage of the Hippuran through the kidneys can be detected by placing scintillation counters over them, together with one over the heart to provide a reference count. Figure 45 shows the counters in position.

**Figure 46 (left)**

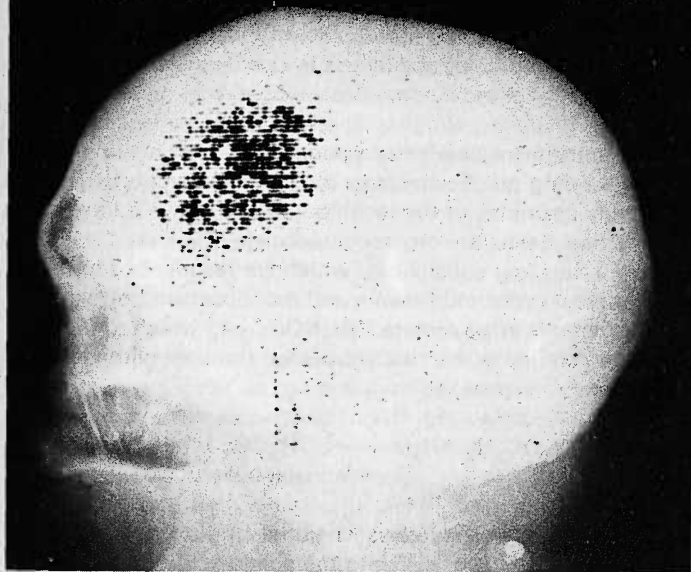
A normal renogram for a person with two healthy kidneys. Notice how the Hippuran builds up rapidly in each kidney and then dwindles away from each.

*By courtesy of the Director, The Radiochemical Centre, Amersham.*



**Figure 49**

Scan of a brain tumour, superimposed on an X-ray of the skull.  
*Photograph UKAEA, by courtesy of the National Hospital, London.*



### **Tracer studies in biology and chemistry**

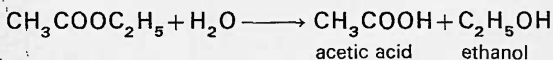
The biologist and the chemist make wide use of labelled compounds. One of the most useful radioisotopes for the biologist interested in agricultural problems is phosphorus 32. Plants need phosphorus as an element of their diet, and fertilizers which contain phosphorus in the form of phosphates are given to them. The total amount of phosphate which a plant takes up during its growth can be determined by chemical analysis but this will not tell us how much phosphate came from the soil and how much from the added fertilizer. However, using a fertilizer whose phosphate is labelled with phosphorus 32 solves this problem. Not only can the

**Figure 48**

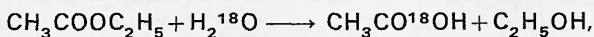
Radioisotope used for locating brain tumours. Scintillation counters placed over the skull, as shown here, detect the radiation emitted from the tumour and, by obtaining scans at right angles, the exact location of the tumour can be established. Such knowledge is of great value to the surgeon.  
*Photograph, UKAEA, by courtesy of St Bartholomew's Hospital, London.*

biologist determine which phosphate makes the best fertilizer for a particular plant but he can also find the times during its growth when the uptake of phosphate is highest. This information helps the farmer to decide just when to fertilize crops for maximum effect.

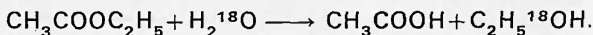
The chemist uses labelled compounds to assist him in understanding the mechanisms of chemical reactions. There are many examples of the technique. Let us have a look at a simple one. Esters are organic molecules, often pleasant-smelling substances, which are responsible for the fragrance of fruits and flowers and the 'bouquets' of wines. A typical ester is ethyl acetate,  $\text{CH}_3\text{COOC}_2\text{H}_5$  which, under suitable conditions, can be hydrolysed (reacted with water) as follows:



The problem to be solved is: where has the oxygen atom from the water molecule gone? Into the acetic acid or into the ethanol? The answer is obtained by using water labelled with the oxygen 18 isotope. (This isotope is not radioactive, which is cheating a little in an article about radioisotopes, but the reader may be prepared to overlook that since the example is a simple one to follow!) With  $\text{H}_2^{18}\text{O}$  we get either



or



The mass spectrometer is now used to examine the ethanol formed in the hydrolysis and shows that the oxygen 18 is present in it.

### Biological effects of radiation

The fact that radiation has biological effects has been known for a long time. In 1895, Emil Grubbe, a physicist working in America, developed dermatitis (skin inflammation) on his hands whilst studying cathode ray discharge tubes. Later that year, Professor Röntgen announced his discovery of X-rays

and Grubbe realized that such radiation could have been generated in his experiments and have caused his dermatitis. During the course of Madame Curie's work on the separation of uranium from its ores, Professor Becquerel borrowed from her a specimen of the radioactive material for a demonstration elsewhere in Paris. He put the phial in his waistcoat pocket and was surprised to find the next day that a red patch had developed on his skin beneath the phial. Many of the pioneer workers in the field of radioactivity received severe, and in some cases fatal, doses of radiation.

The biological effects of radiation are due to interactions of the radiations with the atoms and molecules of the body. Radiation contains a lot of energy and this is transferred to atoms and molecules as the radiation penetrates the tissues. As a result, ionization or break-up of molecules occurs. If the dose of radiation is sufficient, observable results are produced in the body, for example dermatitis leading to skin cancers, loss of hair, leukaemia (cancer of the blood), vomiting, haemorrhages, and diarrhoea. Effects like these are called 'somatic effects' and a combination of them occurs in radiation sickness which can follow a large dose of radiation and may lead to death.

Radiation also affects the body in a manner which cannot be seen in the individuals receiving the dose but which appears in their descendants. This 'genetic effect' is due to damage caused to the 'double helix' of DNA, the key molecule in the genes which determine an individual's characteristics.

All biological tissue is made up of cells which contain complex molecules, including DNA, suspended in a fluid which is principally water. At birth, the body of a baby contains about  $2 \times 10^{12}$  cells and this number has increased to about  $4 \times 10^{13}$  in an adult. Growth involves processes of cell division, a single cell dividing into two whose genetic characteristics are identical. If a cell is damaged by radiation, of such a kind that damage occurs to the DNA molecules, the faulty DNA is reproduced exactly when the cell divides, and continues to be reproduced as the body grows.

For this reason, radiation exposure is particularly dangerous to young people in whose bodies cell division is proceeding rapidly during their growth. At one time it was common practice to X-ray pregnant women to determine, for example, the position in which the foetus was lying in the uterus. Such X-rays are now taken only if they are absolutely essential for medical reasons. In the foetus, cell division is particularly rapid and serious genetic damage can be caused to the unborn child if it is exposed to X-rays during the early months of pregnancy.

In full grown adults cell division has slowed down but the reproductive organs, the testes and ovaries, need special protection from radiation. For example, the testes produce spermatozoa by processes involving cell division and if radiation damage occurs to cells involved in these processes, faulty genetic information will be continually reproduced.

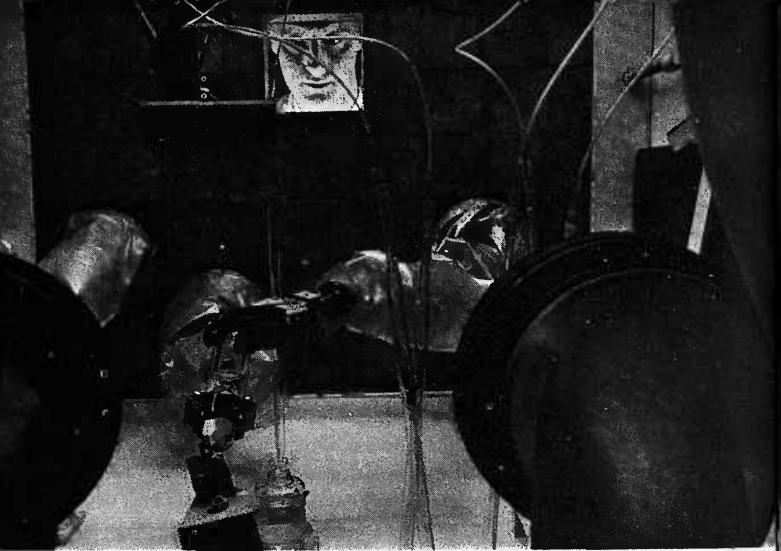
With a sufficiently high dose of radiation the reproductive power of a living organism can be destroyed. This has been used to good effect in the control of some insect pests. A particularly obnoxious insect, the American screw worm fly, has been virtually eliminated from the south western states of America by the use of radiation. The fly lays its eggs in wounds and sores of farm animals, and the larvae which hatch feed on the flesh of their hosts. When they are fully grown they drop off and pupate in the soil. The life cycle takes only four weeks so the pest spreads rapidly. In 1953, the U.S. Department of Agriculture discovered that screw worm pupae irradiated with  $\gamma$ -rays from cobalt 60 produced sterile male flies. Female screw worm flies (which mate only once) showed no preference for fertile males over sterile ones. Of course, mating with a sterile mate produced eggs that would not develop. Vast numbers of sterile males from  $\gamma$ -irradiated pupae were dropped from aircraft over the island of Curacao, then infested with screw worm fly. By 1955, not one case of screw worm infestation was recorded there. The technique is now widely used to control screw worm fly and experiments are going on in attempts to control other insect pests by similar methods.

All exposure to radiation produces biological damage and this is a generally accepted principle upon which health physicists concerned with the problems of radiation protection work. No matter what standards are set regarding minimum exposure risk is always involved, for it is necessary to balance the harmful effects on the individual or his children against the benefits of using radiation at all. The aim in radiation protection is to prevent all unnecessary exposure. There is, however, a dose of radiation which no one can avoid; this comes from the background radiation in nature to which we are all exposed. Background radiation arises from cosmic rays, and from the various naturally occurring radioisotopes that are distributed in the Earth's crust and atmosphere. Some background radiation comes from inside our bodies as a result of eating foods containing natural radioisotopes such as potassium 40.

### **Isotopes as radiation sources**

Radioisotopes have many uses in which the properties of the radiations they emit are employed. Before we begin to talk about some of them, however, it is necessary to explain the meaning of a term which we shall have occasion to use. The curie (Ci) is a unit which measures the activity of a radioisotope. When a radioisotope has a disintegration rate of  $37 \times 10^9$  per second, it is said to have an activity of one curie. The disintegration rate of a radioisotope depends upon its half-life; thus  $2 \times 10^{-5}$  kg of strontium 90 (half-life = 28 years) has an activity of one curie, whilst more than  $10^3$  kg of uranium (half-life =  $4.5 \times 10^9$  years) is required to give the same activity. Care is always necessary when using radioisotopes because the radiation they emit can interact with living cells and produce changes in their natural functioning. The danger increases with the energy of the radiation so that  $\gamma$ -emitters need particular care. Protection by shielding the source from the operator is comparatively simple for  $\beta$  particles. Even in air, their range is limited, being about 1 metre for 0.5 MeV particles and 10 metres for particles of 3 MeV. In dense materials, their ranges are much shorter, but the absorption of high energy  $\beta$  particles in matter can give rise to what is known as *Bremsstrahlung* (from the German





**Figure 50**

A plant for processing multicurie quantities of  $\beta$ -emitting isotopes (mainly strontium 90): a rear view of the dispensing section.

*Photograph, UKAEA.*

*bremsen*, to brake, and *Strahl*, a stream). When electrons penetrate matter they are slowed down by electrostatic interaction with the nuclei of atoms. Bremsstrahlung is radiation produced during this slowing down process and it is often more penetrating than the  $\beta$ -radiation which produced it. For efficient  $\beta$ -shielding, materials are used which do not produce much Bremsstrahlung. Such materials are of low atomic number, i.e. of low nuclear charge. Aluminium, Perspex, and thick rubber are employed; Perspex 6 mm thick will absorb  $\beta$  particles up to 1 MeV in energy, whilst 25 mm absorbs all up to 4 MeV energy. Shielding against  $\gamma$ -radiation is much more difficult. Unlike charged particles  $\gamma$ -radiation is not completely absorbed by any material, however thick. Instead, the intensity of the radiation is progressively reduced by shielding until it reaches a level safe for those working with it. Concrete, iron, and lead are commonly used as  $\gamma$ -radiation shields.

Workers using radioisotopes are given constant checks to make sure that they do not receive an excessive dose of radiation. For recording the dose received the most widely used device is the film badge, which is a piece of photographic film in a special holder, attached to the worker's clothing. The films are collected at suitable intervals for processing and the amount of blackening is used to estimate the dose received.

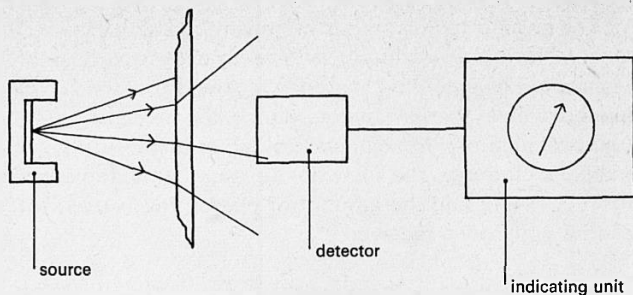
There is one final problem, and it is a very big one, concerned with radioisotopes. This is the problem of their disposal after use. To take an example, in a moderate-sized hospital department, hundreds of millicuries of short-lived radioisotopes may be administered daily. As much as 30 per cent of this may find its way into liquid waste products which must be disposed of. Obviously it cannot be allowed into the natural sewage system without some preliminary storage to allow some decay. This is not the place to go into the various methods which have been devised to eliminate the danger of contaminating our environment by radioactive materials, but a great deal of effort is made on an international scale to cope with this growing problem.

Now let us turn to some of the industrial uses of the radiation from radioisotopes.

### **Thickness gauges**

Radioisotope gauges are used for measuring the thickness of things ranging from electroplated layers and paint films to steel sheet for car body manufacture. The property of the radiation which is being exploited in such applications is its ability to penetrate matter. Beta particle sources are commonly used for this work, provided that the material is not too thick, say, up to 1.5 mm of iron or 4.5 mm of aluminium. For thicker materials,  $\gamma$ -sources must be used and these can cope with thicknesses of iron up to 0.1 m.

The advantage of radioisotope thickness gauges is that no contact with the material is required and they can be used on



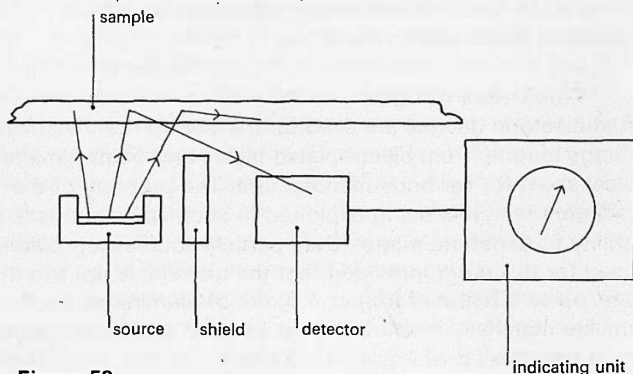
**Figure 51**

Schematic transmission thickness gauge.

*By courtesy of UKAEA.*

continuously produced material which may be passing under the gauge at high speed. This lack of contact is also very valuable if the material is at a high temperature, if it is soft, or if it has a good surface finish which would be scratched by contact gauges.

Another method, which is used to measure surface coatings, relies on backscattering of radiation. The amount of backscattering depends on the thickness of the surface coat.



**Figure 52**

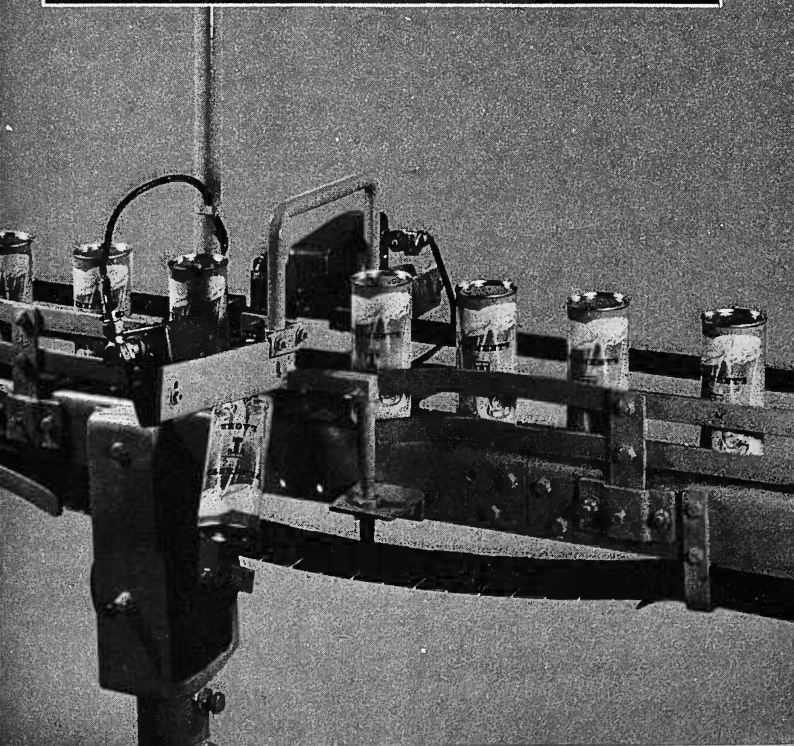
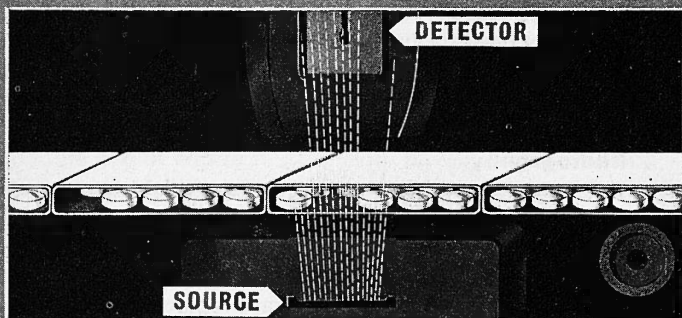
Schematic backscattering thickness gauge.

*By courtesy of UKAEA.*

**Figure 53**

The diagram (inset) shows how radioisotopes are used to check the fullness of packages. Radiation from an appropriate radioisotope source will be absorbed by the contents. If enough radiation passes through to a detector this means that a package is not full enough. In the photograph, radiation has activated a device causing the faulty product (a can of beer) to be rejected.

*Photographs, UKAEA*

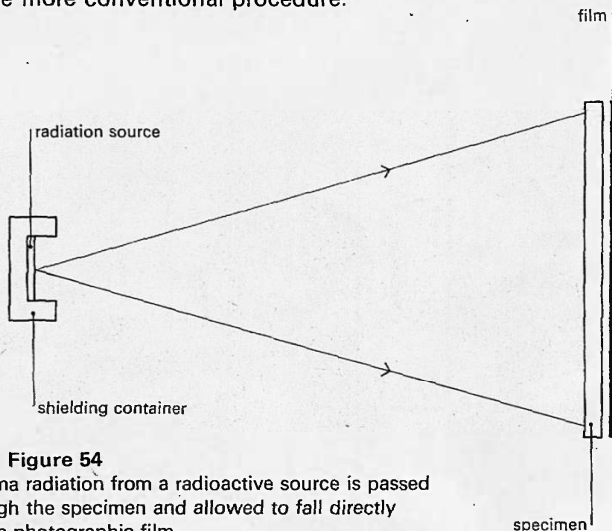


Closely allied to the use of radioisotopes in thickness gauging is a method of checking whether packages have been properly filled. If a package passing over the source is only partly full, sufficient radiation reaches the detector to provide an electrical signal that activates a device which throws the faulty product off the production line. (See figure 53.)

The same principle can be used to check the level of liquids in sealed storage vessels, for example to check whether liquid  $\text{CO}_2$  cylinders used for fire-fighting are full or not. A gamma source is used because of the thickness of the walls of vessels used to hold liquefied gases.

### Radiography

X-rays have been used for many years as a reliable means of inspecting the interiors of solid objects such as castings, mouldings, and, of course, human beings. Radioisotopes emitting  $\gamma$ -radiation are being increasingly used for radiography of metal objects, the  $\gamma$ -rays replacing the X-rays in the more conventional procedure.



**Figure 54**

Gamma radiation from a radioactive source is passed through the specimen and allowed to fall directly onto a photographic film.

*By courtesy of UKAEA.*

A gamma source of about  $10^3$  curies would be needed to give an output equal to that of an industrial X-ray machine. In practice, sources of between 0.5 to 200 curies are used so that exposure times are relatively long compared to X-ray machines. This is not often a serious disadvantage in many applications however. The radioisotopes cobalt 60, caesium 137, iridium 192, and thallium 170 are used as gamma sources.

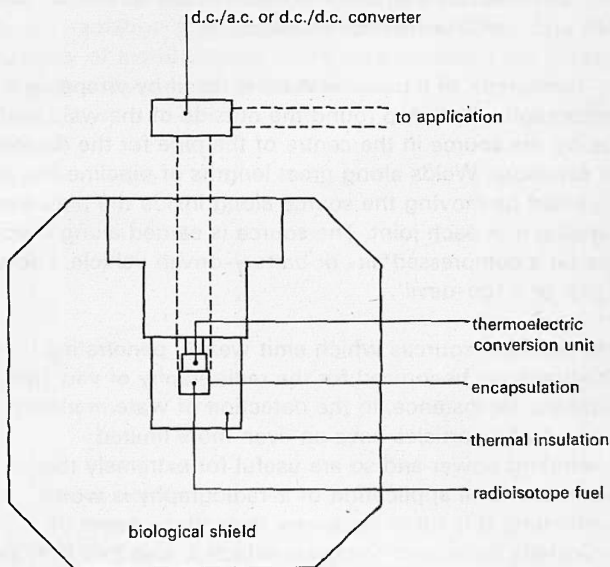
There are several kinds of situations in which it is more convenient to use radioisotopes in preference to X-ray machines. Inspection of welds between pipeline sections out in the desert is one example. The  $\gamma$ -ray source is light and portable and of course it requires no power supplies. Owing to its small size, it is often possible to place the radioisotope source in a position where an X-ray machine could not go. Such sources can also be used under water to inspect ships' hulls and welds in harbour installations.

A  $\gamma$ -radiograph of a pipeline weld is taken by wrapping a photographic film strip round the outside of the weld and placing the source in the centre of the pipe for the duration of the exposure. Welds along great lengths of pipeline can be inspected by moving the source along inside the pipe and stopping it at each joint. The source is carried along inside the pipe on a compressed air- or battery-driven vehicle, known as a 'pig' or a 'go-devil'.

Beta radiation sources which emit weakly penetrating radiation have been used for the radiography of very thin materials, for instance, in the detection of watermarks in paper. Alpha particles have an even more limited penetrating power and so are useful for extremely thin specimens. One application of  $\alpha$ -radiography is worth mentioning. It is often necessary to produce paper of particularly consistent thickness which is also free from pin holes or other blemishes. Such quality paper is, for example, required in the manufacture of paper-dielectric capacitors. Alpha radiography of such paper shows up flaws and deviations from standard thickness very easily.

## Energy from radioisotopes

When the radiation emitted by a radioisotope is absorbed by material, the material becomes warm. The temperature difference can be used to generate electrical energy. There is an increasing demand for radioisotope-powered generators for space satellites and for terrestrial use in remote places. Such generators, using sources of about 500 curies, have been used to power marine navigation lights on buoys, remote weather station installations, submarine cable repeater amplifiers, and land-based navigation lights. They have a life of about ten years, during which they require no maintenance, and this factor helps to offset the cost of the device. About a dozen radioisotopes are suitable as heat sources; strontium 90 and caesium 137 being two that are often used. The power available from such generators is usually low, perhaps about 50 watts.

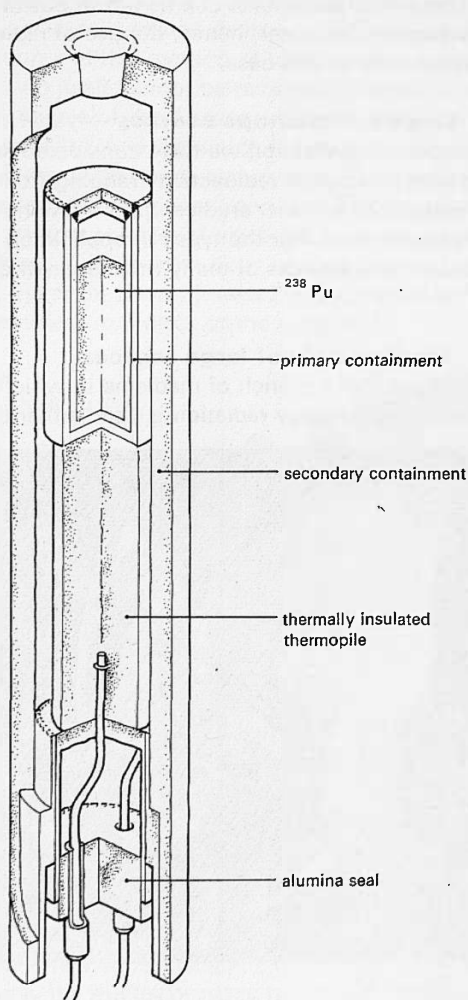


**Figure 55**

Radioisotope powered thermoelectric generator.

*By courtesy of UKAEA.*

Radioisotope units have also been used to power cardiac pacemakers. In some heart diseases, the electrical impulses from the nervous system which regulate the beating of the



**Figure 56**

Isotope battery (approximate size  $45 \times 15$  mm).  
By courtesy of UKAEA.



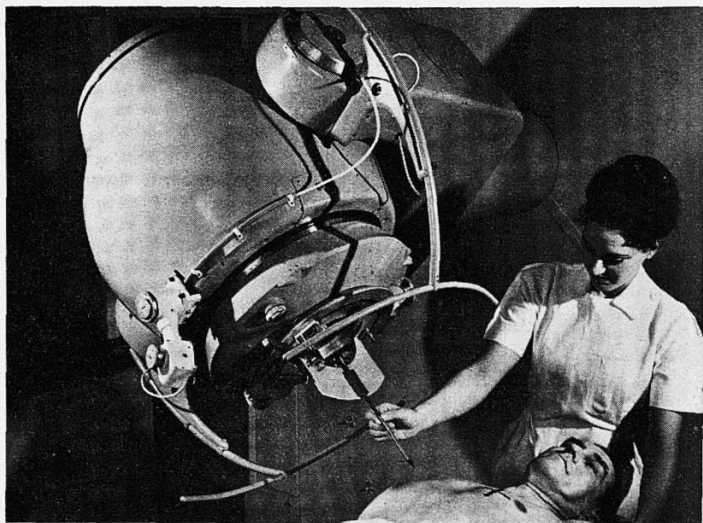
heart are faulty. A pacemaker is an artificial source of electrical pulses and such a device can be placed inside a patient's body to take over from his own pacemaking system. The longer the pacemaker can be left in position without maintenance the better; hence, the use of radioisotope-powered units in this case.

### **Large radioisotope sources**

The types of application we have considered so far have employed sources of radioactivity ranging from micro- or millicurie sizes in tracer studies up to a few hundred curies in power generators. For the types of application we are going to consider now, sources of many thousands of curies are called for.

### **Medical uses of large sources**

Radiotherapy is a branch of medicine in which the destructive power of high energy radiation is used either to destroy or to



**Figure 57**

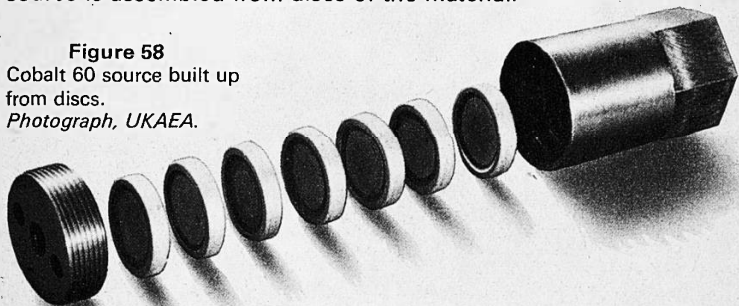
Arranging the pointer of a 5000-curie radiocobalt unit to ensure that the beam of radiation is accurately directed to a tumour in the patient's lung.  
*Photograph, UKAEA. By courtesy of the Hammersmith Hospital, London.*

control the growth of unwanted tissue, such as a cancer. A cancer is made up of normal body cells that have somehow 'gone wrong'. Their internal chemistry is deranged and they grow in an uncontrolled fashion, producing a mass of tissue; the cancer. Cancer cells can be destroyed by exposing them to X- or  $\gamma$ -radiation and this method of treatment is used either when the growth itself cannot be removed by surgical means or in the early stages of the disease when the cancer is small. It is often possible to cure this much feared disease today, especially if it is detected in its early stages. Cobalt 60 gamma sources of up to 6000 curies are used in radiotherapy and caesium 137 gamma sources of up to 2000 curies are in use. Large sources are built up from discs or rods of the radioisotope; figure 58 shows how a 2000-curie cobalt 60 source is assembled from discs of the material.

**Figure 58**

Cobalt 60 source built up from discs.

*Photograph, UKAEA.*



Sometimes, radiotherapy is carried out internally, either by inserting needles containing the radioisotope (usually radium) into the tumour or by implanting a 'seed' of radioisotope in the tissue which is to be destroyed. Millicuries of radioisotopes are needed in such procedures.

Even bigger sources of radioisotopes than those already mentioned are used in industrial processes. One such process, which is related to medicine, is the bulk sterilization of articles. Today the doctor or nurse rarely has to sterilize a syringe and needle before giving an injection. The syringes themselves are made of plastic rather than glass and are



sealed up together with the needle in individual paper packs. Thousands of these packs at a time are exposed to gamma radiation from cobalt 60 sources, which kills all bacteria in them. Once the pack has been opened and the sterile syringe and needle have been used, they are thrown away and a new pack awaits the next patient. The United Kingdom Atomic Energy Authorities' package irradiation plant at Wantage has a cobalt 60 source of 500 000 curies. This is large but it begins to look quite small when compared to the 2 000 000 curie unit used for bulk sterilization in Victoria, Australia.

All manner of things are sterilized by gamma irradiation: bandages, dressings, surgical sutures, scalpel blades, and, of course, the packs in which such things are despatched to their users. Provided that the food itself is not damaged by the irradiation, pre-packed foods can be sealed in plastic containers and treated in sterilization plants to destroy decay-producing bacteria.

High energy radiation sources are used in the manufacture of a novel material, the wood-plastic composite. Wood is first impregnated with a chemical, the monomer, which on exposure to  $\gamma$ -radiation polymerizes and completely fills the natural pore structure of the wood with an inert plastic. Wood treated in this way no longer shrinks or expands with changes in atmospheric conditions, and it is resistant to decay and to attack by fungi or insects. The material can take a high gloss finish which enhances the natural beauty of the wood so that it can be used for decorative, as well as functional purposes.

It is the penetrating power of the  $\gamma$ -radiation which makes the manufacture of wood-plastic composites feasible. The radiation penetrates right to the heart of the wood, so ensuring that the polymerization process occurs throughout the material.

#### **Figure 59**

A surgeon placing a seed of yttrium 90 into the pituitary gland of a patient through an incision in the upper part of the nose.

*Photograph, UKAEA. By courtesy of the Hammersmith Hospital, London.*

# Reading references

## Notes on references

**1** *Classical scientific papers (physics)* (1964) Mills & Boon. This book gives facsimile reproductions of famous scientific papers in 'modern' physics.

**1A** Paper 2: Rutherford, E. (1903) 'The magnetic and electric deviation of the easily absorbed rays from radium.' *Philosophical magazine*, (6), 5, 177–87.

The main object of your reading could well be to understand from the diagrams the special methods that Rutherford used to detect the small deflections.

Magnetic fields are given in c.g.s. units. Multiply by  $10^{-4}$  to obtain the field in the SI unit ( $\text{N A}^{-1} \text{m}^{-1}$  or tesla).

The 'activity 19,000' on the second page is probably a figure comparing the activity of the radium with that of some fixed amount of uranium.

**1B** Paper 4: Rutherford, E. and Royds, T. (1909) 'The nature of the alpha particle from radioactive substances.' *Philosophical magazine*, (6) 17, 281–6.

This is a facsimile of the original report, in which it was described how alpha particles were collected and how the spectrum formed by passing a discharge through the gas showed that helium had been formed.

The details of the construction and evacuation of the apparatus are of interest. The exhaustion was 'completed with the aid of the charcoal tube cooled by liquid air' because charcoal has the property of being able to absorb a large amount of gas, particularly when cold. The charcoal can be 're-activated' by heating.

This paper is also a good example of the thoroughness with which an experiment can be performed in order to forestall objections that the results could be explained in other ways.

This is identical to reference 5.

**1C** Paper 20: Wilson, C. T. R. (1912) 'On an expansion apparatus for making visible the tracks of ionizing particles in gases and some results obtained by its use.' *Proc. R. Soc., A*, 87, 277–92.

A description is given of the construction and working of Wilson's first expansion cloud chamber including such things as opening a valve by allowing a weight to fall. Probably the most useful part of this paper is the latter half in which tracks produced by alpha, beta, and gamma rays are described and discussed.

**1D** Paper 8: Geiger, H. and Marsden, E. (1909) 'On a diffuse reflection of the alpha particles.' *Proc. R. Soc., A*, **82**, 495–500.

This is an account of the experiment which first showed that alpha particles could be deflected through large angles. Three factors are investigated:

- 1** The relative amount of reflection from different metals.
- 2** The relative amount of reflection from a metal of varying thickness. The amount increases with thickness up to a certain maximum, indicating that it is not a surface phenomenon.
- 3** The fraction of the incident alpha particles which are reflected. It was shown that only about 1 in 8000 of the incident particles were reflected through an angle of  $90^\circ$ , for platinum and, indirectly, for gold.

This account is identical to the one given in reference 2B.

**1E** Paper 10: Geiger, H. and Marsden, E. (1913) 'The laws of deflexion of alpha particles through large angles.' *Philosophical magazine*, (6), **27**, 604–23.

This is a description of the experiment which set out to test the theory which Rutherford had proposed to explain the diffuse reflection of alpha particles. Five points were investigated concerning the number of deflected alpha particles:

- 1** Variation with angle – should be proportional to  $\text{cosec}^4(\phi/2)$ .
- 2** Variation with thickness of scattering material – should be proportional to the thickness  $t$  provided  $t$  is small.
- 3** Variation with atomic weight of scattering material (this was assuming the magnitude of the central charge of the atom was proportional to the atomic weight) – the variation should be proportional to the square of the central charge.
- 4** Variation with velocity  $u$  of incident alpha particles – should be proportional to  $1/u^4$ .
- 5** The fraction of particles scattered through a definite angle. From this it is possible to calculate the magnitude of the central charge on the scattering atoms.

The first four of the above points completely verified Rutherford's theory. Because of the small fraction of alpha particles which were scattered, the fifth point mentioned above was not satisfactorily covered and gave values which were probably correct to 20 per cent. Chadwick's improvement of this experiment is given in reference 2C. Chadwick's error was estimated to lie between 1 and 2 per cent.

**1F** Paper 12: Rutherford, E. (1914) 'The structure of the atom.' *Philosophical magazine*, (6), 27, 488–98.

Paper 13: Rutherford, E. (1920) 'Nuclear constitution of atoms.' *Proc. R. Soc. A*, 97, 374–400 (first 6 pages only).

The first part of this is identical to reference 2D. The second part is similar but is dated six years later and only the first six pages need be read.

**2** Conn, G. K. T. and Turner, H. D. (1965) *The evolution of the nuclear atom*. Iliffe.

This book tells the story of the evolution of the nuclear atom in the words of those who carried out each phase of the work, with a connecting narrative by Conn and Turner.

**2A** Chapter 4, 'Theories of atomic structure (1897–1907).'

Following on from the discovery of the electron this chapter presents the various models which were proposed (not including the Rutherford-Bohr model) to try to fit the electron into the atom. The main message is that serious work was done on such models as Thomson's 'plum pudding' and that the models do go some way towards accounting for observable phenomena.

The reading will have to be fairly selective because such things as the Zeeman effect are mentioned which you will probably not have met before and the mathematics in places is rather fierce. If you skip the bits you don't understand, you will still gain something of value.

**2B** Chapter 5, 'The atomic nucleus.'

This chapter deals in some detail, descriptive and mathematical, with the alpha particle scattering events which led to Rutherford's nuclear atom. The start is reasonably easy and includes a reproduction in full of Geiger's and Marsden's paper, 'On a diffuse reflection of the alpha particles', which started the sequence of events.

Rutherford's interpretation of the results follows and since it is mainly mathematical and difficult to follow it could be omitted except for a summary of the consequences which is given on page 142. The latter part of the chapter from page 146 is easier to understand and it deals in detail with the confirmation by Geiger and Marsden of Rutherford's theory. Geiger's and Marsden's paper is also reprinted in reference 1D.

**2C** Chapter 6, 'Atomic electrons and the charge on the nucleus.'

You will find it hard to follow the detailed evidence quoted, and you should give up if it is too hard. But you may be able to get a general sense of the kinds of evidence which were found to support the view that an atom had as many charges on its nucleus as its number in the Periodic Table.

More detail is given than is needed for the physics course of Chadwick's determination of the nuclear charge, an account of which starts on page 202. Chadwick used the equation derived by Rutherford, which is quoted, with definitions of the various symbols, on page 205. Chadwick used a scattering foil in the shape of a washer (an annular ring) to increase the number of particles detected. The mathematics associated with this is given and need not be followed. The final equation (page 207) is very simple. Results for platinum, silver, and copper are given on pages 210 and 211 and these are important. There may be some confusion because the symbol  $N$  is used for atomic number (as explained on page 204) and the symbol  $Z$  is used to denote the number of alpha particles counted.

## **2D** Chapter 6, as in reference 2C, starting on page 192.

There is a summary, given by Rutherford in 1914, of the development of the 'nucleus theory' of atomic constitution to that time. It ends on page 202 and is identical to the first part of reference 1F.

## **3** Romer, A. (ed.) (1964) *The discovery of radioactivity and transmutation*. Dover.

This is a collection of original papers about radioactivity together with commentary and clarifying notes by the editor.

### **3A** Paper 2: Becquerel H. (1896) 'On the invisible radiations emitted by phosphorescent substances.' *Comptes rendus*, Paris, **122**, 501–503.

Paper 3: Becquerel, H. (1896) 'On the invisible radiations emitted by salts of uranium.' *Comptes rendus*, Paris, **122**, 689–694.

These are two of the early papers written by Becquerel concerning his discovery of radioactivity. They are easy to read, non-mathematical, and record his failures and errors as well as his successes.

A 'lamella' is a thin sheet, and a 'Leyden jar' was used for storing electric charge in exactly the same way that capacitors do today.

### **3B** Paper 11: Rutherford, E. and Soddy, F. (1902) 'The radioactivity of thorium compounds. II. The cause and nature of radioactivity.' *J. Chem. Soc., Transactions*, **81**, 837–860.

Only parts I, II, and V of this rather long paper need be read. Parts III and IV may be of interest to chemists.

The paper is mainly about thorium and a radioactive constituent of thorium which was called thorium X because, at the time, nobody knew what it was. It is, in fact, an isotope of radium ( $^{224}\text{Ra}$ ) which is formed as thorium decays. Part I gives the scope of the paper. Part II describes how thorium and ThX are separated and presents results which show how the thorium regains its activity as it reforms more ThX, and how the separated ThX decays. If you can, you should check the decay curves which are given and see if they are exponential.



Part V describes how attempts were made (unsuccessfully) to influence the decay of ThX and the recovery of thorium.

**3C** Paper 13: Rutherford E. and Soddy, F. (1903) 'Radioactive change.' *Philosophical magazine*, (6), 5, 576–591.

It may be best only to read paragraph 7, page 163, which contains order of magnitude calculations of the energy of radioactive changes. This paragraph is also quoted in this *Students' book*, in the section entitled 'Radioactivity and the nuclear atom' (page 78).

The units are not the same as our SI system.

$$v = 2.5 \times 10^9 = 2.5 \times 10^7 \text{ m s}^{-1}$$

$$e/m = 6 \times 10^3 = 6 \times 10^7 \text{ C kg}^{-1}$$

$$e = 6 \times 10^{-10} \text{ electrostatic units} = 2 \times 10^{-19} \text{ C}$$

$$\text{energy } 10^{-5} \text{ erg} = 10^{-12} \text{ J}$$

$$10^{15} \text{ ergs} = 2.4 \times 10^7 \text{ gramme calories} = 10^8 \text{ J}$$

$$1 \text{ gramme calorie} = 4.2 \text{ J}$$

At the bottom of page 164 current and charge are in 'electromagnetic units'. Multiply by 10 to obtain data in amperes or coulombs.

**3D** Paper 14: Curie, P. and Laborde, A. (1903) 'On the heat spontaneously released by the salts of radium.' *Comptes rendus*, Paris, 136, 673–675.

This should be read in conjunction with paragraph 7 of the paper mentioned in the previous reference, 3C. An experiment is described to measure the heat given out by radium. You should compare the result obtained with that deduced by Rutherford and Soddy (reported in reference 3C). The necessary conversion factors are given in the note about reference 3C. The 'small calorie' mentioned by Curie and Laborde is the gramme calorie (as opposed to the large calorie which is the kilogramme calorie). It equals 4.2 joules.

**4** Project Physics (1971) Reader, Unit 5 *Models of the atom*. Holt, Rinehart & Winston, New York.

This reader contains a number of articles to interest those who want to see the study of atoms in a larger perspective, or who would like to know more about the people involved. See particularly Feynman, 'Looking for a new law', to get ideas about how new ideas are born. A comparison of the discoveries Feynman discusses with what you know of the discovery of the nuclear atom would be useful. See also Guillemin, 'Ideas and theories', and Hoffmann, 'The new landscape of science', for anticipations of the ideas of wave mechanics (discussed in the Nuffield course in Unit 10).

**5** Project Physics (1971) Reader, Unit 6 *The nucleus*. Holt, Rinehart & Winston, New York.

Rutherford, E. and Royds, T. 'The nature of the alpha particle from radioactive substances.'

This is identical to reference 1B.

**6** Gentner, W., Maier-Leibnitz, H., and Bothe, W. (1954) *Ab atlas of typical expansion chamber photographs*. (School edition.) Pergamon.

Look especially at figures 5, 10, 12, 14, 15, and 28–32, and read the commentary on each.

**7** Arons, A. B. (1965) *Development of concepts of physics*. Addison-Wesley.

**7A** Chapter 32, 'Radioactivity.'

This is very similar to reference 10A but gives slightly more detail and rather more quotations from the people involved in the original work. The chapter is easy to read as far as section 9 when the rate of decay of a radioactive substance is discussed. Section 9 will only be easy if you are familiar with the differential calculus.

Sections 10 and 11 will probably be too difficult mathematically but they are nevertheless important and you should have a look at them to see if anything is familiar. Section 12 is easier and you should pick your way through it, concentrating on the discussion about half-life.

The last section of the chapter is a comment about how the nature of physics was changing in the nineteenth century, and it is worth reading.

**7B** Chapter 33, 'Physics of atoms: the nuclear model.' Sections 9–15.

This bit of reading starts with a simple calculation of the size of a water molecule using a knowledge of density, the mole, and the Avogadro constant – very similar to that done in Unit 1 with copper. A discussion of Thomson's 'plum pudding' atom then follows before the chapter goes on to give an account of the alpha particle scattering experiments which established the existence of a small, massive nucleus. At the start of this there is a calculation using energy which leads to a value for the size of a nucleus. You know the equations which are used and you could do the calculation yourself.

Rutherford's theory of atomic structure as a result of Geiger's and Marsden's first scattering experiment is explained, and then it is shown how their second experiment tested this theory.

8 Bennet, G. A. G. (1968) *Electricity and modern physics*. (MKS version.) Edward Arnold. Chapter 16, 'Nuclear physics'.

This chapter starts by presenting in a direct textbook fashion a brief account of the discovery of radioactivity and the identification of the three types of radiation. It has a useful section on safety precautions and one on detecting instruments. The nucleus is dealt with very quickly and more time is given to nuclear transformations and radioactive decay, when a bit about isotopes and radioactive dating is included. The last part of the chapter from page 311 onwards deals with the nucleus in more detail and may be omitted.

The experiments with a pulse electrometer which are mentioned at the beginning of the chapter can be done with an electrometer if there is time. There is some useful information on the operation of a Geiger-Müller tube on page 290.

The work on statistical fluctuations and on beta and gamma absorption curves and the inverse square law is worth reading but there will probably not be an opportunity for doing many of the experiments which are suggested. Pages 294–311 contain the main parts of this chapter for our purposes and involve the identification of radioactive particles, a short section on the discovery of the nucleus, and work on radioactive decay.

There are some very good cloud and bubble chamber photographs.

9 Caro, D. E., McDonell, J. A., and Spicer, B. M. (1962) *Modern physics*. Edward Arnold.

9A Chapter 5, 'The discovery of radioactivity.'

A historical approach to the discovery of radioactivity and the detection and properties of  $\alpha$ ,  $\beta$ , and  $\gamma$  rays. It includes a description of Rutherford's magnetic deflection of  $\alpha$  particles and also his electric deflection of  $\alpha$  particles. These experiments show that  $\alpha$  particles are emitted in groups which have a single, well-defined energy and they also enable the velocity and specific charge ( $q/M$ ) to be found. Rutherford's and Royds's identification of  $\alpha$  particles is described.

The spread of energies of  $\beta$  particles is mentioned and so also is the relativistic variation of mass with velocity.

Radioactive decay and transformation involve the exponential and half-life. If you find the mathematics too difficult, then omit this bit. Reference 8 is very similar but the mathematics is easier.

## **9B Chapter 11, 'Detectors of nuclear radiations.'**

This chapter discusses the ionization chamber, the GM counter, the scintillation counter and photomultiplier tube, the Wilson cloud chamber, the diffusion cloud chamber, and the bubble chamber, and adds a little on photographic emulsions and on the detection of neutrons.

## **9C Chapter 1, 'Growth of atomic concepts.'**

Summarizes the rise of atomic theory in chemistry – mainly Dalton and Avogadro, and in physics – mainly kinetic theory. Does not get involved in the structure of the atom.

## **9D Chapter 8, 'The electric charges in atoms.'**

This is mainly about the alpha particle scattering experiment. It sets out Rutherford's conclusions as a result of assuming an inverse square law of repulsion from a positively charged nucleus, and describes Geiger's and Marsden's test of Rutherford's hypothesis.

## **10 Holton, G. and Roller, D. H. D. (1958) *Foundations of modern physical science*. Addison-Wesley.**

### **Chapter 36, 'Radioactivity.'**

A brief account is given of Becquerel's discovery of radioactivity and of the work of the Curies in discovering polonium and radium. The nature of alpha, beta, and gamma rays is discussed. Don't worry about the little bit of mathematics concerned with the bending of charged particles in a magnetic field. (You will be dealing with this problem later and you may also have done it at O-level. When we deal with it later we will use the symbol  $B$  for the effect of the magnetic field instead of  $\mu_0 H$  which is used in this book.) For the moment, just get the general sense.

The way in which radioactive decay causes one substance to change into another is explained and this also includes an important piece of mathematics which deals with the rate at which substances decay. This is quite well explained and you should read through it carefully.

## **10B Chapter 34, 'The atomic model of Rutherford and Bohr.'**

This presents in a non-mathematical way the essential points of the alpha particle scattering experiment which established the existence of the atomic nucleus. It includes a discussion about the charge on the nucleus and about the size of the nucleus.

There is no need to go beyond page 620 into the solution proposed by Bohr of how to fit electrons into atoms which contain a small positively charged nucleus.

**11** Project Physics (1971) Text, Unit 5. *Models of the atom*. Holt, Rinehart & Winston, New York.

**11A** *Prologue*: 'The major purpose of the prologue is to develop the story of atomic theory from antiquity to the early years of the nineteenth century.' It briefly summarizes the ideas of the Greeks, the work of the alchemists, and the ideas of the eighteenth and early nineteenth century chemists. The prologue ends by referring to the chapters which are to follow and which develop in more detail the later ideas about atomic theory.

**11B** Chapter 19, section 19.3 on Rutherford's nuclear model of the atom and 19.4 on nuclear charge and size.

These deal with the alpha scattering experiment on the same lines as reference 9D. They enlarge on the significance of the atomic number and mention the work of Moseley and X-ray spectra. You need not follow the latter closely. A final paragraph summarizes some of the deficiencies of the Rutherford model.

The brief discussion of the Thomson model at the end of Chapter 18 may be of interest.

**12** Project Physics (1971) Text, Unit 6 *The nucleus*. Holt, Rinehart & Winston, New York.  
Chapter 21, 'Radioactivity.'

Very similar to reference 9A, but is a little more detailed about the early history and contains some reference to applications. The idea of decay and half-life is developed.

**13** PSSC (1965) *Physics*. Second edition. Heath.  
Chapter 32, 'Exploring the atom.'

This reference is fairly mathematical. A historical approach is not used. Rutherford's theory of the nuclear atom is stated, together with a Coulomb force of repulsion between alpha particles and nuclei. A 'hill' which simulates a  $1/r^2$  law of repulsion is described and the results from this hill are shown to agree with those from Geiger's and Marsden's experiment. Information about the dependence of the angle of scatter on  $Z^2$  is quoted and also the variation of angle of scatter with energy of the alpha particles. Reference 14 is identical.

**14** PSSC (1968) *College physics*. Raytheon.  
Chapter 26, 'The Rutherford atom.'

This is identical to reference 13.

**15** Rogers, E. M. (1960) *Physics for the inquiring mind*. Oxford University Press.

**15A** Chapter 39, 'Radioactivity and the tools of nuclear physics.'

Nature and properties of  $\alpha$ ,  $\beta$ , and  $\gamma$  rays.

Some cloud chamber photographs.

Radioactive decay and transmutation – there is a page on exponential decay and half-life.

Detectors, main GM tubes, and cloud chambers.

**15B** Chapter 40, 'Atoms: experiment and theory.'

Short but very valuable chapter which summarizes the atomic theory from Greek ideas to the early model of the nuclear atom. You may ignore the short discussion on instability which quotes  $\nabla^2 V = 0$  as the mathematical statement of the inverse square law.

There is an important bit about alpha particles having to come much closer to a positive nucleus than the electrons around the nucleus in order to experience sufficiently strong forces to slow them down and bounce them back. This is included in a section at the end of the chapter which very clearly sets out the reasoning behind the alpha particle scattering experiment, quotes results, and shows how these results support Rutherford's hypothesis.

**16** Andrade, E. N. da C. (1964) Science Study Series No. 29.  
*Rutherford and the nature of the atom.* Heinemann.

**16A** Chapters 3 and 4, selected parts on radioactivity.

These two chapters are centred round the life story of Rutherford. They contain sections on Becquerel's discovery of uranium radiation (page 42), alpha and beta radiation (page 43), Pierre and Marie Curie (page 51), the discovery of radium (page 54), the properties of thorium emanation (page 57), collaboration with Soddy (page 62), the nature of alpha and gamma radiations (page 65), the theory of radioactive disintegration (page 70) and the alpha particle (page 87). These are all fairly short and easy-to-read sections, and contain a lot of personal details about Rutherford and his life.

**16B** Chapter 5. The first half of the chapter is about alpha scattering. It starts with the appointment of Rutherford to the Chair of Physics at Manchester and goes on to give an intimate account of the alpha particle scattering experiment and of the events which led up to it.

(The chapter goes on to deal with Moseley's experiments with X-ray spectra, Bohr's model of the atom, and isotopes. These sections are worth reading but could be omitted.)

**17** *Students' book*, Unit 5, 'Radioactivity and the nuclear atom.'

See pages 70 to 102 of this book.

**18** Romer, A. (1964) Science Study Series No. 10 *The restless atom*. Heinemann.

**18A** Chapters 1, 2, and 3 on the discovery of radioactivity (24 pages).

The first chapter summarizes the evidence for atoms and the appearance of the Periodic Table up to the end of the nineteenth century when Röntgen discovered X-rays. The second, very short, chapter deals with the way Becquerel was interested in the fluorescence produced by X-rays and by chance discovered radioactivity. The third chapter tells of the work of the Curies in discovering polonium and radium.

**18B** Chapter 7, 'Rays and transformation.'

Chapter 9, 'Radium and helium.'

Chapter 12, 'Numbers, alpha particles and helium.'

These three chapters set out the identification of alpha particles as helium nuclei. They include electric and magnetic deflection, the Rutherford-Royds experiment, and the development of Geiger counters. The descriptions make clear the difficulties and uncertainties which faced Rutherford and his colleagues in the early days of work on radioactivity.

**18C** Chapter 13, 'Alpha particle scattering.'

Chapter 16, 'The nuclear atom.'

Chapter 13 puts together all the events which led to the alpha particle scattering experiment, from the 'insignificant' effect that, without a good vacuum, a beam of alpha particles causes a blur instead of a clean line on a photographic plate, to the checking by Geiger and Marsden of Rutherford's hypothesis. The second chapter takes up the idea of a nuclear atom and very quickly and non-mathematically summarizes Bohr's development of an 'orbit' atom model based on the Rutherford model.

**19** Lewis, J. L. and Wenham, E. J. (1970) Longman Physics Topics *Radioactivity*. Longman.

Background booklet discussing the types of radiation, a little history, the Rutherford model, transmutation, and some uses of radioactive isotopes.

**20** Shire, E. S. (1971) Longman Physics Topics *Rutherford and the nuclear atom*. Longman.

Background booklet about Rutherford, describing his early work as well as alpha particle scattering.

# Further reading

## Books

- Baez, A. V. (1967) *The new college physics*. Freeman.
- Bronowski, J. (1960) *The common sense of science*. Penguin.
- Feynman, R. P. (1965) *The character of physical law*. BBC publications.
- Hughes, D. J. (1964) Science Study Series No. 1 *The neutron story*. Heinemann.
- Hurley, P. M. (1964) Science Study Series No. 5 *How old is the Earth?* Heinemann.
- Millikan, R. A. (1963) Phoenix Science Series *The electron*. University of Chicago Press.
- Moroney, M. J. (1956) *Facts from figures*. Penguin.
- Rothman, M. A. (1966) *The laws of physics*. Penguin.
- Weaver, W. (1963) Science Study Series No. 24 *Lady Luck*. Heinemann.

## Reprints

- Crow, J. F. (1959) 'Ionizing radiation and evolution.' *Scientific American* Offprint No. 55.
- Deevey, E. S. (1952) 'Radiocarbon dating.' *Scientific American* Offprint No. 811.
- Dirac, P. A. M. (1963) 'The evolution of the physicist's picture of nature.' *Scientific American* Offprint No. 292.
- Hurley, P. M. (1949) 'Radioactivity and time.' *Scientific American* Offprint No. 220.
- Reynolds, J. H. (1960) 'The age of the elements in the solar system.' *Scientific American* Offprint No. 253.



# Formulae, symbols, and data

## Formulae

Electrons, alpha particles, and nuclei behave pretty much like point electric charges, so the formulae for their field, their potential, and for the forces between them are useful in atomic physics:

$$\text{Electric field } E = \frac{Q}{4\pi\epsilon_0 r^2}$$

$$\text{Electric potential } V = \frac{Q}{4\pi\epsilon_0 r} \text{ if } V = 0 \text{ when } r \text{ is very large.}$$

$$\text{Force} = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2} = Q_1 E \text{ if } E \text{ is the field due to the particle of charge } Q_2.$$

$$\text{Potential energy} = QV.$$

The collision or scattering of one particle and another involves dynamics:

Momentum =  $mv$     Momentum is conserved, but it is necessary to remember that it is a vector quantity.

Kinetic energy =  $\frac{1}{2}mv^2$     Energy is conserved. In an electric field, kinetic energy plus potential energy is constant (as it is in other fields).

*Note.* Beta particles, energy several MeV, go so fast that  $\frac{1}{2}mv^2$  no longer gives their kinetic energy. If you try it, you will find that  $v$  comes out faster than the speed of light. Equations from relativity have to be used. Momentum is not  $mv$  and kinetic energy is not  $\frac{1}{2}mv^2$  at high velocities. At low velocities, these formulae are good to a high degree of accuracy, while not being exact.

Mathematics is useful in understanding radioactive decay:

$dN/dt = kN$  has the solution  $N/N_0 = e^{kt}$ , where  $N_0$  is the value of  $N$  at  $t = 0$ . In decay,  $k$  is negative in sign.

*Half-life.* The time for the number of atoms  $N$  to fall to  $N/2$ .

$N$  always rises or falls by a constant factor for equal changes in  $t$ .

The quantum nature of light helps to link energy levels and the frequency of light emitted by atoms.

Energy of a quantum =  $hf$ .

Maximum kinetic energy of a photo-electron =  $hf - W_0$ .

$W_0$  is the energy the electron must give up as it escapes.

## Symbols

The atomic number  $Z$  is the number of protons in the nucleus. The mass number  $A$  is the number of protons and neutrons in the nucleus. An isotope is written as a symbol in the form  ${}^{60}_{27}\text{Co}$ , where  $A = 60$  and  $Z = 27$ . Since the value of  $Z$  can be found if it is known that the element is Co, it is often omitted, and people often write or speak about, for example, 'cobalt 60'.

## Data

$$e = 2.718\,281\,8\dots$$

$$\ln 10 = 2.302\dots$$

$$\lg e = 0.434\,3\dots$$

$$\text{Charge on an electron } e = -1.6 \times 10^{-19} \text{ C.}$$

$$\text{Charge on a proton} = +1.6 \times 10^{-19} \text{ C.}$$

$$\text{Mass of an electron} = 9.1 \times 10^{-31} \text{ kg.}$$

$$\text{Mass of a proton} = 1.7 \times 10^{-27} \text{ kg.}$$

$$\text{Mass of an alpha particle} = 4 \times 1.7 \times 10^{-27} \text{ kg.}$$

$$\text{Charge on an alpha particle} = +2 \times 1.6 \times 10^{-19} \text{ C.}$$

$$\text{Velocity of electromagnetic waves} = 3.0 \times 10^8 \text{ m s}^{-1}.$$

$$\text{Coulomb force constant } 1/4\pi\epsilon_0 = 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2}.$$

$$\text{Planck constant } h = 6.6 \times 10^{-34} \text{ J s.}$$

$$\text{Avogadro constant} = 6.0 \times 10^{23} \text{ mol}^{-1}.$$

$$\text{One electronvolt} = 1.6 \times 10^{-19} \text{ J.}$$

$$\text{One curie (Ci)} = 3.7 \times 10^{10} \text{ disintegrations per second.}$$

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**This *Students' book* contains a summary of Unit 5, *Atomic structure*, and questions on its main work. The Unit is divided into four Parts: 'Radioactivity and the nature of atoms', 'The Rutherford model of the atom', 'Exponential decay', and 'New ideas and problems about atoms'. The book also includes answers to the questions, chapters on 'Exponential changes', 'Radioactivity and the nuclear atom', and 'Radioisotopes', notes on reading references and a list of further reading, and notes on relevant formulae, symbols, and data.**