Physics

Teachers' guide **Unit 5**

Atomic structure

Nuffield Advanced Science

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Nuffield Advanced Science

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Physics Teachers' guide Unit 5

Atomic structure

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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

The Teachers' guide

This volume is intended to contain whatever information and ideas are required for the *day to day teaching of the Unit.* Not every teacher will need all of it all of the time: sometimes the summary and the list of experiments will come nearer to meeting the need.

The main text contains, on the righthand pages, a detailed suggested teaching sequence, which teachers can adopt or adapt. The facing lefthand pages carry practical details, suggested questions, references, and background information for teachers in the form of a commentary on the text. This commentary also indicates aims of the teaching, and points out links with other parts of the course.

At the end, there are some appendices containing material needed on occasion only, and lists of apparatus and teaching aids for the Unit. These lists include details of books and articles referred to in this *Guide*.

Introduction

One of the themes that runs through this Advanced Physics course is the attempt to explain large-scale things in terms of small-scale things. Within this theme, understanding more about the nature of atoms plays a big part. This culminates in Unit 10, *Waves, particles, and atoms.* Unit 5 is half way to Unit 10 both in time and in subject matter. It provides some of the rewards to be got from fitting together ideas, like those of electric charge and field from Unit 3, *Field and potential,* into new patterns to explain new things. We suggest that these ideas should be fitted together now because it is unlikely that students would perceive this aspect of the structure of the course if they had to wait until Unit 10 before it happened.

Unit 5 provides some of the ideas needed for later work. The central idea is that of the Rutherford model of the atom. The evidence for this model is discussed, taking the opportunity to talk briefly again about models and theories in physics. In Part Four, attention is turned from the nucleus back to the problems of the energy and arrangement of electrons in atoms, revising and extending work from Unit 1, *Materials and structure,* and Unit 2, *Electricity, electrons, and energy levels,* on the sizes and energy levels of atoms. It is this problem that will be the concern of Unit 10; in Unit 5 we merely point to the existence of such problems, without offering solutions.

Part Four also contains a short piece on radiation quanta. This is intended to assist with the work of Unit 9, *Change and chance,* making it possible to take that Unit at any time after Unit 5. It is also relevant to Unit 8, *Electromagnetic waves,* and should ease the teaching about photons in Unit 10. Teachers might omit the section on photons if they intend to take Unit 9 at a late stage, and can incorporate the work on photons into Unit 8 or into Unit 10.

The subject matter of Unit 5 is deliberately modest in scope. The nature of the nucleus is only discussed in passing, and no formal teaching of nuclear fission, or fusion, or of ideas about fundamental particles is suggested. Despite the obvious interest of such matters, they do not fit into the shape of the course as a whole, and time cannot be found for them. No doubt an interesting course could be constructed which gets much value from nuclear physics: it might be better than our course, but it would also be a course with a different shape.

The subject matter of Unit 5 has been chosen so as to help develop skills of importance in the course. Part Three contains some more of the mathematics of the first order differential equation and of exponential change, first met in Unit 2. We think this is worth the time, firstly because the exponential function has later uses in the course, mainly in Unit 9, *Change and chance,* but also because the ability to cope with the mathematics of change is one of the most important skills a physicist, chemist, biologist, or engineer can hope to possess. The ideas developed about chance and randomness will also be useful in Unit 9.

One other major sort of skill is developed in Unit 5: that of reading books and papers and of extracting information from them. The whole approach of Part One is built round this aim. The methods suggested are discussed at length in the text and commentary for Part One.

Summary of Unit 5

Time: about four weeks.

(Numbers in brackets refer to suggested experiments, listed on page 7.)

Part One
Radioactivity and the nature of atoms

Time: up to a week.

In Part One, most of the ideas used in later Parts make an appearance, particularly ideas about the nature of alpha particles and of other radioactive radiations, the Rutherford model of the atom, and the process of radioactive decay. These topics appear briefly in the fifth year of the Nuffield O-level Physics course, and some of them in the Nuffield O-level Chemistry course. So Part One takes the opportunity to send students off to books and papers to find out more, and to clarify ideas they already have. It is hoped that this will extend their ability to read effectively.

Part One is not all reading: a dozen experiments (5.1 to 5.12) are suggested, so that a selection can be made from them. Each student or pair of students can then have an individual task comprising an experiment, a related piece of reading, and perhaps a problem to do. Reports of the experiments and reading can be given and discussed when the relevant point in a later Part is reached.

Suggested topics for study

The nature and energy of radiations from radioactive substances (5.1 to 5.5), emphasizing alpha particles because of their importance in the later discussion of Rutherford scattering. Collisions and scattering of nuclear particles, and the dynamics of collisions (5.6 to 5.8), together with reading about Rutherford scattering. Radioactive decay, the exponential form of the decay curve, and the importance of chance and randomness (5.8 to 5.12). It is not necessary that all these areas be covered at the same time, and radioactive decay can be left until work on Part Three begins.

Part Two
The Rutherford model of the atom

Time: less than a week.

This Part collects together ideas about alpha particles, and about Rutherford scattering, from Part One. It serves to emphasize what is important in what students have read of these matters. It also draws special attention to the problem of whether the atom has a small nucleus which is charged, and to a test of whether alpha particles behave as if scattered by an inverse square law force.

Suggested sequence

The nature of alpha particles, and their energy (5.13). Scattering by a charged nucleus; use of a gravitational analogue of a $1/r$ potential to simulate Rutherford scattering and to obtain data which may be compared with those of Geiger and Marsden (5.14). Test of the Rutherford model. Calculation of energies from the electrical inverse square law.

Part Three
Exponential decay

Time: up to a week.

This Part collects together another set of ideas from Part One, those of radioactive decay and chance. The explicit form of the exponential function is produced (this having probably not been reached in Unit 2). The function is presented as a solution of a first order differential equation, and a graphical technique for step-by-step integration is suggested, similar to that suggested in Units 2 and 4.

Suggested sequence

Radioactive decay and an analogue using dice (5.15). The constant chance of decay per unit time. The equation $\Delta N = -kN\Delta t$.

Graphical solution of the equation when $k = 1$. Comparison with graphs of $N = a^t$ to suggest the form $N = e^t$ for the solution.

Value of e. The form $N/N_0 = e^{kt}$ in general, with k positive or negative. Testing growth and decay data for exponential form, using logarithmic graphs.

The *Students' book* contains a section, 'Exponential changes', which takes students through this work in a series of questions.

Radioactive decay and recovery. Applications of radioactivity.

Part Four
New ideas and problems about atoms

Time: about a week.

This Part contains some clearing up of ideas from earlier Parts; those of atomic number and nuclear charge, of transmutation, and the existence of isotopes. Then it recalls ionization energies from Unit 2 and sees how these energies fit together with the Periodic Table series of atoms of steadily increasing nuclear charge. Lastly, radiation quanta are introduced and linked to energy levels.

Suggested sequence

Atomic number and nuclear charge. Summary of ideas about atoms. The nucleus; possible existence of neutrons. Isotopes and transmutation.

Ionization energies of the elements. Sizes of atoms. Evidence that light energy comes in lumps. Simple photo-electric effect (5.16). Quantitative photo-electric effect, Planck's constant (5.17). The 4.9 eV energy level spacing in mercury and the emission and absorption of the corresponding ultra-violet line (5.18).

Choosing one's own path

We hope and expect that teachers will find their own ways of using the material in this Unit. The detailed teaching programme laid out in the following pages represents as good a way of handling the material as we have been able to find in the light of experience in the trials, but should not be thought of as more than a possible, fairly well tested way of achieving the aims we decided upon. No doubt others can and will do better.

But teachers will know that it is the detail that counts in successful teaching, and so the *Guide* is full of particular teaching suggestions and practical details. We hope that these will help those who are uncertain how to handle either new material, or old material taught in a new way for unfamiliar aims.

The summary and list of experiments will, it is hoped, assist those who have taught the course a few times and no longer need to refer to all of the detailed teaching suggestions, as well as those who feel confident that they can make up their own teaching programme out of their previous experience. We also hope that the summary will provide an overall view of the work suggested. Such a view is necessary for keeping a sense of perspective and direction, both when one is immersed in particular detailed teaching suggestions and comments, and when students lead the teaching off in an unpredictable direction by contributing their own ideas.

It seems fair to add that the summary, taken on its own, could mislead. It cannot easily indicate the aims of pieces of work in any precise way, or find words to express the relative seriousness or lightness of particular episodes. Nor should a phrase one might find in a current examination syllabus always be taken here to imply the same work as it would imply there.

Experiments suggested for Unit 5

Experiments 5.1 to 5.12 are a list from which experiments, together with reading and problems, may be selected to make up individual tasks for students.

Part One

Radioactivity and the nature of atoms

Time: the time for Parts One, Two, and Three should be assessed together. Parts Two and Three grow out of the reports on tasks undertaken in Part One, and they serve to clarify and emphasize the main points raised in Part One.

By the end of a week, reports on tasks in Part One should be coming in, and work from Part Two could be under way. Together, Parts One, Two, and Three should occupy rather less than three weeks, with Parts One and Three occupying up to a week each, and Part Two taking rather less than a week. But these times will not be separately identifiable, because of the overlap between the work of the three Parts.

These times assume the background knowledge provided by the Nuffield O-level Physics course. Classes without this background may need more time.

Explaining the shape of the Unit, and its purpose, to students

The discussion opposite might more usually find its place in the commentary, rather than in the teaching material. While not pretending that the arguments could be put to students as they stand, we think that the Unit will benefit from such an introduction, so we have put an outline in the text. Students will, if they undertake the individual tasks suggested, need some idea of where it is all going. Luckily, many of them will know something of the destination – the nuclear model of the atom, radioactive decay, the variety of uses and dangers of radiations – and so be able to appreciate the notion of trying to find out more about the routes which lead there.

Learning from reading

This is not the only occasion on which students are asked to learn from reading. They may have been asked to do so in Unit 1, *Materials and structure,* when discussing composite materials. Unit 2, *Electricity, electrons, and energy levels,* involved some selected extracts from papers. Looking ahead, Unit 7, *Magnetic fields,* will involve further individual reading, about devices that use magnetic fields. To our minds, the development of the skills needed to learn in this way is no less important than the things learned; indeed, for some of the material suggested, such as the nature of beta radiation, the skills are arguably more important than the knowledge.

The introduction to *Students' book,* Unit 5, has a passage which attempts to explain the thinking behind the work of this Unit.

Organizing the work of the Unit as a whole

It may not be convenient to run all the suggested tasks first, before drawing out consequences of the things learned, in Parts Two, Three, and Four. That would concentrate most of the practical work near the beginning, and in the trials, some students felt this to be unsatisfactory. A good way would be to assign students to one task of experiment, reading, and problem at the start, picking out especially those which are needed for the discussion in Part Two, 'The Rutherford model of the atom'. The teaching of Part Two could begin almost at once, drawing upon results of experiments and information from reading as these are produced. Then later on, probably near the start of teaching Part Three, 'Exponential decay', another set of tasks could be given. These could be of a wider variety, and might only involve an experiment, or an experiment and a very limited piece of reading. Part Four, 'New ideas and problems about atoms', is deliberately planned to look back over the evidence and theories developed so far, as well as to look forward to new problems. It can be used to draw the threads together at the end. Some of it can be tackled using problems in the *Students' book*, so the need for problems in a second set of tasks is reduced.

We think that two of the experiments ought to be enough for a student. One may be enough in some circumstances. Apparatus problems can be eased by having some students start with reading while others start with an experiment.

Reasons for studying radioactivity

There are two sorts of reason for studying radioactivity, which are appropriate to the Advanced Physics course:

1 Radioactive decay provides much of the experimental evidence upon which the modern understanding of the structure of atoms is built.

2 The uses of and dangers from radioactivity look likely to be increasingly important for our civilization, and some citizens at least ought to understand the issues well enough to influence decisions in a sensible direction.

Part One of this Unit is concerned with the evidence: with what experiments have to tell about the nature of radioactive decay, and the different kinds of radiation from radioactive substances. Part Two is about arguments leading from this evidence to a picture of an atom having a tiny massive core, or nucleus. Part Three is about using a mathematical model to describe the decay process, and about how chance and randomness are involved. Part Four comes to few conclusions: it summarizes the lack of understanding still remaining even after the ideas presented in this Unit are clear, and looks forward to Unit 10, *Waves, particles, and atoms,* when some of these outstanding problems will be examined again. This last Part also serves to draw attention back from nuclei to atoms.

Experimenting and reading individually as a way of learning to learn

The work of Part One is presented in the form of a series of individual tasks for single students or for pairs of students. Teachers will have to decide on suitable tasks for each student, bearing in mind the following purposes and what they know of individual students' qualities, not to mention practical considerations of space and apparatus available.

Each task may consist of an experiment, with instructions; a piece of reading research; and a problem. Reasons for using this pattern are:

1 The reading, together with preparing a report on it, should help develop the skill needed to extract information and ideas from books.

2 Some of the reading puts a student in contact with the writing of the people who actually developed the ideas, and this may be more interesting than hearing about them at third or fourth hand. It should also help them to realize that these ideas were invented, by people, in response to problems of understanding experimental evidence, and were tested by devising new experiments.

3 By being left alone with experiments of their own, and by being asked to tell others what they have found, students may become better at working in an independent, mature way.

4 A problem related to reading, experiment, or to both, can clarify ideas by putting them to use, can show a student that the ideas can be used in several ways, and can show that something has been learned.

Guide to the selection of tasks

We do not think it proper for us to attempt to decide what should go into each task of experiment, reading, and problem. Nor would it be practicable to do so, since schools will have different apparatus problems, different books, and, above all, differing students. But the selection of suitable tasks is a formidable one, and we have tried to help as much as possible.

Experiments to be done individually clearly need instructions. We have picked out twelve experiments, of varying length and difficulty. Written outline instructions for each appear in the *Students' laboratory book.* The experiments also appear below, in this *Guide,* together with lists of apparatus as usual. The number of experiments is larger than is needed for 16 students working in pairs, so that teachers have considerable freedom of choice.

Teachers will properly feel free to introduce other relevant experiments of their own, but will then need to produce suitable outline instructions for them. In this *Guide*, each experiment is associated with suggestions for suitable reading and for suitable problems.

Reading references appear in the *Students' book* as a collected list of references to specific parts of specific books. Each has a short note indicating what to look for, what to omit, and some assistance with other difficulties; for instance, with unfamiliar units. It is important that students realize that they will each look at only one or two of the books referred to. Each student or pair will need to be given one reading reference.

Some of the references overlap, and some contain identical material. These overlaps are indicated, so that teachers can either choose one out of several references, and can cover the ground with fewer books, or, in the case of an important subject, can arrange that two students may cover the same ground without having to ask them to share one volume.

The list of references is collected together in the list on page 125. Teachers will wish to add others of their own, and to provide comparable notes. Each reference gives also the experiments with which it might be associated, while the experiments in the text carry references which could go with them. We hope in this way that teachers will have an easily used starting point, but will be encouraged to use the material flexibly. As time goes by, and their experience of what is possible grows, together with their knowledge of the available materials, the job should become easier, It is to be expected that, to start with, mistakes will occur, and students will be assigned tasks which are too easy or too hard for them.

Details of other reading recommended in this *Guide* are given in the list 'Other books and reading for Unit 5' on page 128.

Problems suitable for use in tasks appear in the *Students' book.*

Each experiment in the text that follows is assigned one or more of the problems we think likely to be useful to make up a task involving that experiment. Each student or pair will need to be given one problem.

Using radioactive sources in schools

The attention of teachers is drawn to Department of Education and Science Administrative Memorandum 1/65, 'The use of ionizing radiations in schools, establishments of further education, and teacher training colleges', issued by the Establishment and Organization Branch, Department of Education and Science, Elizabeth House, York Road, London SE1.

The memorandum gives regulations concerning the type, quantity, and use of radioactive sources in schools. Of particular significance for first year sixth forms is the regulation which forbids students under the age of 16 to use radioactive sources other than the naturally occurring isotopes of potassium, uranium, and thorium.

Radioactivity is rather well suited to this approach because:

1 The problem of what atoms are like depends for an answer on bringing together many threads of evidence, and this can be made evident by doing just that in the classroom.

2 The behaviour and applications of radioactive materials and radiations are very varied, and this can be illustrated by the variety of tasks going on at one time. Most of the things that can be done in a school laboratory are of only modest importance in themselves, but taken together they add up to a useful picture of the properties and uses of radioactive radiations.

3 The experiments which cannot be done in school – principally alpha particle scattering – are crucial to the argument for a nuclear atom model. They can only be read about, reported indirectly, or seen on film. So one may as well make a virtue of necessity, and use this as one occasion on which to develop skill in reading and reporting, since this must be developed at some places in the course.

Students ought to be given some idea, based on the reasons given above, of why this work is being tackled in this way. Many will know already that physicists, chemists, and others imagine atoms to have a small nucleus. It can be put to them that the job is to find out why people ever came to think that way, and how they could have done so without ever seeing an atom, let alone seeing inside one.

Topics covered by experiments suggested for tasks

The experiments are listed on page 7. They cover three main sorts of topic.

Nature and properties of radiations: experiments 5.1 to 5.5.

Scattering and collisions: experiments 5.6 to 5.8.

Radioactive decay: experiments 5.9 to 5.12.

Of the first group, experiment 5.2 is the most important, for it gives evidence about the energy of alpha particles, which will be crucial to an understanding of the argument for a nuclear atom model in Part Two. Experiment 5.1, dealing with the magnetic deflection of beta particles, is useful, not so much for itself, as for illustrating how a similar, harder, job might be done for alpha particles. Experiments 5.3, 5.4, and 5.5 are good background experience of cloud chamber tracks, penetrating power of radiations, and the photographic effect of radiations. Not all need be done, but some should be. Experiment 5.5 is probably the least important.

The experiments in the second group bear directly on Part Two, 'The Rutherford model of the atom'. Experiment 5.6, an attempt to observe large angle alpha scattering, is the most central but the most difficult. Experiment 5.7 is about frictionless puck collisions, and may or may not be needed, depending on students' previous experience. Experiment 5.8 shows the knock-on of protons by alpha particles, and is a valuable illustration of nuclear collision processes.

Overlaps in apparatus required for experiments 5.1 to 5.12

It will not always be easy to provide the apparatus these experiments require. This must be a factor in choosing, assigning, and timing experiments. Table 1 shows the requirements for major items.

Item		*Experiment* 5.1	5.2 a	5.2 b	5.3	5.4	5.5	5.6	5.7	5.8	5.9	5.10	5.11*	5.12
130/1	scaler (not ratemeter)			✓										✓
130/1	scaler (ratemeter acceptable)	✓				✓					✓			
130/4	solid state detector			✓										
130/5	thin window GM tube	✓				✓					✓			✓
16	radium source						✓							✓
195/1	pure gamma source				✓	✓								
195/2	pure beta source	✓				✓								
195/3	pure alpha source		✓			✓								
1006	electrometer		✓									✓		
14	e.h.t. power supply		✓											
28	diffusion cloud chamber				✓			✓		✓				
19/1 /2	CO_2 cylinder and dry ice attachment				✓			✓	✓	✓				
133	camera								✓					

Table 1

Note Experiment 5.15, in Part Three, also uses dry ice for cloud chambers. If a block is bought for experiments 5.3, 5.6, 5.7, and 5.8, it will be convenient to fit experiment 5.15 in at the same time.

*Experiment 5.11 uses none of these items.

Experiment
5.1 The magnetic deflection of beta particles

130/1	scaler
130/3	GM tube holder
130/5	thin window GM tube
195/2	pure beta source
196	source holder
50/3	magnet Eclipse Major *or*
92 I	mild steel yoke *and*
92 B	Magnadur magnet 2
503-6	retort stand base, rod, boss, and clamp 2
1 M	lead block

The third group of experiments relates to Part Three, 'Exponential decay'. Experiments 5.9 and 5.10 are both observations of decay, and could be alternatives. Experiment 5.11, using dice to simulate decay, is simple but important. It could become a demonstration, or a joint class effort. Experiment 5.12 is tedious but useful, illustrating the random variations in count rate from a source.

The pages which follow, to the end of Part One, give details of these experiments, outlines of suggested reading, and problems, and indications of the use that will be made of the information from the experiments in later parts of the Unit.

Experiment
5.1 The magnetic deflection of beta particles

This experiment is similar to demonstration 133, Nuffield O-level Physics *Guide to experiments V.* It is fairly simple and is better suited to slow or inexperienced students. An alternative for fast or ambitious students is demonstration 5.13, the magnetic deflection of alpha particles. This is much more difficult. Another alternative is the electric deflection of beta particles, which is also difficult.

Students who are not sure of rules for the direction of magnetic deflection can check the sign of the charge on the particles by comparing the direction of deflection with that obtained for electrons in a fine beam tube, item 61.

The results of the magnetic deflection of beta particles are not needed directly in later Parts, but an understanding of how magnetic deflection can be used to give evidence for the sign of the particles' charge will be helpful in discussing the nature of alpha particles, which plays a big part in Part Two, 'The Rutherford model of the atom'.

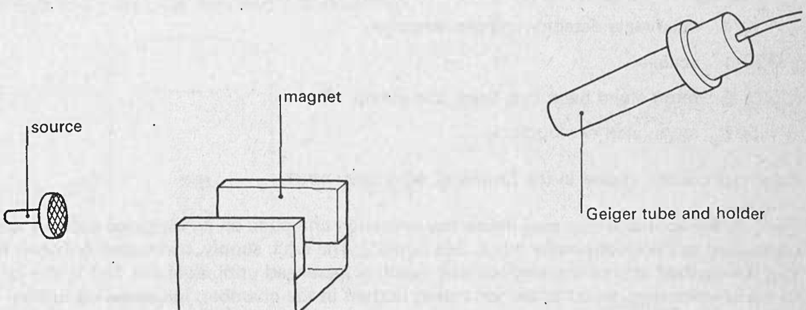


Figure 1
Magnetic deflection of beta particles.
(The lead block is not shown.)

Brief instructions appear in the *Students' laboratory book.*

The Eclipse Major magnet can be used with apparatus arranged as in Nuffield O-level Physics *Guide to experiments V,* demonstration 133.

A pair of Magnadur magnets on a steel yoke, taken from the O-level Westminster electromagnetic kit (item 92) serves quite well. Figure 1 shows one possible arrangement of the apparatus.

Only the holder, not the GM tube, may be gripped by a clamp. The other clamp can be used to hold the source. The lead block may be useful for preventing radiation from reaching the GM tube directly. A ratemeter may be substituted for the scaler.

Problem

Choose one from the *Students' book.* Question 8, about the design of an experiment for detecting the electric deflection of beta particles, would be an appropriate choice.

Experiment
5.2 The number of ions produced by an alpha particle

5.2a Measuring the ionization current

1006	electrometer with $10^9\ \Omega$ input resistor
1008	ionization chamber
195/3	pure alpha source
14	e.h.t. power supply
1003/1	milliammeter (1 mA)
196	source holder
1000	leads

5.2b Counting alpha particles from the source

130/4	solid state detector and pre-amplifier
130/1	scaler
503–6	retort stand base, rod, boss, and clamp *2*
507	stopwatch or stopclock

Brief instructions appear in the *Students' laboratory book.*

For 5.2a the source is mounted inside the ionization chamber, on an insulated support which is to be connected to the electrometer input. See figure 2. The e.h.t. supply, connected between the chamber and the earthed side of the electrometer input, is increased until, at about 750 V, the current flowing in the electrometer, equal to the ionization current in the chamber, increases no further.

The display meter is used to find the p.d. across the $10^9\ \Omega$ electrometer input resistor, from which the current through the resistor can be calculated. (The p.d. across the resistor is in the range 0–1 V, and is *not* the same as the p.d. across the chamber provided by the e.h.t. supply.)

Suggested reading

An appropriate piece of reading would include something on the nature of radioactive radiations, particularly about the use of magnetic deflection. Evidence about alpha particles is of particular interest in this Unit. Choose one from:

1A *Classical scientific papers (physics)*, Paper 2, Rutherford, 'The magnetic and electric deviation of the easily absorbed rays from radium'.

9A Caro, McDonell, and Spicer, *Modern physics,* Chapter 5, is more general, wider ranging, and more easily understood than references 5A and 1A. It includes evidence from magnetic deflection.

18B Romer, *The restless atom,* Chapters 7, 9, and 12, cover much the same ground as reference 9A but less formally.

Experiment
5.2 The number of ions produced by an alpha particle

The idea is to measure the ionization current produced by alpha particles from a pure alpha source. As the charge on an ion is of the order of the charge on an electron, the number of ions produced per second can be estimated. This is experiment 5.2a.

The number of ions from each alpha particle requires a further estimate, namely the number of alpha particles produced by the source each second. This can be estimated roughly either from the stated source strength, or, better, in a subsidiary experiment 5.2b, in which the particles emitted are counted.

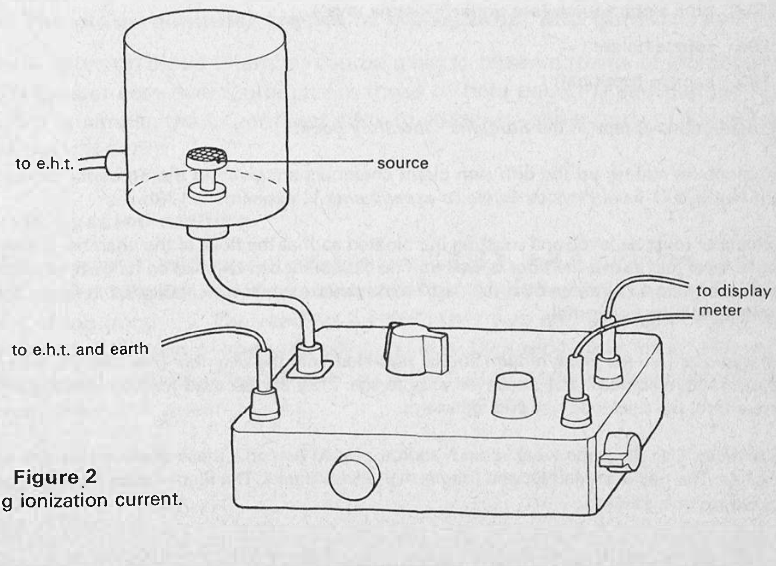


Figure 2
Measuring ionization current.

For 5.2b, the solid state detector is placed about 20 mm from the source, holding each in suitable clamps. If the detector has sensitive area A, and observes C counts in unit time, the number N of alpha particles emitted by the source in unit time is given by

$$N = (A/B)\,C$$

where B is the area at the detector, at a distance r from the source, into which all the particles from the source go. An acceptable estimate for B might be $2\pi r^2$, or somewhat less, to allow for shielding by the sides of the source. (This gives the 'emitting strength' of the source; the source produces more particles but they are absorbed in its casing and do not affect any experiment with it.)

One curie is 3.7×10^{10} disintegrations per second. This may be used to compare the strength measured in 5.2b with the strength marked on the source, or to use the strength marked on the source to estimate the number of particles emitted in unit time if 5.2b is not attempted. The marked value is likely to exceed the measured value, for the foil in which the active material is sealed absorbs some particles, and the marked activity may refer to the total amount of material in the source, half of the particles from which go 'backwards' into the source casing and are absorbed there.

Problems

The experiment involves some calculation, and no extra problem may be needed. If a problem is wanted, questions 5, 6, or 7 in the *Students' book* are suitable. These are about the energy of radiations.

Experiment
5.3 The cloud chamber tracks of alpha, beta, and gamma rays

28 diffusion cloud chamber

47 illuminant

27 transformer

19/1/2 CO_2 cylinder and dry ice attachment

1056 methylated spirit

195/1 pure gamma source
or
195/3 pure alpha source (see under 'Gamma rays')

196 source holder

133 camera (optional)

Brief instructions appear in the *Students' laboratory book.*

Instructions for setting up the diffusion cloud chambers are given in the *Students' laboratory book* and in Nuffield O-level Physics *Guide to experiments V,* experiment 128b.

The chamber must be level, and must be illuminated so that the floor of the chamber is dark while the sensitive layer just above the floor is well lit. The illuminant can be used on its own, or with a +7 diopter lens (item 112) and a card with a 10 mm aperture cut in it, as indicated in figure 3. The lamp filament should be horizontal.

Alpha particles Use the weak radium source provided with the chamber (*not* item 16, which is a 5–10 μCi radium source). The tracks are easy to see. They can be used for final levelling, adjusting the chamber until the tracks do not drift sideways.

Beta particles Use the same weak radium source, placed behind a piece of aluminium foil which absorbs the alphas. The tracks are fainter and longer than alpha tracks. The illumination must be good, and a darkened room is advised.

The experiment is of interest in Part Two of this Unit, for it can be used to give evidence for the energy of a typical alpha particle, needed for estimating how close such a particle might approach to a nucleus in a head-on collision. It is of practical interest in bringing out the meaning of the unit of activity, the curie, and in illustrating the large ionizing power and correspondingly short range of alpha particles.

Suggested reading

Suitable reading will discuss the nature of the radiations, emphasizing estimates of their energy. Choose one from:

1B *Classical scientific papers (physics),* Paper 4, Rutherford and Royds, 'The nature of the alpha particle from radioactive substances'. This paper reports the famous experiment identifying alpha particles with helium nuclei.

3C Romer (ed.), *The discovery of radioactivity and transmutation,* Paper 13, Rutherford and Soddy, 'Radioactive change'. It will be best to concentrate on section 7, page 163, which gives an interesting series of order of magnitude estimates.

3D From the same book as reference 3C, Paper 14, Curie and Laborde, 'On the heat spontaneously released by the salts of radium'.

5A Project Physics, Reader, *Unit 6* also reproduces the paper referred to above, reference 1B. (Reference 5A is identical with reference 1B.)

17 Students' book, Unit 5, *Atomic structure,* 'Radioactivity and the nuclear atom', contains most of the extract suggested in reference 3C, with notes on the unfamiliar units.

Experiment

5.3 The cloud chamber tracks of alpha, beta, and gamma rays

The simple diffusion cloud chamber can be used to observe tracks of alpha particles, and, with greater care over illumination, those of beta particles and gamma rays. Although it is simple, the experiment adds to students' experience of the differences between the radiations.

Suggested reading

The reading assigned with one of experiments 5.3, 5.4, or 5.5 ought to survey the historical growth of evidence for an atomic picture of matter, culminating in the discovery of radioactivity. The reading for the other two can be about the properties and detection of the radiations, or may be specifically about the discovery of radioactivity. Choose one from the list on page 21, for each of these three experiment and reading tasks.

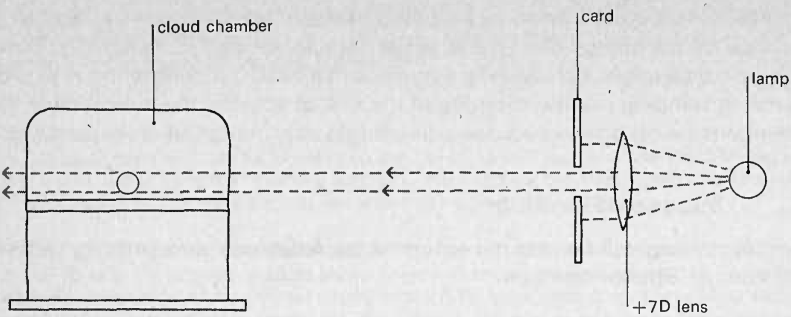


Figure 3
Cloud chamber with lens-assisted illumination.

Gamma rays If item 195/3 is ^{241}Am it can be used as a gamma source, though intended as a 'pure' alpha source. It produces a little weak gamma radiation, and may simply be placed on the top of the cloud chamber so that the chamber wall absorbs the alphas and the gamma rays enter the chamber. The pure gamma source, item 195/1, can also be used. This is best kept in its lead container, put near the chamber. Short 'worm-like' tracks caused by recoil electrons can be seen.

Photographing tracks Occasionally, a student may care to try photographing tracks. The illumination system shown in figure 3 is suitable. Fix the camera above the top of the chamber, focused on infinity, with an auxiliary lens over the camera lens. The sensitive layer should lie in the focal plane of the auxiliary lens.

Problems

Choose one from the *Students' book*, questions 5, 6, or 7. Question 7, about calculating the number of ions in a cloud chamber track, is especially appropriate.

Historical growth of evidence for atoms

9C Caro, McDonell, and Spicer, *Modern physics,* Chapter 1 (no radioactivity).

11A Project Physics, Text, *Unit 5,* Prologue.

15B Rogers, *Physics for the inquiring mind,* Chapter 40.

17 Students' book, Unit 5, *Atomic structure,* 'Radioactivity and the nuclear atom'.

18A Romer, *The restless atom,* Chapters 1–3.

Properties and detection of radiation; discovery of radioactivity

1C *Classical scientific papers (physics),* Paper 20, Wilson, 'On an expansion apparatus for making visible the tracks of ionizing particles in gases'.

3 Romer (ed.), *The discovery of radioactivity and transmutation.*

3A Papers 2 and 3, Becquerel, 'On the invisible radiations emitted by phosphorescent substances' and 'On the invisible radiations emitted by salts of uranium'.

3B Paper 11, Rutherford and Soddy, 'The cause and nature of radioactivity', parts I, II, and V only.

6 Gentner, Maier-Leibnitz, and Bothe, *An atlas of typical expansion chamber photographs.* See particularly figures 5, 10, 12, 14, 15, 28–32 (especially suitable for this experiment).

7A Arons, *Development of concepts of physics,* Chapter 32 (similar to reference 10A).

8 Bennet, *Electricity and modern physics* (MKS version), Chapter 16.

9A Caro, McDonell, and Spicer, *Modern physics,* Chapter 5.

9B Caro, McDonell, and Spicer, *Modern physics,* Chapter 11.

10A Holton and Roller, *Foundations of modern physical science,* Chapter 36.

12 Project Physics, Text, *Unit 6,* Chapter 21 (very similar to reference 9A).

15A Rogers, *Physics for the inquiring mind,* Chapter 39.

18B Romer, *The restless atom,* Chapters 7, 9, and 12.

Experiment

5.4 The penetrating power of alpha, beta, and gamma rays

195/1–3	pure gamma, pure beta, pure alpha sources
196	source holder
130/1	scaler
130/3	GM tube holder
130/4	solid state detector and pre-amplifier
130/5	thin window GM tube
130/6	gamma GM tube (not essential)
507	stopwatch or stopclock
503–6	retort stand base, rod, boss, and clamp *2*
501	metre rule
1052	absorbers for alpha, beta, and gamma rays (see below)
1055	Vernier callipers (or micrometer screw gauge)

Details are given in the *Students' laboratory book.* Students need to be instructed which experiments they are to select.

Item 1052, the collection of absorbers, should contain cigarette paper; ordinary paper; thin glass and Perspex sheets; aluminium cooking foil; aluminium sheet of several thicknesses sufficient to cover the range 1–5 mm; lead sheet or blocks to cover the range 5–20 mm thickness.

a 'Range of alpha particles in air' uses the solid state detector or a very thin window GM tube. The energy of the alpha particles can be found from the graph of range against energy provided.

b 'Range of beta particles in aluminium' again yields the (maximum) energy from a graph.

c '"Half thickness" of lead for gamma rays' also gives the energy of the radiation.

d 'Relation between absorber thickness and radiation transmitted' and also

e 'Relation between source to detector distance and intensity received' both involve data collection and graph plotting. They illustrate some of the safety factors involved in controlling dosage from radiation.

A ratemeter can be substituted for the scaler in **b**, **c**, **d**, and **e**.

Problems

The experiments themselves may involve enough in the way of problems. If others are needed, see *Students' book*, questions 5, 6, or 7. These problems are about the energy of radioactive radiations.

Experiment

5.4 The penetrating power of alpha, beta, and gamma rays

This experiment has a number of possible parts, those suggested in the *Students' laboratory book* being:

a **Range of alpha particles in air**

b **Range of beta particles in aluminium**

c **'Half thickness' of lead for gamma rays**

d **Relation between absorber thickness and radiation transmitted**

e **Relation between source to detector distance and intensity received**

If apparatus is available, these may be divided up among more than one group of students. Only in rare cases should a student attempt more than, say, two parts.

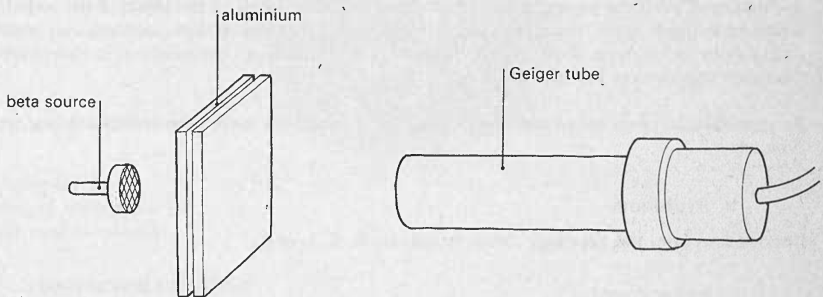


Figure 4
Range of beta particles in aluminium.

Suggested reading

The reading assigned with one of the experiments 5.3, 5.4, or 5.5 ought to survey the historical growth of evidence for an atomic picture of matter, culminating in the discovery of radioactivity. This experiment, being rather long, may be most suitable for such reading, as the reading can be quite short and not very detailed. Alternatively, reading about the properties and detection of the radiations, or about the discovery of radioactivity, is appropriate.

Suitable references are given with experiment 5.3. Choose one from that list. Mainly historical references (references 9C, 11A, 15B, 17, 18A) are listed first.

Experiment

5.5 Photographic detection of radiation

16 radium source

1054 dental X-ray film
or
1054 fast bromide paper
and
1054 developer and fixer

Brief details appear in the *Students' laboratory book.*

Use of the dental X-ray film, which contains its own developer and fixer, avoids the need for a dark-room, but involves some expense. The film can be bought from normal apparatus suppliers, who usually stock it for their X-ray apparatus. The source is just placed face down on the film pack for 20 to 30 minutes.

In a darkroom with a suitable safelight, the source can be placed face down on the sensitive surface of fast bromide paper ('hard' paper is better than 'soft') for a similar exposure time, after which the paper is developed. With the paper, the alpha particles produce nearly all the effect. If the sensitive paper is wrapped in black paper, the alphas are stopped, and the exposure time becomes very much longer; probably some hours or days. The film is faster, and develops an exposed patch, due mainly to betas, in the much shorter time indicated above.

It is possible, but very time consuming, to repeat Becquerel's work with sensitive paper and salts of uranium.

Problems

Choose one from the *Students' book*, questions 5, 6, 7, or 8.

Experiment

5.6 Large angle scattering of alpha particles

28 diffusion cloud chamber

47 illuminant

27 transformer

191/1/2 CO_2 cylinder and dry ice attachment

1056 methylated spirit

1055 gold foil (see below)

Instructions appear in the *Students' laboratory book.* They assume that the foil is available mounted as described below.

See Nuffield O-level Physics *Guide to experiments V,* experiment 128b, for the method of setting up the cloud chamber. The chamber must be level, and well lit, as in experiment 5.3.

Mounting the foil The gold foil should be about 10^{-2} mm thick, a piece 35 mm by 20 mm being needed. Cut this from a larger sheet with a new razor blade, the foil being sandwiched between sheets of tissue paper and resting on a hard surface.

Experiment
5.5 Photographic detection of radiation

While of no major importance, this experiment illustrates the way in which radioactivity was first discovered, and may be of interest to students who are interested in such matters as the uptake of elements by plant or animal tissues, which can be followed by similar means using tracers.

The simplest form of the experiment needs no dark room, and requires little effort. A student who wishes to repeat some of Becquerel's work will have to be prepared to give exposures lasting for several hours or days.

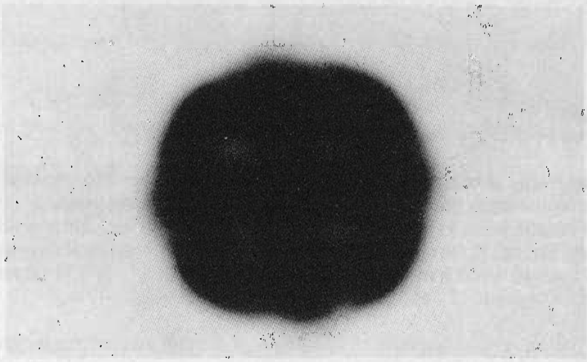


Figure 5
The fogging of dental film by a 5–10 μCi radium source.

Suggested reading

It is natural to suggest reading about Becquerel's work to go with this experiment. The original reports, translated, appear in reference 3A, from Romer (ed.), *The discovery of radioactivity and transmutation.* Paper 2, 'On the invisible radiations emitted by phosphorescent substances' and paper 3, 'On the invisible radiations emitted by salts of uranium' are the relevant papers. Very brief extracts appear in the *Students' book,* under 'Radioactivity and the nuclear atom' (reference 17).

Other suitable reading appears in the list with experiment 5.3. One of the groups of students doing experiments 5.3, 5.4, or 5.5 ought to be given reading which covers the historical growth of ideas about atoms.

Experiment
5.6 Large angle scattering of alpha particles

This experiment is an attempt to see one or two instances of large angle scattering of alpha particles passing through a thin foil, by watching cloud chamber tracks over a long period. It is not certain to succeed, but even a failure has some value in emphasizing the rarity of such events: a lesson which ultimately points to the small size of nuclei.

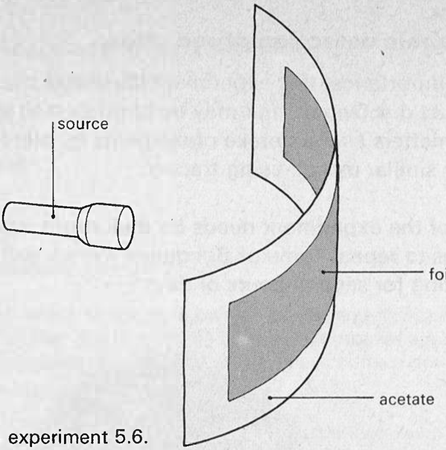


Figure 6
A mount for the gold foil in experiment 5.6.

Figure 6 shows a way of mounting the foil. The mount *must* have a low thermal conductance to avoid disturbing the temperature gradient in the chamber. A mount in the shape of a half-cylinder can be cut from the small plastic tubes in which screws or nails are sometimes sold in small quantities, or may be made from a 40 mm by 25 mm piece of *thin* acetate sheet softened in boiling water and bent to shape round a small cylinder (a 35 mm film cassette will serve). Cut an aperture 30 mm by 15 mm in the mount.

Smear a little diluted gum or acetone on the edges of the foil, and roll the mount over the foil so that the foil covers the aperture.

Arrangement of foil within the chamber Put the foil near the middle of the chamber. Push the source forward until its emitting surface is at the centre of curvature of the mount and foil. Then tracks can be seen before and after passing through the foil. A few will be deflected through a modest angle; very rarely, a large angle scattering (maybe 30 degrees) may be seen. At least a quarter of an hour's observation time is needed.

Problems

Choose one from the *Students' book,* questions 19 to 25, especially question 19 on the size of a nucleus.

Suggested reading

The reading to go with experiments 5.6, 5.7, and 5.8 can very naturally be reports of the alpha particle scattering experiment suggested by Rutherford and performed by Geiger and Marsden, or can be accounts of the significance of the experiment. Choose one from the list below, for each of these experiment and reading tasks. Full details are given in the book list at the end of this *Guide*.

4 Project Physics, Reader, *Unit 5*, articles surveying atomic physics.

Accounts of the alpha scattering experiment and its significance

7B Arons, *Development of concepts of physics,* Chapter 33, sections 9–15.

9D Caro, McDonell, and Spicer, *Modern physics,* Chapter 8.

10B Holton and Roller, *Foundations of modern physical science,* Chapter 34.

11B Project Physics, Text, *Unit 5,* Chapter 19.

13 PSSC, *Physics,* Chapter 32.

14 PSSC, *College physics,* Chapter 26 (identical to reference 13).

16B Andrade, *Rutherford and the nature of the atom,* Chapter 5 (biographical).

17 Students' book, Unit 5, *Atomic structure,* 'Radioactivity and the nuclear atom', includes a short description of the discovery of alpha scattering, and very brief extracts from the paper by Geiger and Marsden.

18C Romer, *The restless atom,* Chapters 13 and 16.

Original papers

1 *Classical scientific papers (physics).*

1D Paper 8, Geiger and Marsden, 'On a diffuse reflection of the alpha particles. (The paper which reported the first evidence of large angle scattering. It also appears in reference 2B.)

1E Paper 10, Geiger and Marsden, 'The laws of deflexion of alpha particles through large angles'. (The scattering experiment. Also in reference 2B.)

1F Paper 12, Rutherford, 'The structure of the atom'. (Also in reference 2D.) See also paper 13, Rutherford, 'Nuclear constitution of atoms', first six pages only.

2 Conn and Turner, *The evolution of the nuclear atom* (all rather tough).

2B Chapter 5 introduces the Geiger and Marsden paper, and reproduces some of it.

2C Chapter 6, pages 202–213, Chadwick's measurement of the nuclear charge.

2D Chapter 6, pages 192–202, Rutherford's summary of the nuclear model (identical to the first part of reference 1F).

Experiment

5.7 Collisions between pucks in two dimensions

95	Edinburgh CO_2 pucks kit (see figure 7)
161	gantry for CO_2 pucks kit (see figure 7)
19/1/2	CO_2 cylinder and dry ice attachment
134/1	motor driven stroboscope
133	camera
1054	film, monobath developer/fixer
1054	P153 daylight printing paper, paper developer, and fixer
	slide projector

Details of suggested experiments appear in the Students' laboratory book. See Nuffield O-level Physics, *Guide to experiments IV*, Appendix I and Appendix II, for details of stroboscopic photography, film development, and the use of daylight printing paper.

The experiment is best assigned to students whose dynamics needs revision. As indicated opposite, it may be omitted in favour of an experiment with an analogue representing inverse square law repulsion. See page 52 for details.

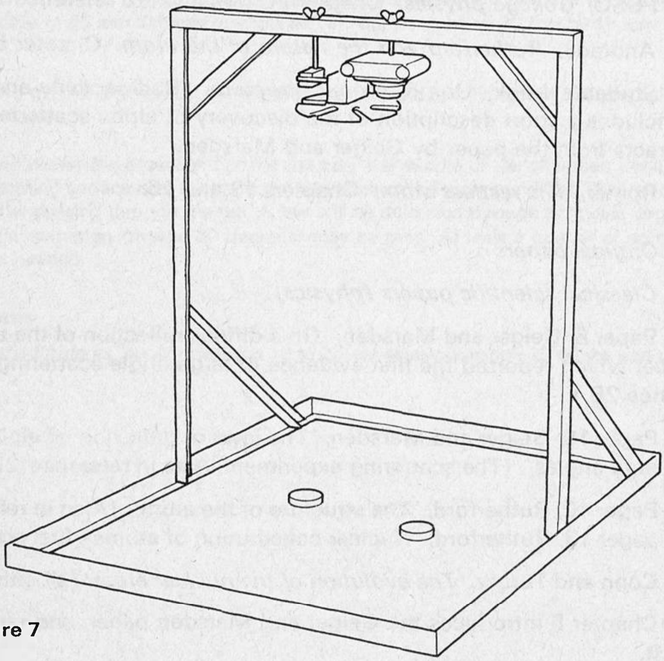


Figure 7

Problems

Choose one from the *Students' book*, questions 19 to 25, especially question 22 on the dynamics of a nuclear collision.

Experiment

5.7 Collisions between pucks in two dimensions

This experiment provides revision, if it is needed, of ideas required for the discussion of collisions of alpha particles with massive nuclei, with helium nuclei, and with protons. The last is used in experiment 5.8, the first two in discussion in Part Two.

The essential ideas are those of momentum conservation applied to elastic collisions. Students will need to know that the particles need not touch in order to 'collide', and for this purpose the magnetized pucks are ideal. The low recoil velocity of a massive 'target', the high recoil velocity of a 'target' less massive than the particle which hits it, and the right angle between the paths of 'target' and 'bullet' when the masses are equal and the target was originally at rest, are all needed.

If such ideas are already clear, demonstration 5.14a, the gravitational analogue of inverse square law repulsion, is a possible substitute for experiment 5.7

Suggested reading

The reading to go with experiments 5.6, 5.7, and 5.8 can very naturally be of reports of the alpha particle scattering experiment suggested by Rutherford and performed by Geiger and Marsden, or of accounts of the significance of the experiment. A list of references, from which one item needs to be chosen, appears with experiment 5.6.

Alternatively, reference 6, Gentner, Maier-Liebnitz, and Bothe, *An atlas of typical expansion chamber photographs,* is well suited to this experiment. In this, figures 28–32 show collisions of alpha particles with nuclei of differing masses. Figures 36–38 are of interest, showing collisions between electrons. Figure 87 is one of the famous early transmutation photographs obtained by Blackett and Lees.

Source of bubble chamber photographs

As an optional and rather expensive extra item, schools might consider obtaining 'Introduction to the detection of nuclear particles in a bubble chamber'. (For details see the list entitled 'Films, film loops, and visual material' on page 124.) This contains fourteen stereoscopic transparencies of bubble chamber events and a simple viewer. Only frame 2, showing multiple proton scattering, with several right-angle forks seen in three dimensions, is of direct interest in this course. The curvature of paths in magnetic fields, especially the picture of a spiralling electron in frame 1, is of some interest in Unit 7.

Experiment

5.8 Knock-on of protons by alpha particles

28	diffusion cloud chamber
47	illuminant
27	transformer
19/1/2	CO_2 cylinder and dry ice attachment
1056	methylated spirit
195/3	pure alpha source
1053	expanded polystyrene sheet, 10 mm thick (see below)
1053	pins, 20 mm long (see below) *4*
1053	polythene sheet (see below)
1055	cork borer

Details for students appear in the *Students' laboratory book.* They assume that the special source holder described below has been made up.

Construction of special source holder The source holder has to contain the 5–10 μCi alpha source within the chamber, behind a polythene sheet, in such a way that ions from the source do not swamp the chamber, and that the temperature gradient in the chamber is undisturbed.

Figure 8 shows a suitable form of construction. The holder is built from two pieces of expanded polystyrene sheet 10 mm thick and cut to about 15 mm on a side. One has a 4 mm hole to take the 4 mm plug on the source; the other is bored with a hole just large enough to take the wide end of the source.

The two pieces together contain the source, which is covered with a small square of polythene sheet, and the whole held together with pins at the corners. The polythene must be *just* thick enough to stop all the alpha particles from the source. Polythene from food bags is often suitable. Make one very small pin prick in the centre of the polythene.

Observations The source in its holder is placed on the floor of the chamber and to one side, where the usual source normally goes. An occasional alpha particle emerges from the pinhole. Its short range and dense track help identification of the occasional long-range, less dense, fast proton tracks emerging from the polythene.

Problems

Choose one from the *Student's book,* questions 19 to 25, especially question 22 on the dynamics of a nuclear collision.

Experiment
5.8 Knock-on of protons by alpha particles

An alpha particle is four times more massive than a proton, if the identification of alpha particles with helium is correct. It follows that if an alpha particle hits a proton nearly head on, the proton will be knocked on at a high velocity.

Polythene is rich in hydrogen, and so in protons. Fast proton tracks can be observed emerging from a sheet of polythene held in front of a source of alpha particles. The proton tracks have a longer range than the alpha tracks.

The experiment has value in helping to confirm the story about the masses of the particles involved, in letting students see a sub-atomic collision process, and in raising once again the basic dynamical ideas involved.

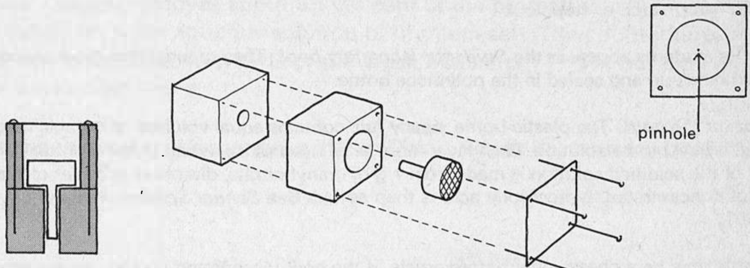


Figure 8
Special source holder.

Suggested reading

The reading to go with experiments 5.6, 5.7, and 5.8 can very naturally be of reports of the alpha particle scattering experiment suggested by Rutherford and performed by Geiger and Marsden, or be of accounts of the significance of the experiment. A list of such references, from which one item needs to be chosen, appears with experiment 5.6.

Figure 28, in reference 6, Gentner, Maier-Leibnitz, and Bothe, *An atlas of typical expansion chamber photographs,* shows a proton knocked on by an alpha particle travelling in wet hydrogen gas.

Alternatively, the paper on the identification of alpha particles with helium nuclei by Rutherford and Royds makes suitable reading. Their paper is reference 1B, *Classical scientific papers (physics),* Paper 4. Reference 5A, Project Physics, Reader, *Unit 6,* also reproduces the paper.

Experiment

5.9 Decay and recovery of protactinium

130/1	scaler
130/3	GM tube holder
130/5	thin window GM tube
1055	polythene bottle (50 cm³)
1056	uranyl nitrate
1056	concentrated hydrochloric acid
1056	isobutylmethylketone (2-methylbutan-3-one) *or*
1056	amyl acetate
503–6	retort stand base, rod, boss, and clamp
507	stopwatch or stopclock

Details for students appear in the *Students' laboratory book.* They assume that the solutions are provided made up and sealed in the polythene bottle.

Contents of the bottle The plastic bottle, nearly full, contains equal volumes of organic reagent and acidified uranyl nitrate solution. Each layer must be as deep as the width of the GM tube window. Each 10 cm³ of the acidified solution is made from 1 g of uranyl nitrate, dissolved in 3 cm³ of water, to which 7 cm³ of concentrated hydrochloric acid is then added. See *School Science Review,* **45**, 157, page 601.

The bottle may be a cheap, chain-store article, if the cork washer and plastic cap are protected by a sheet of thin polythene screwed under the cap. This also prevents leakage. A better quality bottle, with a snap-on polythene cap, will leak less easily, but the walls must be thin or many beta particles will be stopped by them, and count rates will be undesirably low. Glass bottles are too thick, usually, and polystyrene bottles are attacked by the contents of the bottle.

Observations The bottle is shaken for 10–15 seconds and placed at once beside the GM tube so that the window of the tube is opposite the top half of the bottle, as in figure 9. As soon as the layers have separated, the scaler can be started, and counts taken at 10-second intervals without stopping it. Or a 10-second count can be taken every half minute. A ratemeter is an acceptable substitute.

To observe recovery, repeat with the GM tube window opposite the lower layer, or, for a better count rate, turn the GM tube so that its window faces upwards and stand the bottle on top of the tube.

Problems

Choose one from the *Students' book,* questions 9 to 18.

Experiment

5.9 Decay and recovery of protactinium

In this experiment, ^{234}Pa is extracted from a solution containing its parent ^{234}Th and grandparent ^{238}U, with which it is in equilibrium. It is extracted by an organic reagent, and the decay of the ^{234}Pa after extraction can be followed. It is also possible to follow the recovery of ^{234}Pa in the solution from which some was removed.

The decay scheme is:

$$^{238}U \xrightarrow[\alpha]{} {}^{234}Th \xrightarrow[\text{low energy }\beta]{} {}^{234}Pa \xrightarrow[\substack{2.32\,\text{MeV}\\ \beta}]{} {}^{234}U \xrightarrow[\alpha]{}$$

	^{238}U	^{234}Th	^{234}Pa	^{234}U
Half-life	4.5×10^9 years	24.1 days	72 seconds	2.5×10^5 years

The organic reagent removes about 95 per cent of the protactinium, some uranium, but no thorium from the aqueous solution of uranium salt. The counter does not detect either the alpha particles from ^{238}U or the weak betas from ^{234}Th, but only records the energetic betas from ^{234}Pa.

This experiment will be of importance in Part Three, which discusses exponential decay.

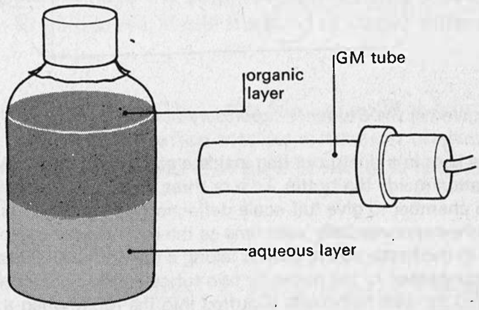


Figure 9
Decay of protactinium.

Suggested reading

The reading to go with experiments 5.9, 5.10, 5.11, and 5.12 can reasonably be about radioactive decay, the randomness inherent in this process, and perhaps a little about transmutation and decay schemes. For each experiment, choose one from the list on page 35.

Experiment

5.10 The decay of radon

1006	electrometer, with $10^{11}\ \Omega$ input resistor	
1008	ionization chamber	
1066	'thoron' generator	
1003	milliammeter (1 mA)	
1033	cell holder, each with four U2 cells	*2*
1000	leads	

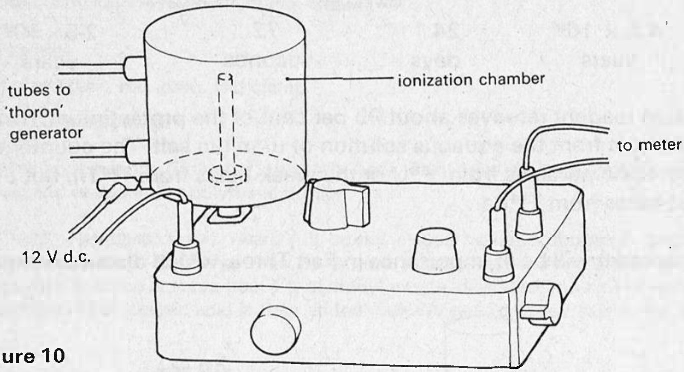


Figure 10
Decay of radon.

Details for students are given in the *Students' laboratory book.*

The thorium hydroxide is kept in a dustproof bag inside a soft polythene bottle, and radon builds up to its equilibrium concentration inside the bottle. Two or three sharp squeezes of the bottle pass enough radon into the ionization chamber to give full-scale deflection – that is, an ionization current of 10^{-11} A. This current then diminishes exponentially with time as the radon in the chamber decays. The radon concentration builds up in the bottle again, maybe taking a few minutes to reach equilibrium. For safety, the chamber should be connected to the bottle by two tubes, so that air circulates between them, and neither radon or powdered thorium hydroxide is puffed into the room when the bottle is squeezed.

The ionization chamber plugs into the electrometer input socket, and has a probe rod running up its centre. The 12 V supply is connected between the ionization chamber and the earthed input of the electrometer. The electrometer is switched so as to measure current. Some ionization chambers are supplied with both solid and gauze covered lids; the solid lid is required.

Problems

Choose one from the *Students' book,* questions 9 to 18.

3 Romer (ed.), *The discovery of radioactivity and transmutation.*

3B Paper 11, Rutherford and Soddy, 'The cause and nature of radioactivity', parts I, II, and V only.

3C Paper 13, Rutherford and Soddy, 'Radioactive change', section 7 only.

7A Arons, *Development of concepts of physics,* Chapter 32.

8 Bennet, *Electricity and modern physics* (MKS version), Chapter 16.

9A Caro, McDonell, and Spicer, *Modern physics,* Chapter 5.

10A Holton and Roller, *Foundations of modern physical science,* Chapter 36.

12 Project Physics, Text, *Unit 6,* Chapter 21.

15A Rogers, *Physics for the inquiring mind,* Chapter 39.

Experiment 5.10 The decay of radon

The experiment tells the same story as does experiment 5.9, and is the less important of the two because the recovery of radon in the parent material is not easy to follow. The experiments together have the value of emphasizing that the exponential decay pattern is common to all decays, while the time of decay differs from material to material.

The ^{220}Rn is descended from ^{232}Th, in the form of solid thorium hydroxide, kept in a plastic bottle. The radon gas is puffed into an ionization chamber, and the ionization current is measured at intervals. No GM tube or scaler is required, the electrometer being the detecting instrument.

The decay scheme is:

$$^{232}\mathrm{Th} \xrightarrow{\alpha} {}^{228}\mathrm{Ra} \xrightarrow{\beta} {}^{228}\mathrm{Ac} \xrightarrow{\beta} {}^{228}\mathrm{Th} \xrightarrow{\alpha} {}^{224}\mathrm{Ra} \xrightarrow{\alpha} \boxed{{}^{220}\mathrm{Rn} \xrightarrow{\alpha} {}^{216}\mathrm{Po} \xrightarrow{\alpha}}$$

	^{232}Th	^{228}Ra	^{228}Ac	^{228}Th	^{224}Ra	^{220}Rn	^{216}Po
Half-life	1.4×10^{10} years	6.7 years	1.1 hours	1.91 years	3.6 days	52 seconds	0.16 second

Note that the ^{220}Rn decays into ^{216}Po, which itself decays, also by emitting an alpha particle, with a very short half-life. In experiment 5.15 in Part Three, students will be able to observe the pairs of alpha particles originating from each ^{220}Rn decay. This experiment could be taken now, but it seems best to arrange that all students can see it, so it has been suggested as a class experiment in Part Three.

Suggested reading

The reading to go with experiments 5.9, 5.10, 5.11, and 5.12 can reasonably be about radioactive decay, the randomness inherent in this process, and perhaps a little about transmutation and decay schemes. A list of suitable references appears with experiment 5.9. Choose one for each experiment.

Experiment

5.11 Radioactive decay analogue

1055 die *100*

1054 graph paper

Details appear in the *Students' laboratory book,* together with an explanation of why the experiment may be thought worth while.

The dice need to be kept in a box, so that they may be shaken around before casting them out on the table. At each throw, those with one particular face uppermost are removed, and the number left is counted. Those left are then returned to the box for another throw. Up to ten throws may be needed before the supply of dice is pretty well exhausted. The 'half-life' is between three and four throws.

Figure 11 illustrates the result that may be expected, idealized a good deal. Fluctuations are substantial. They can be reduced by repeating the exercise several times, and averaging.

Problems

Choose one from the *Students' book,* questions 9–18.

Film

The PSSC film 'Random events' is of considerable interest, and could be used here, or in Part Three. It is excellent, but not essential.

Randomness

Randomness, emphasized here and in experiment 5.12, will be needed as a concept later in the course. Unit 9, *Change and chance,* is almost wholly built around the idea. Unit 10, *Waves, particles, and atoms,* needs it too, in a less obvious but equally important way. Students ought to be told that the ideas, seemingly rather trivial, will be of great service later on.

Experiment

5.11 Radioactive decay analogue

The particular point of this experiment is to bring out that a collection of objects, each of which has a fixed chance of decay in a given time, will, as a result of the random selection of those which decay in any interval, diminish in number according to the exponential pattern found for radioactive decays. This will be important in Part Three.

One analogue uses dice, as suggested opposite, and has the advantage that dice are strongly linked in a student's mind with random events. Indeed, 'like the throw of dice' is what 'random' probably means to most people. Other analogues, such as those using many ball bearings rolling down a slope, give smoother exponential curves and logarithmic lines, but it is usually less clear how a *constant* chance of decay is built into the analogue.

Devices employing water running out of tubes are *not* recommended, because they involve no random element.

The suggested experiment simply involves throwing a large number of dice onto a table several times. Each time those that fall with, say, five pips uppermost are removed, being supposed to have 'decayed' in the 'time interval' represented by one throw of all the dice. Graphs of the number of dice remaining, and of the logarithm of that number, are plotted against 'time', that is, against the number of throws.

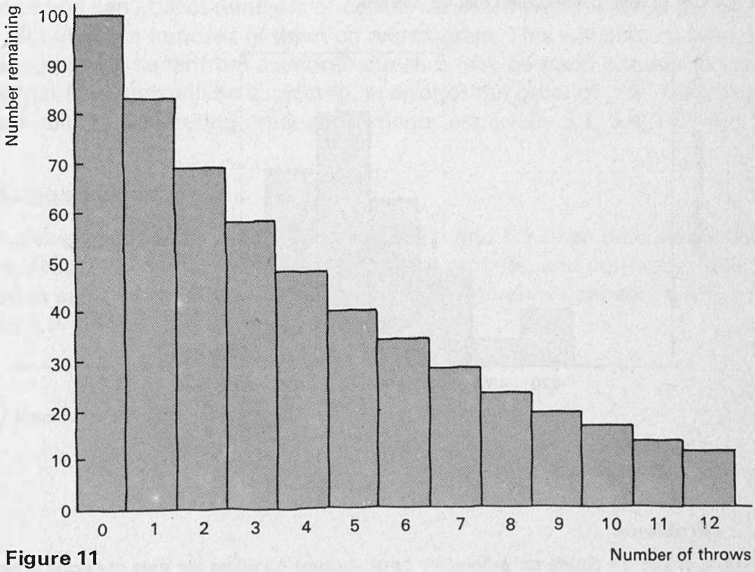


Figure 11
Decay of dice.

Experiment 5.12 Random variation of count rate

130/1	scaler
130/3	GM tube holder
130/5	thin window GM tube
16	radium source *or* item 195/1 *or* 195/2
196	source holder
507	stopwatch or stopclock
503–6	retort stand base, rod, boss, and clamp

Details are given in the *Students' laboratory book.*

To obtain results which show a good spread in values, within a reasonable time, the count rate must be neither too high nor too low. It is suggested that the source position be adjusted until the rate is around 50 per second. Then in a ten-second interval there will be about 500 counts, with a standard deviation of the order of 20 counts. If the interval is mistimed by 0.2 second, the resulting error in the count will only be about half the standard deviation.

It is possible for a nimble pair of students to take a count in every alternate ten-second interval, using the intervening interval to reset the scaler and write down the previous count. 50 such sets of data then take up to twenty minutes to collect.

The experiment is tedious, and should not be pressed upon those who cannot see its point. Figure 12 shows the sort of histogram which can be plotted.

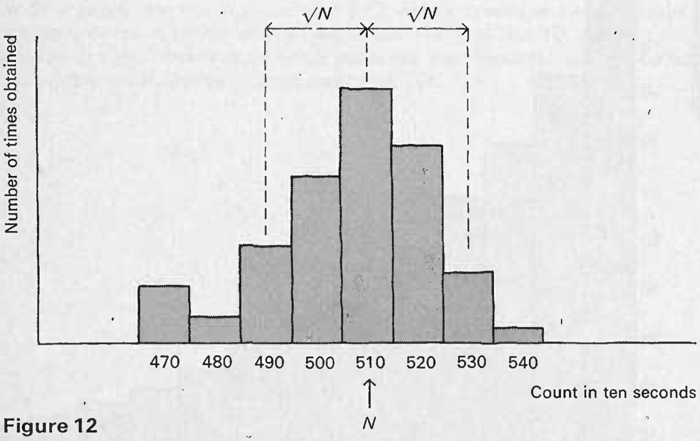


Figure 12
Random variation of counts.

Problems

The instructions in the *Students' laboratory book* suggest handling the data obtained in several ways, and may well be enough by way of problems for this experiment. See also the *Students' book,* questions 9 to 18.

Suggested reading

The reading to go with experiments 5.9, 5.10, 5.11, and 5.12 can reasonably be about radioactive decay, the randomness inherent in this process, and perhaps a little about transmutation and decay schemes. A list of suitable references appears with experiment 5.9. Choose one for each experiment.

Experiment

5.12 Random variation of count rate

This experiment makes a practical point and a theoretical one. The practical point is that reliable values of the number of counts in a second from a radioactive source can only be obtained by waiting until a large number of counts has accumulated. The theoretical point, no less important, but harder to make in a short time, is that the evidence that individual radioactive decays are random must come from seeing whether the numbers that are observed in different times fit the numbers that would be observed if chance alone were deciding when atoms should decay.

Strictly, the theoretical point can only be made by showing that the numbers counted within a fixed time fit a Poisson distribution. The labour of arguing out the shape of the distribution and of collecting the data to check it is too great, so a more rough and ready approach is needed.

At least, students can collect numbers of counts obtained within a fixed period of time, and plot fifty or a hundred of them on a histogram. This will show a marked spread, though it will be far from a smooth curve. It may be good enough to justify the rough rule that N counts will be subject to an error of the order of $\sqrt{N}$. This result is needed as a help in interpreting other experiments, especially 5.1, 5.4, 5.9, and 5.11.

Suggested reading

The reading to go with experiments 5.9, 5.10, 5.11, and 5.12 can reasonably be about radioactive decay, the randomness inherent in this process, and perhaps a little about transmutation and decay schemes. A list of suitable references appears with experiment 5.9. Choose one for each experiment.

Part Two

The Rutherford model of the atom

Time: see page 9. This Part emphasizes and clarifies ideas from Part One, about the Rutherford model. It adds to that work only two extra demonstrations, one optional. The main new item is a quantitative test of the Rutherford model. The work of this Part should take up less than a week of the time taken for the Unit.

Aims of Part Two

General aims and approach

In Part One, students will have done much experimenting and reading of an individual kind. Not all students will have done all the experiments, or have read all the suggested material. This Part aims to bring out for all students one of the central issues of this Unit: the evidence for the Rutherford model of the atom with a small electrically charged nucleus. Part Two can thus serve as a summary of one set of issues from Part One (Part Three deals with another set), and indicate to students which are the important, and which the less important, aspects of the things they have been looking at.

We suggest that much of the teaching can be done by those students who have studied the relevant material or done the relevant experiments. The teacher, besides helping to shape and clarify discussion, can also bring out good and bad features of the students' accounts of their work, as a way of teaching them to read and express themselves more effectively. We hope that if students try to read and experiment, try to use the knowledge gained in discussion with others, and have their efforts criticized (as well as having the implicit criticism of other students who are trying to understand them), that they may make some improvement in the complex skills of learning by themselves which are particularly relevant to one general aim of the course. It is this strategy that leads us to suggest dividing the work in Part One amongst the students, so that they do have to learn from one another.

Other aims

The argument that links the scattering of alpha particles, according to a $1/\sin^4(\phi/2)$ law, with the Rutherford model is an interesting but intricate piece of mathematics. It is tempting to use this with the aim of showing how, in physics, tough and detailed analysis is sometimes needed to link a proposed model to the raw facts of experiment. But we think that this particular piece of mathematics is too fierce for most students, and so do not propose to try to achieve that aim at this point. Teachers who wish to make such a point could, of course, try presenting the argument (see Appendix A).

Instead, we propose the use of a gravitational analogue of the electrostatic inverse square law force around the nucleus, so that the scattering may be investigated empirically. The analogue gives the teacher something fresh to offer, so that Part Two is not all recapitulation. Thus this Part may aim to illustrate again the use of models. It can show that an electrical model of the atom may be conceived, which uses ideas built up in a quite different context (Unit 3, Part Three). It can also show that analogies from other parts of physics – especially the analogy of a potential 'hill' or 'well' – may be very useful as an aid to imagination and prediction. This particular analogy will be used again later on, in Unit 10, *Waves, particles, and atoms,* at the end of the course.

Gravitational analogue

The gravitational analogue was developed as a teaching device at the University of Lancaster. It appears in PSSC *Physics* (second edition) page 599 (*College physics*, page 487).

Single collision

The Thomson model of the atom would only produce small amounts of scattering, so that a large scattering angle would be the chance result of many encounters. The number of large angle scatterings observed, though small, was too big on the Thomson model by a factor of some 10^{30}. Also, as a 'random walk' situation, the number scattered would be proportional to the square root of the thickness of the foil, not, as observed to the thickness.

Rutherford was surprised by the large angle scattering of alpha particles because it directly contradicted the atom model which at that time had the greatest currency – Thomson's model.

Background to the development of the Rutherford model

Students will probably be aware from general reading, from their chemistry, and from Nuffield O-level Physics that people picture atoms as having a small nucleus surrounded by electrons. This Part is about the invention, or 'discovery', of that model by Rutherford in the early years of this century. It is concerned with how such a model may be arrived at from the results of experiments and be supported by them.

The relevant experiments are those which investigate what happens when alpha particles pass through matter, which is why students have, in Part One, spent time looking at the behaviour of alpha particles. Teachers may like to quote Rutherford's own words, from his last public lecture, about the crucial experimental observations. They appear in the *Students' book* in the chapter entitled 'Radioactivity and the nuclear atom' (reference 17).

> 'Now I myself was very interested in the next stage, . . . and I would like to use this example to show how you often stumble upon facts by accident. In the early days I had observed the scattering of α-particles, and Dr Geiger in my laboratory had examined it in detail. He found, in thin pieces (foils) of heavy metal, that the scattering was usually small, of the order of one degree. One day Geiger came to me and said, "Don't you think that young Marsden, whom I am training in radioactive methods, ought to begin a small research?" Now I had thought that too, so I said, "Why not let him see if any α-particles can be scattered through a large angle?" I may tell you in confidence that I did not believe that they would be, since we knew that the α-particle was a very fast massive particle, with a great deal of energy, and you could show that if the scattering was due to the accumulated effect of a number of small scatterings the chance of an α-particle's being scattered backwards was very small. Then I remember two or three days later Geiger coming to me in great excitement and saying, 'We have been able to get some of the α-particles coming backwards. . . ." 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. On consideration I realized that this scattering backwards must be the result of a single collision, and when I made calculations I saw that it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus. It was then that I had the idea of an atom with a minute massive centre carrying a charge.'
>
> *From Rutherford, E. 'The development of the theory of atomic structure', in* Background to modern science *(1938), ed. Needham, J. and Pagel, W., Cambridge University Press.*

To call the discovery an accident does Rutherford's genius less than justice. He saw the deep significance of a result that might have meant nothing to many physicists.

Too much certainty

It would be so easy in this work to convey an idea that physicists had, or have, a very clear understanding of the atom. Teachers will be aware of the limitations of the naïve model presented here, and will need to use their skill to point out these limitations.

An impression of certainty is likely to be reinforced by teaching in chemistry and other subjects, which, for their own good reasons, make it desirable to treat such a model as 'established fact' in order to go on and use it.

Scientists know that a statement such as 'The nucleus consists of protons and neutrons' is treated on some occasions as if it were 'known' to be 'true', but on others as a highly dangerous speculation. Language and pictures lie in wait, ready to trap the unwary into unjustified certainty. 'Fundamental particles' do disintegrate; nuclei, neutrons, and protons, pictured as tiny blobs of stuff, do have wave properties which make them hard to pin down. And these are only the difficulties we know about.

A sixth form student should, we think, be slowly coming to recognize that it is all too easy to say or imagine more than one actually knows.

Questions 34 and 35 in the *Students' book* explore the issue of certainty in science. Students may find the following helpful:

Bronowski, *The common sense of science*.

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

Feynman, *The character of physical law*.

Rothman, *The laws of physics*.

Teachers may like to look at:

Hanson, *Patterns of discovery*.

Popper, *Conjectures and refutations*.

Thomson's model

Thomson's 'plum pudding' model was a more serious affair than many textbooks allow. It was an effort to solve the stability problem; that is, to make up a model that did not conflict with a general theorem, well known for some time, that any static arrangement of point charges could not be stable under electrical forces alone. Teachers can find out more about the model in Boorse and Motz, *The world of the atom*, Vol. 1, page 613.

Electrons in atoms

Teachers can here refer back to Unit 2, *Electricity, electrons, and energy levels,* where evidence for the existence of electrons was discussed. The evidence that all atoms seem to contain one sort of particle – the electron – may need strengthening. It is that the charged particles which can be got from all elements, by heating them or by having an electrical discharge in them, share common properties. The property Thomson measured was the mass to charge ratio, which is discussed in Unit 7, *Magnetic fields*.

Rough numerical estimates

Several times in the course, we have suggested occasions when the importance of rough estimating might be brought out, and when students could try it themselves. It seems a good idea to point to a scientific paper by two masters, Rutherford and Soddy, who do it too.

Discussion of the events and evidence leading to the invention of the Rutherford model

Some such introduction as the above may lead to reports from students who have been reading about the historical background to the problem of the nature of atoms (references 2A, 11A, 15B).

Students also have a summary of the history, in the *Students' book,* under 'Radioactivity and the nuclear atom' (reference 17), so that all students have the opportunity to read a little about it. This summary contains shortened extracts from some of the reading references (reference 3A, the work of Becquerel; reference 3C, the energy of alpha radiation; references 1D, 1E, 2B, the work of Geiger and Marsden). It also contains a short extract from the writing of J. J. Thomson about his 'plum pudding' model of the atom.

Points to bring out in discussion are:

1 The idea of an 'uncuttable' atom is very old, serving to explain the changes of matter from one form to another in terms of rearrangements of atoms that are themselves unchanged.

2 The discovery, by Thomson, that all substances contain identical particles – electrons – showed that atoms might not be 'uncuttable'. It then seemed that they were probably electrical in nature, and that it might be possible to think of the atoms of different elements as being made up of different numbers of the same elementary particles. These ideas date back to Faraday and Prout, of course.

3 The discovery of radioactivity showed that atoms contained large sources of energy, and also provided the tool, in the form of alpha particles, which was to provide new information about the nature of atoms.

4 Some points about the way physics develops may be made. Whether there are 'accidental' discoveries (radioactivity, large angle scattering of alpha particles) may be thought an open question, but there are certainly unexpected discoveries. If these seem to bear on a long standing problem, physicists feel free to speculate about possible applications of the new discoveries to the old problems, even if the speculations are not much supported by hard evidence. Where possible, physicists make numerical estimates, even if they have to be very rough. The Rutherford–Soddy paper (reference 3C), is a good example.

Speculation

Speculation is a respectable activity. Some have wondered whether electricity and gravity have a common origin; indeed Faraday tried some experiments to attempt to discover a link, and more recently theorists have tried to build theories linking them. In a different field, it has been speculated whether the positive and negative charges in atoms might not exactly balance, the difference being responsible for the expansion of the Universe, explained as due to electrical repulsion between large quantities of matter each with a net charge. Present evidence tells against this ingenious suggestion.

Alpha particles – reading references and experiments

Students who have read references 1A, 1B, 7A, 9A, 10A, 15A, 17, 18A (especially 1A and 1B), should have a contribution to make to discussion. Reports from those who have done experiments 5.2 (number of ions from an alpha particle), 5.3 (cloud chamber observations), 5.4 (differences between α, β, and γ radiation), 5.6 (large angle scattering), 5.7 (right-angle forks in collisions), and 5.8 (proton knock-on) will also be relevant.

Right-angle forks

The right-angle fork produced by the collision of a particle with another of the same mass, at rest, was used in the Nuffield O-level course as evidence for the nature of alpha particles. See Nuffield O-level Physics *Teachers' guide V,* page 305.

For photographs see:

Gentner, Maier-Leibnitz, and Bothe, *An atlas of typical expansion chamber photographs* (reference 6).

Lawrence Radiation Laboratory, 'Introduction to the detection of nuclear particles in a bubble chamber' (see page 124).

Lewis and Wenham, *Radioactivity* (reference 19).

Rogers, *Physics for the inquiring mind,* figure 39–10 (reference 15).

a

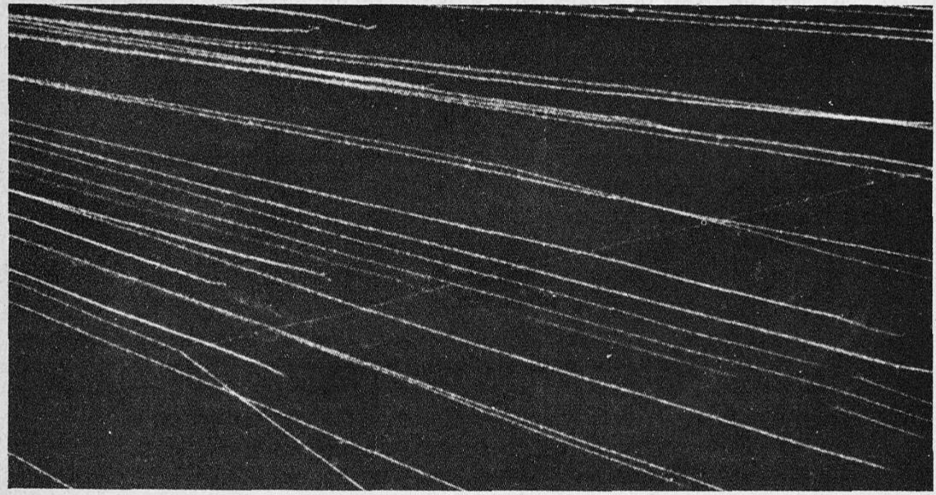


Figure 13

Collisions of alpha particles with (a) hydrogen, (b) helium, and (c) nitrogen.
a *Photograph, Science Museum, London, by courtesy of Blackett, P. M. S., and Lees, D. S. (1932)* Proc. R. Soc. (A) *136, 325.*

The nature of alpha particles – summary of evidence from reading and experiments

Students will know from their reading that alpha particles were the tool used by Rutherford, and by Geiger and Marsden under his direction, to obtain evidence for the nuclear model of the atom. So it is necessary to know what they are, how fast they travel, how much energy they have, and so on. One should also understand how people came to think they might know these things.

Points to bring out in discussion are:

1 The evidence that alpha particles are ionized helium atoms (helium nuclei). Rutherford's and Royds's experiment (references 1B, 5B) and evidence from collision 'forks' in cloud chambers both bear on this point.

If students did experiment 5.7, photographing collisions of pucks, they will have had a question on the theory of the right-angle fork when the masses are equal, with one puck at rest before an elastic collision. Figure 13 shows several alpha particle collisions.

The right-angle fork in helium indicates that an alpha particle has the same mass as a helium atom.

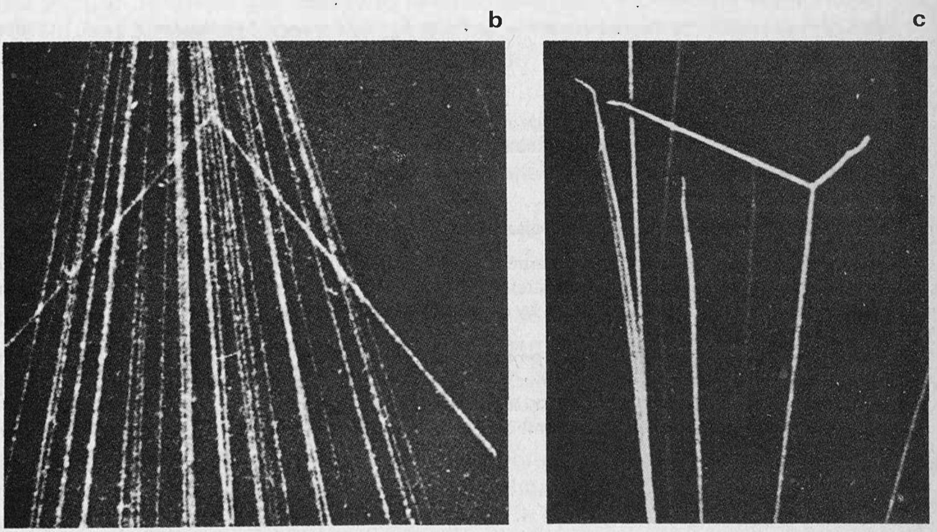


Figure 13 *(continued)*

b *Photograph, Science Museum, London, by courtesy of Blackett, P. M. S. (1925)* Proc. R. Soc. (A) *107, 349.*
c *Photograph, Professor P. M. S. Blackett.*

Students' book

Questions 1 to 3 are general, serving as background to the work on radiation. Questions 4 to 7 concern the energy of alpha particles. Questions 19 to 25 are about scattering and the nucleus. Question 19 is a simplified nuclear size calculation, using scattering data. Question 22 is about the dynamics of collisions.

Relevant reading references and experiments

Energy of alpha particles

Reference 3C especially, and 3D.

Relevant experiments are:

5.2 The number of ions produced by an alpha particle

5.4 The penetrating power of alpha, beta, and gamma rays

Collisions

References 6, 15A, and 19 contain photographs like figure 13.

Relevant experiments are:

5.6 Large angle scattering of alpha particles

5.7 Collisions between pucks in two dimensions

5.8 Knock-on of protons by alpha particles

Students whose tasks included these references or experiments should be able to contribute to the discussion.

Electronvolt

Although not an SI unit, the electronvolt is useful as a unit of energy. See *Students' book,* question 2.

Spinthariscope

If a spinthariscope is available some students might observe the flashes in a blacked-out room. If the dial of a luminous wristwatch is held close to the eye, fluctuations in intensity can be seen. Dark adaptation is essential for both.

Evidence that alpha particles usually pass right through atoms

Experiment 5.2 showed that an alpha particle might produce some 10^5 ions. Experiment 5.3 shows that the track of the particle is nevertheless straight. Experiment 5.6, on large angle scattering, shows that alpha particles usually are not deflected by a thin foil some thousands of atom diameters thick.

The *Students' book,* question 19, has a problem (suggested as part of the task to go with experiments 5.6, 5.7, or 5.8) in which the size of a nucleus is estimated from Geiger's and Marsden's early result that a foil 6×10^{-7} m thick produces one alpha particle in 8000 turned through more than a right angle. This calculation sets an upper limit on the radius of the nucleus, which turns out to be about 6×10^{-14} m.

2 The energy of an alpha particle is of the order of several million electronvolts, that is, of the order of 10^{-13} J per particle. It is worth emphasizing that this is a very large energy for a single atom-sized object to have. Indeed, a single alpha particle can produce a visible flash of light in a fluorescent material. Sample energies are given in table 2.

Isotope	**Range in air at atmospheric pressure, 288 K, in metres**	**Energy of alpha particle in millions of electronvolts**
Uranium 238	2.67×10^{-2}	4.2
Radium 226	3.39×10^{-2}	4.77
Polonium 214	6.95×10^{-2}	7.68
Polonium 210	3.84×10^{-2}	5.30
Polonium 212	8.57×10^{-2}	8.78

Table 2
Energies of alpha particles.

The velocity of an alpha particle of energy, say, 1 MeV, is worth calculating. It is also amusing to compare the energy of an alpha particle with that of a rifle bullet on a mass for mass basis (that is, as if they had the same energy per kilogramme).

3 Although alpha particles do make collisions with atoms in gases or foils, and these collisions turn their paths through large angles, the most important first observation is that they usually pass straight through. The alpha particle appears to tear through 10^5 or so gas molecules without being much deflected, and through 1000 or more metal atoms in a row. In the metal, there is not much space between the atoms, so how could the particle get through? Perhaps an atom is mostly 'empty space'.

The rarity of 'major' collisions suggests that there may be a very small massive centre to an atom – the nucleus. Students can report their observations on scattering.

The occasional turning of an alpha particle through a large angle was discovered by Geiger and Marsden.

In a short time Rutherford saw a possible explanation. There was something in the way, but it was so very small that it was not often hit directly. It also had to be massive. Why? (Alpha particles have the mass of light atoms, and travel fast. Anything less massive than an atom would be knocked straight on.)

The experiment on the knock-on of protons, reported by those who did it, may lend force to this interpretation, but need not be emphasized too much. The alpha particles bombard a polythene film. The polythene is rich in hydrogen, so that occasionally a long track may be seen, quite different from an alpha track, as a proton flies across the chamber after being kicked out of place. If hydrogen atoms are four times less massive than alpha particles, the high velocity of knock-on is to be expected.

Optional demonstration

5.13 Magnetic deflection of alpha particles

16	radium source (5 μCi)
130/4	solid state detector and pre-amplifier
130/1	scaler
13	vacuum pump
8H	rubber bung (bromine diffusion kit)
1055	glass T-piece (outside diameter 9 mm), limb length 20 mm
1055	PVC tubing (outside diameter 12 mm, bore 8 mm), 150 mm in length
1055	glass tubing (outside diameter 8–9 mm, standard wall), 120 mm in length.
1055	rubber or PVC tubing (outside diameter 8 mm, bore 5 mm), small piece
50/3	magnet Eclipse Major
503–6	retort stand base, rod, boss, and clamp *2*
1053	razor blade

Construction Join the length of PVC tubing to the glass T-piece and the glass tube, with a 10 mm overlap. To make an airtight joint, soften the end of the PVC in boiling water, push it over the glass, and allow to cool. Take care when joining the solid state detector to the system. Do not allow anything to touch the gold surface, and do *not* push hot, wet PVC tubing onto the detector. It is necessary to form the end of the PVC tube first with a suitable glass tube or rod until it has the correct bore.

Figure 14 shows the construction of the apparatus.

Use Before inserting the source, clamp the bung and the glass tube so that the tubes are in a straight line, as checked by looking down them. Then insert the source and pump air from the apparatus. Do *not* connect the detector to its pre-amplifier, which applies a bias to it, while the air is being removed or let in.

When the air has been removed, connect the detector to the pre-amplifier and the pre-amplifier to the scaler. A count rate of about 30 per minute may be expected.

Now raise the clamp holding the glass tube by about 10 mm, bending the PVC tube into a shallow arc, until the count rate just falls suddenly as alpha particles no longer reach the detector.

Then place the magnet around the bent PVC tube so as to provide a horizontal magnetic field. If the count rate is not partially restored, turn the magnet round. If no effect is seen, the detector has probably been raised too far.

Film of the Geiger and Marsden experiment

The Nuffield Advanced Physics project collaborated with Rank and Mullard to produce the film 'The Rutherford model of the atom', in which Geiger's and Marsden's experiment is repeated. The film uses school apparatus as far as possible, though the source needed is far too strong for school use. Results are taken at several angles, and the film shows that the variation of number of particles with angle is the same as that which would be expected if the force between nucleus and alpha particle followed an inverse square law.

Mathematical theory of Rutherford scattering

The theory is given in Appendix A for teachers who want it to hand. A few students might appreciate seeing it.

Optional demonstration

5.13 Magnetic deflection of alpha particles

It may help, in summarizing the evidence for the nature of alpha radiation, to show that alpha particles can be deflected by a magnetic field. The small amount of deflection obtained is the most important point.

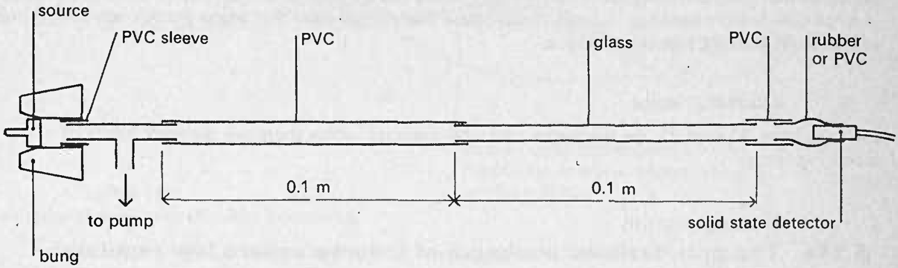


Figure 14
Magnetic deflection of alpha particles.

The Rutherford model: scattering by a charged nucleus

Thomson's work seemed to show that atoms contain negatively charged electrons. Rutherford's idea was that the positive charge in an atom was concentrated in a small space, and was responsible for the large angle scattering of alpha particles.

He could not know that this was the only force responsible, or that the inverse square law would still work down to these very small distances, but he had to make some such assumptions in order to have something definite to test. It was this idea, together with these assumptions, worked out in the form of testable consequences, that Geiger and Marsden set out to check by a careful study of the number of alpha particles scattered in varying directions. Their experiment has been repeated on film.

The central point to test was, did the scattering behave as it should do if the particles were being acted on by an inverse square law? The path of an alpha particle could not be followed in detail. All that could be observed was the direction in which the particles went into a foil, and the numbers coming out in various directions. The test had to be indirect, relating the pattern of those numbers to the expected inverse square law behaviour. Many such tests in physics have to be indirect. This one will take some effort to understand, even though it is not proposed to examine the theory in any detail.

The path of an alpha particle near a charged nucleus

The motion of a charged bombarding particle as it swings round close by a repelling nucleus is rather hard to calculate. But it can be simulated by a model of the situation, which uses gravitation to produce the repelling force. The gravitational analogue hill may be produced. See figure 16.

Reading about the Rutherford model from Part One

The particularly relevant references are 1D, 1E, 1F or 2B, 2C, 2D from papers, and 7B, 9D, 10B, 11B, 13, 14, 15B, 18C from textbooks.

The teaching in Part Two amplifies what students will have got from their reading. The particular point that will need especial attention is the way in which the detailed results of alpha particle scattering give evidence that the scattering force follows an inverse square law. This may, but very likely will not, emerge clearly from reading, though students are likely to be clear that alpha particle scattering provides evidence for a small, massive nucleus.

Students' book

See questions 21 and 23, on the paths taken by particles when there are different kinds of scattering force.

Demonstration

5.14a The gravitational analogue of inverse square law repulsion

1028 alpha scattering analogue

1054 graph paper

1055 drawing board

95B wedges *4*

1055 spirit level

71 lycopodium powder

At the time of writing, these gravitational analogues are only available as metal spinnings, and are too expensive to recommend in quantity. It is hoped that they may soon become available as plastic mouldings, and be cheap enough for a school to have one between, say, four students.

Use of the hill Allow the ball to roll down the chute and on to the hill. To avoid a bounce at the lip of the hill, it may be necessary to place the bottom of the chute against the hill. An attempt to aim the ball directly at the centre, so that it rolls up and back again, will at least reveal that the angle through which the ball's path turns depends on the direction of aim.

Qualitative test: angle and speed Fix the chute so that a ball rolled from the top is deflected by a small amount, say 30°. Then roll the ball from lower down the chute, when it will be deflected more. The comparison of this result with those of Geiger and Marsden for scattering at different velocities, may have the advantage of starting discussion about the connection between the motion of one ball on the hill and the scattering of many alpha particles falling in a random hail on many atoms.

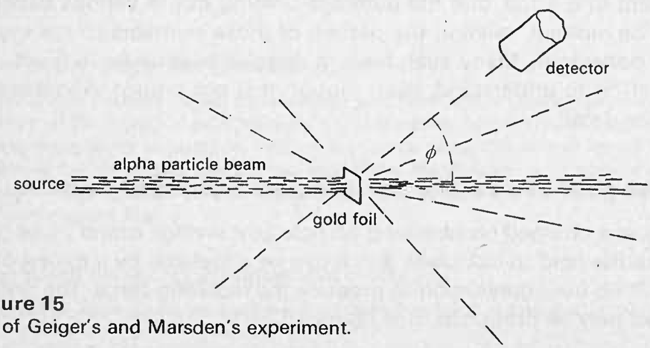


Figure 15
Rough sketch of Geiger's and Marsden's experiment.

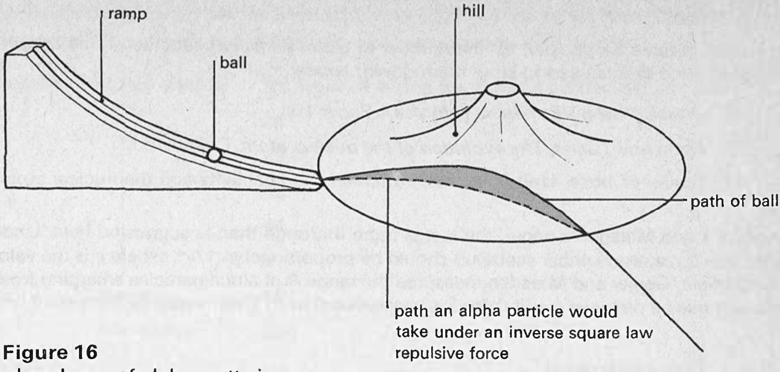


Figure 16
Gravitational analogue of alpha scattering.

Demonstration
5.14a The gravitational analogue of inverse square law repulsion

How will a ball rolled onto the hill travel? Try it, and see how the path changes as the direction of aim is changed. Questions about the energy of a ball rolled straight up the hill (*no swerving – hard to do) can bring out that the ball would stop where its* potential energy became equal to the original kinetic energy. Students may recall from Unit 3 that in an inverse square law electric field, the potential energy varies as $1/r$. Here is yet another occasion when a bit of one kind of physics proves useful elsewhere: indeed, if ions and nuclei were not very much like point charges it might well not be worth learning about the electrical inverse square law.

The hill has been manufactured so that a ball climbing it has potential energy that varies as the reciprocal of the distance from the centre. The hill has a $1/r$ shaped profile.

A qualitative test

If the ball is rolled more slowly at the hill, it is deflected more, even though the aim is kept the same. The path of a single alpha particle cannot be observed. But students should be able to report from their reading that Geiger and Marsden allowed a random hail of alpha particles to fall on the many atoms in a foil and observed how many were seen by a detector set at various angles, as suggested in figure 15.

Geiger's and Marsden's apparatus appears in references 1E and 2B, and in the *Students' book*, under 'Radioactivity and the nuclear atom' (reference 17).

On the hill analogue, a ball turns through a bigger angle if it runs more slowly. If the hill is a good model, that is, if alpha scattering does depend on an inverse square law force, a slow moving alpha particle should be turned through a bigger angle than a fast moving one, if both happen to pass equally near a nucleus.

Sources of data

The results in table 3 opposite, for the number of alpha particles scattered at one angle against the number of mica sheets used to slow them down, appear in:

1E *Classical scientific papers (physics),* Paper 10.

2B Conn and Turner, *The evolution of the nuclear atom,* Chapter 5.

17 Students' book, Unit 5, *Atomic structure,* 'Radioactivity and the nuclear atom'.

In Geiger's and Marsden's paper, the test is more thorough than is suggested here. Under an inverse square law force, the number scattered should be proportional to $1/v^4$, where v is the velocity of the alpha particle. Geiger and Marsden measured the range R of alpha particles emerging from the layers of mica, and used a previous result that v^3 is proportional to R. Their results confirm the $1/v^4$ prediction.

Demonstration

5.14b The number of particles scattered at various angles

In this test, which is quantitative, the ball bearings are aimed so that they would have passed at various distances p from the centre of the hill (figure 17) and the angles ϕ through which they turn are recorded.

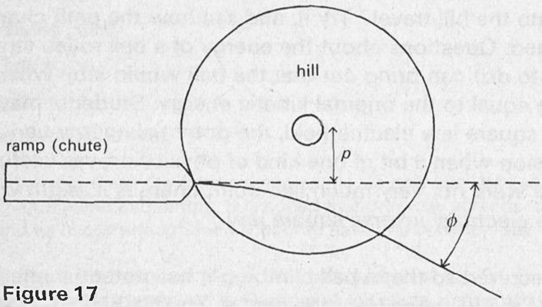


Figure 17

The graph paper is pinned to the board and then levelled. The 'hill', placed so that its centre is above a convenient intersection of rulings on the paper, is outlined with a pencil to locate its position. The ramp should be positioned parallel to various rulings and just touching the hill so that the ball bearing may be rolled down the ramp at various known aiming errors p ranging from 10 mm to about 60 mm. The ball is now released from the same point on the ramp at various aiming errors p. The height of release should be chosen so that the scattering angle ϕ is at least 120° when p is at its smallest, say 10 mm.

It will be found that there is quite a large spread in scattering angle, especially at large angles, which does not vanish even if the greatest care is taken over releasing the ball. It is convenient to place a pin in the ramp as a stop so as to achieve reproducible release conditions. A simple technique for observing the scattering is to dust coloured chalk or lycopodium powder over the paper, and to roll the ball several times at each value of p. The tracks can be seen (edge on to the board) as clear straight swathes through the powder, and it is quite easy to lay a ruler along a 'mean' path direction and draw a 'mean' path. The amount of the variation in an angle can also be observed, and recorded. Such variation is very small at large p, but is extremely noticeable at small values of p, and it is not worth going below 10 mm aiming error.

It is reported that the kind of carbon paper supplied for copying handwriting (not typing) will record the path of a ball rolling over it, which eliminates the need for messy powder.

So Geiger's and Marsden's results should show that if the alpha particles are slowed down, a bigger proportion of them are turned through any one angle.

Number of mica sheets		Number of alpha particles counted per minute
0		24.7
1		29.0
2		33.4
3		44
4		81
5	speed	101
6	decreasing	255

Table 3

From table VII of Geiger, H. and Marsden, E. (1913) 'The laws of deflexion of alpha particles through large angles.' Phil. Mag. (6), ***27**, pages 604 to 623.*

Table 3 is extracted from Geiger's and Marsden's results. It confirms the expected variation of number scattered with speed. The alpha particles were slowed down by making them go through a varying number of thin mica sheets. The greater the number of sheets, the slower the speed.

The gravitational analogue, and so the inverse square law, pass this qualitative test. The analogue can next be used in a more quantitative test.

Demonstration

5.14b The number of particles scattered at various angles

When the ball is rolled along paths which would pass a distance p from the centre of the hill, the smaller p, the larger the angle ϕ through which the ball's path is turned.

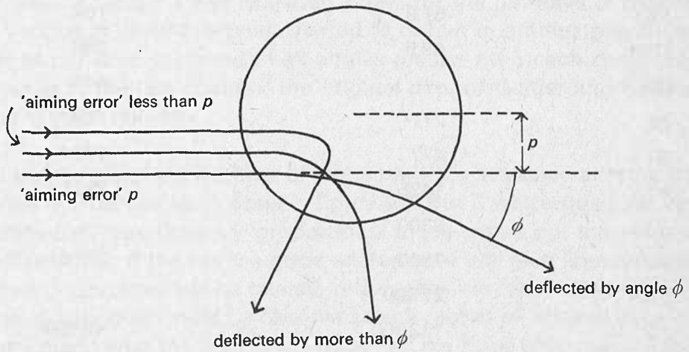


Figure 18

Figure 18 shows the paths of balls on the hill, as p is varied. The paths are essentially two-dimensional, but an alpha particle can go above and below, as well as to the side of a nucleus. Figure 19 illustrates possible alpha particle paths in three dimensions.

Mathematical theory of scattering

Appendix A gives a version of the scattering theory, for teachers to see. A few students may like to look at it.

The full theory shows that a particle aimed at a distance p from the nucleus will swing through an angle ϕ where p is proportional to cot $(\phi/2)$, if the force is inverse square. The hill gives a fair straight line plot of ϕ against cot $(\phi/2)$. The number scattered at more than an angle ϕ is proportional to $\cot^2(\phi/2)$, and this is the form of the graphs suggested opposite.

A detector of fixed area set at various angles ϕ intercepts different proportions of the particles scattered at angle ϕ as ϕ changes. The net effect of this solid geometry is to make the number detected proportional to $1/\sin^4(\phi/2)$. It is this relationship that can be tested directly with scattering data. We have chosen to manipulate the data so as to avoid the troubles with solid geometry.

Appendix B shows how the numbers of particles scattered at more than angle ϕ, given in table 4, were calculated from Geiger's and Marsden's data. Note that it is not a simple matter of adding up, because the detector intercepts a different proportion of the particles scattered at angle ϕ as ϕ varies.

Students' book

The data calculated from Geiger's and Marsden's results appear in the chapter entitled 'Radioactivity and the nuclear atom'. The diagrams in this section may assist in the argument opposite, which is summarized in that chapter.

Angle ϕ in degrees	Number of particles detected in fixed time at angle ϕ (Geiger and Marsden)	Numbers proportional to number of particles scattered at more than angle ϕ
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	27300	—
15	132000	45800

Table 4

The essential point is that it is still true that a particle aimed at a distance from the nucleus smaller than p will be deflected by an angle larger than ϕ, but such particles will be those which fall within an *area* of radius p. (For the hill, those scattered by more than ϕ fell within a width $2p$ either side of its centre.)

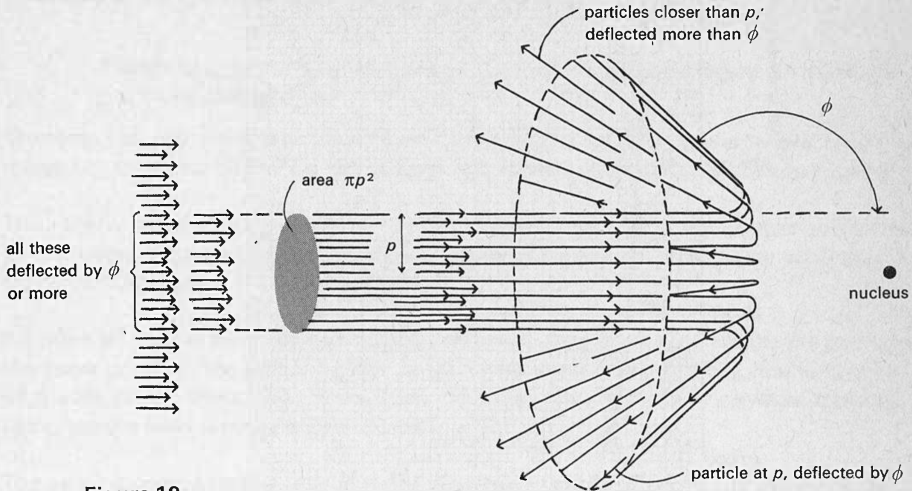


Figure 19

Test of the inverse square law analogue

The area of a circle of radius p, through which particles pass that will be scattered by more than ϕ, is πp^2. If the incoming hail of particles allows equal numbers to fall everywhere, the number passing through area πp^2 will be proportional to p^2.

This can be used to link results got with the hill to those recorded by Geiger and Marsden. In table 4 Geiger's and Marsden's data for the numbers of particles detected at various angles have been treated to obtain quantities proportional to the total number of particles scattered at all angles greater than each specified angle. The latter appear in the last column; the original data of Geiger and Marsden appear in the second column.

A graph can be plotted of the number of alpha particles scattered at more than any angle ϕ against ϕ. This has been done in figure 20. But it was argued above that the number scattered at more than ϕ is proportional to p^2, where p is the aiming error that leads to a deflection ϕ. If the hill is a good analogue, it will give corresponding pairs of values of p and ϕ which would be related in the same way as similar values for an alpha particle, if only they could be observed. So a plot of p^2 against ϕ for measurements made with the hill should have just the same shape as the graph of the number scattered at more than ϕ against ϕ, taken from alpha scattering data.

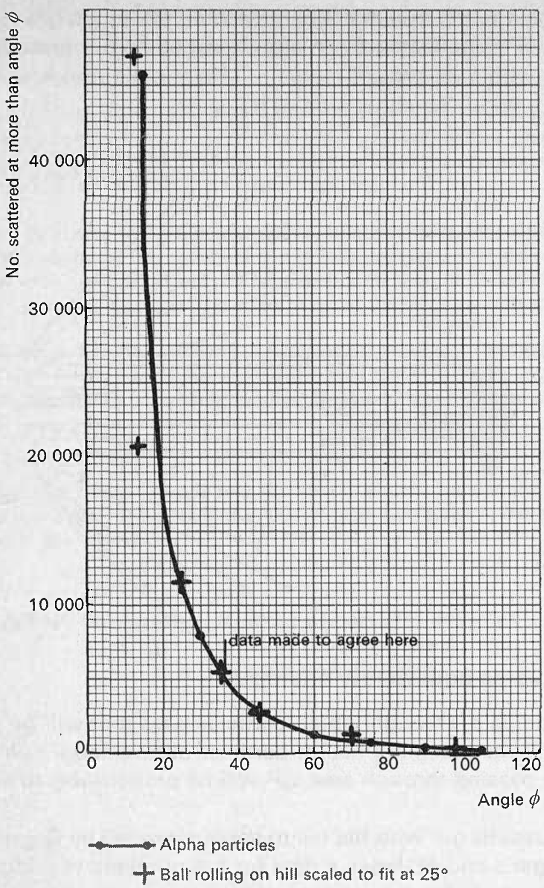


Figure 20
Comparison of Geiger's and Marsden's results with the gravitational hill analogue.

Inadequacies of the gravitational analogue

The hill model is not perfect, of course. The ball rolls on it, and its spin energy and momentum will make its path differ from that of a projectile in a $1/r$ potential. The hill cannot extend out as far as it should, so that the weak field area at large r is missing. This matters for small angle deflections because the ball would spend a long time in this weak-force region and would be appreciably deflected (a few degrees). Some energy is lost by the ball as it rolls. The centre of gravity of the ball is some distance above the surface, and is not at the same distance from the centre of the hill as the point where the ball touches the hill. The rolling ball has a vertical component of velocity. These remarks are made here so that teachers may introduce a proper note of caution when, as is to be hoped, pupils question the adequacy of the model.

Students' book

See questions 24 and 25 which involve calculations of the electrical energy changes when an alpha particle is scattered by a charged nucleus.

If the force is truly inverse square, and if the hill is a faithful analogue of such a force, the two graphs should agree. The two sets of data will have to be brought onto a common scale – there is no simple way of telling what alpha energy and what nuclear charge the hill and ball experiment represents. So it is necessary to make the two lots of data fit at one point, and see if the rest fall into line.

Plotting graphs to test the agreement of the analogue with alpha particle scattering

Students can plot the last column of the alpha scattering data against angle, over the range 15° to about 100°. The hill data are too variable near 180° to be worth using.

Then the value of p^2 for the hill should be compared with an alpha particle value read off the curve at some middling angle, about 45°, and multiplied to agree with the alpha particle value.

All other p^2 values are then multiplied by the same factor, and the results plotted onto the same graph as the alpha particle curve. There should be a good agreement, with all the hill points lying close to the curve. This has been done on the graph opposite using results from an experiment with the hill.

The small discrepancies at 10° and 15° arise because the hill does not extend to very large distances. At its lip it is still 10 mm or so above the level it would reach at large radii.

What does the test mean?

To test the speculation that an alpha particle might be swung round near a nucleus by an electrical force varying as $1/r^2$, a large-scale model of such a situation was made, using a hill and gravity to supply the force. Tests show that a ball rolled on such a hill is scattered in just the way that an alpha particle is scattered by a nucleus. There is support, therefore, for the view that the forces exerted by a nucleus follow an inverse square law down to distances right inside an atom.

An 'electrical' atom

The calculation opposite is meant to emphasize that when a model like Rutherford's can be made more than a descriptive picture, and can be made to fit in with other quantitative knowledge – about the electrical inverse square law in this case – it becomes possible to extract much more information from it. Trivial seeming experiments with charged polystyrene balls (Unit 3) make possible calculations of forces deep inside the atom, when a model links the two together.

The point is worth making because this linking together is so characteristic of physics. Understanding the nature of inquiry calls for this kind of general grasp of the way the subject works, and is as much a part of the course as detailed knowledge of what the Rutherford model is.

Guesses

Students sometimes do not like making guesses, but it is worth encouraging them to practice, if only because of their surprise at the size of the answer.

Part Four

In Part Four, alpha scattering will again be taken up, this time to describe in outline the evidence for the charge Ze on a nucleus of atomic number Z, which was assumed in the calculation opposite.

An electrical calculation of the size of a nucleus

If it is true that inverse square law electrical forces act right down to the closest distance an alpha particle comes to a nucleus, then a nucleus must be smaller than that distance.

How close would a 5 MeV alpha particle come to a gold nucleus in a head-on collision? The initial kinetic energy of the alpha particle is 5×10^6 eV or 8×10^{-13} J If it collides head on, it will pause at a distance r where all the kinetic energy is converted into electrical potential energy. Gold is element number 79: if it is true that the nucleus of gold has 79 electron charges, while an alpha particle, the nucleus of element number 2, has 2 charges, both positive, the potential energy of the alpha particle is:

$$\text{potential energy} = \frac{(2e)\ (79e)}{4\pi\varepsilon_0 r} \text{ where } \frac{1}{4\pi\varepsilon_0} = 9 \times 10^9\ \text{N m}^2\ \text{C}^{-2}.$$

Since the massive nucleus will acquire little kinetic energy, this potential energy will nearly equal the original kinetic energy. Equating them gives $r = 5 \times 10^{-14}$ m. What is the electric potential at that distance?

$$V = \frac{79e}{4\pi\varepsilon_0 r} = 2.5 \times 10^6 \text{ volts.}$$

Why is this just half the energy of the alpha particle in electronvolts?

What is the 'turn-around' force at that distance of closest approach? 'Guess – would it equal the weight of a man, a book, a pencil, one eyelash, one cell of your body, or one atom?'

The electric field E at that distance is:

$$E = \frac{V}{r} = \frac{2.5 \times 10^6}{5 \times 10^{-14}} = 5 \times 10^{19}\ \text{V m}^{-1}.$$

The force on a charge of $2e$ is $2(1.6 \times 10^{-19})(5 \times 10^{19}) = 16$ newtons.

This is about the same as the weight of a mass of 1.5 kilogrammes – an enormous force to find exerted on a single atomic particle. The book was the best guess.

[illegible]

[illegible] nucleus [illegible]

Rocky [illegible] would [illegible] potential energy [illegible] nucleus [illegible] coulomb [illegible] [illegible] converted into electrical potential energy. Gold is element number 79, so that the nucleus of gold has 79 electron charges, while an alpha particle, the nucleus of element number 2, has 2 charges. Both positive, the potential energy of the alpha particle is:

$$\text{potential energy} = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r} \quad \text{where} \quad \frac{1}{4\pi\varepsilon_0} = 9 \times 10^{9}\ \text{N m}^2\ \text{C}^{-2}$$

Since the [illegible] energy [illegible] kinetic energy [illegible] equal the original kinetic energy [illegible] What is the electric potential at that distance?

$$V = \frac{Ze}{4\pi\varepsilon_0 r} = [illegible] \times 10^{7}\ \text{volts}$$

Why is this just half the energy of the alpha particle in electronvolts?

What is the 'turn-around' force at that distance of closest approach? [illegible] is just the weight of [illegible] [illegible] out of your [illegible] calculations?

The electric field E at that distance is:

$$E = \frac{V}{r} = \frac{2.5 \times 10^{7}}{5 \times 10^{-14}} = 5 \times 10^{20}\ [illegible]$$

The force on a charge of 2e is $2(1.6 \times 10^{-19})(5 \times 10^{20}) = 16$ newtons.

This is about the same as the weight of a mass of 1.6 kilograms [illegible] an enormous force to find exerted on a single atomic particle. The book was also [illegible]

Part Three

Exponential decay

Time: see page 9. Part Three takes up and develops mathematical ideas which arise out of experiments and reading about exponential decay in Part One. It should occupy up to a week.

Much of Part Three need not be taught in the classroom, as structured questions are provided in the section 'Exponential changes' in the *Students' book* to take students individually through the arguments involved. Teaching time can be given mostly to the discussion needed to clear up difficulties and confusions.

Results from Part One

Results from experiments 5.9, 5.10, 5.11, and 5.12 are needed at this stage, or as the argument develops. If the tasks are taken in two stages, these are the experiments to concentrate on now.

Some of the reading from Part One will have stressed the random nature of radioactive decay.

Students' book

Questions 10 to 15 concern half-life and decay.

Chance

The few pages in the *Students' book* entitled 'Chance and randomness become part of physics' at the end of 'Radioactivity and the nuclear atom', may provide suitable extra reading. The point of starting the argument opposite with dice rather than with the radon experiment is to make it easier for students to look at the experiment expecting to see random events.

Experiment

5.15 Decay of radon in a cloud chamber

28 diffusion cloud chamber

47 illuminant

27 transformer

19/1/2 CO_2 cylinder and dry ice attachment

1056 methylated spirit

1055 cork (to fit hole in cloud chamber)

1066 'thoron' generator

See the *Students' laboratory book* and Nuffield O-level Physics *Guide to experiments V*, experiment 128b, for details of setting up the cloud chamber.

It is convenient to set the chamber up at first using the weak radium source provided with it, to make sure it is working. Then the source can be removed, and a puff of air containing ^{220}Rn be blown in through the side hole, which is then sealed off with a cork. It is only necessary for each student to have access to the 'thoron' (^{220}Rn) generator; one may be enough for a class.

As usual, to obtain clear tracks, the top of the chamber should be rubbed with a dry duster to charge it. This helps to clear stray ions, and makes the tracks sharper.

Radioactive decay – a chance process

In the analogue decay experiment 5.11 with dice, what proportion is left after each throw? What proportion should be left after each throw? (5/6.)

How many 5/6 reductions will halve the number of dice?

Throws		
1	$5/6 = 0.834$	
2	$5/6 \times 5/6 = 0.695$	
3	$5/6 \times 5/6 \times 5/6 = 0.580$	(half-life between 3 and 4 throws)
4	$5/6 \times 5/6 \times 5/6 \times 5/6 = 0.485$	

What proportion is left after two half-lives? (Not zero.) The meaning of 'half-life' needs to be brought out. If a comparison with the decay of charge on a capacitor is made, the lack of random chance effects in the latter case needs a mention. Why in the dice experiment is the proportion left after each throw approximately 5/6? There are six possible ways a die could fall and in only one of them will, say, five pips be uppermost, if chance decides the fall.

If one of the dice were marked and observed during the dice-throwing experiment, when would it decay? (You can't tell; it could decay at the first throw or the last throw.) All that can be said is that, approximately, the proportion that is left after each throw is 5/6 (the proportion that decays is 1/6). This could be tried as a demonstration if there is any doubt.

Experiment
5.15 Decay of radon in a cloud chamber

The tracks should be observed over a period of about 5 minutes. The randomness and the decay of activity are easy to observe. Comparisons can be made with the arguments about the dice-throwing experiment. Does a single atom behave like a die in the analogue decay experiment? (Yes.) The random throws of dice imitate radioactive decay quite well. The results of experiment 5.12 can be drawn on to reinforce the point on randomness.

The experiment has another valuable aspect. Events happen at random places and at random times, but each decay produces two tracks, not one. This could not happen by chance. The reason is that each ^{220}Rn decay produces a ^{216}Po nucleus, which decays with a very short half-life (0.16 second), emitting another alpha particle. The class can see transmutation at work. See the decay scheme given with experiment 5.10.

Fixed chance of decay per unit time

The arguments leading to $\Delta N = -kN$ are incomplete. The only sure evidence that decay is truly random is that the number of decays in different times (from an essentially constant strength source) follows a Poisson distribution. Such an argument would be beyond all but a few students. The pages entitled 'Chance' at the end of 'Radioactivity and the nuclear atom' in the *Students' book* attempt to outline the argument informally.

A further important element in the argument is that the decay rate does not depend upon temperature, or on physical or chemical state. Several of the reading references make this point.

Time in seconds	Number at beginning	Number decaying in 2 seconds	Number left after interval	Rate of decay $\Delta N/\Delta t$ per second
0	10000	2000	8000	1000
2	8000	1600	6400	800
4	6400	1280	5120	640
6	5120	1024	4096	512
8	4096	819	3277	410
10	3277	655	2622	328
12	2622	524	2098	262
14	2098	420	1678	210
16	1678	335	1343	168
18	1343	269	1074	134
20	1074	215	859	108
22	859	172	687	86
24	687	137	550	69

Table 5
Numerical example of decay

The chance of decay

In one minute, about half the ^{220}Rn nuclei decay. In one second, a constant small fraction of them decay (*not* 1/120). The rate of decay is the number of nuclei decaying per second.

For dice, at each throw, a constant small fraction of the total tends to 'decay'. The 'rate of decay' has no meaning, unless one imagines throws to represent time intervals.

At one throw of the dice, if there are N dice thrown and ΔN of them 'decay', it is to be expected that

$$\Delta N = -\tfrac{1}{6} N$$

The minus sign shows that 'decayed' dice are removed, decreasing N.

Nobody, so far as we know, casts dice to decide the fate of a nucleus. There is no succession of 'throws', at each of which a nucleus may, or may not, decay. But the experiments done on radioactive decay suggest that a pretty constant fraction of the nuclei present decay in any fixed time. That suggests writing $k\Delta t$ for the chance that a nucleus will decay in an interval Δt. k is the chance of decay per unit of time (unit s^{-1}). Then if there are N atoms at the start of an interval Δt, there will on average be $Nk\Delta t$ of them decaying in that interval. $k\Delta t$ replaces the constant 1/6 appropriate to dice.

Thus $\quad \Delta N = -Nk\Delta t$

or $\quad \Delta N/\Delta t = -kN$

This is like an equation from Unit 2, for the charge on a capacitor:

$$\Delta Q/\Delta t = -kQ$$

As with that equation, the time interval Δt must be small enough for Q not to change much within Δt; that is, $\Delta Q/Q$ must be small. Even so, the equation does not perhaps deserve the full equals sign, and $\approx$ might be fairer.

Like the decay of charge on a capacitor, the equation $\Delta N/\Delta t = -kN$ leads to a dwindling away at a decreasing rate, as a numerical example now shows.

Numerical example of decay

Let there be $N = 10000$ nuclei as yet unchanged into another type of nucleus, and let k be 0.1 s^{-1}. If $\Delta t = 2$ seconds, the number decaying in the first 2 seconds is 2000, leaving 8000 unchanged. The number decaying in the next 2 seconds is smaller, being the same fraction of only 8000, coming to 1600. Table 5 shows the example worked out for several successive intervals. A smaller time interval would be better, but more tedious. Note also that random fluctuations are being ignored, though one could expect the 2000 decays in the first interval to fluctuate by perhaps 50 decays.

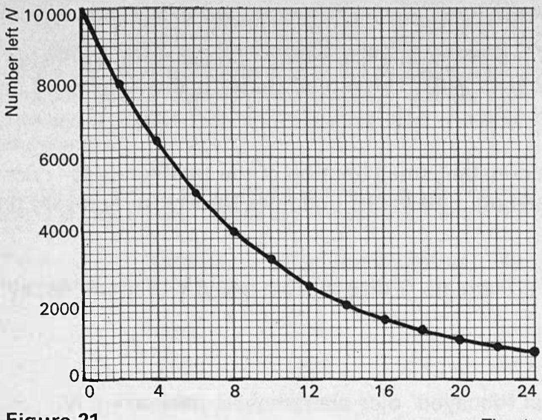


Figure 21
N against *t* for calculated decay of 10 000 atoms.

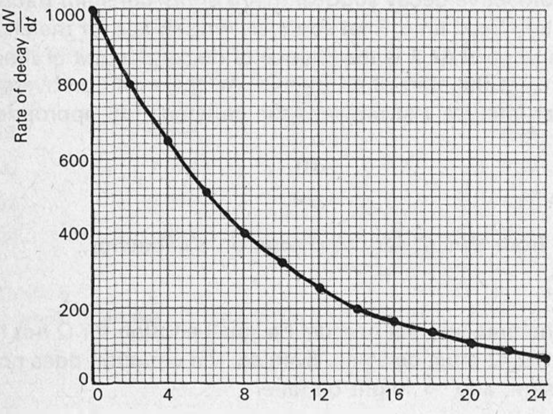


Figure 22
d*N*/d*t* against *t* for calculated decay of 10 000 atoms.

Students' book

Question 14 uses the curie in a calculation.

It is worth while plotting graphs of both N and $\Delta N/\Delta t$ against t, as in figures 21 and 22. The two graphs have a very similar shape. Indeed the values of $\Delta N/\Delta t$ are each 0.1 of the corresponding values of N, and if the scale for $\Delta N/\Delta t$ is ten times larger than that for N, the graphs are identical. But *of course* they are the same; that is what the equation says:

$$\Delta N/\Delta t = 0.1N$$

Does an actual decay curve have this shape?

The experimental curves for protactinium or radon 220 (experiments 5.9, 5.10) dwindle down in the same general way. The half-life can be found, and students can test whether the half-life is the same at two or three different parts of the curve. Such measurements of half-life show that the decay curve is a constant ratio curve. That is, in equal intervals of time the curve drops by the same ratio. The same is true of the results for dice. This constant ratio property is a property of curves which are fitted by the equation $\Delta N/\Delta t = -kN$. (It may be helpful to consider how the ratio for a small time Δt could be written in terms of N and ΔN. From $\Delta N/N = -k\Delta t$, the ratio of two successive values of N is $1-k\Delta t$. If k is constant, the ratio is constant.)

Activity – the curie

Sources are marked with 'strengths' or activities in curies, though a school source is likely to have an activity measured in microcuries. One curie is 3.7×10^{10} disintegrations per second, and is roughly the activity of one gramme of radium. Note that an activity is a rate of decay, dN/dt. Students do not need to keep in mind the size of a curie, but they should know that sources are labelled for strength with their rate of decay.

The exponential function

The form of the curve for the decay of radioactive nuclei or for the decay of charge on a capacitor is of rather general interest. These are called exponential changes. Such changes arise whenever the rate of change of something or other is proportional to how much of that something there presently happens to be. This was the case for radioactivity and for leaky capacitors; it can apply to other changes, such as the growth of bacteria or the spread of an epidemic. The last two examples concern growth, not decay, and it is growth that is now the subject of discussion leading to a mathematical equation for exponential changes.

The problem

For an equation like $\Delta N/\Delta t = -0.1N$, the previous numerical example yielded a graph. Whatever the constant, here 0.1, the general shape of the graph is the same, though it naturally slopes more steeply the larger the constant. It happens that all such graphs are described by an equation of one mathematical form, with one constant to be adjusted to fit the steepness or shallowness of the curve. Such a function is called a *solution* of the rate of change equation (differential equation).

Mathematics – the exponential

This is one of the occasions on which we suggest that mathematical ideas can and should be taught within physics teaching. There are several things to be learned here. The suggested approach will, we hope, reveal more of what kind of thing a differential equation is, and what finding solutions of such equations amounts to. This is worth while because of the great importance of differential equations in all sorts of pure and applied science. In the process, the idea of a derivative should also become clearer.

Further, the function studied here – the exponential – is of wide interest and importance. Indeed, if one allows complex exponents, a large fraction of the functions of interest in science can be cast into exponential form. We do not suggest going so far, but the understanding of the exponential function with real exponents may well help later learning in this area.

Within the course, the exponential has a significant role. It appears in the Boltzmann factor $e^{-\Delta E/kT}$, in Unit 9, *Change and chance*. It has already appeared in discussions of capacitor discharge, though not necessarily in explicit form, and will be used again in Unit 6, *Electronics and reactive circuits,* in discussing the response of RC and RL circuits to pulses.

However, our main concern is with helping learning in the future, when students will certainly meet differential equations, their solutions, and the exponential function on many occasions. We regard some facility in these matters as part of the skill needed by a scientist, and so as a part of the course, not as a sort of mathematical top dressing. Nor do we think it is necessarily true that students can be sharply divided into the 'haves' and 'have nots' with regard to mathematics, provided that time and effort are given to teaching a modest amount of mathematics as well as possible.

Other approaches

The graph-drawing approach suggested in the text, and supported by the section 'Exponential changes' in the *Students' book,* seems to us a helpful one, combining a minimum of algebraic manipulation with a detailed, numerical look at 'how the thing goes'. But it is not the only approach. Appendix C gives two others, one based on an algebraic version of the graphical argument, and the other on differentiating a series. Maybe none of these will be suited to classes with considerable mathematical expertise.

Students' book

The section 'Exponential changes' in the *Students' book* contains a series of questions which show students how to test for an exponential change, and then develop the graphical approach to the exponential function which is outlined in the text. The section is intended to enable students to work by themselves with little outside assistance. It may even be that no direct teaching, except for a concluding summary, will turn out to be needed.

What would a graph to fit the recipe $\Delta N/\Delta t = +0.1N$ look like? It would grow and grow, rather than continually dwindle away. And the bigger N became, the faster it would grow. Such a pattern might fit an epidemic, if N were the number of people with 'flu, say, and the number of new cases in a week were proportional to the number of infectious people around. Indeed, isolation hospitals are a way of breaking this vicious link, and stopping the growth.

To find a mathematical form, it is best to keep things as simple as possible, and here it will be best to make the constant, 0.1 above, equal to 1. Then the equation looking for a solution is just $\Delta N/\Delta t = 1.0N$. The problem is to find a function which fits this recipe for change.

Graphical approach to the exponential function

The approach is in two steps. First, the form $N = a^t$ is seen to have the necessary property of increasing by equal multiples when t increases in equal steps. This can be brought out with a numerical example or, more formally, in the following way.

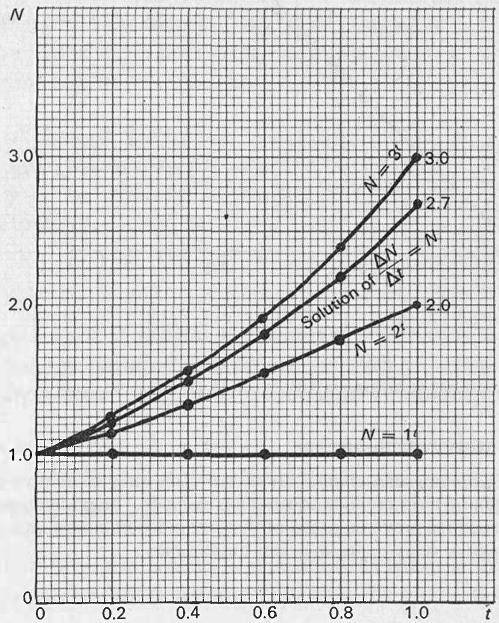


Figure 23
Plots of $N = 1^t$, $N = 2^t$, $N = 3^t$, and solution of $dN/dt = (1.0)N$.

It is convenient to plot graphs of $N = 1^t$ (trivial), $N = 2^t$, and $N = 3^t$ for values of t from 0 to 1, using tables of logarithms. See figure 23. The graphs can be inspected to see if, say, $2^{0.0}$, $2^{0.2}$, $2^{0.4}$, $2^{0.6}$ increase in constant ratio. The link with the addition of exponents upon multiplication can be brought out: what, for example, is the value of

Note on accuracy of graphical solution

Figure 24 shows the simplest method, in which the slope of the next segment is decided by the previous value of N. This value is always too low, so the curve is not as steep as it ought to be. The proper value of N to use would be that in the middle of the segment to be drawn, but that value is as yet unknown. The simple method gives a graph which, if accurately drawn, will rise to $N = 2.59$ instead of $N = e = 2.718...$ at $t = 1$.

A better method, but one not always worth the effort, is to take the value of N that decides the slope of the next segment from the value it would have at the *middle* of that segment, if the graph is drawn on at the same slope as before. In figure 24, N would be equal to 1.15 at the middle of the second segment if the slope of the first were continued. This would give $\Delta N = 0.115$ instead of $\Delta N = 0.11$ for the increase of N over the second segment.

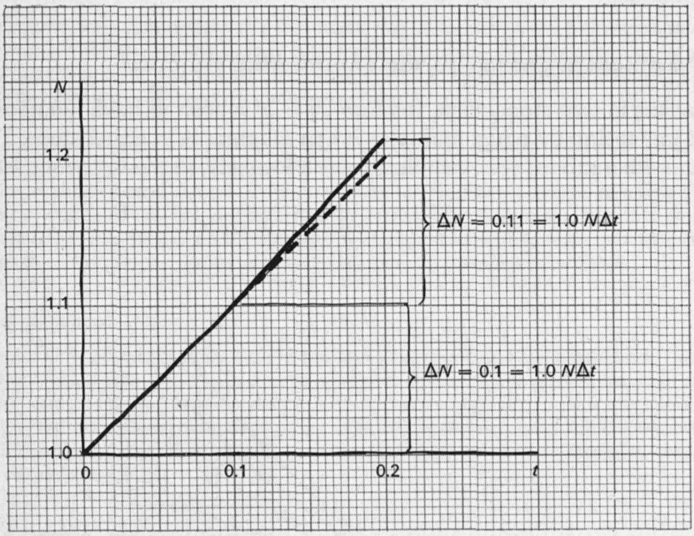


Figure 24

First two steps of a graphical solution of $\Delta N/\Delta t = (1.0)\ N$.

Supplementary mathematics

The Teachers' guide, *Supplementary mathematics*, contains material to give extra practice in these ideas for students not taking mathematics as a parallel subject. The understanding of the arguments about the exponential requires previous grasp of the properties of exponents, and this too will probably need practice, despite earlier work on indices and logarithms.

$2^{3.2}$? 2^3 is equal to 8; $2^{0.2}$ can be taken from the graph and $2^{3.2}$ found by multiplying them together.

More formally, the exponents of the series a^t, a^{2t}, a^{3t} increase in equal steps t. But $a^{2t} = a^t \times a^t$; $a^{3t} = a^t \times a^t \times a^t = a^{2t} \times a^t$. Each term is larger than the one before by the factor a^t.

Construction of a solution to $\Delta N/\Delta t = 1.0N$

On the same axes as the graphs above, a step-by-step graphical solution to the equation $\Delta N/\Delta t = 1.0N$ can be constructed. Taking time intervals Δt of 0.1, starting with $N = 1.0$ initially, the solution is constructed by drawing segments of the graph one after the other as short straight lines with slopes given by the equation. Figure 24 illustrates the process. The technique is just like those used in Units 2 and 4 for capacitor discharge, and for acceleration graphs.

At $t = 1.0$, the solution rises to a value of nearly 2.7, where $N = 2^t$ has risen to the value 2.0, and $N = 3^t$ to the value 3.0. It may now seem reasonable to propose the form $N = 2.7^t$ for the graphical solution, and write this as $N = e^t$, where e is a number, near 2.7, that can be found more accurately by more accurate versions of the graphical solution process, or its equivalent.

To show that $N = e^{kt}$ may be the form of a solution of $\Delta N/\Delta t = kN$, a graphical solution of $\Delta N/\Delta t = 0.7N$ might be constructed. It is close to the curve $N = 2^t$. Tables, or the first graphical solution, show that $e^{0.7}$ is nearly 2.0. Thus when $k = 0.7$, the solution seems to be $N = (e^k)^t$, or $N = e^{kt}$.

Summary

The growth equation $\Delta N/\Delta t = kN$ has a solution of the form $N = a^t$, where a is some number. This form has the required property of yielding a 'constant ratio' curve; one which increases N by a fixed factor when t increases in equal steps.

When $k = 1.0$, and $N = 1.0$ at $t = 0$, the value of a seems to be near 2.7, more accurately 2.718. . . , where this is the never-ending number e. This number e is the value of a for which the slope of $N = a$ is equal to 1.0 at $t = 0$, $N = 1.0$.

The graphical solution provides a rough estimate of e. More accurate methods are available, but all amount to doing arithmetic to find the value of N at $t = 1.0$.

It may seem that to cope with $\Delta N/\Delta t = kN$, one would need a table of values of the number a in $N = a^t$ appropriate to each value of k. This is not so. The required value of a is just e^k, and the solution (for $N = 1.0$ at $t = 0$) is $N = e^{kt}$.

A minus sign looks after the case of decay. If $\Delta N/\Delta t = -kN$, the solution is $N = e^{-kt}$. This curve falls and falls, being the same as $N = 1/e^{kt}$.

Application to population growth

Students of biology should be quick to notice that the exponential model is a good fit to population growth when the number of new individuals is proportional to the number of individuals present. This will arise, for instance, in the growth of yeast or the production of yoghurt, the necessary condition being that the rate of reproduction is not slowed down by population pressure upon, say, food resources. See Nuffield Advanced Biological Science Laboratory Guide *Organisms and populations* (the growth of yeast is studied in investigation 5.1).

Students' book

The section 'Exponential changes' contains several examples, drawn from outside physics, of changes that are exponential, or are partly so.

Other changes

Teachers might care to collect experimental data. For example, the change of the current in, or the resistance of, a thermistor with temperature could repay study. Biologists may have means of following the growth of the number of cells in a culture, using a device that measures the light intensity they absorb or even by making direct counts, though this is hard. At a simpler level, the temperature difference between a pan of hot water and its surroundings falls more or less exponentially with time.

Recovery

When students report on experiment 5.9, in which they follow the growth of protactinium activity in a layer from which it, but not its parent thorium, has been removed, it may be desirable to follow up with some discussion of the recovery curve.

Such discussion is perhaps best seen as an opportunity for the class to think about rates of change in a fresh but fairly simple context. Detailed recall of the shape of recovery curves need not be expected, but commonsense argument about the rise, fall, or steady activity that may arise in simple situations does form part of the course.

It may be that a few questions asked at the time of a report on experiment 5.9 will bring out all the necessary points.

Students' book

See question 15, about a water analogue of decay and recovery.

References for teachers

See *Classical scientific papers (physics)* (reference 1), page 14, or Romer (ed.), *The discovery of radioactivity and transmutation* (reference 18) pages 127–8.

The paper by Rutherford and Soddy reproduced in these references was one of the earliest to disentangle the growth and decay of active elements in a series. The pages mentioned show graphs of activity.

In general N is not 1.0 at $t = 0$. This turns out to be easy to cope with. If $N = N_0$ at $t = 1$, then N/N_0 is 1.0 at that time. If $\Delta N/\Delta t = kN$, then also $\Delta(N/N_0)/\Delta t = k(N/N_0)$. N has just been scaled down by the factor N_0. So $N/N_0 = e^{kt}$ is the solution, which may be written $N = N_0 e^{kt}$.

It may be better to assert this last point if the extra argument to establish it would be too great a burden.

Testing curves for the exponential property

The arguments suggested above have stressed the 'equal ratio' property that distinguishes exponential changes from others. The use of logarithms in the plotting of curves of $N = a^t$ should readily suggest testing for exponential change of a quantity by plotting its logarithm against time (or whatever other variable is concerned). Students should try one or two such tests on data provided, including some that are not exponential.

Radioactive decay and recovery

Figure 25 shows the familiar decay of a radioactive substance X plotted against time, with N_0 atoms at $t = 0$. What will be the plot of the number of atoms of the element Y that X turned into, if Y does not decay? (Broken line.) Suppose there are no atoms of Y to begin with. How many will there be after a very long time? (Nearly N_0.) How fast will the number of atoms of Y rise to begin with? (As fast as the number of atoms of X falls.)

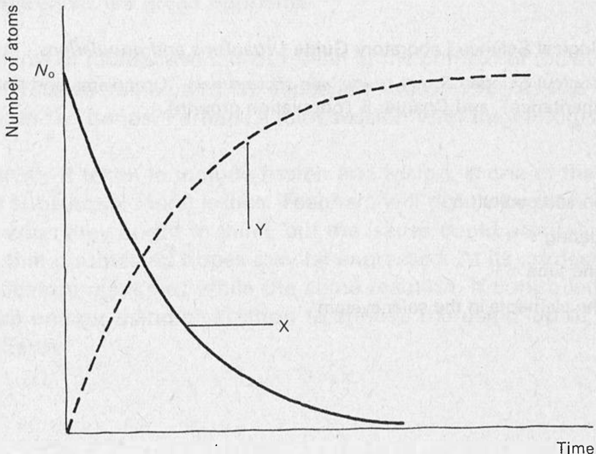


Figure 25

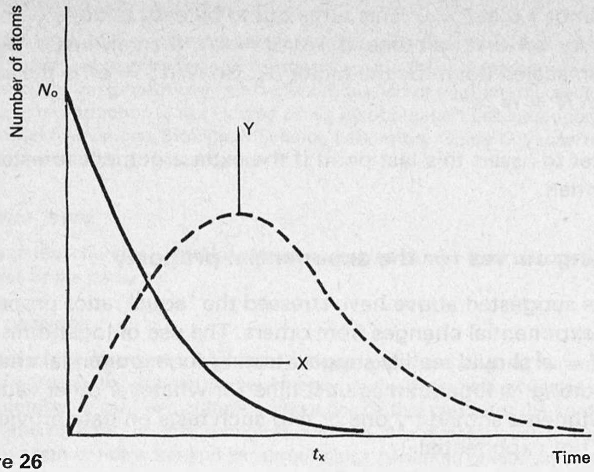


Figure 26

Students' book

The section 'Radioisotopes' describes a wide variety of applications of radioactivity. Questions 30 and 31 could also be a basis for class discussion.

Further reading

Books

Hurley, *How old is the Earth?*

Putman, *Isotopes.*

Nuffield Advanced Biological Science Laboratory Guide *Organisms and populations.*

Nuffield Advanced Biological Science *Study guide*; see second part, 'Organisms and populations', Chapter 2 (radiation, inheritance), and Chapter 5 (population growth).

Reprints

Crow, 'Ionizing radiation and evolution'.

Deevey, 'Radiocarbon dating'.

Hurley, 'Radioactivity and time'.

Reynolds, 'The age of the elements in the solar system'.

Now suppose that Y is also radioactive. The class may be able to explain why the number of atoms of Y falls exponentially (broken line in figure 26) beyond t_X where there are hardly any atoms of X left. (Almost no more Y atoms being produced.) Initially, the number of atoms of Y rises almost as fast as the number of X atoms falls, since there are very few Y atoms yet, and the number decaying is small, if the half-life of Y is not too short.

The experiment with protactinium (experiment 5.9) is another application of similar ideas. The parent of protactinium, ^{234}Th, has a half-life of about a fortnight, so its decay will not appreciably reduce the amount of it that is present during one laboratory session. Its rate of production of protactinium is essentially steady. But the protactinium that is produced decays with a short half-life. The amount of it present builds up until as many protactinium nuclei decay in a second as are produced in a second. As the rate of production is nearly steady, so is the amount present, in the long run.

Note also that the ^{234}Th comes from ^{238}U, with half-life over 10^9 years. The sample is more than a few weeks old, so the amount of ^{234}Th has also stabilized. The number of protactinium decays recorded in a second, when this is steady, is equal to the number of uranium decays in a second.

Applications

The discussion of radioactivity and decay ought also to give emphasis to possible applications. A range of suitable background reading should be available, and several references are given opposite.

The problems of radioactive fall-out, seen in the context of the ever present background radiation, deserve some mention, especially those elements like ^{90}Sr which follow calcium into the bones. Perhaps a joint session with the biologists could be arranged.

Radioactivity, if taken to include fission and fusion, is one of the branches of physics that raise substantial moral issues. Teachers will rightly be wary of seeming to tell students what they ought to think, but the issues could profitably be brought into the open, so that doubts and hopes may be expressed. At its crudest, the hydrogen bomb may yet destroy mankind; while the same reaction, if controlled, may be the only way for an energy-using civilization to survive the using-up of the stock of fossil fuels on Earth.

[illegible]

The experiment with protactinium [illegible], is another application of similar ideas. [illegible] laboratory session, the rate of production of protactinium is [illegible] steady, but [illegible] protactinium that is produced decays with a short half-life. [illegible] As the rate of production is nearly steady, [illegible]

[illegible]

Applications

[illegible]

[illegible]

[illegible]

Part Four

New ideas and problems about atoms

Time: this Part may occupy about a week, the first half of the week on short accounts of atomic number, isotopes, and transmutation, and the second half on recalling ionization energy from Unit 2 and introducing quanta.

It would be easy to spend twice that time, but it would not be profitable so far as the main aim of this Part is concerned. This is to show in outline how a new model, such as the Rutherford model, at once raises many new problems. Some of these problems can be settled quickly; others are much deeper and harder. A slow pace, with much detailed factual teaching, will make it hard for students to achieve such an overall view. Rather, they should have a brief 'conducted tour'.

New ideas and problems

In the course as a whole, Unit 5 is a halfway house on the way towards such understanding of the structure of atoms as will emerge in the end. Unit 10, *Waves, particles, and atoms* will offer another look at this problem, bringing to bear on it knowledge of waves, particle dynamics, electric charge and potential, chance, energy levels, photons, and spectra.

The function of Part Four is twofold. It looks forward to this later work by raising, though not by solving, some of the problems that will be involved. It also looks back at earlier work on energy levels and links this with the Rutherford model.

Part Four is meant to contribute towards a general aim of the course, that of understanding the nature of physical inquiry. It makes two particular points about how physics works. The standing of a model like the Rutherford model can be discussed, showing its strengths and also its imperfections. The most significant imperfection for the course as a whole is the failure of the model to say much about how the electrons are disposed around the nucleus, or to explain the existence of discrete energy levels. In addition, the work of Part Four illustrates how a new idea often raises a host of new problems and suggests many new lines of inquiry. The Rutherford model prompts one to ask what the charge on the nucleus is and how it relates to the serial number of elements in the Periodic Table, what a nucleus is made of, how elements change as a result of radioactive decay, and so on. These issues are examined briefly in Part Four.

One further idea is introduced, to help with later work in Units 9 and 10. This is the idea that light delivers and carries off energy in lumps, or photons. Photons, and the problem of a dual wave-particle model, will receive a fuller treatment in Unit 10, so the treatment now can be quite brief. It is suggested that, after noting that gamma rays are capable of, for instance, ionizing air whilst visible light is not, the photo-electric effect should be used to provide some evidence that light of frequency f delivers energy in lumps of size $E = hf$, h being Planck's constant. Finally, a link with Unit 2 can be made by seeing how the energy levels of mercury atoms are related to the frequency of the radiation they emit.

Background for teachers: evidence for nuclear charge as the periodic serial number

There are several pieces of evidence, all too difficult to present in detail to students at this stage.

1 *The absolute and relative amounts of alpha scattering*

The theory (Appendix A) shows that the scattering depends on Z^2, and Geiger and Marsden compared the amount of scattering from different elements. See pages 174–7 of *Classical scientific papers (physics)*, or page 160, Conn and Turner, *The evolution of the nuclear atom.* Because mass number A is nearly equal to twice the atomic number Z, this test does not show whether the charge is equal to Z or to A, but only that it varies in proportion to either.

But the absolute proportion of particles scattered at some angle does give a measure of Z. See *Classical scientific papers (physics)*, page 180, or *The evolution of the nuclear atom*, page 162.

Chadwick made more precise measurements some years later.
See table 6 on page 85 of this *Guide* for the results obtained by Geiger and Marsden and those obtained by Chadwick.

New ideas and problems raised by the Rutherford model

Often in physics, a new idea, model, or theory which was produced to solve one problem, raises a host of new problems and suggests a number of new lines of thought. The Rutherford model is a good example. If an atom is a nucleus plus electrons, what picture can be formed of the differences between elements?

Atomic number and the Periodic Table

One view of the atoms of different elements would be to suppose simply that they all differ, each having the properties needed to explain the behaviour of that element. But if atoms are made of nucleus plus electrons, perhaps the differences between atoms can be understood in terms of how they are built up of these parts.

Before the suggestion that atoms might be made up of simpler parts, chemists had found that the elements could be arranged in a serial order, when they showed interesting patterns of repeating behaviour. They put the elements in serial order, more or less by weight but not hesitating to make small adjustments if putting a slightly heavier element before a slightly lighter one made the agreement of properties within the groups of the table work better. So far as chemical behaviour goes, then, atomic number – or serial order in the list – is a rather better guide than atomic weight. That is how the serial order was decided.

A look at the table confirms that while the atomic number Z goes up in steps of one (naturally), the mass number A rises a little irregularly but roughly in steps of two. If the nucleus is charged, what will be the charge on it? Will there be Z positively charged particles, or A positive particles? Does the charge have to do with chemical properties, or is it irrelevant to them?

Physics could help if it could find some physical behaviour that depends on the charge on the nucleus, and measure it, atom by atom. Perhaps the charge itself could be measured.

The charge on the nucleus from the scattering experiment

The alpha particle scattering experiment gave evidence that the nucleus is electrically charged. It can also be used to measure how much charge the nucleus has, although the experiment is very difficult to do, and the calculation is not easy. Roughly, the bigger the charge on the nucleus, the larger the angle through which it turns an alpha particle coming at it with a certain 'aiming error'. By counting just how many particles actually are swung through a certain angle, it is possible to tell roughly how many electron charges the nucleus has.

The calculation is lengthy, and it may be best just to look at the answers obtained by Geiger and Marsden, and later by Chadwick.

2 *Evidence from X-ray wavelengths*

Moseley, in two papers reprinted in *Classical scientific papers (physics)*, reports the remarkable work in which he measured X-ray wavelengths for many elements. Even without a theory it can be seen that the measurements support Z rather than A as a fundamental measure of the number of charged building bricks in the atom. In 1913, of course, Bohr's theory had recently been published, and so Moseley was able to use it to suggest a plot of $\sqrt{\text{frequency}}$ against atomic number, and to obtain straight line graphs.

Question 40 (optional) in the *Students' book* can be used for a brief look at Moseley's evidence later in Part Four, when $E = hf$ has been introduced as giving the energy of a photon.

3 *Amount of X-ray scattering*

Barkla showed that the amount of scattering of X-rays, which was supposed to depend on how many electrons the atoms had, was consistent with the number of electrons per atom being about half the atomic weight. If atoms are neutral, this also supports a nuclear charge of Z rather than A.

4 *The wavelengths of X-ray absorption edges*

When X-rays of varying wavelength pass through materials, each element has a sharp increase of absorption at a characteristic wavelength, when inner electrons absorb energy. In effect, this evidence bears the same relation to Moseley's as the absorption spectrum of, say, sodium bears to its emission spectrum.

The 'sausage machine'

Figure 28 is an attempt, though not perhaps a very effective one, to tell students that a calculation can be made and to say what goes into it, without laying the calculation out in detail. The calculation, a version of which appears in Appendix A, is long rather than very difficult. Students who wish to see how it goes should certainly be shown it, though it does not form part of the course. Seeing the argument laid out may increase their respect for mathematics as a tool for physical thinking, and may bring home to them the wide gulf that may exist between the experimental data and their interpretation in terms of a model.

Figure 28, and the answers obtained by Chadwick, appear in the *Students' book*, in 'Radioactivity and the nuclear atom'.

Measurement of Z from alpha particle scattering

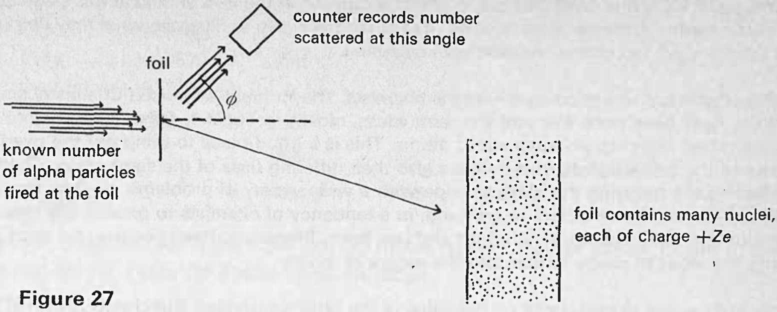


Figure 27

The problem is, how big a charge Ze should the nuclei have in order to scatter the observed number of alpha particles? As one might guess (but it is not easy to prove), the bigger the charge the more alpha particles are deflected through large angles. Using dynamics, knowledge of electrical forces, and the geometry of the arrangement of source, foil, and detector, a calculation can link the experimental data to the problem of how big Z is. If the problem were being solved by a computing machine, one might imagine a 'sausage machine' picture of the process of calculation, as in figure 28. Table 6 gives the answers.

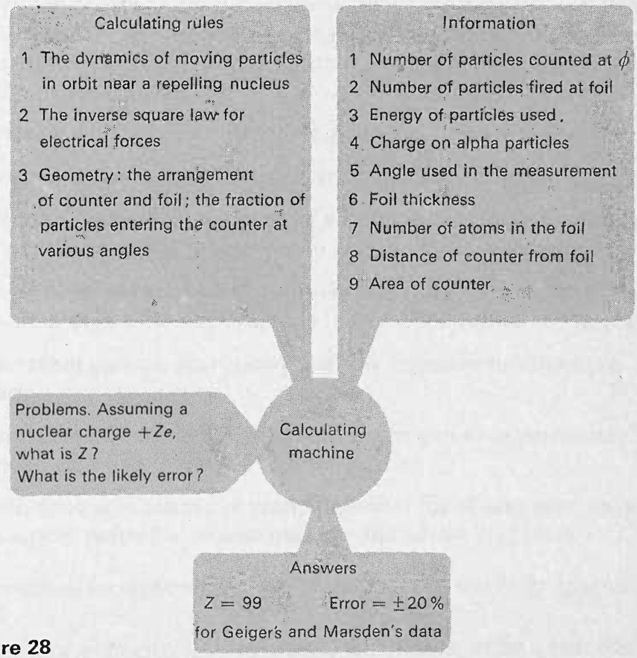


Figure 28

Links with chemistry teaching about models of atoms

A summary of ideas and problems, such as that suggested in the text, should at this stage aim not only to collect together ideas the class 'knows', but should also aim to illustrate what they do not know or what they 'know', but cannot support with evidence.

It will be important here to consult with the chemists. The Nuffield Advanced Chemistry course will, by this point, have developed many of the same ideas, mostly in Topic 4. Other chemistry courses will have contained differing amounts about atoms. This is a good place to bring out the overlap in interests of the two subjects, and perhaps also their differing uses of the same ideas. Chemists will be more inclined to try using the ideas to cope with a wide variety of problems, such as those of bonding. This may be reflected, in teaching, in a tendency of chemists to present the ideas as briefly as possible, so as to have time to go on and use them. Physicists, however, may be more interested in using the ideas to probe further into the nature of atoms.

Neither party ought to cast doubt on the value of the other's activities. But chemists should be aware of the danger of accepting as a 'fact' some model or picture of an atom which is in need of further critical examination and development. And physicists should beware of having too limited a perspective; of failing to see the broad relevance of an atomic model for other people's problems.

These considerations suggest that this is a very good stage for a little examination, amongst students who are studying both physics and chemistry, of questions about which of the things being said are facts, which are fair inferences from some model, and which go beyond what a particular model or evidence can support.

	Element	Mass number	Atomic number	Z from scattering
Geiger and Marsden, using data on p. 622 of their paper (1913)	gold	197	79	99 ± 20
Chadwick (1920)	gold	197	79	77.4 ± 1.0
	silver	108	47	46.3 ± 0.7
	copper	63.5	29	29.3 ± 0.5

Table 6

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

This is an example of the way a model is often used in physics. Rutherford's model pictured an atom as having a small, charged nucleus. The model was promptly used to measure what the charge would be if the model were adequate. Further, the model was at once linked to other questions, in particular the question of what physical facts might underlie the serial order of elements in the Periodic Table.

Summary of ideas and evidence

In order to link the work of this Unit together, and to go back to evidence from earlier work (especially that about energy levels from Unit 2), as well as to reveal problems to come, students can be asked what they know about atoms, and how this relates to the Rutherford model. It should become clear that they have not yet seen evidence for some points, particularly a proton plus neutron picture of the nucleus. Some such list as the following might emerge:

An atom is normally electrically neutral, and about 10^{-10} m in size.

Electrons can be removed from it, thus leaving a positive ion.

Alpha particle scattering suggests a massive positively charged nucleus at the core of the atom, about 10^{-14} m in size.

The charge on this nucleus is numerically equal to the atomic number of the element, if the electronic charge is taken as the fundamental unit of charge.

The smallest particle associated with the negative fundamental charge is the electron.

The smallest particle associated with the positive fundamental charge is the positively charged hydrogen ion, the proton.

Atomic mass is in excess of atomic number for all elements except hydrogen. It is roughly twice the atomic number, but varies irregularly.

The mass of an electron is $\frac{1}{1800}$ of the mass of the hydrogen ion or proton.

Atoms take in energy only in lumps, which tend to be a few electronvolts in size. Nuclear energies, by contrast, are in the million electronvolt range.

The neutron

We do not suggest giving a detailed account of Chadwick's discovery of the neutron. Despite the obvious attractions, this course will say little about nuclear physics, simply in order to find time to consider other matters more effectively. So an extremely brief treatment is suggested. Perhaps the teacher, or a student, could prepare a short duplicated account of the discovery, so as not to spend too much time pursuing the argument in class.

Other reading

Interested students might look at:

Caro, McDonell, and Spicer, *Modern physics*, (reference 9) page 131.

Classical scientific papers (physics), (reference 1) page 245.

Hughes, *The neutron story*.

PSSC, *College physics*, (reference 14) page 313.

PSSC, *Physics* (2nd edition) (reference 13) page 415.

Project Physics, Reader, Unit 6, *The nucleus* (reference 5).

Project Physics, Text, Unit 6, *The nucleus* (reference 12).

The PSSC books are useful because they give a brief summary of the evidence and arguments which led Chadwick to the discovery of the neutron. The Project Physics *Reader, Unit 6*, contains a particularly interesting account by Chadwick of how he was led, by Rutherford's speculation that a neutron might exist, into a whole series of experiments, some of them quite crazy, which bore no fruit for many years. The account illustrates very well how physics is often a matter of speculation, and of good or bad luck, as well as showing how Chadwick, who was looking for neutrons, saw that the evidence pointed in that direction when those who discovered the evidence did not see it.

Why are there not electrons in the nucleus?

In Unit 10, *Waves, particles, and atoms*, Part Three, it will be shown that electrons cannot be inside a nucleus. To cram them down into so small a space requires so short a de Broglie wavelength, and, from $\lambda = h/mv$, so large a momentum, that the electrons would fly out again at once. At this stage, it may be best to say that theory gives reasons for rejecting a protons plus electrons picture of the nucleus and that a sketch of the theory will come later.

Several questions arise. Those which will be looked at further in Part Four are:

How is a nucleus of mass number A and charge Z made up?

What happens to a nucleus that decays by emitting alpha, beta, or gamma rays?

What can be said about the number, energy, and arrangement of the electrons in an atom?

The mass of a nucleus: neutrons

The nucleus could be built up in several ways. It could consist of A protons and $(A-Z)$ electrons. If positive electrons exist then there might be Z positive electrons attached to a nucleus containing A particles each with mass the same as a proton, but having no charge – if such particles exist. Or there could be Z protons and $(A-Z)$ of these postulated uncharged particles. All these arrangements would give a numerically balanced atom as far as charge and mass were concerned.

They also leave problems. Until about 1930 the only 'fundamental' atomic particles known were the proton and the electron. The possibility of a neutral particle – perhaps a proton-electron combination – was suggested by Rutherford. Why would it be hard to detect? (No charge, so little or no ionization.)

From 1914 to 1932, some people thought that there might be such neutrons, but no one observed them. Then Chadwick, who had spent, off and on, much time looking for neutrons, found them.

It was known that when alpha particles bombarded beryllium, a very penetrating radiation was emitted. Chadwick found that if this radiation fell on material like wax which contains plenty of hydrogen, fast protons (hydrogen nuclei) emerged. Compare experiment 5.8 in which alpha particles themselves knock protons out of such material.

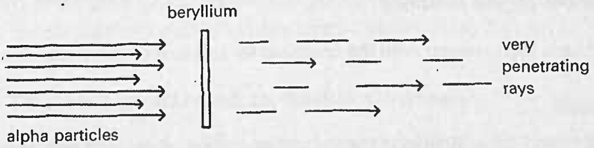


Figure 29

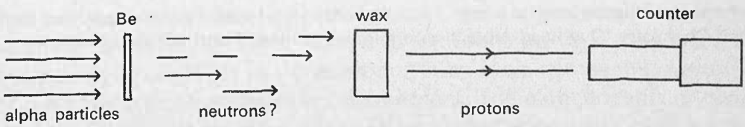


Figure 30

Cautions about a neutron–proton model of the nucleus

Chadwick 'observed' the neutrons outside the nucleus; that may not be conclusive evidence that they exist inside. The neutron could still be a proton–electron pair. The nature of neutrons, and of other particles for that matter, is of course still far from clear. No one has any very clear idea of whether they are 'ultimate' or are made up of other particles. A free neutron is in fact radioactive with a half-life of 12.5 minutes, and turns into a proton, an electron, and a neutrino.

Isotopes from an applied standpoint

It may be profitable to link all the discussion opposite to applications. Much material appears in the section 'Radioisotopes' in the *Students' book*, together with a summary of the main ideas.

Neutrons may be treated as the product of atomic piles; isotopes as medically and industrially useful tools. For example, the radioactive isotope iodine 131 can be used to study the functioning of the thyroid gland, which takes up iodine. In this instance, the fact that the isotope is chemically the same as 'normal' iodine is vital, but so is the fact that it is radioactive. Many other examples appear in 'Radioisotopes'.

We hope that students will become more aware of the social and practical implications of physics. Teaching a part of the material from an applied point of view may assist this aim.

Students' book

See questions 27, 28, 29 which are all about transmutation and its effect on atomic mass and atomic number.

Knowledge of the radioactive displacement laws

We think that the rules for the changes of mass number and atomic number ought to be presented to students as a small but interesting problem which uses the knowledge they have gained. If the rules were seen by students as one more thing to learn by heart, it would have been better to omit them. Questions in an examination will normally give the information and ask for it to be used, rather than requiring a memorized rule to be repeated back or be used mechanically.

Plots of ionization energy

See PSSC *College physics,* figure 35–9, and Nuffield Advanced Chemistry *Students' book 1,* page 91. The latter gives ionization energies in kJ mol^{-1}. A rough conversion is simple, for 10 eV per atom is nearly 1000 kJ mol^{-1} (more nearly, 965 kJ mol^{-1}). See also Nuffield Advanced Chemistry 'Overhead projection originals', number 24 and number 8.

There is much to be said for a joint session with the chemists for this part of the work.

Students' book

See questions 32 and 33 which contain plots of the ionization energy of the elements as in figure 31, and of atomic radii as in figure 32. These questions can probably replace direct teaching of the points suggested in the text, about ionization energies and atomic sizes.

Plot of atomic volumes

A plot of atomic volumes may be a useful supplement to the table of atomic radii. See Nuffield Advanced Chemistry 'Overhead projection originals', number 7 and number 23.

He argued from dynamics, and the speed of the protons, back to the mass that neutrons would have to have, if they were the penetrating radiation, and showed that the mass would be about that of a proton. Other arguments eliminated the other obvious possibility, that the radiation was gamma rays.

The discovery of the neutron adds much to the attraction of a model of the nucleus made up of Z protons and $(A-Z)$ neutrons, of total mass number A. The Rutherford model seems to be capable of further development.

Isotopes and transmutation

Nowadays, neutrons can be obtained in large numbers from the piles of uranium or plutonium that also supply some of our electricity. When they bombard matter, 'new' elements are formed with, sometimes, more neutrons than usual. Different atoms, with the same number of protons and electrons but with different masses, occupying the same place in the PeriodicTable, are called isotopes.

Many are radioactive, and emit charged particles, so producing different chemical elements. The miracle of transmutation, dreamed of by the alchemists, has come true, and with serious as well as hopeful consequences for our civilization.

A brief discussion of the changes produced when alpha and beta radiation is emitted may make these ideas clearer. The changes are:

	Change of atomic number	**Change of mass number**
α decay	-2	-4
β decay	$+1$	0
γ emission	associated with either of the above processes	

This, with regret, is all that will be said about the nucleus in this course. To go further, into such matters as nuclear fission or nuclear fusion, or to discuss the many fascinating problems of fundamental particles like positrons and mesons would take too long. Such matters are of undoubted importance, but art is long and life is short.

The energy needed to ionize an atom

So far as the Rutherford model goes, a neutral atom whose nucleus has atomic number Z will have Z electrons somewhere around the nucleus. But the model does not say where they are, what energy they have, or how they might be arranged or move.

Unit 2, Part Five, on energy levels, produced some evidence about the energy needed to remove an electron from an atom; that is, to ionize the atom. It suggested also that atoms have energy levels. That is, the electrons in an atom can each have only one of a series of possible definite energies at one moment. The atom accepts or gives up energy in lumps whose size is fixed by the difference in energy between pairs of levels.

Z	1	2	3	4	5	6	7	8	9	10
element	H	He	Li	Be	B	C	N	O	F	Ne
energy/eV	13.6	24.6	5.4	9.3	8.3	11.3	14.5	13.6	17.4	21.6
Z	11	12	13	14	15	16	17	18	19	20
element	Na	Mg	Al	Si	P	S	Cl	Ar	K	Ca
energy/eV	5.1	7.6	6.0	8.1	10.5	10.4	13.0	15.8	4.3	6.1
Z	21	22	23	24	25	26	27	28	29	30
element	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
energy/eV	6.6	6.8	6.7	6.8	7.4	7.9	7.9	7.6	7.7	9.4
Z	31	32	33	34	35	36	37	38	39	40
element	Ga	Ge	As	Se	Br	Kr	Rb	Sr	Y	Zr
energy/eV	6.0	7.9	9.8	9.8	11.8	14.0	4.2	5.7	6.4	6.9
Z	41	42	43	44	45	46	47	48	49	50
element	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn
energy/e	6.9	7.1	7.3	7.4	7.5	8.3	7.6	9.0	5.8	7.3
Z	51	52	53	54	55	56	57	58	59	60
element	Sb	Te	I	Xe	Cs	Ba	La	Ce	Pr	Nd
energy/eV	8.6	9.0	10.5	12.1	3.9	5.2	5.6	—	—	6.3
Z	61	62	63	64	65	66	67	68	69	70
element	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
energy/eV	—	5.6	5.7	6.2	—	—	—	—	—	6.2
Z	71	72	73	74	75	76	77	78	79	80
element	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg
energy/eV	6.1	7	7.9	8.0	7.9	8.7	9	9.0	9.2	10.4
Z	81	82	83	84	85	86	87	88	89	
element	Tl	Pb	Bi	Po	At	Rn	Fr	Ra	Ac	
energy/eV	6.1	7.4	7.3	8.4	—	10.7	—	5.3	6.9	

Table 7
Energy needed to remove one electron from an atom of an element.

The energy needed to ionize an atom by removing one electron from it has been measured for many elements. Sometimes, electron bombardment methods like those described in Unit 2 can be used. Often, a more indirect way is better. This involves looking at the wavelengths of light emitted by atoms of the element. A little will be said about this method in Unit 5, and more in Unit 10, *Waves, particles, and atoms.*

For the moment, the values themselves are worth inspecting. Table 7 gives ionization energies for most elements, while figure 31 shows the energy plotted against atomic number.

The first thing to notice is that the energies run in the range 4 to 24 electronvolts (400 to 2400 kJ mol^{-1}), a typical value being 10 eV (1000 kJ mol^{-1}). At what distance from a singly charged ion (charge $+ 1.6 \times 10^{-19}$ C) would the electric potential be 10 V? Using $V = Q/4\pi\varepsilon_0 r$ from Unit 3, with $1/4\pi\varepsilon_0 \approx 9 \times 10^9$ N m^2 C^{-2}, the distance r is of the order 10^{-10} m. This is the order of magnitude of the dimensions of an atom suggested by X-ray evidence in Unit 1, and also by evidence from oil drops and from kinetic theory in the Nuffield O-level Physics course. So the ionization energies fit in with other ideas.

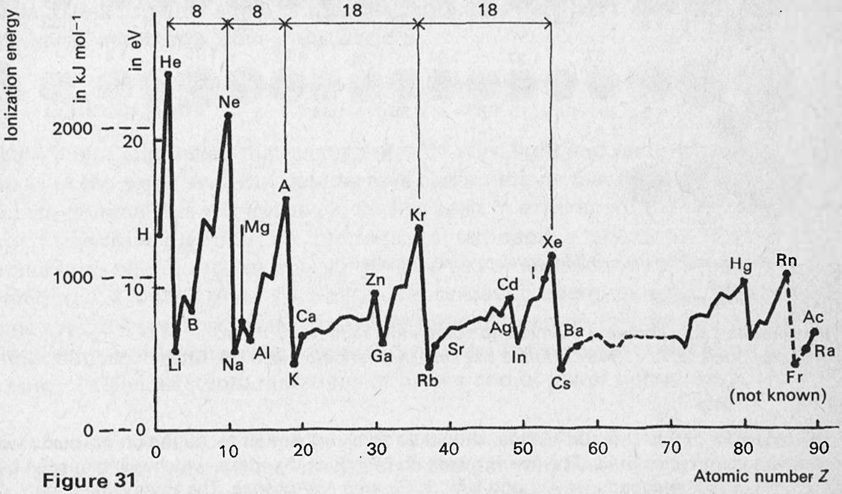


Figure 31
Ionization energies of the elements.

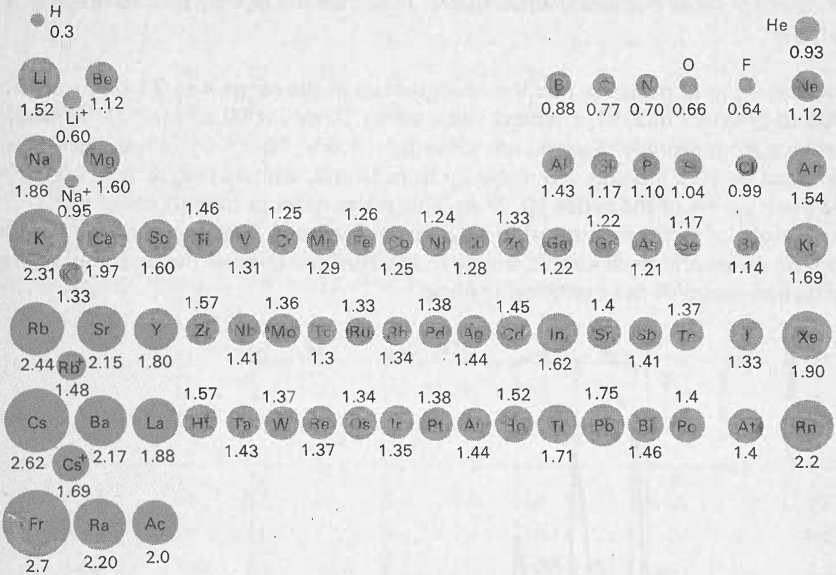
Peculiar periodic variations of ionization energy

One may also notice the significant peaks and troughs in the plot of ionization energy across the Periodic Table.

Elements like Li, Na, K, Rb, and Cs are easy to ionize. Others like Ne, Ar, Kr, and Xe are not. But an element in the second list differs in nuclear charge and number of electrons from the corresponding element in the first list by only one unit.

Orbitals and closed shells

A caution may be needed about whether one should take stories about closed shells as explanations of the periodic properties of atoms. If these stories are the consequences of a wave mechanical theory and the Pauli exclusion principle they do constitute an explanation in some sense. But for a student whose knowledge does not extend beyond a Rutherford model and the facts of periodicity, such stories only spin words around what he or she already knows, adding no new ideas but dressing up old ones in brighter clothes. This is not to despise such stories; they have their place. But it is well to know whether one is saying anything new or not.



(Atomic radii determined from covalent bond distances)

Figure 32

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

Time

The remainder of this Unit, on quanta, should be taken rather lightly. All the points made will be covered again in later Units. The aim is merely to introduce the ideas, which will be useful background for Unit 8, *Electromagnetic waves,* and Unit 9, *Change and chance.* The three experiments involved can and should be covered in no more than three periods.

General arguments that suggest the existence of quanta

The arguments suggested in the text have the merit of capitalizing on students' recent experience with gamma rays, which, of all electromagnetic radiations, are the most particle-like. But it would be easy to get into long discussions which, for lack of clear evidence, cannot be resolved. Such discussions would find a happier place later in the course, when they can be considered at length, when students have more experience to bring to bear, and when, as in Unit 10, more of the evidence and argument is laid out in written material for students. Because that later opportunity will come, and will be supported by the text of the combined *Students' book and Teachers' guide* for Unit 10, it will be best to keep the discussion very brief at present. It may be better to omit it altogether, and pass straight to the photo-electric effect.

Figure 32 indicates that the atoms of alkali metal elements, which are easy to ionize, are large and that they become a good deal smaller when one electron is removed to form an ion. This fits with a view that such atoms have one electron rather a long way from the nucleus, so being rather loosely bound. But why the dramatic changes in properties from Ne to Na, from Ar to K, and from Kr to Rb; changes which only involve one more elementary charge on the nucleus and one more electron in the atom? It seems that the extra electron is an unwelcome guest in such instances. Such sudden drops in ionization energy appear at intervals of 2 – 8 – 8 – 18 – 18 elements in the series. Why these magic numbers; are electrons numerologists?

These questions cannot be answered using only a simple Rutherford model, and any further answers will have to wait until Unit 10. A whole new theory of electrons in atoms turns out to be needed. When such a theory was developed, chemistry and physics really did join hands at last.

This theory came from the discovery that electrons, besides behaving like small charged particles, also have wave properties. As a first step in that direction, this Unit concludes by showing some of the evidence for a similar behaviour of light; that besides being wavelike, it is also lumpy or granular. This lumpiness will make it possible to link together some of the ideas about waves from Unit 4 with others about energy levels and atoms from Units 2 and 5.

'Lumpy light'

In Unit 4 it was suggested that gamma rays, X-rays, light and radio waves were all radiation of the same sort. But gamma rays can do things that light cannot. In particular, gamma rays will ionize air, as was seen in experiment 5.3 and as will have emerged from reading about the properties of radioactive radiations. If an air molecule is to be ionized, an energy of some ten or so electronvolts must be delivered to it. (Table 7 gives 14.5 eV as the ionization energy of a nitrogen atom.) Gamma rays, X-rays, and some ultra-violet radiation can do this, while light, infra-red, and radio radiation cannot. How does this division cut across the electromagnetic spectrum? (It divides it into radiations of higher and of lower frequency.)

It is also worth noting that when gamma rays were detected by a Geiger tube, the tube responded with single, random counts, as if the gamma rays were arriving as separate parcels. While that fact may seem to tell more about Geiger tubes than about gamma rays, it would be explicable if a feeble beam of gamma rays carried its small total energy in rather large, scarce packets. And this fits with the fact that when the source is taken further away, the counts diminish in number according to an inverse square law, just as if the same number of energy parcels each of the same size were spread out over a larger space.

Such arguments are not compelling, but they suggest a further exploration of the possibility that electromagnetic waves have granular as well as wavelike behaviour, and of the suggestion that the size of the lumps depends upon the frequency.

Demonstration

5.16 Simple photo-electric cell

1006	electrometer, with 10^{11} Ω input resistor, or 10^{-11} A range
1003/1	milliammeter (1 mA)
1033	cell holder with four U2 cells
189	ultra-violet lamp
1056	magnesium ribbon, 100 mm long
1055	glass plate
1055	wire gauze 70 mm × 60 mm; for example, 20 mesh copper
503–6	retort stand base, rod, boss, and clamp
52 K	crocodile clip
1053	razor blade
1000	leads

Figure 33 shows a suitable arrangement. Scrape the magnesium ribbon with the razor blade to expose clean metal, turn over about 20 mm at one end, and push this end into the electrometer input socket.

Make a gauze cylinder 60 mm tall by wrapping the gauze round a former 15 to 20 mm in diameter. Turn out the last few millimetres, as shown in figure 33, to give a means of clamping the cylinder over the ribbon, and of making connection to the cylinder. The gauze should rise above the ribbon, screening the ribbon from electrical disturbances. (We found that the gauze was not higher than the ribbon in several cases where the experiment apparently 'didn't work'.)

Using a 10^{11} Ω input resistor to the electrometer (current up to 10^{-11} A), there should be at least half scale deflection when the ultra-violet lamp is some 0.1–0.2 m from the ribbon.

A glass plate absorbs the ultra-violet and the current falls to zero. A copper or iron rod in place of the magnesium gives no photo-electric effect. Replacing the copper gauze with iron gauze makes no difference.

Some types of electrometer may be provided with a zinc plate and a gauze collector, with which the effect can be obtained using visible light.

Difficulties of doing photo-electric effect experiments

The photo-electric effect is easy enough to show qualitatively, but a careful investigation which disentangles the effects of the materials from which the emitter and collector are made, and which shows that the air plays no part (unless X-rays or gamma rays are used) requires much more apparatus, time, and expense. Quantitative work is even more troublesome.

So experiments 5.16 and 5.17 should be presented merely as the first steps on a long road which has been travelled by other people.

Demonstration
5.16 Simple photo-electric cell

Figure 33 shows an arrangement that gives an opportunity for some simple deductions to be made about the photo-electric effect.

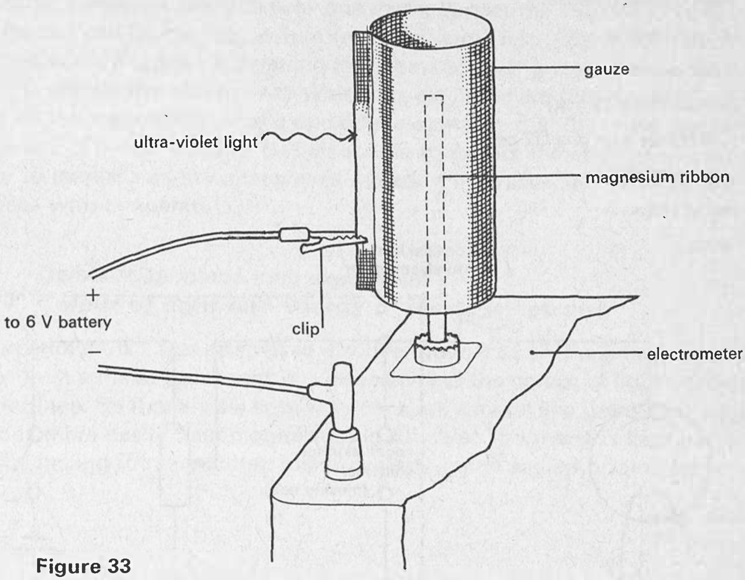


Figure 33
Simple demonstration of the photo-electric effect.

This experiment is about removing electrons from metals, as opposed to removing them from individual atoms. Ultra-violet light is shone through a gauze cylinder onto a clean magnesium ribbon. A small potential difference between the ribbon and the gauze assists any electrons emitted by the magnesium to go to the gauze.

What radiation causes a current? A glass plate put in front of the ultra-violet lamp stops the effect, but lets visible light through. Here is another instance of high frequency ultra-violet radiation doing something that lower frequency visible light cannot do. X-rays and gamma rays will also eject electrons from metals, but the sources available in a school will eject too few electrons to produce a measurable current.

What carries electricity between the gauze and the ribbon? Air? If air, the current should reverse when the battery is reversed. (It does not.)

Are carriers given off by one or both electrodes? Changing the material of an electrode which emits carriers may affect the current. Substituting less reactive metal for magnesium stops the current, but changing the material of the gauze has no effect.

Demonstration and long experiment

5.17 Colour of light and energy of photo-electrons

1068	parallel beam projector
59	l.t. variable voltage supply
69	high dispersion prism
1074	photo-electric cell
1006	electrometer
1003/1	milliammeter (1 mA)
1033	cell holder with one U2 cell
1053	card with slits
1067 F	set of stops
1000	leads

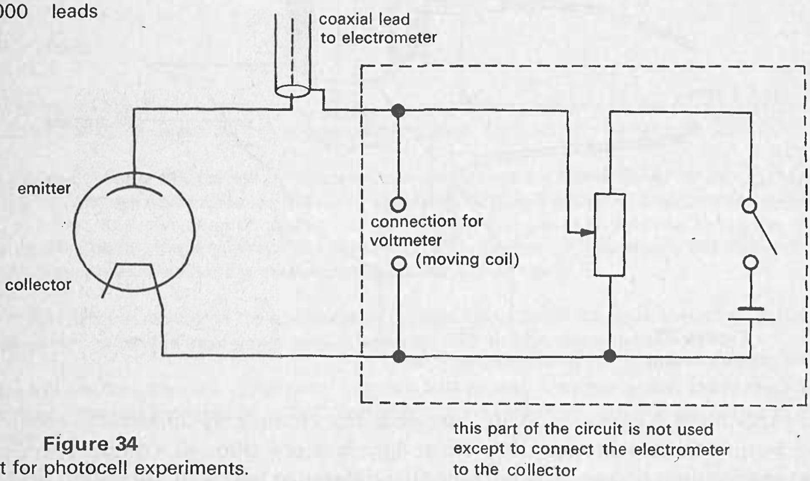


Figure 34
Circuit for photocell experiments.

Spectrum Cut a slit about 2 mm wide in the card, and place the slit over the aperture of the tube containing the photocell, as shown in figure 35. The parallel beam projector, with the prism on its front platform, is then placed so as to cast a spectrum on the card, the spectrum being formed at minimum deviation. The lamp may be overrun by up to 30 per cent to obtain a brighter spectrum. It is best to work in dim light, and shield the photocell from stray light as well as possible.

Circuit See figure 34. The circuit does not use all the facilities that may be provided with the photocell, these being intended for experiments in which a p.d. is applied to the cell from a battery, using a potentiometer and a moving coil voltmeter. In this circuit, if there is a battery, it should be removed or switched out of circuit. The circuit, and the technique suggested below, are suited to an electrometer whose input resistance can be made as high as $10^{13}\ \Omega$, usually by removing the resistor altogether. An electrometer with switched voltage ranges may have resistors of the order of $10^{11}\ \Omega$ permanently across the input, and may be better suited to the balance voltage technique for which a battery and potentiometer are provided.

Before connecting the electrometer to the photocell, place a 1.5 V dry cell across its input, and alter the sensitivity until the display meter is at full scale. Then connect the electrometer to the cell, the positive input going to the potassium emitter, and physically remove any input resistor or switch the electrometer so that it will act as a voltmeter of the highest possible resistance.

If electricity will only pass from the gauze to the magnesium, and the magnesium emits the carriers, what is the sign of the charge on the carriers? What are the carriers likely to be? Answers to these questions cannot be obtained by inescapable deduction. They are just likely answers which may be tested by more experiment.

Discussion can move towards how one might expect the radiation to cause electrons to be thrown out by the magnesium (or potassium, etc). Any metal throws out electrons when it is hot enough and the atoms are being well shaken. The hotter the metal the greater the energy with which the electrons are thrown out. Can radiation, falling on the magnesium, shake up surface atoms so that they lose electrons in the same way? If it can, it might be reasonable to expect the emitted electrons' kinetic energy to increase as the intensity of radiation increases, in the same way as it increases with temperature.

Demonstration and long experiment

5.17 Colour of light and energy of photo-electrons

This experiment is a first attempt to discover how, if at all, the energy of electrons ejected from a metal varies with the intensity and the colour of light shining on a metal surface. So that visible light may be used, a metal like potassium which loses electrons more easily than magnesium is suitable. The metal is kept permanently clean by having it in a vacuum inside a ready-made sealed photo-electric cell.

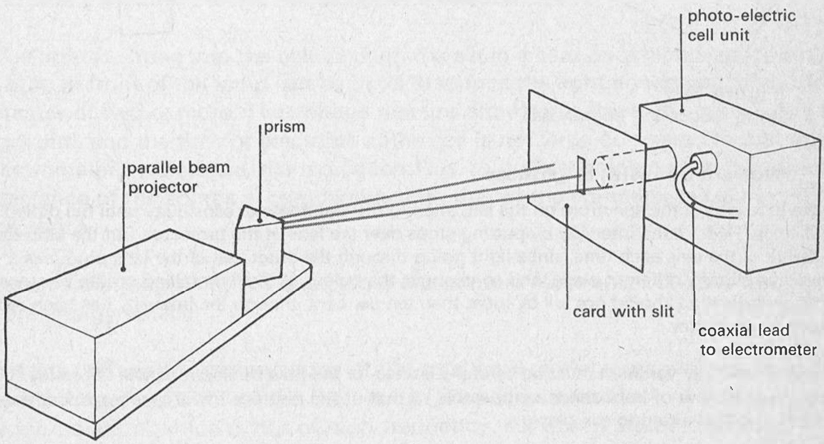


Figure 35
Photo-electric cell with a spectrum shone on it.

A simple experiment is best. The electrometer is connected directly across the photocell to act as a voltmeter. When light is shone on the cell, electrons travel from the emitting surface to a collecting wire, which is made of a metal that does not emit electrons in visible light and, we hope, has no trace of potassium on it. From the moment the light starts to shine, the voltmeter indication rises, but ultimately becomes steady.

Variation with colour

With the electrometer short-circuited, position the spectrum so that the dark region beyond the red falls on the slit. Then, with the electrometer switched to read the p.d. across the photocell, sweep the spectrum from red to violet *slowly* across the slit. Allow time for the p.d. to rise to a steady value at each stage.

The reading rises beyond the violet, in the ultra-violet. Beyond that, it stays steady, even if the light is cut off altogether. When no light falls on the cell, the electrometer cannot discharge. If it is momentarily short-circuited, the reading stays at zero beyond the ultra-violet or in the dark, but rises again in the visible or ultra-violet to the values seen before.

If the spectrum is swept back from violet to red the reading falls, though one would expect it not to do so, since low energy electrons ought not to be able to reach a collector across a high potential difference. The reason is that some potassium gets onto the collector, and some electrons flow the 'wrong' way. This is a point to be avoided by smooth demonstration technique, not one to introduce and explain. So it is best to avoid the change from violet towards red without first short-circuiting the electrometer. If the collector can be heated to drive off potassium on it, the reverse current can be reduced. Note the readings of the electrometer when red light and when violet light shines on the slit.

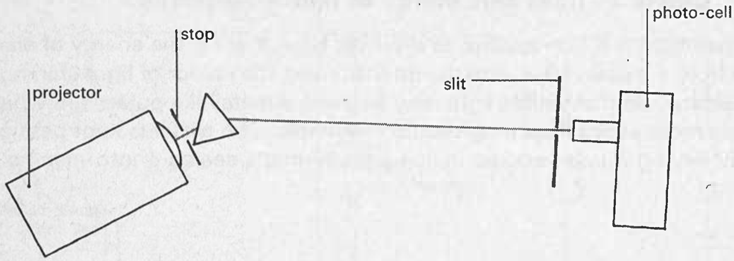


Figure 36
Using a stop to reduce the brightness.

No variation with brightness

Shine the blue part of the spectrum on the slit, altering the electrometer sensitivity until the deflection is near full scale. Reduce the intensity by putting stops over the lens of the projector. Put the stop exactly in the centre of the lens each time, since light going through the outer part of the lens produces a spectrum in a slightly different place, and so changes the colour of the light falling on the photocell. The voltage indication should not fall by more than ten per cent, though the intensity has been reduced by a much larger factor.

The range of intensity variation must be carefully limited, or the flow of electrons will fall so low that the electrometer, now of impedance comparable to that of the photocell, will give a reduced reading. This needs to be admitted to the class.

Although the independence of electron energy and brightness is crucial to the message of the photo-electric effect, it cannot be established with complete security using school apparatus. Nor is it always easy to explain everything that happens. Some cells, if kept in the dark but connected to an electrometer, deliver a p.d. They may be acting as little batteries, or the cause may be something else.

Reading

Millikan, *The electron,* Chapter X, describes how Millikan developed means for measuring the energy of electrons ejected from various metals by radiations of various frequencies. These results supplement experiment 5.17.

The collector now has a negative charge, as it would if electrons had accumulated on it and charged up the effective capacitance across the electrometer. The steady potential difference indicates that few more electrons are arriving at the collector (only those required to pass through the very high input resistance of the electrometer). If the *potential difference is, say, half a volt, then the electrons from the emitter must be* ejected with energy no more than half an electronvolt each, or they would continue to arrive. So the electrometer indicates the maximum energy of ejected electrons, as long as it draws a current small compared to the number of electrons ejected in a second.

Variation with colour

Now a spectrum can be cast on a card with a slit in it, behind which is the photocell. As the spectrum, from red to violet, is moved across the slit, there is a steady rise of the potential difference developed across the cell. The rise continues into the ultra-violet. It seems that the higher the frequency of the light, the larger the maximum energy of ejected electrons. More accurate investigations show that the maximum energy is proportional to the frequency.

No variation with brightness

Suppose that the light somehow shakes electrons out of the metal. Brighter light ought to shake them harder and give them more energy. But it is not so, and a trial can illustrate the point, though not establish it beyond doubt.

Blue light is shone into the cell through the slit in a card on which a spectrum is shone. A stop in front of the lamp can be used to reduce the light energy reaching the cell by a factor of two or more. The voltage remains almost constant. (Naturally, if the light is very dim, and the flow of electrons in the cell is not large compared to that through the electrometer's resistance, the indication falls, as it always does when the effective resistance of the source is comparable with that of the voltmeter measuring the p.d. across it.)

It seems that bright light of one colour ejects more electrons, but does not give them more energy apiece.

This fits with earlier observations of the total lack of electrons emitted from some metals if the frequency of the light is too low, as with the lack of any ionization of air by radiation which is not of high frequency. All observations would be explained if radiation of frequency f could deliver energy in parcels, or quanta, of size E given by $E = hf$, where h is a constant. It is necessary also to suppose that an electron will not emerge from a metal, or indeed from an atom of a gas, unless it has at least some energy E_0. The last point has already been shown for gas atoms, which will not ionize unless given the energy E_0 which is the ionization energy discussed just previously.

The following textbooks give a summary of the results of photo-electric experiments.

Baez, *The new college physics,* Chapter 49.

Bennet, *Electricity and modern physics* (MKS version) (reference 8), Chapter 13.

Caro, McDonell, and Spicer, *Modern physics* (reference 9), Chapter 3.

Holton and Roller, *Foundations of modern physical science* (reference 10), Chapter 32.

Project Physics, Text, Unit 5, *Models of the atom* (reference 11), Chapter 18.

PSSC, *College physics* (reference 14), Chapter 31.

PSSC, *Physics* (second edition) (reference 13), Chapter 33.

Rogers, *Physics for the inquiring mind* (reference 15), Chapter 44, especially figure 44–6.

Measurement of Planck's constant

It is best to leave a more careful attempt to measure h to an interested student, as a long experiment done at any convenient time. Details are given in the *Students' laboratory book.*

Students' book

Question 36 is about the interpretation of the photo-electric effect.

The constancy of Planck's constant

The demonstration cannot support every assertion one might like to make. The complexities are such as to make it inadvisable to try to test whether the maximum energy of electrons is proportional to frequency.

Further, the constant obtained even if this were so might depend on the material used. Millikan showed that it did not, so h may be a universal constant. That h is an important universal constant comes later still, when it appears in a number of different contexts, such as black body radiation and electron diffraction. Hints of this appear in Unit 10. For the moment, it is best to pass such matters by, aiming only to let students make a first acquaintance with quanta and Planck's constant.

Students' book

Questions 37 and 38 are about sizes of quanta, and the number of quanta emitted in a second by various sources. They could replace the teaching suggested under 'Sizes of quanta'.

Film loop

The film loop 'X-ray diffraction 1. Production of the X-ray beam' made for this Project and suggested for Unit 1 could be shown again. It helps to show that X-ray quanta are big enough to count one by one.

Film

The 16 mm sound film 'The velocity of gamma rays', produced by Rank Mullard in conjunction with the Project, could be shown here if it was not used in Unit 4.

Quanta and energy levels in Unit 10

The discussion of quanta and the energy levels of an atom emitting or absorbing light is developed much more fully in Unit 10, *Waves, particles, and atoms,* where experiment 5.18 may be repeated. Although it rounds off Unit 5 nicely, linking it back to several other pieces of earlier work, the experiment and argument could be deferred until Unit 10. They should be deferred if the class will be unable to grasp the use of a grating to measure wavelength.

Planck's constant

The quantity h is called Planck's constant, after the man who first introduced it into physics. It is a constant which says just how grainy light is; how big the quanta of energy will be at any particular frequency.

In the experiment, the maximum energy $(hf - E_0)$ was of the order of 1 electronvolt, of of the order of 10^{-19} J, when the frequency was of the order of 10^{15} Hz. So the energy hf should exceed 10^{-19} J, and h should exceed 10^{-34} J s.

Lack of knowledge of E_0 can be circumvented by recording the change of the maximum energy of ejected electrons with frequency. A rough value may be found by noting that red light, $f = 4.5 \times 10^{14}$ Hz, ejects electrons with energy about 0.2 electronvolts, while violet light, $f = 7.5 \times 10^{14}$ Hz, may give them an energy as much as 1.4 electronvolts.

$$h = \frac{(1.4 - 0.2)}{(7.5 - 4.5) \times 10^{14}} = 4 \times 10^{-15} \text{ electronvolts per hertz}$$

$$h = (4 \times 10^{-15})(1.6 \times 10^{-19}) = 6.4 \times 10^{-34} \text{ joules per hertz, or J s}$$

This calculation should be treated as a rough estimate, to show the principle. Another estimate of h will emerge from experiment 5.18. The photo-electric estimate may be deferred until a student has taken some more careful measurements.

Sizes of quanta

Figure 37 illustrates the relative sizes of the quanta of energy associated with different parts of the electromagnetic spectrum, discussed in Unit 4, Part One. Some simple calculations are worth doing.

BBC Radio 2 is broadcast at 1500 m wavelength, frequency 2×10^5 Hz, power 400 kW. One quantum has energy about 10^{-28} J or 10^{-9} eV. The transmitter will emit about 4×10^{33} of them in a second.

The wavelength of X-rays used in X-ray diffraction in Unit 1 was about 1.5×10^{-10} m, frequency 2×10^{18} Hz, which is 10^{13} times the frequency of Radio 2. So the X-ray quanta will be 10^{13} times more energetic than the radio quanta. With energy 10^4 eV each, they might be more conspicuous. Indeed, the first of the four film loops of X-ray work shows the substantial random fluctuations of the count rate from a weak beam of X-rays detected by a Geiger tube. X-ray and gamma ray quanta can easily be detected individually; radio quanta can not.

Visible quanta lie in between, with energy of two or three electronvolts. One watt of visible light conveys some 10^{19} quanta each second, so detecting individual quanta is difficult.

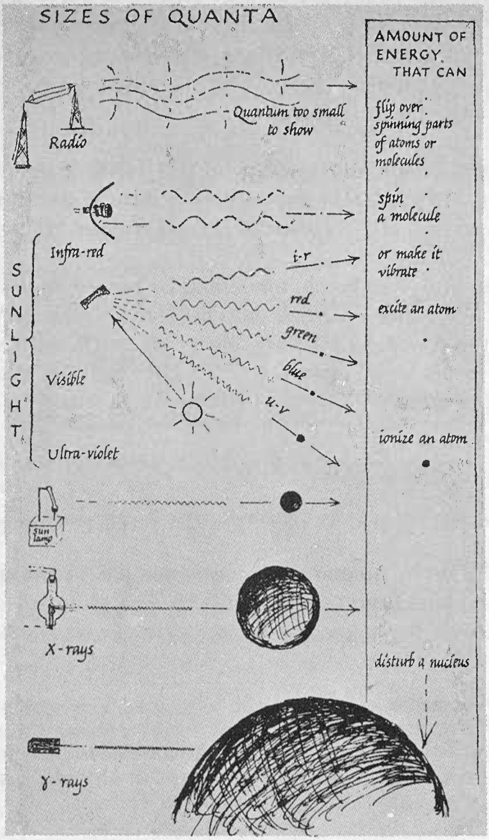


Figure 37
Sizes of quanta.
From Rogers, E. M. (1960) Physics for the inquiring mind, *Oxford University Press; reprinted by permission of Princeton University Press.*

Demonstration
5.18 Spectrum of mercury vapour

1071	mercury discharge lamp
1073	concave reflection grating
1053	screen with slit (see below)
1053	strip of fluorescent paper, 20 mm wide, green
503–6	retort stand base, rod, boss, and clamp
535	polythene bottle with a little mercury
3 G	microscope slide

Gamma ray quanta can have energies in the million electronvolt range, and they and X-rays can ionize atoms easily, while light cannot, for the ionization energy is of the order of 10 electronvolts. The large difference in quantum energy is the main reason why gamma and X-rays seem to differ so much from visible light.

Quanta and energy levels

An electron needs a certain amount of energy to knock it out of a metal, and a quantum of light energy can supply that need. An electron needs a certain energy – the ionization energy – to knock it out of an atom. Can light do that, too? Certainly, a gamma ray can, but what about radiations of lower frequency?

Take mercury as an example. In Unit 2, Part Five, some reason was given for supposing that a mercury atom could accept energy in lumps. 4.9 electronvolts were enough to raise an electron from the lowest level to one of the higher levels.

If the frequency of visible light corresponds to some two or three electronvolts quantum energy, at what frequency and wavelength would quanta of 4.9 eV, about twice that energy, be found? (In the ultra-violet, at wavelengths around 2×10^{-7} m, half that for the violet.) Do mercury atoms absorb, and perhaps emit, quanta of this size?

Demonstration
5.18 Spectrum of mercury vapour

Set up a mercury lamp (which has no glass envelope that would absorb radiation at this wavelength) behind a slit so that its radiation falls onto a concave reflection grating, which projects its spectrum on a fluorescent card. See figure 38. A number of lines will be seen. The yellow, green, and violet lines (5.8, 5.46, and 4.4×10^{-7} metre, respectively) can be identified by their colour using ordinary white paper.

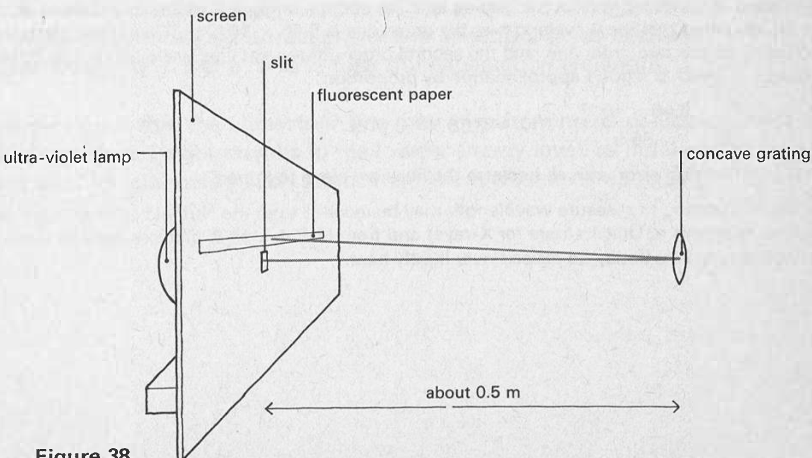


Figure 38
Production of mercury spectrum using a reflection grating.

Safety

This experiment involves ultra-violet light and mercury vapour; both potentially dangerous. Please observe the safety precautions mentioned below.

Screen

This must be large enough to protect the class from stray ultra-violet radiation, being at least 0.3 m high and 0.6 m wide. *Students should not look directly at the source.* A 1 mm slit is needed in the centre of the screen so that when the screen rests on one long edge the slit comes opposite the aperture in the ultra-violet source. Figure 38 shows the arrangement. A strip of green fluorescent paper is pinned across the screen on top of white, non-fluorescent paper.

Spectrum

Fix the grating at a distance equal to its radius of curvature (about 0.5 m) from the screen, so as to cast a spectrum back on the screen, with the zero order image of the slit in focus and just above the slit. Then turn the grating so that the diffracted orders lie over the horizontal strip of fluorescent paper, but fall partly on the white paper, as in figure 39. Any ultra-violet lines appear only on the fluorescent paper, while visible lines are seen on both. Run the lamp at a low level.

Experiments

Put a microscope slide over the slit; the ultra-violet lines vanish.

Gently squeeze a polythene bottle with a *little* mercury in it so that the vapour comes out just in front of the grating. The lines fade or vanish for a moment. *Close the bottle immediately.*

Measure the distances between the zero order line, the first order green line, and the second order ultra-violet line near the green line.

If the lamp can be run at a higher current, a more complete mercury spectrum can now be shown. The effect of cold mercury vapour is usually less marked at high current, and may then be unobservable.

If only the weak ultra-violet source (item 189) is available, the spectrum will be too weak to be seen by a class, and it will be necessary to photograph it beforehand using bromide paper. The ultra-violet lines can be identified if half the slit is covered by a microscope slide.

Calculation of wavelength

Calculation of wavelength from the grating spacing and the angle is possible, but there is much to be said for assuming that the wavelength of the green line is 5.46×10^{-7} m. Then if the green line is 86.5 mm from the zero order line, and the second order ultra-violet line, wavelength λ, is 80 mm from this line, λ is given to a good approximation by proportion.

$$\frac{2\lambda}{80} \approx \frac{5.46 \times 10^{-7}}{86.5} \qquad \lambda \approx 2.53 \times 10^{-7}\ \text{m}$$

The trigonometrical error is small because the lines are close together.

The use of a grating to measure wavelength may be recalled from the Nuffield O-level Physics course, and from mentions in Unit 1 (there for X-rays) and from Unit 4. Unit 8, *Electromagnetic waves,* will deal with it again, so it may be passed over lightly here.

Students can be given transmission gratings through which to look at a discharge tube if they are not sure what to expect. But on the fluorescent card, though not on the paper, there are two or more lines, one much nearer to the zero order spectrum and the other apparently of slightly shorter wavelength than the green line. Figure 39 shows what the lines may look like.

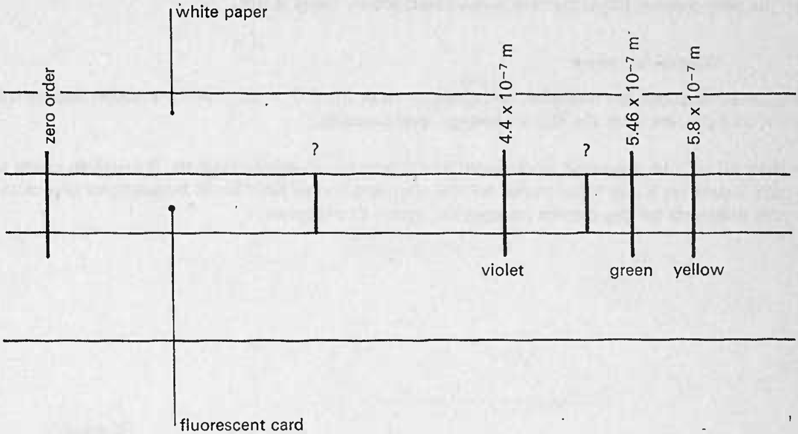


Figure 39
Mercury spectrum using a reflection grating.

The line very near the zero order may be the one we are interested in, but what about the other?

Put a microscope slide in front of the slit, so that the light must pass through it. Both the new lines disappear. The disappearance of the line between the green and the violet, although the green line on one side and the violet line on the other side are unaffected, and although the microscope slide is colourless, implies that the two new lines are first and second order displays of the same wavelength. If so, a calculation of the wavelength from measurements of the spectrum gives between 2.50 and 2.55×10^{-7} metre. This is near the expected wavelength.

The suggestion is that the ultra-violet line may arise from mercury atoms whose energy drops by 4.9 electronvolts to the lowest energy level, as indicated in figure 40. Perhaps such quanta could push atoms from the lowest level up again.

Energy levels of mercury

See Unit 2, Part Five. The energy levels of mercury appear in figure 59 in the *Students' book*, Unit 2. It is important in the argument that the class is clear that the energies can be, and were, measured quite independently of evidence from spectra.

It is of course the case that most energy levels are measured, for accurate values, from spectra. If this were the only means, the argument would be circular, but it is not.

Students' book

Question 39 is about the emission and absorption of the 2.5×10^{-7} m ultra-violet line by mercury vapour, and the link with the 4.9 eV energy level spacing.

Question 40 is to be regarded as optional, but may interest some students. It involves using some of Moseley's data on X-ray frequencies for the elements to see how these frequencies give some further physical evidence for the atomic number sequence of elements.

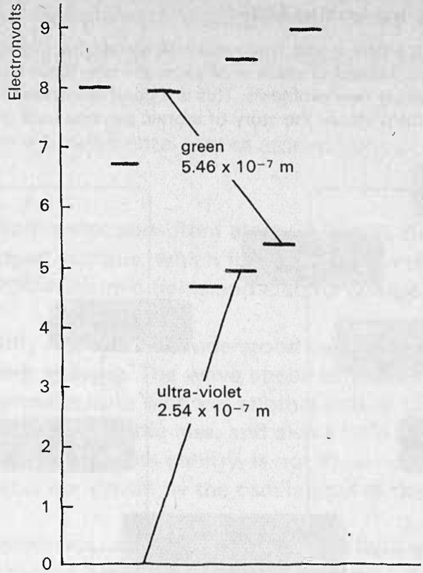


Figure 40
Origin of ultra-violet mercury line, and of one other line.

Using light to give mercury atoms energy

Squeeze a polythene bottle containing a little mercury so that the vapour comes out just in front of the reflection grating and the light must pass twice through the vapour. The deep ultra-violet lines (2.54×10^{-7} m) disappear, but the others remain.

It is pretty likely that most atoms in cold mercury vapour will be in the lowest energy level. So the quantum whose wavelength is 2.54×10^{-7} m corresponds to a jump up from this level. (The other, visible, lines don't vanish because there are few, if any, atoms in high levels waiting to jump higher.)

If this quantum corresponds to 4.9 electronvolts energy, Planck's constant can be found from its frequency.

$$E = 4.9 \text{ eV} = 7.85 \times 10^{-19} \text{ J}$$
$$f = c/\lambda = 1.18 \times 10^{15} \text{ Hz}$$
$$h = E/f = 6.6 \times 10^{-34} \text{ J s}$$

To be quite sure, it would be necessary to see if the other lines in the spectrum fit in with other energy level spacings and with the same value of Planck's constant. That comes later, in Unit 10, *Waves, particles, and atoms.* For now, the agreement with the photo-electric value of h may be enough to give some confidence that wavelength, frequency, and energy have been correctly paired off.

Looking back and looking ahead

One aim of the course as a whole is that students understand how physics works. An important part of this is the great interconnectedness of ideas in physics; the way ideas from several areas can come together and be used to tackle new problems. This is a good opportunity to emphasize that aspect of physics, particularly as Unit 5 closes the story of atomic physics until it is reopened in Unit 10.

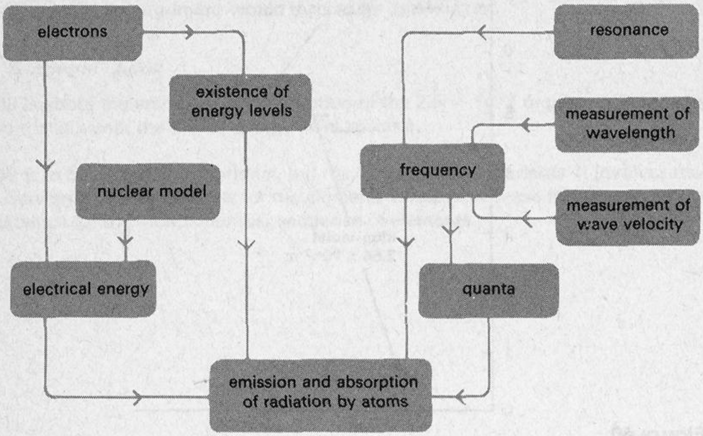


Figure 41
Ideas linked together in discussion of experiment 5.18.

Summary: one experiment linking many parts of physics

This experiment contains much of the physics done so far in the course, and points the way to much to come.

It is about energy levels – a fundamental fact of atomic behaviour, but one yet to be explained in this course.

The energy needed to remove electrons from atoms is in part electrical, coming from the attraction of the charged nucleus, which first appeared in this Unit. So the experiment is indirectly about electric fields and electric charge.

It is about waves, too. Only if waves are understood can the wavelength be calculated from the grating spacing. The wave speed is needed for finding the frequency. And this experiment links with yet another part of Unit 4: it is a resonance effect as well. Light of frequency a little less, and also a little more, than that corresponding just to 4.9 electronvolts energy, is not absorbed. The mercury atom behaves rather like an oscillator driven by the oscillations of the light.

The experiment points to several new questions. What is light really like? What is it about light that makes charged particles like electrons jump? Presumably light is in some way electrical. Unit 8, *Electromagnetic waves,* is about this. How can a wave deliver energy in quanta? And why do atoms have energy levels, and why do the levels and ionization energies have the size they do have? Unit 10 is about these things.

Appendices

Appendix A
Rutherford scattering

Dynamics of alpha particle path

Figure 42 shows the (hyperbolic) path of an alpha particle, mass *m*, charge *q*, travelling with initial velocity *u*, aimed so that, if undeflected, it would pass a distance *p* from a nucleus of charge *Q*.

If the nucleus is very massive it recoils very little, and the path is symmetrical about a line NO passing through the nucleus. The alpha particle reaches a velocity *u* again as it recedes far from the nucleus (conservation of energy), and has been deflected through an angle ϕ.

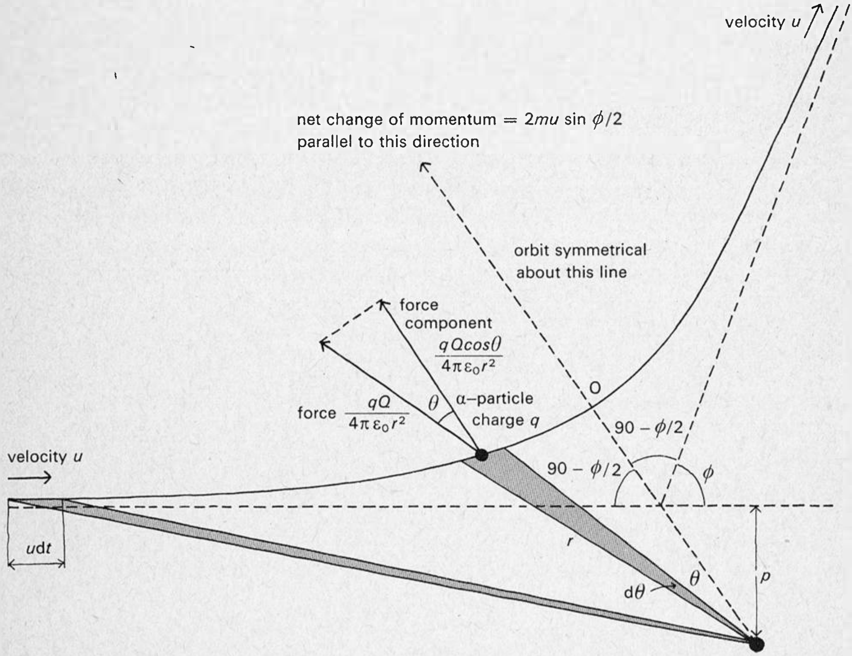


Figure 42

There is no net change of momentum of the alpha particle perpendicular to the line NO, but there is a change of momentum parallel to this direction, because the alpha particle is deflected.

From figure 42:

$$\text{net change of momentum along NO} = 2\,mu \sin(\phi/2) \qquad \mathbf{1}$$

Suppose that the deflection is due to coulomb repulsion between nucleus and alpha particle. Figure 42 shows the alpha particle when it happens to be a distance r from the nucleus. The central coulomb force $\dfrac{qQ}{4\pi\varepsilon_0 r^2}$ is along a direction making an angle θ with the line NO. It has a component parallel to this line, which in time dt gives an impulse contributing to the deflection of the alpha particle.

$$\text{Contribution to impulse along NO} = \left(\frac{qQ}{4\pi\varepsilon_0 r^2}\right)\cos\theta \mathrm{d}t \qquad 2$$

Figure 42 shows the change $\mathrm{d}\theta$ of the angle θ in time $\mathrm{d}t$, during which the path sweeps out the area $r^2\mathrm{d}\theta$ (shown shaded) of the triangle of angle $\mathrm{d}\theta$ at the nucleus N.

Far from the nucleus, the alpha particle will travel a distance $u\mathrm{d}t$ in an equal time $\mathrm{d}t$, sweeping out an area $pu\mathrm{d}t$ (also shaded). Under any central force, all such areas are equal (Kepler's Law, alternatively from conservation of angular momentum).

$$pu\mathrm{d}t = r^2\mathrm{d}\theta \qquad 3$$

Substituting for $\mathrm{d}t$ from **3** into **2**:

$$\text{contribution to impulse along NO} = \left(\frac{qQ}{4\pi\varepsilon_0 pu}\right)\cos\theta \,\mathrm{d}\theta \qquad 4$$

Note that r^2 cancels if and only if the force law is inverse square. The total impulse along NO may be found by integrating **4**, with θ varying from $-(90-\phi/2)$ to $+(90-\phi/2)$.

$$\text{Total impulse along NO} = \left(\frac{qQ}{4\pi\varepsilon_0 pu}\right)\int_{-(90-\phi/2)}^{+(90-\phi/2)}\cos\theta\mathrm{d}\theta$$

$$= \left(\frac{qQ}{4\pi\varepsilon_0 pu}\right) 2\cos(\phi/2) \qquad 5$$

The total impulse along NO **(5)** is equal to the change of momentum along NO **(1)**, giving:

$$2\,mu\sin(\phi/2) = \left(\frac{qQ}{4\pi\varepsilon_0 pu}\right) 2\cos(\phi/2)$$

Whence $\dfrac{2p}{b} = \cot(\phi/2)$ 6

where $b = \dfrac{qQ}{4\pi\varepsilon_0(\frac{1}{2}mu^2)}$ is the distance of closest approach in a 'head-on' collision with the nucleus. Equation **6** is the fundamental scattering law; the rest of the argument concerns the geometry of the experiment.

Geometry of scattering experiment

As shown in figure 43, a detector of finite width set at distance R from the foil, at angle ϕ, detects particles deflected into a range $d\phi$ of angles.

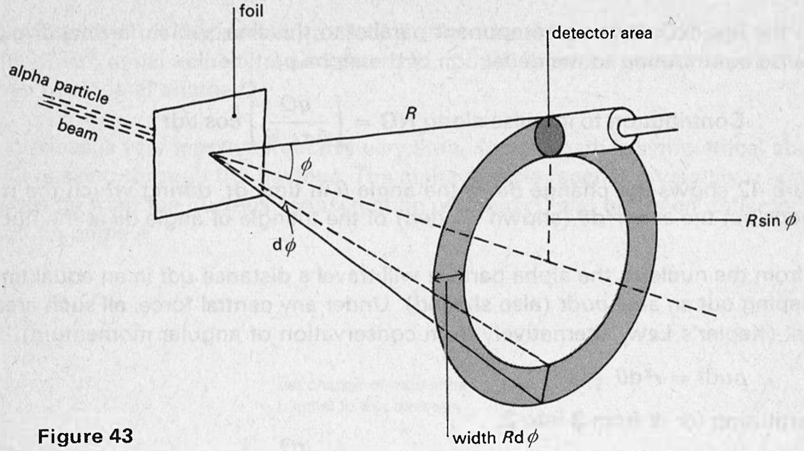


Figure 43

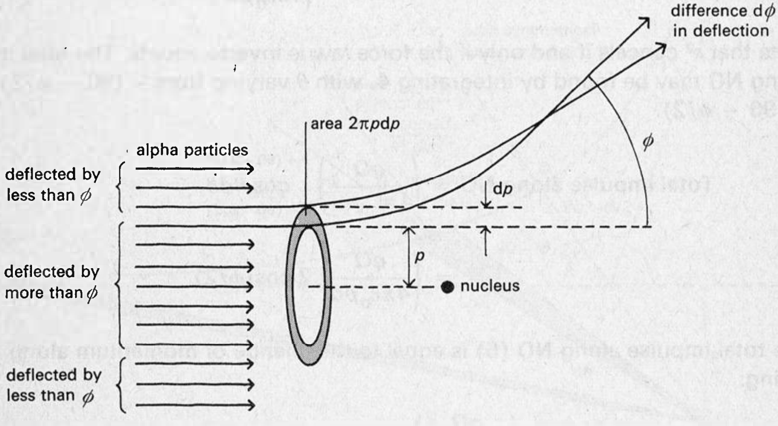


Figure 44

As shown in figure 44, particles deflected into an angular range $d\phi$ must have passed through a ring of area $2\pi pdp$ out of the area A of the beam, which, if there were only one scattering nucleus, would happen to a fraction $2\pi pdp/A$ of the particles. But there are ntA nuclei in the path of the beam, where n is the number per unit volume and t the foil thickness. Multiplying:

$$\text{in range } d\phi\text{, near angle } \phi\text{, fraction of deflections} = (2\pi pdp)nt \qquad 7$$

Substituting for p from **6** into **7**:

fraction of deflections in range $d\phi$

$$= 2\pi\left[\frac{b}{2}\cot(\phi/2)\right]\left[\frac{b}{4}\operatorname{cosec}^2(\phi/2)\right] nt d\phi \quad \mathbf{8}$$

since, differentiating **6**, $dp = \frac{b}{4}\operatorname{cosec}^2(\phi/2)\, d\phi$.

Referring back to figure 43, not all the particles deflected into the interval $d\phi$ reach the detector, which covers only part of the ring shaped area, width $R d\phi$, area $(2\pi R \sin\phi)\, R d\,\phi$, through which they pass.

$$\text{Proportion detected} = \frac{\text{detector area}}{2\pi R^2 \sin\phi\, d\phi} \quad \mathbf{9}$$

Combining **8** and **9**:

fraction of incident alpha particles reaching detector

$$= \left[\frac{b^2 nt}{8}\right] \frac{[\cot(\phi/2)]\,[\operatorname{cosec}^2(\phi/2)]}{R^2 \sin\phi} [\text{detector area}]$$

Expanding $\sin\phi$ as $2\sin(\phi/2)\cos(\phi/2)$ yields

fraction of incident alpha particles reaching detector

$$= \frac{b^2 nt}{16R^2 \sin^4(\phi/2)} [\text{detector area}] \quad \mathbf{10}$$

Equation **10** is the Rutherford scattering prediction. Since

$$b = \frac{qQ}{4\pi\varepsilon_0(\frac{1}{2}mu^2)}$$

the scattering is proportional to Q^2, and to $1/u^4$ as well as to $1/\sin^4(\phi/2)$ and to the foil thickness, t.

Appendix B
Numbers of alpha particles scattered at more than angle ϕ

Geiger's and Marsden's data, columns I and II of table 8, represent numbers of alpha particles scattered into a small fixed area of a detector at an angle ϕ to undeflected particles.

For the purposes of the teaching suggested, using a gravitational analogue of alpha scattering, the numbers of particles scattered at angles *greater than* ϕ are given in this *Guide* and in 'Radioactivity and the nuclear atom' in the *Students' book* (reference 17). They were calculated as follows.

As shown in Appendix A, figure 43 and equation **9**, the number of particles scattered into an angular interval $d\phi$ is given by multiplying the number N reaching a detector of fixed area by the expression $(2\pi R^2 \sin\phi)/(\text{detector area})$. Column III of table 8 gives values of $\sin\phi$, and column IV gives $N \sin\phi$ and is thus, for fixed R and fixed detector area, proportional to the numbers of particles scattered into the fixed angular interval subtended by the detector. Values shown in brackets in column IV were obtained by graphical extrapolation or interpolation, so that the data could be tabulated at 15° intervals.

Column V gives numbers proportional to the area below the graph (figure 45) between angle ϕ and 180°, which area is proportional to the number of particles scattered at more than ϕ.

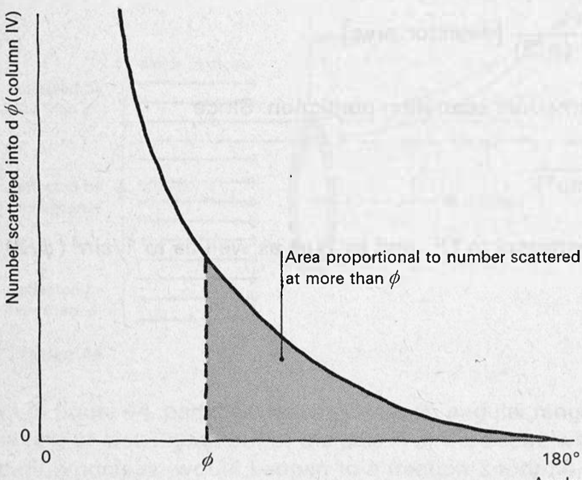


Figure 45

I Angle in degrees	II No. scattered into fixed area	III	IV Proportional to no. scattered into fixed angular interval	V Proportional to no. scattered at more than angle ϕ (approximate)
ϕ	N	$\sin\phi$	$N\sin\phi$	
180	—	—	(0)	0
165	—	—	(8)	8
150	33.1	0.500	16.5	32
135	43.0	0.707	30.4	79
120	51.9	0.866	45.0	154
105	69.5	0.966	67.1	266
90	—	—	(115)	448
75	211	0.966	204	767
60	477	0.866	413	1384
45	1435	0.707	1014	2811
37.5	3300	0.609	2010	—
30	7800	0.500	3900	7725
22.5	27 300	0.383	10 460	—
15	132 000	0.259	34 200	45 800

Table 8

Appendix C
Alternative arguments about the exponential function

Compound interest

People invest money because they expect interest on it: that is, at an annual rate of 10 per cent, capital C has 10 per cent of C added to it in a year. If the new, larger capital is left invested, in the next year the larger capital brings a larger return.

Starting with capital C_0, and a 10 per cent annual rate, the growth is:

10% rate

Capital	Year
C_0	0
$C_1 = C_0\,(1 + 1/10)$	1
$C_2 = C_0\,(1 + 1/10)^2$	2
$C_3 = C_0\,(1 + 1/10)^3$	3
....	
$C_t = C_0\,(1 + 1/10)^t$	t

In other discussions of growth, it has been simple and convenient to imagine an increase equal to the original amount present, equivalent to an extortionate interest rate of 100 per cent. In such circumstances, capital would double every year:

100% rate (doubling)

Capital	Year
C_0	0
$C_1 = C_0\,(1 + 1)$	1
$C_2 = C_0\,(1 + 1)^2$	2
....	

For the growth of bacteria , for instance, doubling in a short time is not so unreasonable. But such growth does not occur in annual (or even monthly or daily) jumps. To get closer to such growth situations, think of the increase taking place more often, but being smaller in size so as to keep the initial rate of rise the same. That is, *one might imagine adding half the capital twice a year, or one-fifth five times a year.*

In general, adding $1/n$ of the capital n times a year leads to:

Capital	**Year**
C_0	0
$C_{1/n} = C_0\left(1 + \frac{1}{n}\right)$	after $1/n$ of a year
$C_{2/n} = C_0\left(1 + \frac{1}{n}\right)^2$	after $2/n$ of a year
$C_1 = C_0\left(1 + \frac{1}{n}\right)^n$	after 1 year (n/n)
$C_t = C_0\left(1 + \frac{1}{n}\right)^{nt}$	after t years

The factor $\left(1 + \frac{1}{n}\right)^n$ is the amount by which capital is multiplied after unit time. If different values of n are tried, and the factor is calculated, it comes to:

n	$\left(1 + \frac{1}{n}\right)^n$	
1	2	(doubles in unit time)
2	2.25	
3	2.37	
10	2.59	(this is equivalent to a 10-step graph as suggested in the text, figure 23)
100	2.70	
1000	2.717	
10 000	2.718	

The value of $\left(1 + \frac{1}{n}\right)^n$ comes closer and closer to a number near to 2.72 (more exactly 2.718 281 8 . . .) as n becomes larger. This is the number e. If n becomes indefinitely large, so that the growth is continuous and not in jumps, instead of

$$C_t = C_0\left(1 + \frac{1}{n}\right)^{nt} \text{ after } t \text{ years (above)}$$

we can write

$$C_t = C_0 e^t \quad \text{putting } e = \left(1 + \frac{1}{n}\right)^n \text{ where } n \text{ is large}$$

That is, for continuous growth in which

$$\frac{dC}{dt} = C$$

after time t, starting at C_0, we shall have $C_t = C_0 e^t$.

The *exponential function* $C = C_0 e^t$ is the *solution* of the *differential equation* $\frac{dC}{dt} = C$.

The equation $\frac{dC}{dt} = kC$ has the solution $C_t = C_0 e^{kt}$.

Value of e from a series

Consider again the equation

$$\frac{dN}{dt} = N$$

What is wrong with $N = A$ as an answer? $\left(\frac{dN}{dt} \neq N\right)$

Try $N = Bt$, possibly $N = \frac{C}{t}$ or $\frac{D}{t^2}$.

No one such expression works. Make a new assumption about N; suppose that we can get near enough by taking a whole sequence of such expressions:

$N = A + Bt + Ct^2 + Dt^3 + \ldots$ as far as we need to go.

The curve we want is the one in figure 46.

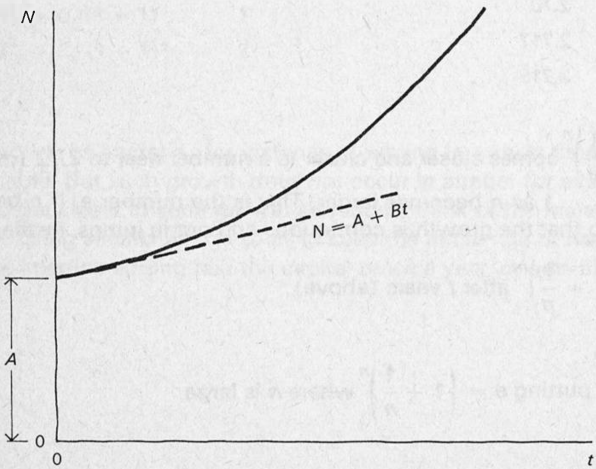


Figure 46

To begin with, a straight line fits quite well. Then it goes wrong. So add a bit of t^2: the fit may improve if we have just enough. If we allow ourselves the right amounts of t, t^2, t^3, etc, we might do quite well.

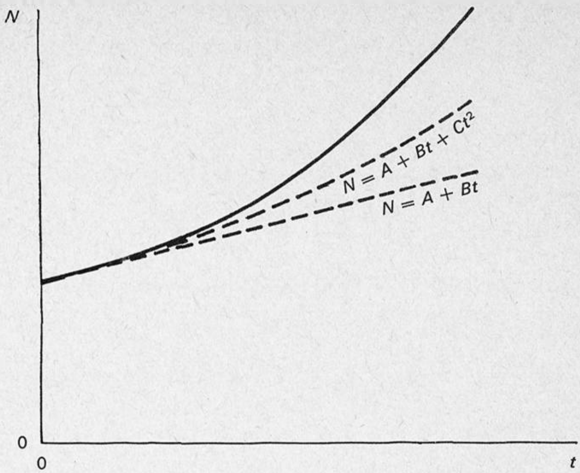


Figure 47

Our only problem now is to determine a series of values A, B, C, D, etc, which will fit the exponential curve. But we do have some help. We know that if we differentiate this expression, we must, if our mathematical model is correct, arrive back again at N.

$$\frac{dN}{dt} = B + 2Ct + 3Dt^2 + 4Et^3 + 5Ft^4 + \dots$$

Can $\dfrac{dN}{dt} = N$? Only if $A = B$. But other terms change with time.

However, the series for $\dfrac{dN}{dt}$ can be differentiated again:

$$\frac{d^2N}{dt^2} = 2C + 2 \times 3Dt + 3 \times 4Et^2 + \dots$$

Only if $2C = B = A$ will $\dfrac{d^2N}{dt^2} = \dfrac{dN}{dt} = N$.

Continuing the same process, one ends up with:

$$N = A\left(1 + t + \frac{t^2}{2} + \frac{t^3}{2 \times 3} + \frac{t^4}{2 \times 3 \times 4} + \dots\right)$$

Suppose $t = 1$. The expression in brackets then comes to 2.72, the number e.

Lists of films, loops, books, and apparatus

Films, film loops, and visual material

16 mm films

'The Rutherford model of the atom.' Colour, sound, 16 minutes. Reference no. 21.7852. Rank Film Library, Rank Audio Visual Ltd, P.O. Box 70, Great West Road, Brentford, Middlesex.

'The velocity of gamma rays.' Colour, sound, 16 minutes. Reference no. 21.7853. Rank Film Library.

'Random events.' Black and white, sound, 31 minutes. Reference no. 900 4116–5. PSSC Physics Teaching film. Distributed by Sound Services Film Library, Wilton Crescent, Merton Park, London, S.W.19. (This film may be useful, but is not essential.)

8 mm film loop

'X-ray diffraction 1: Production of the X-ray beam.' Standard 8. Reference no. XX 1663. Penguin.

Overhead projector material

Nuffield Advanced Chemistry (1970) 'Overhead projection originals'. Penguin. These are paper masters from which transparencies may be made. Numbers 7, 8, 23, and 24 may be useful.

Photographs of particle tracks

Lawrence Radiation Laboratory (1964) 'Introduction to the detection of nuclear particles in a bubble chamber.' Reference no. A33–2809. Ealing Scientific Ltd, 15, Greycaine Road, Watford, WD2 4PW, Hertfordshire.

This booklet includes 14 stereoscopic pictures of bubble chamber events together with a stereoscopic viewer. All are beautiful; only one or two are directly useful in the course.

Books and further reading

Reading references suggested for Part One

Each of the experiments in Part One carries with it a list of possible relevant reading references drawn from the list below. Each reference has a number, and the references are listed with these numbers in the *Students' book*. In the *Students' book*, each reference also has a commentary on the points of especial importance in it, on particular difficulties, and on other matters. For brevity, in the list below, the comments only indicate the subject matter to be found in each reference. Teachers should consult the *Students' book* for help in assessing the difficulty of each reference.

References 1 to 6 contain reproductions of original work. References 1 and 2 overlap very much, and may be regarded as alternatives. The two papers referred to in reference 5 also appear in reference 1. Reference 3, however, contains papers not reproduced in other references, and is a useful supplement to reference 1 or its equivalent.

References 7 to 15 are textbooks of one kind or another. There is much overlap between them, and not all are needed. References 9 and 15 are particularly useful, and offer a nice contrast in style.

References 16 to 20 are in the nature of background reading. Again there is considerable overlap. Reference 18 is particularly useful. Reference 17, part of the *Students' book*, Unit 5, contains extracts intended to assist schools which suffer from a shortage of books.

List of suggested references

1 *Classical scientific papers (physics)* (1964). Mills & Boon.

1A Paper 2; Rutherford on the electric and magnetic deflection of alpha particles.
Experiments 1, 2, 3, 4, 5.

1B Paper 4; Rutherford and Royds on the nature of alpha particles. Identical with reference 5A.
Experiments 1, 2, 3, 4, 5.

1C Paper 20; Wilson on the cloud chamber.
Experiments 2, 3, 4.

1D Paper 8; Geiger's and Marsden's early paper showing that there were alpha particles scattered back. Similar to reference 2B.
Experiments 6, 7, 8.

1E Paper 10; Geiger's and Marsden's test of the Rutherford model. Similar to reference 2B.
Experiments 6, 7, 8.

1F Papers 12, 13; Rutherford summarizes the development of his model. Paper 13, first six pages. Paper 12 is identical with reference 2D.
Experiments 6, 7, 8.

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

2A Chapter 4; atom models, including Thomson model, but not Rutherford.
Experiments 1, 2, 3, 4, 5.

2B Chapter 5; narrative about alpha scattering, with two papers from Geiger and Marsden. Needs selective reading.
Experiments 6, 7, 8.

2C Chapter 6; the charge on the nucleus. Paper by Chadwick (results, page 210, are useful).
Experiments 6, 7, 8.

2D Chapter 6; page 192, Rutherford summarizes the development of his model. Identical with reference 1F.
Experiments 6, 7, 8.

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

3A Papers 2, 3; Becquerel on the discovery of radioactivity.
Experiments 3, 5.

3B Paper 11; Rutherford and Soddy on the cause and nature of radioactivity (Parts I, II, V only).
Experiments 1, 2, 3, 4, 5.

3C Paper 13; Rutherford and Soddy, on radioactive change. Probably section 7 only, on energy.
Experiments 1, 2, 3, 4, 5, 9, 10, 11, 12.

3D Paper 14; Curie and Laborde on the heat from radium.
Experiments 1, 2, 3, 4, 5.

4 Project Physics (1971) Reader, Unit 5, *Models of the atom,* Holt, Rinehart & Winston, New York. Articles surveying atomic physics.
Experiments 6, 7, 8.

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

5A Rutherford's and Royds's paper identifying alpha particles with helium nuclei. Identical with reference 1B.
Experiments 1, 2, 3, 4, 5.

6 Gentner, W., Maier-Leibnitz, H., Bothe, W. (1954) *An atlas of typical expansion chamber photographs.* (School edition.) Pergamon. See figures 5, 10, 12, 14, 15, and 28–32 showing mainly alpha tracks, and collisions with nuclei of varying mass.
Experiments 3, 4, 6, 7, 8.

7 Arons, A. B. (1965) *Development of concepts of physics.* Addison-Wesley.

7A Chapter 32; similar to reference 10A, but more detailed and more historical. Changes in physics in the nineteenth century.
Experiments 1, 2, 3, 4, 5.

7B Chapter 33; size of molecule, Thomson model, alpha scattering, Rutherford model.
Experiments 6, 7, 8.

8 Bennet, G. A. G. (1968) *Electricity and modern physics* (MKS version). Arnold. Discovery of radioactivity, safety precautions; detectors. Transformation and decay.
Experiments 1, 2, 3, 4, 5, 9, 10, 11, 12.

9 Caro, D. E., McDonell, J. A., and Spicer, B. M. (1962) *Modern physics.* Arnold.

9A Chapter 5; history of radioactivity: alpha, beta, and gamma rays; methods of detection. Radioactive decay and transmutation.
Experiments 1, 2, 3, 4, 5, 9, 10, 11, 12.

9B Chapter 11; methods of detecting radiations.
Experiments 1, 2, 3, 4, 5.

9C Chapter 1; the growth of ideas about atoms.
Experiments 1, 2, 3, 4, 5.

9D Chapter 8; the alpha scattering experiment; Rutherford model.
Experiments 6, 7, 8.

10 Holton, G., and Roller, D. H. D. (1958) *Foundations of modern physical science.* Addison-Wesley.

10A Chapter 36; discovery of radioactivity; alpha, beta, and gamma rays.
Experiments 1, 2, 3, 4, 5.

10B Chapter 34; alpha scattering (non-mathematical).
Experiments 6, 7, 8.

11 Project Physics (1971) Text, Unit 5, *Models of the atom.* Holt, Rinehart & Winston.

11A Prologue; history of atomic theory.
Experiments 1, 2, 3, 4, 5.

11B Chapter 19; alpha particle scattering, atomic number, Moseley and X-ray spectra.
Experiments 6, 7, 8.

12 Project Physics (1971) Text, Unit 6, *The nucleus.* Holt, Rinehart & Winston. Chapter 21; history of the discovery of radioactivity. Decay and half-life explained.
Experiments 1, 2, 3, 4, 5, 9, 10, 11, 12.

13 PSSC (1965) *Physics* (second edition). Heath. Chapter 32; alpha scattering; Rutherford model. A gravitational analogue is described. Identical with reference 14.
Experiments 6, 7, 8.

14 PSSC (1968) *College physics.* Raytheon. Chapter 26; identical with reference 13.

15 Rogers, E. M. (1960) *Physics for the inquiring mind.* Oxford University Press.

15A Chapter 39; alpha, beta, and gamma rays; methods of detection. Radioactive decay and transmutation.
Experiments 1, 2, 3, 4, 5, 9, 10, 11, 12.

15B Chapter 40; history of the growth of atomic theory, leading to alpha scattering and the Rutherford model.
Experiments 3, 4, 5, 6, 7, 8.

16 Andrade, E. N. da C. (1964) Science study Series No. 29 *Rutherford and the nature of the atom.* Heinemann.

16A Chapters 3, 4; account of Rutherford's early work, with something on Becquerel. More personal than a textbook.
Experiments 1, 2, 3, 4, 5.

16B Chapter 5; history of alpha scattering experiments.
Experiments 6, 7, 8.

17 Nuffield Advanced Physics (1971) Students' book, Unit 5, *Atomic structure.* Chapter on 'Radioactivity and the nuclear atom'. Penguin. Summary of history, with extracts from Thomson, Becquerel, Rutherford, and Geiger and Marsden.
Experiments 2, 5, 6, 8.

18 Romer, A. (1964) Science study Series No. 10 *The restless atom.* Heinemann.

18A Chapters 1, 2, 3; evidence for atoms. Discovery of radioactivity.
Experiments 1, 2, 3, 4, 5.

18B Chapters 7, 9, 12; identification of alpha particles, development of Geiger counter.
Experiments 1, 2, 3, 4, 5.

18C Chapters 13, 16; alpha scattering; Rutherford model. Little mathematics.
Experiments 6, 7, 8.

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.
Experiments 3, 4, 5, 6, 7, 8.

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.
Experiments 2, 4, 6, 8, 9, 10, 12.

Other books and reading for Unit 5

The following lists contain only those books and reprints not listed on pages 125–7 as reading references. Page numbers of references in this *Guide* appear in bold type.

For students

Books

Baez, A. V. (1967) *The new college physics.* Freeman. **100**.
Bronowski, J. (1960) *The common sense of science.* Penguin. **44**.
Feynman, R. P. (1965) *The character of physical law.* BBC publications. **44**.
Hughes, D. J. (1964) Science study Series No. 1. *The neutron story.* Heinemann. **86**.
Hurley, P. M. (1964) Science study Series No. 5. *How old is the Earth?* Heinemann. **76**.
Millikan, R. A. (1963) Phoenix Science Series. *The electron.* University of Chicago Press. **98**.
Moroney, M. J. (1956) *Facts from figures.* Penguin.
Putman, J. L. (1960) *Isotopes.* Penguin. **76**.
Rothman, M. A. (1966) *The laws of physics.* Penguin. **44**.
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. **76**.
Deevey, E. S. (1952) 'Radiocarbon dating.' *Scientific American* Offprint No. 811. **76**.
Dirac, P. A. M. (1963) 'The evolution of the physicist's picture of nature.' *Scientific American* Offprint No. 292. **44**.
Hurley, P. M. (1949) 'Radioactivity and time.' *Scientific American* Offprint No. 220. **76**.
Reynolds, J. H. (1960) 'The age of the elements in the solar system.' *Scientific American* Offprint No. 253. **76**.

For teachers

Boorse, H. A. and Motz, L. (1966) *The world of the atom* Volume 1. Basic Books Inc. **44**.
Hanson, N. R. (1958) *Patterns of discovery.* Cambridge University Press. **44**.
Nuffield Advanced Biological Science (1970) Laboratory Guide *Organisms and populations* Penguin. **74, 76**.
Nuffield Advanced Biological Science (1970) Study Guide *Evidence and deduction in biological science.* Penguin. **76**.
Nuffield Advanced Chemistry (1970) *Students' book I.* Penguin. **88**.
Nuffield O-level Physics (1967) *Teachers' guide V.* Longman/Penguin. **46**.
Peacocke, T. A. H. (1964) 'Nuclear chemistry.' *School Science Review.* **157**, 597. **32**.
Popper, K. R. (1963) *Conjectures and refutations.* Routledge and Kegan Paul. **44**.

	Apparatus	Experiment
1M	lead block	5.1
3G	microscope slide	5.18
7I	lycopodium powder	5.14
8H	rubber bung (bromine diffusion kit)	5.13
13	vacuum pump	5.13
14	e.h.t. power supply	5.2
16	radium source	5.5, 5.12, 5.13
19/1/2	CO_2 cylinder and dry ice attachment	5.3, 5.6, 5.7, 5.8, 5.15
27	transformer	5.3, 5.6, 5.8, 5.15
28	diffusion cloud chamber	5.3, 5.6, 5.8, 5.15
47	illuminant	5.3, 5.6, 5.8, 5.15
50/3	magnet, Eclipse Major	5.1, 5.13
52K	crocodile clip	5.16
59	l.t. variable voltage supply	5.17
69	high dispersion prism	5.17
92B	Magnadur magnet	5.1
92I	mild steel yoke	5.1
95	Edinburgh CO_2 pucks kit	5.7
95B	wedges	5.14
130/1	scaler	5.1, 5.2, 5.4, 5.9, 5.12, 5.13
130/3	GM tube holder	5.1, 5.4, 5.9, 5.12
130/4	solid state detector and pre-amplifier	5.2, 5.4, 5.13
130/5	thin window GM tube	5.1, 5.4, 5.9, 5.12
130/6	gamma GM tube	5.4
133	camera	5.3, 5.7
134/1	motor driven stroboscope	5.7
161	gantry for CO_2 pucks kit	5.7
189	ultra-violet lamp	5.16
195/1	pure gamma source	5.3, 5.4
195/2	pure beta source	5.1, 5.4
195/3	pure alpha source	5.2, 5.4, 5.8
196	source holder	5.1, 5.2, 5.3, 5.4, 5.12
501	metre rule	5.4
503-6	retort stand base, rod, boss, and clamp	5.1, 5.2, 5.4, 5.9, 5.12, 5.13, 5.16, 5.18
507	stopwatch or stopclock	5.2, 5.4, 5.9, 5.12
535	mercury	5.18
1003	milliammeter (1 mA)	5.2, 5.10, 5.16, 5.17

1006	electrometer	5.2, 5.10, 5.16, 5.17
1008	ionization chamber	5.2, 5.10
1028	alpha scattering analogue	5.14
1033	cell holder	5.10, 5.16, 5.17
1052	absorbers for alpha, beta, and gamma rays	5.4
1053	*Local purchase items*	
	polythene sheet	5.8
	pins, 20 mm long	5.8
	expanded polystyrene sheet, 10 mm thick	5.8
	razor blade	5.13, 5.16
	card with slits	5.17
	screen with slit	5.18
	fluorescent paper	5.18
1054	*Expendable items*	
	P153 daylight printing paper, paper developer, and fixer	5.7
	film, monobath developer/fixer	5.7
	dental X-ray film	5.5
	fast bromide paper	5.5
	developer and fixer	5.5
	graph paper	5.11, 5.14
1055	*Small laboratory items*	
	dice	5.11
	glass T-piece (outside diameter 9 mm) limb length 20 mm	5.13
	polythene bottle (50 cm^3)	5.9
	cork borer	5.8
	PVC tubing (outside diameter 12 mm, bore 8 mm) 150 mm in length	5.13
	glass tubing (outside diameter 8–9 mm, standard wall) 120 mm in length	5.13
	rubber or PVC tubing (outside diameter 8 mm, bore 5 mm) small piece	5.13
	gold foil	5.6
	Vernier callipers	5.4
	drawing board	5.14
	spirit level	5.14
	cork	5.15
	wire gauze, 70 mm × 60 mm; for example, 20 mesh copper	5.16
	glass plate	5.16
1056	*Chemicals*	
	magnesium ribbon, 100 mm	5.16
	amyl acetate	5.9
	methylated spirit	5.3, 5.6, 5.8, 5.15

	isobutylmethylketone (2-methylbutan-3-one)	5.9
	concentrated hydrochloric acid	5.9
	uranyl nitrate	5.9
1066	'thoron' generator	5.10, 5.15
1067F	set of stops	5.17
1068	parallel beam projector	5.17
1071	mercury discharge lamp	5.18
1073	concave reflection grating	5.18
1074	photo-electric cell	5.17

Index

Where significant information is contained in an illustration, the page reference is italicized. In general, odd-numbered page references are to the main text, and even-numbered references are to commentary material.

Editor **Jon Ogborn**

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A *Teachers' guide* has been produced for each of the ten Units forming the Advanced Physics course. This is the *Guide* for Unit 5, *Atomic structure.* It is intended to provide whatever information and ideas are required for the day-to-day teaching of the Unit. The book begins with an Introduction setting out the purpose of the Unit, a summary of the Unit, and a list of suggested experiments. Following this, the main text consists of four Parts, 'Radioactivity and the nature of atoms', 'The Rutherford model of the atom', 'Exponential decay', and 'New ideas and problems about atoms'. It contains teaching suggestions, details of experiments, and a commentary giving background information and other guidance. There are also Appendices on 'Rutherford scattering', 'Numbers of alpha particles scattered at more than angle ϕ', and 'Alternative arguments about the exponential function', and lists of relevant films, loops, books, and apparatus. Notes on reading references are provided.

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