DOCUMENT RESUME

ED 071 909 SE 015 546

TITLE	Project Physics Handbook 6, The Nucleus.
INSTITUTION	Harvard Univ., Cambridge, Mass. Harvard Project Physics.
SPONS AGENCY	Office of Education (DHEW), Washington, D.C. Bureau of Research.
BUREAU NO	BR-5-1038
PUB DATE	68
CONTRACT	OEC-5-10-058
NOTE	34p.; Authorized Interim Version
EDRS PRICE	MF-$0.65 HC-$3.29
DESCRIPTORS	Instructional Materials; Laboratory Experiments; *Laboratory Manuals; *Nuclear Physics; Physics; *Physics Experiments; *Science Activities; Science Experiments; Secondary Grades; *Secondary School Science
IDENTIFIERS	Harvard Project Physics

ABSTRACT

Five experiments and nine activities are presented in this Unit 6 handbook. The experiments are related to random events, ranges of alpha and beta particles, half-lives, and radioactive tracers. The activities are concerned with the energy measurement in beta radiation, demonstration with sugar cubes, ionization by radioactivity, magnetic deflection of beta rays, exponential decay in concentrations, neutron detection problem analogue, chain reaction model, nuclear fission and fusion, and peaceful use of radioactivity. Self-directed instructions, demonstrations, and construction projects are stressed in these activities. The three chapters in the handbook are designed to correspond to three of the four chapters in the text. Notes on the film loop relating to collisions with an unknown object are provided. Also given are illustrations for explanation purposes. The work of Harvard Project Physics has been financially supported by: the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education, and Harvard University. (CC)

Project Physics **Handbook** 6

An Introduction to Physics

The Nucleus

This handbook is the authorized interim version of one of the many instructional materials being developed by Harvard Project Physics, including text units, laboratory experiments, and teacher guides. Its development has profited from the help of many of the colleagues listed at the front of the text units.

The work of Harvard Project Physics has been financially supported by the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education and Harvard University.

Consult the Project Physics text for a partial list of the current and recent staff, consultants and advisory committee.

03-073545-9

90123 69 9876543

Project Physics **Handbook**

An Introduction to Physics **6** **The Nucleus**

Authorized Interim Version [redacted] 1968-69

Distributed by **Holt, Rinehart and Winston, Inc.** New York Toronto

Chapter 21 Radioactivity

Experiments

Activities

Chapter 23 The Nucleus

Activities

Film Loops

Chapter 24 Nuclear Energy; Nuclear Forces

Activities

EXPERIMENT 44 Random Events

In Unit 3 you studied the random behavior of gas molecules, and in the present unit you are learning that some atomic and nuclear events also occur in a random manner.

The purpose of this experiment is to give you some first-hand experience with random events.

What is a random event?

Dice are useful for studying random behavior. You cannot predict with certainty how many spots will show on a single throw. But you are about to discover that you can make useful predictions about the number of times you will observe one, two, or three spots, etc. if you throw a single die 100 times. If you shake a box of 100 dice you can predict with some confidence how many will fall with one spot up, how many with two, etc. If the behavior of the dice is truly random you can use probability theory to make predictions. The theory of probability provides ways to find out if the dice behave randomly and to predict the likely results of a large number of throws. This branch of mathematics has many applications: to the study of automobile traffic flow, the interpretation of faint radar echoes from the planets, the prediction of birth, death and accident rates, and to the breakup of nuclei.

An interesting discussion of the rules and uses of probability theory is found in George Gamow's article, "The Law of Disorder," reprinted in the Unit 3 Reader.

An important characteristic of all truly random events is that each event is independent of the others. That is, even if you throw a die four times in a row and find that a single spot turns up each time, your chance of observing a single spot on the fifth throw is no greater or less than it was on the first throw.

For the events to be independent, it is essential that the conditions under which the observations are made do not change in such a way that one outcome is favored over another.

These conditions are met in each of the three experiments that follow. You are expected to do only one of them. The section "Recording your data," that follows the three descriptions, applies to all the experiments.

A. Twenty-sided dice

A tray containing 120 dice is used for this experiment. Each die has 20 identical faces. (The name for a solid with this shape is icosahedron.) One of the 20 faces on each die should be marked; if not, mark one face on each die with a fiber-tip pen.

Q1 What is the probability that the marked face will appear for any one throw of one die? To put it another way, on the average how many marked faces would you expect to see on top if you shake all 120 dice?

Fig. 1 Photo of dice in use.

Now try it and see how well your prediction holds. Record as many trials as you can in the time available, shaking the dice, pouring them out onto the floor or a large table top, and counting the number of marked faces showing on top.

The counting will go faster if the floor area or table top is divided into three or four sections with a different person counting each section, and another person recording the total count. Work rapidly, taking turns with others in your group if you get tired, so that you can ...t at least 100 trials.

B. Diffusion cloud chamber

A cloud chamber is a device which makes visible the trail left by the particles given off by radioactive atoms. It is a transparent box filled with supercooled alcohol vapor. When an alpha particle passes through, it leaves a trail of ionized air molecules: the alcohol molecules are attracted to these ions and condense into tiny droplets which mark the trail. Your purpose in this experiment is not to learn about the operation of the chamber, but simply to study the degree to which the particles are emitted in a random manner. A barrier with a narrow opening is placed in the chamber, near a sample which emits alpha particles. Count the number of tracks you observe coming through the opening in a convenient time interval, such as 10 seconds. Continue counting for as many intervals as you can during the class period. See the section "Recording your data," below, for further instructions.

C. Geiger counter

A Geiger counter is another device which detects the passage of invisible particles. A potential difference of several hundred volts is maintained between the two electrodes of the Geiger tube. When a beta particle or a gamma ray passes through the tube, the gas in the tube is ionized, which allows a short pulse of electricity to pass through it. The pulse may be heard as an audible click in an earphone, seen as a "blip" on an oscilloscope screen, or cause a change in a number on an electronic scaling device. When a radioactive source is brought near the tube, the count rate goes up rapidly. But even without the source, an occasional pulse still occurs. These pulses are called "background" and are due for the most part to cosmic radiation and to a slight amount of radioactivity always present in objects around the tube.

Use the Geiger counter to determine the rate of background radiation, counting over and over again the number of pulses in a convenient time interval such as 10 seconds.

Recording your data

Record your data as follows: write the numbers from 0 to 20 in order in a column down your paper. If you count 6 pulses on the Geiger counter in one time interval, put a tally mark after the 6 on your paper. If you count 8, put a tally mark after the 8 on your paper.

Make a similar data table if you rolled dice or observed cloud chamber tracks. Continue making tally marks for as many intervals as you can during the class period. When you are through, add another column in which you multiply each number in the first column by the number of tallies opposite it. Whichever experiment you did, your data sheet will look something like the one on the next page.

The third column shows that a total of 628 marked faces (or pulses or tracks) were observed in the 100 trials. The mean is 628 divided by 100, or about 6. You can see that most of the counts cluster around the mean.

Data arranged in this way is called a distribution. The distribution shown was obtained by shaking the tray of 20-sided dice 100 times. Its shape is also typical of Geiger-counter and cloud-chamber results.

Number of events observed in one time interval (n)	Number of times observed (frequency) (f)	Total number of events observed (n × f)
0	|	0
1		0
2	|	2
3	卌 卌	30
4	卌 卌 |||	52
5	卌 卌 ||	65
6	卌 卌 卌 卌 |	126
7	卌 卌 卌 |	112
8	卌 卌 ||	96
9	||||	36
10	||||	40
11	||||	44
12	|	12
13	|	13
		628

A graph of random data

The pattern of your results is easier to visualize if you display your data in the form of a bar graph, or histogram, as in Fig. 2 below.

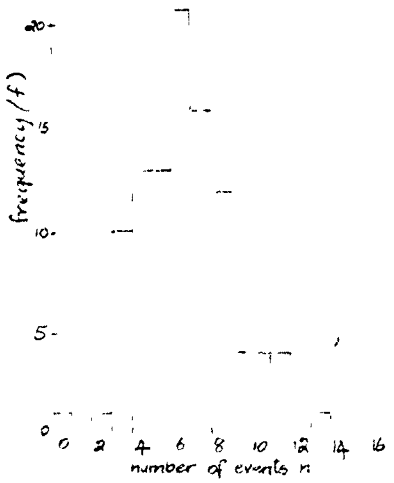


Fig. 2 The results obtained when a tray of 20-sided dice (one side marked) were shaken 100 times.

If you were to shake the dice another set of 100 times, your distribution would not be exactly the same as the first one. However, if sets of 100 trials were repeated several times, the combined results would begin to form a smoother histogram. Figure 3 shows the result you could expect to get if you did 1000 experiments.

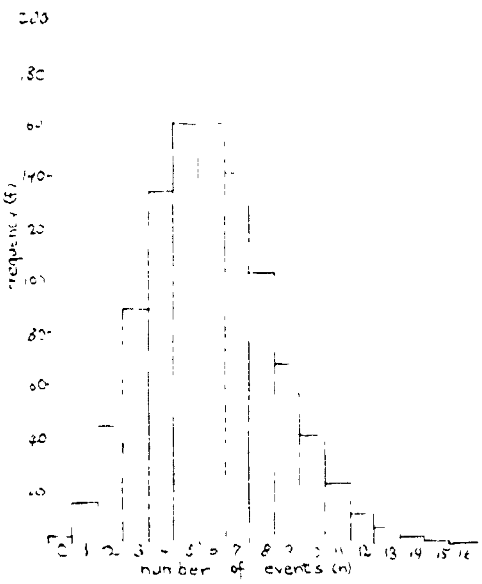


Fig. 3 The predicted results of shaking the dice 1000 times.

Compare this with the results for only ten experiments shown in Fig. 4. As the number of trials increases, the distribution generally becomes smoother and more like the theoretical distribution in Fig. 3.

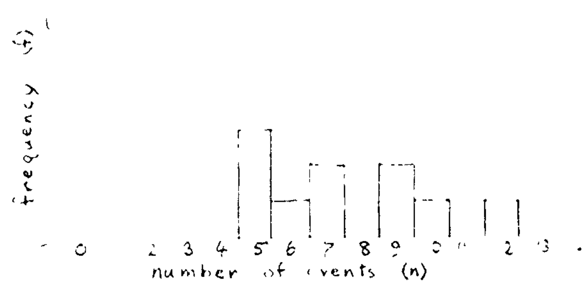


Fig. 4 Results of shaking the dice ten times.

Predicting random events

How can data like these be used to make predictions?

In addition to the mean of a distribution, we also need to know something about how the data spread out around the mean. For the data shown in Fig. 3 the mean is 6.3. Examine the histogram and answer the following questions:

Q2 How many of the observations in Fig. 3 show counts from 5 to 7?

Q3 What fraction is this of the total number of observations?

Q4 How far, going equally to the left and right of the mean, must you go to include half of all the observations? To include two thirds?

For a theoretical distribution like this (which your own results will closely approximate as you increase the number of trials), it turns out that there is a simple rule for expressing the spread of value: if the mean count is M, then 2/3 of the counts will be between $M - \sqrt{M}$ and $M + \sqrt{M}$. Putting it another way: about 2/3 of the values will be in the range $M \pm \sqrt{M}$. For example, for the sample data given here, the mean is 6. The square root of 6 is about 2.4. Locate the points along the base of the histogram (Fig. 3) corresponding to 6 ± 2.4, ($6 - 2.4 = 3.6$, $6 + 2.4 = 8.4$). The chances are two out of three that the number of marked sides showing after any shake of the tray will be in the range 3.6 to 8.4. (Of course, it doesn't really make sense to talk about a fraction of a marked side; one would need to round off to the nearest whole numbers, 4 to 8.)

Q5 Check this prediction. How many of the trials (Fig. 3) did give results in the range 4 to 8? What fraction is this of the total number of trials?

Another example may help make this clear. Suppose you have been counting cloud-chamber tracks and find that the mean of a large number of one-minute counts is 100 tracks. Since the square root of 100 is 10, you would find that about two thirds of your counts would lie between 90 and 110.

Q6 Whether you rolled dice, counted tracks, or used the Geiger counter, study the histogram of your results carefully and then report your mean count and range. Calculate the range as $2\sqrt{\text{mean}}$, and then check your results to see if 2/3 of your counts do lie in the range $M \pm \sqrt{M}$.

If you counted for any one minute the chances are about two out of three that your count C will be in the range mean $\pm\sqrt{\text{mean}}$. This implies that you can predict the mean value even if you had made only a single one-minute count. The chances are about two out of three that the single count C will be within $\sqrt{M}$ of the true mean M.

Turning this statement around, the chances are about 2 out of 3 that the true mean will be within $\sqrt{M}$ of your single count C. If you guess that $\sqrt{M}$ is not too different from $\sqrt{C}$, then you can say that the chances are about 2 out of 3 that the true mean is in the range $C \pm \sqrt{C}$. For the example given above the estimate of the mean count rate is 100 ± 10 counts per minute.

You can decrease the uncertainty in predicting a true mean like this by counting for a longer period. Suppose you continued the count for ten minutes. If you counted 1000 tracks the expected "2/3 range" would be about $1000 \pm \sqrt{1000}$ or 1000 ± 33. The result is 1000 ± 33 counts in ten minutes, or 100 ± 3.3 counts per minute. If you counted for still longer, say 100 minutes, the range would be $10,000 \pm \sqrt{10,000}$ or $10,000 \pm 100$ counts in 100 minutes. Your estimate of the mean count rate would be 100 ± 1 counts per minute. Notice that although the expected range in the total count increases as the count goes up, the uncertainty in the count rate (number of counts per minute) decreases.

You can see from these examples that the higher the total count, i.e. the longer you count for or the more dice rolling experiments you do, the more precisely you can estimate the mean. This becomes important in the measurement of the activity of radioactive samples and many other kinds of random events. To get a precise measure of the activity, we must work with large numbers of counts.

Q7 Take more data to increase the precision of your estimate of the mean, if you have time.

Q8 During one minute you count 10 cosmic ray tracks in a cloud chamber. For how long must you go on counting to get an estimate of the mean with a "2/3 range" that is only 1 per cent of the mean value?

This technique of counting over a longer period is fine as long as the mean count rate remains constant. But it doesn't always. If you were measuring the half-life of a short-lived radioactive isotope the mean count would change appreciably during a ten minute period. The way to increase precision is to count at a higher rate—by having a larger sample or putting the Geiger tube closer to it—so that you can record a large number of counts during a short time.

Q9 In a small town it is impossible to predict whether there will be a fire next week. But in a large metropolitan area, firemen know with remarkable accuracy how many fires there will be. How is this possible? What assumption must the firemen make?

EXPERIMENT 45 Range of Alpha and Beta Particles

An important property of particles from radioactive sources is their ability to penetrate solid matter. In this experiment you will determine the distances which alpha and beta particles can travel in various materials.

Alpha particles are most easily studied in a "cloud" chamber, a transparent box containing super-cooled alcohol vapor. Since they are relatively massive and have a double positive charge, they leave a thick trail of ionized air molecules behind them as they move along. The ions then serve as centers about which alcohol vapor condenses to form tracks of visible droplets.

Beta particles also ionize air molecules as they move. But because of their smaller mass and smaller charge, they form relatively few ions, which are further apart than those formed by alphas. As a result, the trail of droplets in the chamber is much harder to see.

A Geiger counter, on the other hand, can be used to detect beta particles but not alpha particles. Alpha particles lose all their energy in collisions long before they get through even the thin window of an ordinary Geiger tube. Beta particles collide with the atoms in the tube window also but they give up relatively less energy so that their chances of getting through the wall are fairly good.

These are the reasons why we shall count alpha particles using a cloud chamber and beta particles with a Geiger counter.

A. Observing alpha particles

Mark off a distance scale on the bottom of the cloud chamber so that you will be able to estimate, at least to the nearest 0.5 cm, the lengths of the tracks formed (Fig. 1). Insert a source of alpha radiation and a barrier (as you did in the preceding experiment on random events) with a small opening at such a height that the tracks form a fairly narrow beam moving parallel to the bottom of the chamber. Put the cloud chamber into operation following the instructions supplied with it.

Fig. 1

Q1 Watch the tracks carefully until you can record the length of the longest tracks. By about how much do the lengths of the tracks vary?

Count and record also the number of alphas which come through the opening in the barrier in one minute. Measure the opening and calculate its area. Measure and record the distance from the source to the barrier.

Actually you have probably not seen all the particles coming through the opening since the sensitive region in which tracks are visible is rather shallow and close to the chamber floor. You will probably miss the alphas above this layer.

The range and energy of alpha particles

The maximum range of radioactive particles as they travel through an absorbing material depends on several factors including the density and the atom-

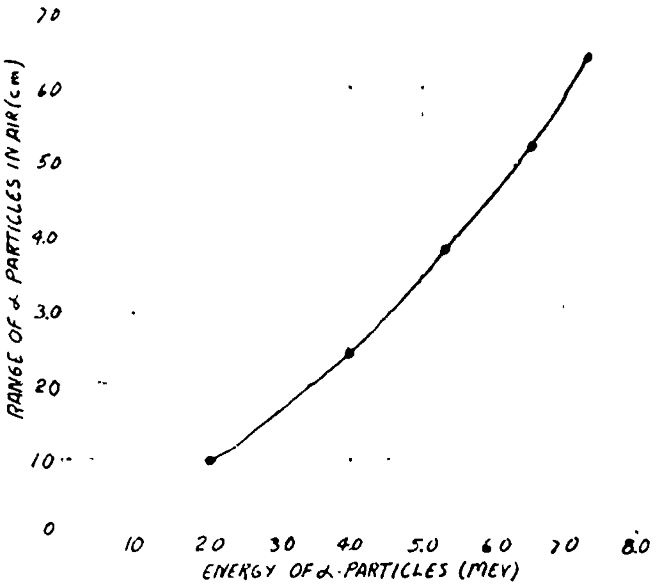


Fig. 2 Range of α-particles in air as a function of their energy.

ic number of the absorber. The graph (Fig. 2) summarizes the results of many measurements of the range of alpha particles traveling through air. The range-energy curve for alpha particles in air saturated with water vapor, as the air is in your chamber, does not differ significantly from the curve shown. You are therefore justified in using Fig. 2 to get a fair estimate of the energy of the alpha particles which you observed.

Q2 What was the energy of alpha particle that caused the longest track you observed? Was there a wide variation in energies, or did most of the particles appear to have about the same energy?

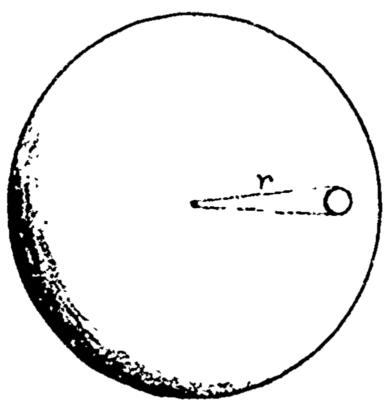


Fig. 3

Now calculate the rate at which energy is being carried away from the radioactive source. From the number of alpha particles per minute passing through an opening of known area at a known distance from the source (Fig. 3) assume that the source is a point and estimate the number of alpha particles per minute leaving the source in <u>all</u> directions. (Hint: Imagine a sphere with the source at its center and a radius r equal to the distance from the source to the barrier. From geometry the surface area of the entire sphere is $4\pi r^2$. You know the approximate rate at which particles are emerging through the small opening. By proportion you can find the rate they must be penetrating the larger area, $4\pi r^2$ of the sphere. The alpha particle source is not a point, but part of a cylinder. This discrepancy, combined with a failure to count those particles that pass through the opening, but not in the active layer, will introduce an uncertainty of as much as a factor of 10.) The total number of particles leaving the source per minute multiplied by the average energy of the particles is the total energy lost per minute.

To answer the following questions, remember that

$$1 \text{ Mev} = 1.60 \times 10^{-13} \text{ joules}$$
$$1 \text{ calorie} = 4.18 \text{ joules}$$

Q3 How many joules of energy are leaving the source per minute?

Q4 How many calories per minute does this equal?

Q5 If the source were placed in one gram of water in a perfectly insulated container, how long would it take to heat the water from 0° C to 100° C?

B. Observing beta particles

After removing all radioactive sources from near the Geiger tube count the number of pulses caused by background radiation in several minutes. Calculate the average background radiation in counts per minute. Then place a source of beta radiation near the Geiger tube, and determine the new count rate. (Make sure that the source and Geiger tube are not moved during the rest of the experiment.) Since you are concerned with the particles from the source, subtract the background count rate.

Next place a piece of absorbing material like a sheet of cardboard or thin sheet metal, between the source and the tube, and count again. Place a second equally thick sheet of the same material in front of the first, and count. Keep adding absorbers and recording counts until the count rate has dropped nearly to the level of background radiation.

Plot a graph on which the horizontal scale is the number of absorbers and the vertical scale is the number of counts per minute.

In addition to plotting single points, show the uncertainty in your estimate of the count rate for each point plotted. You know that because of the random nature of radioactivity, the count rate actually fluctuates around some average value. You do not know what that true average value is; it would ideally take an infinite number of one-minute counts to determine the "true" average. But we know that the distribution of a great number of one-minute counts will have the property that two thirds of them will be closer to the mean number of counts per minute than the square root of the mean number of counts per minute. (See Experiment 44.) From this it follows that about two-thirds of the time, the average of a very large number of counts will be within this same range ($\sqrt{\text{no. of counts}}$) of a particular determination of the count rate.

For example, suppose you have observed 100 counts in one given minute. The chances are two out of three that if you counted for a very long time the mean count rate would be between 90 and 110 counts (between $100 - \sqrt{100}$ and $100 + \sqrt{100}$ counts). For this reason you would mark a vertical line on your graph extending from 110 counts down to 90. In this way you avoid the pitfall of making a single measurement and assuming you know the "correct" value.

If other kinds of absorbing material are available, repeat the experiment with the same source and another set of absorbers. For sources which emit very low-energy beta rays, it may be necessary to use very thin materials, such as paper or household aluminum foil.

The range and absorption of beta particles

Examine the graph which you plotted to show the absorption of beta particles.

Q6 Is it a simple linear graph?

Q7 What would the curve look like if all beta particles from the source were able to penetrate the same thickness of a given absorber material before giving up all their energy?

Q8 If you were able to use different absorbing materials, how did the absorption curves compare?

EXPERIMENT 46 Half-Life—I

The more people there are in the world, the more people die each day. The less water there is in a tank, the more slowly water leaks out of a hole in the bottom.

In this experiment you and your classmates will observe three other examples of quantities that decrease at a rate that depends somehow on the total amount of the "parent" quantity.

Whatever quantity you measure in the following experiments, your objective is to measure the number remaining or leaving at frequent intervals in order to find a common underlying behavior. Your conclusions will apply to many familiar growth and decay processes in nature.

When you experimented earlier with rolling dice and with radioactive decay you were studying random events you could observe one at a time. You found that to predict the frequency of such events you needed the laws of probability. But this time you will deal with a larger number of events, and you will find that the outcome of your experiments is therefore more precisely predictable.

A. Twenty-sided dice

Mark any two sides of each 20-sided die with a felt-tipped marking pen. The chances will therefore be one in ten that a marked surface will be uppermost on any one die when you shake and roll the dice. When you have rolled the 120 dice, remove all the dice which have a marked surface on top. Record the number of dice you removed. With the remaining dice, continue this process of shaking, rolling and removing the marked dice at least twenty times. Record the number you remove each time.

Plot a graph in which each roll is represented by one unit on the horizontal axis, and the number of dice removed after each roll is plotted on the vertical axis.

Plot a second graph with the same horizontal scale, but with the vertical scale representing the number of dice remaining in the tray after each roll.

You may find that the numbers you have recorded are too erratic to produce smooth curves. Modify the procedure as follows: roll the dice and count the dice with marked surfaces on top. Record this number but do not remove the dice. Shake and count again. Do this five times. Now find the mean of the five numbers, and remove that number of dice. The effect will be the same as if you had actually started with 120 × 5 or 600 dice. Continue this procedure as before, and you will find that it is easier to draw smooth curves which pass very nearly through all the points on your graphs.

Q1 How do the shapes of the two curves compare?

Q2 What is the ratio of the number of dice removed after each shake to the number of dice shaken in the tray?

Q3 How many shakes were required to reduce the number of dice in the tray from 120 to 60? From 60 to 30? From 100 to 50?

B. Electric circuit

A capacitor is a device which stores electrical energy. It consists of two conducting surfaces placed very close together but not touching. When the two surfaces are connected to a dry cell, negative charge is removed from one plate and added to the other so that a potential difference is established between the two surfaces. (See Section 14.6 of the Unit 4 text.) If the conductors are disconnected from the cell and connected through a resistor, the charge will begin to flow back from one side to the other. The charge will continue to flow as long as there is a potential difference between the sides of the capacitor. As you learned in Unit 4, the rate of flow of charge (the current) through a conducting path depends both on the resistance of the path and the potential difference across it.

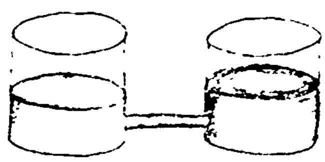


Fig. 1 An analogy: The rate of flow of water depends on the difference in height of the water in the two tanks and on the resistance the pipe offers to the flow of water.

To picture this think of two partly filled tanks of water connected by a pipe running from the bottom of one to the bottom of the other (Fig. 1). When water is transferred from one tank to the other, the difference in height is proportional to the potential energy of the water, just as the potential difference between the sides of a charged capacitor is proportional to the potential energy stored in the capacitor. Water flows through the pipe at the bottom until the water levels are the same in the two tanks. Similarly, charge flows through the resistor connecting the sides of the capacitor until there is no potential difference between the two plates.

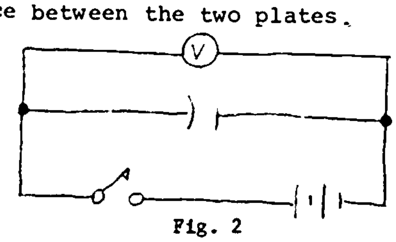


Fig. 2

Connect the battery to the circuit, as in Fig. 2, close the switch, and record the reading on the voltmeter. Now open the switch and take a series of voltmeter readings at regular intervals. Plot a graph, using time intervals for the horizontal axis and voltmeter readings for the vertical.

Q4 How long does it take for the voltage to drop to half its initial value? From one half to one fourth? From one third to one sixth?

Repeat the experiment with a different resistor in the circuit. Find the time required for the voltage to drop to half its initial value. Do this for several different resistors.

Resistance is measured in units called ohms. In terms of the water tank analogy, you can think of a large resistance as comparable to a small pipe which restricts the water flow.

Q5 How does the time required for the voltage to drop to half its initial value change as the resist[illegible]e circuit is changed?

C. Short-lived radioisotope

Whenever you measure radioactivity with a Geiger counter, you must first determine the level of background radiation. With no radioactive material near the Geiger tube, take a count for several minutes and calculate the average number of counts per minute caused by background radiation. This number must be subtracted from any count rates you observe with a sample near the tube, to obtain what is called the net count rate of the sample.

The measurement of background rate can be carried on by one member of your group while another prepares the sample according to the directions given below. Use this measurement of background rate to become familiar with the operation of the counting equipment. You will have to work quite quickly when you begin counting the sample itself.

1. Prepare a funnel-filter assembly by placing a small filter paper in the funnel and wetting it with water. Pour 12 cc of thorium nitrate solution into one graduated cylinder, and 15 cc of dilute nitric acid into another cylinder.

2. Take these materials to the filter flask which has been set up in your laboratory. Your instructor will connect your funnel to the filter flask and pour in a quantity of ammonium phosphomolybdate precipitate, $(NH_4)_3PMo_{12}O_{40}$. The precipitate adsorbs the radioisotope you will be using from the mixture of radioactive elements present in the thorium nitrate solution.

3. Wash the precipitate with several cc of distilled water, and then slowly pour the thorium nitrate solution onto the precipitate. Distribute the solution over the whole surface of the precipitate. Wash the precipitate with 15 cc of dilute nitric acid and wait a few moments while the pump attached to the filter flask dries the sample (Fig. 3).

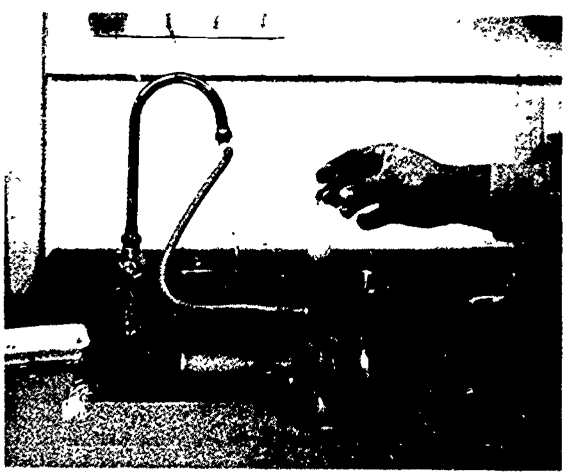


Fig. 3

4. As soon as the sample is dry, remove the upper part of the funnel from the filter flask and take it to the Geiger counter. Make sure that the Geiger tube is protected with a layer of plastic ("Saran Wrap"). Then lower it into the funnel carefully until the end of the tube almost touches the precipitate (Fig. 4).

Fig. 4

You will probably find it convenient to count for one period of 30 seconds in each minute. This will give you 30 seconds to record the count, reset the counter, etc. before beginning the next count. Record your results in a table like this:

background = 12 counts per minute
= 6 per ½ minute

time (mins)	count	net count rate (counts per ½ min)
0 - ½	803	797
1 - 1½	627	621
2 - 2½	,	,
3 - 3½	,	,
4 - 4½	,	,

Try to get about ten readings.

Plot a gr... of net count rate as a function of time. Draw the best curve you can through all the points. From the curve, find the time required for the net count rate to decrease to half its initial value.

Q6 How long does it take for the net count rate to decrease from one half to one fourth its initial value? One third to one sixth? One fourth to one eighth?

Q7 The half-life of a radioisotope is one of the important characteristics which helps to identify it. Using the Handbook of Chemistry and Physics or other reference source, identify which of the decay products of thorium is present in your sample.

Q8 Can you tell from the curve you drew whether your sample contains only one radioisotope or a mixture of isotopes?

Discussion

It should be clear from your graphs and those of your classmates that the three kinds of quantities you observed all have a common property: it takes the same time (or number of rolls of the dice) to reduce the quantity to half its initial value as it does to reduce from a half to a fourth, from a third to a sixth, from a fourth to an eighth, etc. This quantity is the half-life. The relationship between the half-life of a process and the decay rate λ is discussed in your text.

In the experiments on the "decay" of twenty-sided dice, you knew beforehand that the decay rate was one tenth. That is, over a large number of throws an average of one tenth of the dice would be removed for each shake of the tray.

For a large number of truly random events, it can be proved mathematically that the half-life is related to the decay rate λ by the equation:

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

Calculate the half-life of the marked dice from this relationship and compare it with your experimental value.

Q9 If you measured the half-life for capacitor discharge, or for radioactive-decay, calculate the decay rate for that process.

The decay rate is a number that is determined by the physical nature of the objects themselves; it does not depend on the number of objects present. But if you know the decay rate (or half-life) and the amount of decay in a measured time, you can determine the total quantity present at that time. For example, suppose you had a tray containing a very large number of dice of unknown shape, and observed that 50 marked surfaces show on top of the first shake. Suppose also that following the procedure described in this experiment you found the half-life to be about four shakes.

Q10 About how many dice were in the tray at the start? See if you can find an answer for yourself. Our answer is 290. Calculate also the decay rate—that is, the proportion of faces that each die has marked.

On the other hand, the half-life of a very long-lived element such as uranium 238 can be determined by calculating the decay rate—by counting the radioactivity of a known mass of uranium. Knowing that the uranium atom has a mass of 238 atomic mass units and that 1 amu = 1.6×10^{-27} kg, the number of atoms N in a sample of pure uranium 238 can be calculated. Then the number of atoms ΔN decaying per unit time, $\Delta N/\Delta t$, is measured using a Geiger tube or other radiation counter. The decay rate is $\lambda = \frac{\Delta N}{N\Delta t}$, from which the half-life can be calculated with $T_{\frac{1}{2}} = \frac{.693}{\lambda}$.

One last point about the graphs you plotted: clearly the points obtained from each roll of the dice represent separate events. You may wonder if it makes sense to draw a continuous curve through the points, or to measure half-lives in terms of fractions of a shake. When you stop to think about it, the other experiments do not really give continuous curves either, although you can make the points much closer together simply by recording the voltmeter or the Geiger counter readings at much shorter time intervals. If you made the time intervals short enough, you would be observing the passage of individual electrons through the detector. The point of all this is that, although the curves we draw may seem to be rather poor approximations, they do get better and better as we observe more and more events per unit time.

EXPERIMENT 47 Half-Life—II

Look at the thorium decay series printed below. One of the members of the series, radon 220, is a gas. In a sealed bottle containing thorium or one of its salts there will always be some radon gas in the air space above the thorium. Radon 220 has a very short half-life (51.5 sec). The subsequent members of the series, polonium 216, lead 212, etc. are solids. As the radon 220 decays it forms a solid deposit of radioactive material in the bottle. In this experiment you will measure the decay rate of this radioactive deposit.

The set-up is illustrated in Fig. 1, on the next page. The thorium nitrate is contained in a sealed container. The air inside should be kept damp by moistening the sponge with water.

When radon disintegrates,

$$_{86}Rn^{220} \rightarrow {}_{84}Po^{216} + {}_{2}\alpha^{4},$$

the Po atoms formed are ionized, apparently because they recoil fast enough to lose an electron by inelastic collision with air molecules. Because they are ionized (positively charged) we can increase the amount of deposit collected on the top foil by charging it negatively.

The Thorium Series

Name	Symbol	Mode of decay	Half-life
Thorium 232	$_{90}Th^{232}$	α	1.39×10^{10} years
Radium 228	$_{88}Ra^{228}$	β	6.7 years
Actinium 228	$_{89}Ac^{228}$	β	6.13 hours
Thorium 228	$_{90}Th^{228}$	α	1.910 years
Radium 224	$_{88}Ra^{224}$	α	3.64 days
Radon 220	$_{86}Rn^{220}$	α	51.5 sec
Polonium 216	$_{84}Po^{216}$	α, β	0.16 sec
Lead 212	$_{82}Pb^{212}$	β	10.6 hours
*Bismuth 212	$_{83}Bi^{212}$	α, β	60.5 min
Polonium 212	$_{84}Po^{212}$	α	3.0×10^{-7} sec
Thallium 208	$_{81}Tl^{208}$	β	3.10 min
Lead 208	$_{82}Pb^{208}$	Stable	

*Bismuth 212 can decay in two ways: 34 per cent decays by α emission to thallium 208; 66 per cent decays by β emission to polonium 212. Both thallium 208 and polonium 212 decay to lead 208.

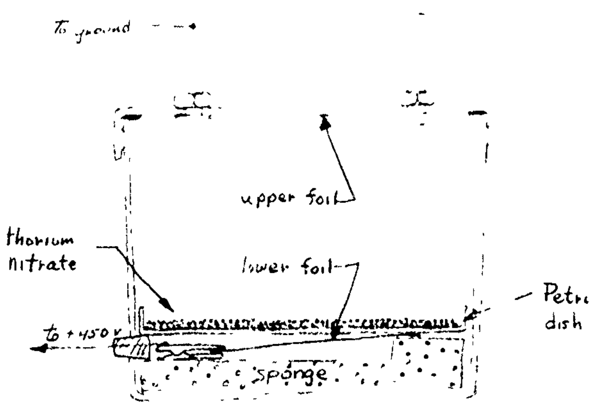


Fig. 1

A convenient way to do this is to use the power supply of the scaler unit. Connect the ground terminal to the upper foil and the +450V terminal to the lower foil. Although the electric field helps, it is not essential; you will get some deposit on the top foil even if you don't set up an electric field in the container.

Before beginning to count the activity of the sample you should take a count of the background rate. Do this far away from the vessel containing the thorium.

To collect a sample of maximum activity the apparatus should stand for about two days. (After two days the deposit is decaying nearly as rapidly as it is formed.) Then remove the upper aluminum foil, place your Geiger counter about one mm above the foil and begin to count. Make sure, by adjusting the distance between sample and the window of the Geiger tube, that the initial count rate is high—several hundred per minute. To get fairly high precision take a count over a period of at least ten minutes (see Experiment 44). Because the deposit decays rather slowly you can afford to wait several hours between counts, but you will need to continue taking counts for several days. Make sure that the distance between the sample and the Geiger tube stays constant.

Record the net count rate and its uncertainty (the "two-thirds" range discussed in Experiment 44). Plot the net count rate against time.

Q1 How does the count rate change with time? Does it take the same time to decrease from the initial rate to one-half, and from one-half to one-quarter? Is there a constant half-life? If so, what is it? (Remember that the deposit contains several radioactive isotopes and each is decaying. The net count rate that you measure is the sum of the contributions of all the active isotopes. The situation is not as simple as it was in Experiment 46 in which the single radioactive isotope decayed into a stable isotope.)

Look again at the thorium series and in particular at the half-lives of the decay products of radon. Try to interpret your observations of the variation of count rate with time.

Q2 Which isotope is present in the greatest amount in your sample? Can you explain why this is so? Make a sketch (like the one on page 22 of the Unit 6 text) to show approximately how the relative amounts of the different isotopes in your sample vary with time. Ignore the isotopes with half-lives of less than one minute.

You can use your measurement of count rate and half-life to get an estimate of the amount of deposit on the foil. The decay rate, $\frac{\Delta N}{\Delta t}$, depends on the number of atoms present, N:

$$\frac{\Delta N}{\Delta t} = \lambda N.$$

The constant λ is related to the half-life by

$$\lambda = \frac{0.693}{T_{1/2}}$$

Experiments

Use your values of counting rate and half-life to estimate N_0, the number of atoms present in the deposit. What mass does this represent? (1 amu = 1.7×10^{-27} kg.) The smallest amount of material that can be detected with a chemical balance is of the order of 10^{-6} gram.

Discussion

It is not too difficult to calculate the speed and hence the kinetic energy of the Po atom. In the disintegration

$$_{86}Rn^{220} \rightarrow {}_{84}Po^{216} + {}_{2}\alpha^{4}$$

the α particle is emitted with energy 6.8 MeV. Momentum is of course conserved at the disintegration. Calculate the speed of the polonium atom. What is its kinetic energy? The ionization energy—the energy required to remove an outer electron from the atom—is typically a few electron volts. How does your value for the polonium atom's kinetic energy compare with the ionization energy?

EXPERIMENT 48 Radioactive Tracers

In this experiment we will deliberately not spell out the exact steps you should follow. This is a chance for you to invent an experiment yourself, and to draw conclusions from it. Most experiments will take more than one class period, and will require careful planning in advance. You will find below a list of books and magazine articles which can help you.

"Tagged atoms"

Radioactive isotopes have been called "tagged atoms" because their location can be specified by detecting their decay products. To see how tagged atoms are used consider the following example.

A green plant absorbs carbon dioxide from the air and by a series of complex chemical reactions builds it into the material of which the plant is made. Suppose you tried to follow the steps in the series of reactions. You can separate each compound from the mixture using ordinary chemical methods. But how can you trace out the chemical steps by which each compound is transformed into the next when they are all jumbled together in the same place?

Tagged atoms could help you.

Put the growing green plant in an atmosphere containing normal carbon dioxide, to which has been added a tiny quantity of CO_2 molecules which contain the radioactive isotope carbon 14 in place of normal carbon 12. In less than a minute after the plant is put into the atmosphere containing the radioactivity can be detected within some, but not all, of the molecules of complex sugars and amino acids being synthesized in the leaves. As time goes on the radioactive carbon enters step by step into each of the carbon compounds in the leaf.

Put the growing green plant in an atmosphere containing normal carbon dioxide to which has been added a tiny quantity of CO_2 molecules which contain the radioactive isotope carbon 14 in place of normal carbon 12. In less than a minute after the plant is put into the atmosphere containing this "tagged" CO_2, the radioactivity can be detected within some, but not all, of the molecules of complex sugars and amino acids being synthesized in the leaves. As time goes on the radioactive carbon enters step by step into each of the carbon compounds in the leaf.

With a Geiger counter one can, in effect, watch each compound in turn to detect the moment when radioactive molecules begin to be added to it. In this way the mixture of compounds in a plant can be arranged in their order of formation, which is obviously a useful clue to chemists studying the reactions. Photosynthesis, long a mystery, has been studied in detail in this way.

Radioactive isotopes used in this way are called <u>tracers</u>. The quantity of tracer material needed to do an experiment is astonishingly small. For example, compare the amount of carbon which can be detected with an analytical balance with the amount needed to do a tracer experiment. Under ideal conditions, a chemical balance might detect a microgram, or 10^{-9} kg of carbon. This is about 10^{17} atoms. (1 amu is 1.6×10^{-27} kg, and a carbon atom's mass is 12 amu.) On the other hand, the very small quantity of radioactive carbon 14 which your school can purchase for student experiments without a special license from the Atomic Energy Commission has a mass of only about 4 micrograms. Yet in this quantity as many as 10^8 atoms decay each minute which can be easily detected with an inexpensive Geiger counter. Even if you needed 100 counts per minute to distinguish the signal from background radiation, and if your Geiger tube caught only 1 per cent of the signals from the sample, the tracer method would still be ten thousand times more sensitive than the balance.

In addition to sensitivity, tracers give you the ability to find the precise location of a given element. Thin sections of a sample can be placed on photographic film and left until enough radiation has reached the film to produce a visible spot. This method can be made so precise that scientists can tell not only which cells of an organism, but which parts of the cell—nucleus, mitochondria, etc.—have taken in the tracer.

Choice of isotope

The choice of which radioactive isotopes to use in an experiment depends on many factors: the nature of the radiation (whether alpha, beta or gamma), the half-life of the isotope, the chemical behavior of the atom, and other factors.

Carbon 14 has several properties which make it a useful tracer. Carbon is a constituent of all living organisms, so radioactive carbon compounds can be used to trace a great variety of processes in plants and animals. On the other hand, the carbon 14 atom emits only beta particles of rather low energy. This low energy makes it impossible to use carbon 14 inside a large liquid or solid sample since all the emitted particles would be stopped inside the sample. The half-life of carbon 14 is about 6000 years, which means that the activity of a sample will remain practically constant for the duration of an experiment. But sometimes the experimenter prefers to use a short-lived isotope so that it will not linger in the sample—or on the laboratory table if it gets spilled.

Some isotopes have chemical properties which make them especially useful for a specific kind of experiment. Phosphorus 32 (half-life 14.3 days) is especially good for experiments involving growing plants, because phosphorus is taken up quickly and used by the plant in the growth process. Practically all the iodine in the human body is used for just one specific process—the manufacture of a hormone in the thyroid gland which regulates metabolic rate. Radioactive iodine 131 (half-life 8.1 days) has been immensely useful as a tracer in unravelling the steps in that complex process.

The amount of tracer to be used is determined by its activity, by the degree to which it will be diluted during the experiment, and by how much radiation can be safely allowed in the laboratory. Since even very small amounts of radiation are potentially harmful to people, safety precautions and regulations must be carefully followed. The Atomic Energy Commission has established licensing procedures and regulation governing the use of radioisotopes. As a student you are permitted to use only limited quantities of certain isotopes and under carefully controlled conditions. However, the variety of experiments you can do is still so great that these regulations need not discourage you from using radioactive isotopes as tracers.

One unit which is used to measure radioactivity of a source is called the curie. When 3.7×10^{10} atoms within a source disintegrate or decay in one second, its activity is said to be one curie. (This is about the activity of 1 gram of pure radium 226.) A more practical unit for tracer experiments is the microcurie (μc) which is 3.7×10^4 disintegrations per second or 2.2×10^6 per minute. The quantity of radioisotope which students may safely use in experiments without special license varies from 0.1 μc to 50 μc, depending on the decay energy and type of radiation.

Notice that even when you are restricted to 0.1 μc for your experiments, you may still expect 3700 disintegrations per second, which would cause 37 counts a second in a Geiger counter that recorded only 1 per cent of them.

Why does a Geiger tube detect such a small percentage of the beta particles that leave the sample? (Review the experiment on the range of beta particles.)

A. Autoradiography

One rather simple experiment you can almost certainly do is to re-enact Becquerel's original discovery of radioactivity. Place a radioactive object—lump of uranium ore, luminous watch-dial with the glass removed, etc.—on a Polaroid film packet or on a sheet of x-ray film in a light-tight envelope. A strong source of radiation will produce a visible image on the film within an hour, even through the paper wrapping. If the source is not so strong, leave it on overnight. To get a very sharp picture, you must unwrap the film in a completely dark room and expose it with the radioactive source pressed firmly against the film.

Polaroid film is developed by placing the packet on a flat surface and passing a metal or hard rubber roller firmly over the pod of chemicals and across the film. The No-Screen x-ray film is processed in a darkroom according to the directions on the developer package.

This photographic process has grown into an important experimental technique called autoradiography. The materials needed are relatively inexpensive and easy to use, and there are many interesting applications of the method. For example, you can grow plants in soil treated with phosphorus 32, or water to which some phosphorus 32 has been added, and make an autoradiograph of the roots, stem and leaves (Fig. 1). Or take a leaf each day from a fast-growing young plant, and show how the phosphorus moves from the roots to

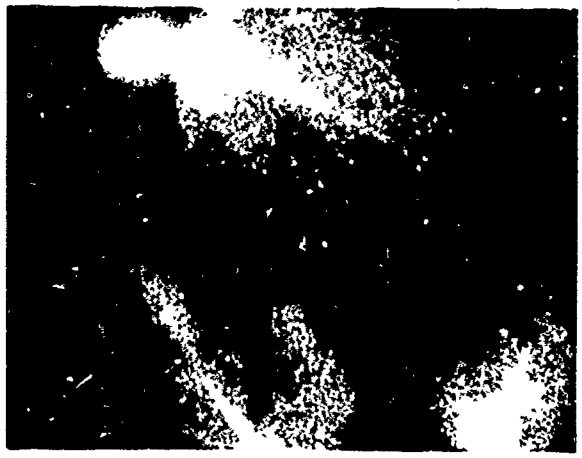


Fig. 1 Autoradiograph made by a high school student to show uptake of phosphorus 32 in coleus leaves.

the growing tips of the leaves. Many other simple autoradiograph experiments are described in the source material listed at the end of this experiment.

B. Chemical reactions and separations

Tracers are used as sensitive indicators in chemical reactions. You may want to try a tracer experiment using iodine 131 to study the reaction between lead acetate and potassium iodide solutions. Does the radioactivity remain in the solute or is it carried down with the precipitate? How complete is the reaction?

Liquids containing beta sources should be transferred with a special pipette or a disposable plastic syringe to a small, disposable container called a planchet, and evaporated so that you count the dry sample. This is important when you are using beta sources, since otherwise much of the radiation would be absorbed in the liquid before it reached the Geiger tube.

You may want to try more elaborate experiments involving the movement of tracers through chemical or biological systems. Students have grown plants under bell-jars in an atmosphere containing radioactive carbon dioxide, fed radioactive phosphorus to earthworms and goldfish, and studied the metabolism of rats with iodine 131.

Experiments

A caution: All these experiments take cooperation from the biology or the chemistry department, and require that safety precautions be observed very carefully so that neither you nor other students will be exposed to radiation.

For example, handle radioisotopes as you would a strong acid; if possible, wear disposable plastic gloves, and work with all containers in a tray lined with paper to soak up any spills. Never draw radioactive liquids into a pipette by mouth as you might with other chemical solutions; use a mechanical pipette or a rubber bulb. Your instructor will discuss other safety precautions with you before you begin.

None of these activities is suggested just for the sake of doing tricks with isotopes. You should have a question clearly in mind before you start, and should plan carefully so that you can complete your experiment in the time you have available.

Some useful articles

"Laboratory Experiments with Radioisotopes for High School Demonstrations," edited by S. Schenberg. U. S. Atomic Energy Commission, 1958. Order from Superintendent of Documents, Government Printing Office, Washington, D. C. 20402 for 35 cents.

"Radioactive Isotopes: A Science Assembly Lecture." Illustrated. Reprints of this article available from School Science and Mathematics. P. O. Box 246, Bloomington, Indiana 47401 for 25 cents.

"Radioisotope Experiments for the Chemistry Curriculum" (student manual 17311) prepared by U. S. Atomic Energy Commission. Order from either Macalaster Scientific Corp., Third Avenue, Waltham, Mass. 02172 or Office of Technical Services, Washington 25, D. C. for 2 dollars. A companion teacher's guide is also available at 1 dollar from the same source.

American Biology Teacher, August 1965, Volume 27, No. 6. A special issue of the magazine devoted to the use of radioisotopes contains several articles of use in the present exercise on tracers. Order single copies from Mr Jerry Lightner, P. O. Box 2113, Great Falls, Montana 59401 for 75 cents.

Scientific American, May 1960. The Amateur Scientist section, page 189, devoted to a discussion of "how the amateur scientist can perform experiments that call for the use of radioactive isotopes." C. L. Stong. Copies of the magazine are available in most libraries or write Scientific American, 415 Madison Ave., New York 17, New York. Reprints of this article are not available.

Scientific American, March 1953, same section (see above) on "scintillation counters and a home-made spinthariscope for viewing scintillations."

"Low Level Radioisotope Techniques," John H. Woodburn. The Science Teacher magazine. November 1960. Order from The Science Teacher, 1201 16th Street, N. W., Washington, D. C. 20036. Single copies are 1 dollar.

Measuring the energy of beta radiation

A device called a beta spectrometer sorts out the beta particles emitted by a radioactive source according to their energy, just as a grating or prism spectroscope spreads out the colors of the visible spectrum. You can make a simple beta spectrometer with two disc magnets and a packet of 4" × 5" Polaroid film. With it you can make a fairly good estimate of the average energy of the beta particles emitted from various sources, by observing how much they are deflected by a magnetic field of known intensity.

You will need two disc magnets arranged as shown in Fig. 1 of the Activity, "Measuring Magnetic Field Intensity," in the Unit 4 Handbook. Be sure the faces of the magnets are parallel and opposite poles are facing each other. Place a beta source behind a barrier made of thin sheet lead with two narrow slits which will allow a beam of beta particles to enter the magnetic field as shown in Fig. 1.

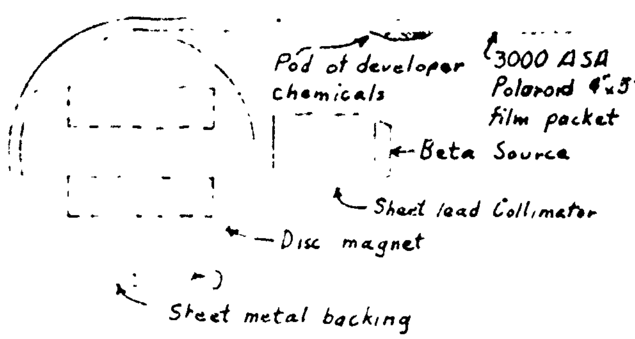


Fig. 1

Bend the sheet of metal into a curve so it will hold a Polaroid film packet snugly around the magnets. Expose the film to the beta radiation for two days. Then carefully remove the magnets without changing the relative positions of the film and beta source. Expose the film for two more days. (The long exposure is necessary because the collimated beam contains only a small fraction of the betas given off by the source, and because Polaroid film is not very sensitive to beta radiation. You can shorten the exposure time to a few hours if you use x-ray film.)

When developed, your film will have two blurred spots on it; the distance between their centers will be the arc length a in Fig. 2.

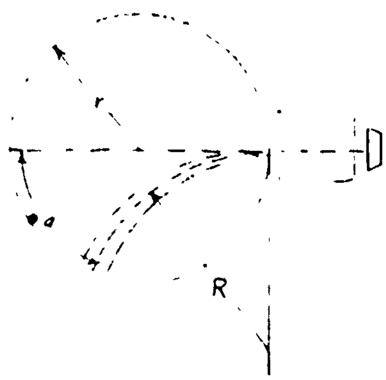


Fig. 2

An interesting mathematical problem is to find a relationship between the angle of deflection, as indicated by a, and the average energy of the particles. It turns out that you can calculate the momentum of the particle fairly easily. Unfortunately, since the beta particles from radioactive sources are traveling at nearly the speed of light, the simple relationships between momentum, velocity and kinetic energy which you learned about in Unit 3 cannot be used. Instead, you would need to use equations derived from the special theory of relativity which, although not at all mysterious, are a little beyond the scope of this course. (The necessary relations are developed in the supplemental unit, "Elementary Particles.") So a table which gives the values of kinetic energy for various values of momentum is provided.

First, you need an expression which will relate the deflection to the momentum of the particle. The relationship between the force on a charged particle in a magnetic field and the radius of the circular path is derived in Sec. 18.2 of the Unit 5 text. This yields the equation

$$Bqv = \frac{mv^2}{R},$$

which simplifies to

$$mv = BqR.$$

Now if you know B, the magnetic field intensity (measured with the current balance as described in the Unit 4 Handbook), and can find R, you can compute the momentum. A little geometry will enable you to calculate R from a, the arc length, and r, the radius of the magnets. A detailed solution will not be given here, but a hint is shown in Fig. 3.

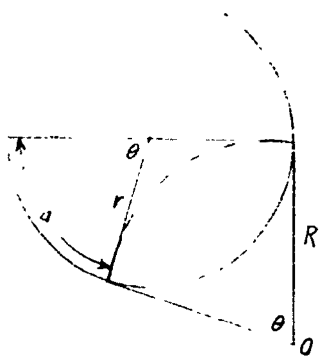


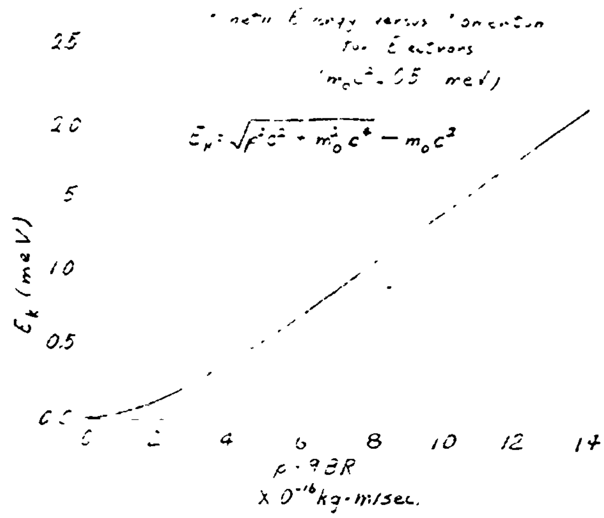
Fig. 3

The angle θ is equal to $\frac{a}{2\pi r} \times 360°$, and you should be able to prove that if tangents are drawn from the center of curvature O to the points where the particles enter and leave the field, the angle between the tangents at O is also θ. With this as a start, see if you can calculate R.

The relationship between momentum and kinetic energy for objects traveling at nearly the speed of light,

$$E = \sqrt{p^2c^2 + m_0^2c^4},$$

is discussed in most college physics texts. The following graph has been plotted using data calculated from this relationship.



From the graph, find the average kinetic energy of the beta particles whose momentum you have measured. Compare this with values given in the <u>Handbook of Chemistry and Physics</u> or another reference book for the particles emitted by the source you used.

You will probably find a value listed which is two to three times higher than the value you found. This is not because your method was at fault. Instead, it is because the value in the reference book is the <u>maximum</u> energy that any one beta particle from the source can have, whereas the value you found was the <u>average</u> of all the betas reaching the film. This discrepancy between the maximum energy which all the betas should theoretically have and the actual observed energy puzzled physicists for a long time. The explanation, suggested by Enrico Fermi in the mid-1930's, led to the discovery of a strange new particle called the neutrino, which you will want to find out about.

A sweet demonstration

In Experiment 46, Half-Life I, it is difficult to show that the number of dice "decaying" is directly proportional to the initial number of dice, because you need more than 120 dice. An inexpensive way to show that N is directly proportional to N is to use at least 400 sugar cubes (there are 198 in 1 pound of the commonly available packages). Mark one face with edible food coloring. Then shake them and record how many decayed as described in Experiment 46.

Ionization by adioactivity

Place a different radioactive sample inside each of several electroscopes. Charge the electroscopes negatively by rubbing a hard rubber comb on wool and touching the comb to the electroscope knob. Compare the times taken for the electroscopes to completely lose their charge, and interpret your observations.

Caution: One electroscope should have no sample in it to check how fast it would discharge without a sample present. What causes this type of discharge?

Magnetic deflection of beta rays

Clamp a radioactive beta source securely about a foot from a Geiger tube. Place a sheet of lead at least 1 mm thick between source and counter

to reduce the count to background level. Hold one end (pole) of a strong magnet above or to the side of the sheet, and change its position until the count rate increases appreciably. Try keeping the magnet in the same position but reversing the two poles; does the radiation still reach the counter? Determine the polarity of the magnet by using a compass needle. If beta rays are particles, what is the sign of their charge? (See Experiment 37 for hints.)

Exponential decay in concentration

Take 1000 cc of water and stir in 10 drops of food coloring. Pour off 100 cc into a beaker. Keep this sample of the beginning concentration. Add 100 cc of water, stir up the mixture, and pour off a second 100-cc sample. Keep repeating until you have collected 10 to 15 samples. How many times would you have to repeat the process to get rid of the dye completely?

Questions:

The original concentration was 10 drops/1000 cc or 1 drop/100 cc. What is the concentration after one removal and the addition of pure water (i.e., one cycle)? What is the concentration after two cycles? After three cycles? And after n cycles? (Answer: $(0.9)^n$ drops/100 cc.)

What is the number of cycles required to reduce the concentration to approximately 1/2 of its original concentration?

Repeat the process, this time removing 500 cc each time. Make a third trial removing 900 cc per cycle. How many trials are required in each of these cases to reduce the concentration to about 1/2 of the original concentration?

At one time physicians prescribed medicines that were very dilute on the theory that many medicines are more effective at low concentrations. A first-potency medicine was one of high concentration, perhaps a 1 molar solution. Second potency was obtained by mixing one part of the first with 100 parts of the solvent. Potencies as high as the fifteenth were considered helpful. How many molecules of first-potency solution would you expect to find in 1 cc of a tenth-potency medicine? In 1 cc of a fifteenth-potency medicine?

Neutron detection problem analogue (Chadwick's problem)

It is impossible to determine both the mass and the velocity of a neutron only from measurements of the final velocity of a target particle of known mass which the neutron has hit. To help understand this, try the following:

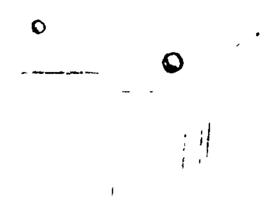


Fig. 1

Set up an inclined groove on a table as shown in Fig. 1. Let a small ball bearing roll part way down the groove, hitting the larger target ball and knocking it off the table. Note the point where the target ball strikes the floor. Now use another, smaller ball as the "neutron." By trial and error, adjust the point of release until the target ball strikes the same spot on the floor as it did when you used the larger "neutron." Therefore two different combinations of mass and velocity for the "neutron" cause the same velocity of the target ball. Are there more combinations of mass and velocity of "neutron" that will give the same result?

The problem is resolved by repeating the experiment, but having the "neutron" collide with two different target balls of different masses. Have the same "neutron" collide with each target ball in turn, and measure the velocities of the targets. Use these velocity values to calculate the mass of the incoming "neutron." (Hint: Refer to Sec. 23.4 of your text. You need only the ratio of the final velocities achieved by the different targets; therefore you can use the ratio of the two distances measured along the floor from directly below the edge of the table, since they are directly proportional to the velocities.) See also Film Loop 49, Collisions With an Unknown Object.

"Incredible as it may seem to those of us who live in the world of anti-matter, a mirror image exists—the reverse of ourselves—which we can only call the world of matter."

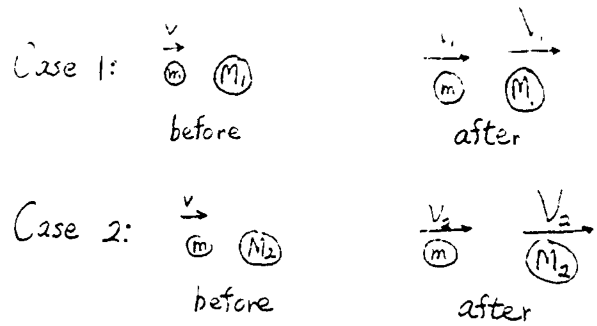
Drawing by Alan Dunn, © 1965 The New Yorker Magazine, Inc.

FILM LOOP 49 Collisions With an Unknown Object

In 1932 Chadwick discovered the neutron by analyzing collision experiments. The Chadwick experiment is discussed fully in Sec. 23.4 of the text. This film offers an opportunity to make a measurement similar in principle to Chadwick's and to use the laws of motion to deduce the mass of an unknown object.

The first scenes show the collision of a small ball with a stationary ball of approximately the same mass, and then a collision with a larger stationary ball. By comparing these events in the same scene, it is clear that the incoming ball has the same velocity in each case. Finally, the slow-motion scenes allow you to measure the velocity acquired by the target ball in each case. The masses of the target balls are known. You can then deduce the mass and velocity of the incoming ball.

Note how similar this is to Chadwick's experiment. He used target particles of known masses (hydrogen and nitrogen nuclei) and measured their recoil velocities. It is the <u>method</u> that is important—the target balls in the film are not in the exact mass ratio that would be necessary if we were to attempt a large-scale version of Chadwick's actual experiment with hydrogen and nitrogen nuclei.



Measurements: The symbols are defined in Fig. 1. The known masses of the target ball are $M_1 = 352$ grams, $M_2 = 4260$ grams. In general, the relative speed of separation of any two objects after collision is less than their relative speed of approach before collision, as indicated by the equation

$$\frac{\text{velocity of separation}}{\text{velocity of approach}} = e.$$

In this equation, e, the coefficient of restitution, would be 1 for a perfectly elastic collision in which no kinetic energy is lost, and would be 0 for a perfectly inelastic collision in which the bodies do not separate. We assume that e (whose value we need not know) is the same in both collisions. Then, since the target ball is stationary in each case, the velocity of approach is v, and therefore

$$V_1 - v_1 = ev$$

$$V_2 - v_2 = ev$$

whence $V_2 - v_2 = V_1 - v_1$, or

$$v_1 - v_2 = V_1 - V_2 \quad \text{(Eq. 1)}$$

Now apply the law of conservation of momentum to each collision:

$$\text{case 1:} \quad mv = mv_1 + M_1V_1 \quad \text{(Eq. 2)}$$

$$\text{case 2:} \quad mv = mv_2 + M_2V_2 \quad \text{(Eq. 3)}$$

Then $mv_1 + M_1V_1 = mv_2 + M_2V_2$

or $m(v_1 - v_2) = M_2V_2 - M_1V_1$ (Eq. 4)

This seems like a useful equation, but remember that the incoming particle is invisible so that v_1 and v_2 are not measurable. By substituting Eq. 1 into Eq. 4 we can replace $(v_1 - v_2)$ by $(V_1 - V_2)$, which can be observed. Then, through Eq. 5, m can be found:

$$m(V_1 - V_2) = M_2V_2 - M_1V_1$$

or

$$m = \frac{M_2V_2 - M_1V_1}{V_1 - V_2} \quad \text{(Eq. 5)}$$

All measurements are to be made on the target balls only—remember that the incoming small ball (the "neutron") is supposed to be unobservable both before and after the collisions. Measure V_1 and V_2 in any convenient unit, such as divisions per second. Then calculate the mass m of the "invisible" unknown particle.

When comparing your experiment with Chadwick's, you should try to answer questions such as these: (1) What was the ratio of the two target masses M_1 and M_2, in your experiment? What was the ratio of target masses in Chadwick's experiment? (2) What was the numerical value of e in Chadwick's actual experiment? (3) If you like algebra, you can derive a formula for the velocity v of the neutron in terms of M_1, M_2, V_1, V_2 and e.

Two models of a chain reaction

Mousetraps

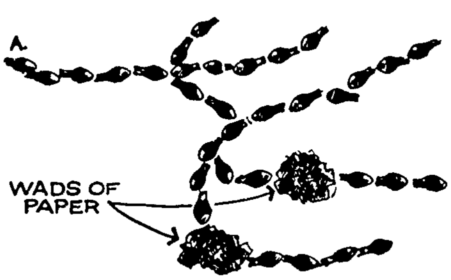
Carefully set six or more mousetraps in a large cardboard box. Place two ping-pong balls or small corks opposite the trigger of each trap. Place a sheet of clear plastic over the top. Then drop one ping-pong ball in through the corner before you slide the cover completely on. Can you imagine the situation with trillions of mousetraps in a much smaller space?

Questions:

What in the nucleus is represented by the potential energy of the mousetrap spring? What do the ping-pong balls represent? Does the model have a critical size? How might you control the reaction?

Match heads

Break off the heads of about a dozen wooden matches, about 1/8 inch below the match head. Arrange the match heads as shown below. At certain points place



pieces of wet paper. Light a match and place it at point A. Observe what happens to the right and left sides of the arrangement. Why is the wet paper in this reaction not like the moderators in an atomic pile? How could you modify this model to demonstrate the function of a moderator.

(Adapted from A Physics Lab of Your Own, Steven J. Mark, Houghton-Mifflin Co., 1964.)

More information on nuclear fission and fusion

The Atomic Energy Commission has issued the following booklets on the practical applications of nuclear fission and fusion:

"Nuclear Reactors"
"Power Reactors in Small Packages"
"Nuclear Power and Merchant Shipping"
"Atomic Fuel"
"Direct Conversion of Energy"
"Power from Radioisotopes"
"Atomic Power Safety"
"Controlled Nuclear Fusion"

All are available free by writing USAEC, P.O. Box 62, Oak Ridge, Tenn. 37831.

Peaceful uses of radioactivity

Some of the uses of radioactive isotopes in medicine or in biology can be studied with the help of simple available equipment. See Experiment 48, Radioactive Tracers, in this handbook.

A few AEC booklets which might provide useful information are:

"Food Preservation by Irradiation"
"Whole Body Counters"
"Fallout from Nuclear Tests"
"Neutron Activation Analysis"
"Plowshare"
"Atoms, Nature and Man"
"Radioisotopes in Industry"
"Nuclear Energy for Desalting"
"Nondestructive Testing"

For experiments see:

"Laboratory Experiments with Radioisotopes," U.S. Government Printing Office, Washington, D.C. 25 cents.

For necessary safety precautions to be taken in working with radioactive materials, see "Radiation Protection in Educational Institutions," NCRP Publication, P.O. Box 4867, Washington, D.C. 20008. 75 cents.

Nuclear power stations, completed or under construction, around the world. Can you account for their distribution?

Picture Credits

Cover: (cartoon) Andrew Ahlgren; (alpha particle tracks in cloud chamber) Professor J. K. Bøggild, Niels Bohr Institute, Copenhagen; (autoradiograph of leaves) from Photographs of Physical Phenomena, © Kodanska, Tokyo, 1968.

All photographs used with film loops courtesy of National Film Board of Canada.