Radioactivity

Dr P Lawson

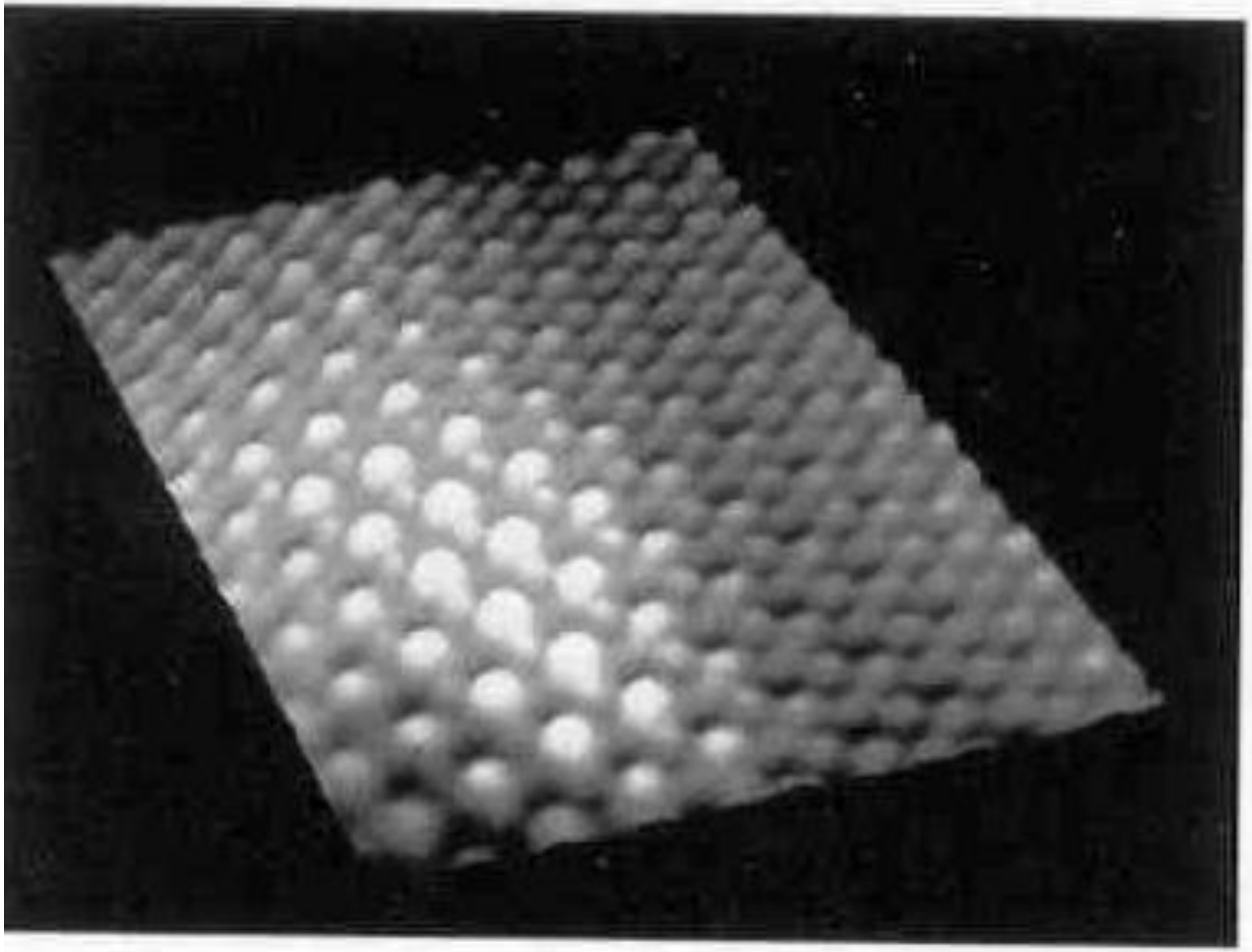


Figure 32.1 Field emission microscope image showing individual atoms of palladium.

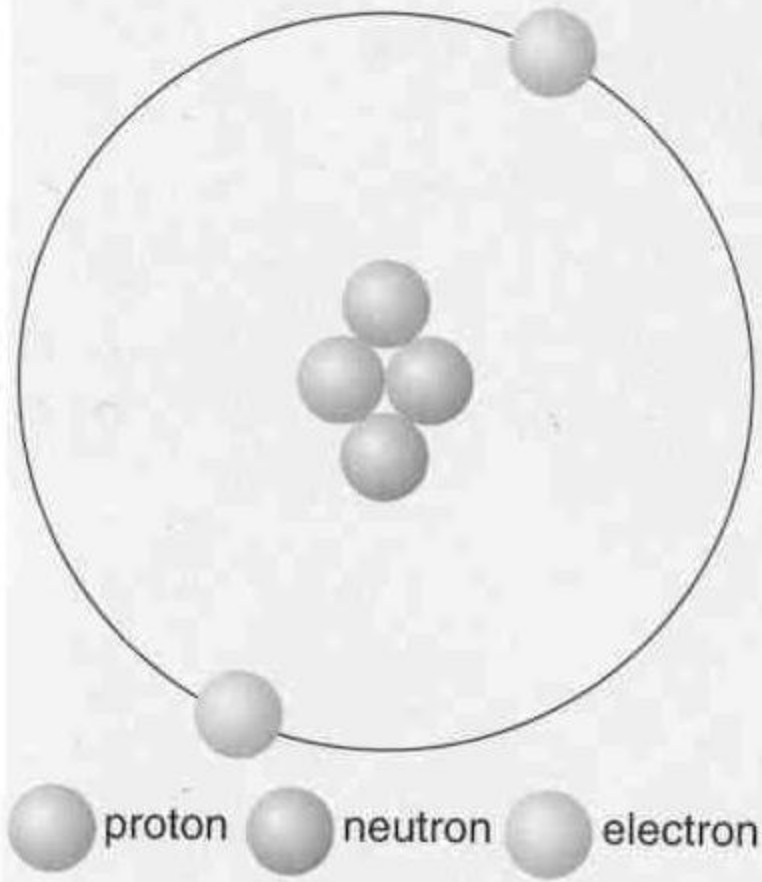
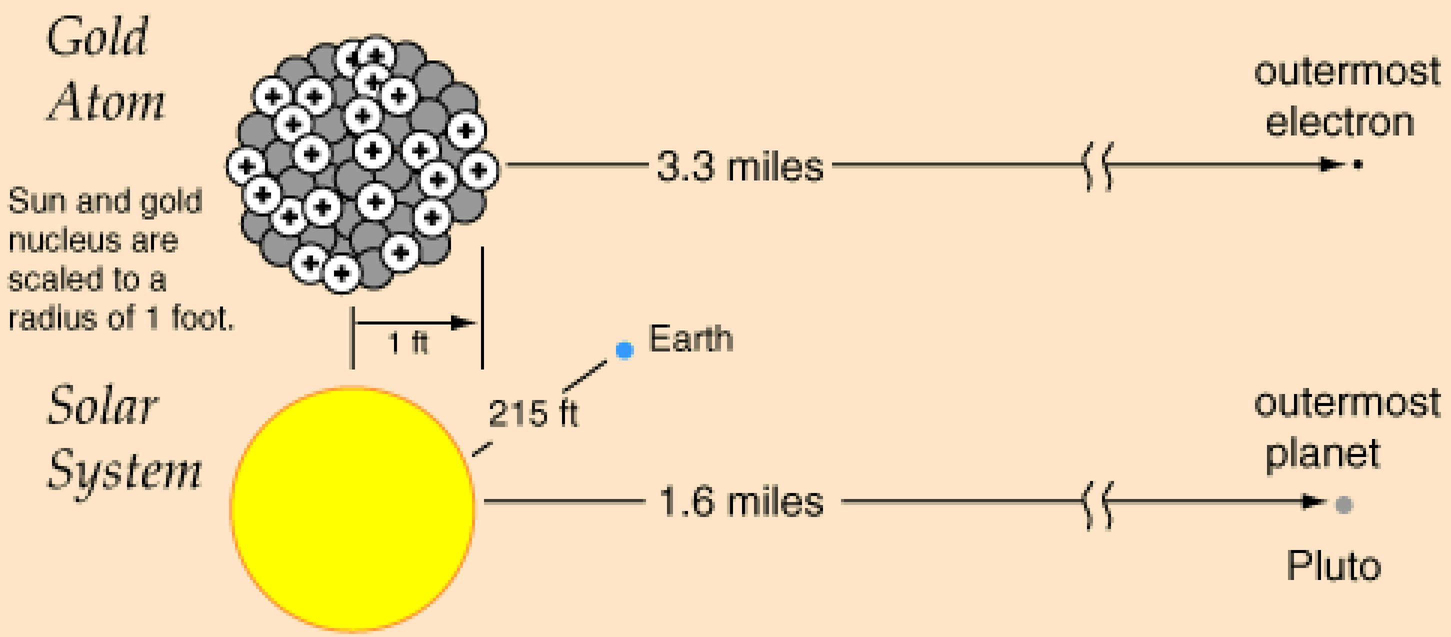


Figure 32.2 The nucleus consists of neutrons and protons. Electrons orbit the nucleus.

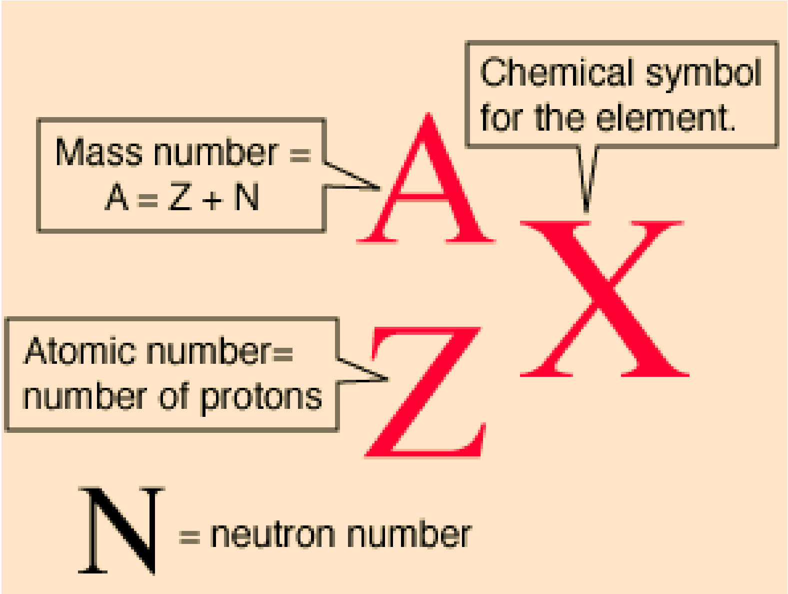
Property	Proton	Neutron	Electron
mass	1.7×10^{-27} kg 1 u (atomic mass unit)	1.7×10^{-27} kg 1 u	9.1×10^{-31} kg 1/1800 u
charge	$+1.6 \times 10^{-19}$ C	0	-1.6×10^{-19} C
description	a nucleon; part of the nucleus	a nucleon; part of the nucleus	in a cloud around the nucleus

Relative scale model of an atom and the solar system

Do you perceive a gold ring to contain a larger fraction of solid matter than the solar system?



On this scale, the nearest star would be a little over 10,000 miles away



A is the nucleon number = total number of protons and neutrons (sometimes called the mass number as it is the mass of the nucleus)

Z is the proton number = number of protons (sometimes called the atomic number because it defines the element)

N is the number of neutrons N = A-Z

Isotopes

A nucleus with a stated proton number and neutron number is called a nuclide. An **isotope** of a nuclide is another nuclide with the same proton number but a different neutron number. $^{12}_{6}C$ and $^{14}_{6}C$ are both isotopes of carbon. They have the same number of protons, but $^{14}_{6}C$ (Figure 32.5) has two more neutrons than $^{12}_{6}C$. The proton number determines the arrangement of the electrons around the nucleus, and so decides the chemical properties of an atom. So all isotopes of a nuclide have the same chemical properties because they have the same proton number. They have different atomic masses, and so have different densities.

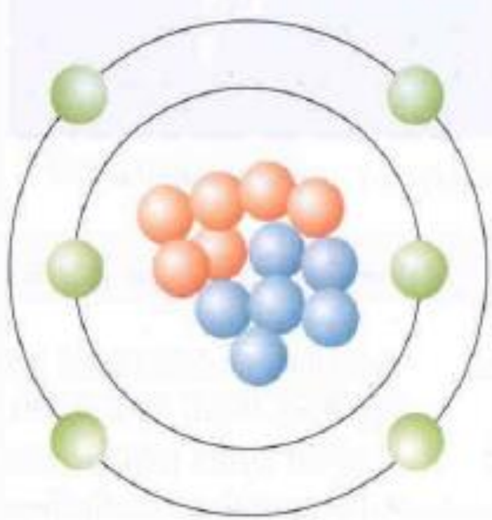


Figure 32.4 Carbon–12 has six protons and six neutrons in the nucleus and six orbiting electrons

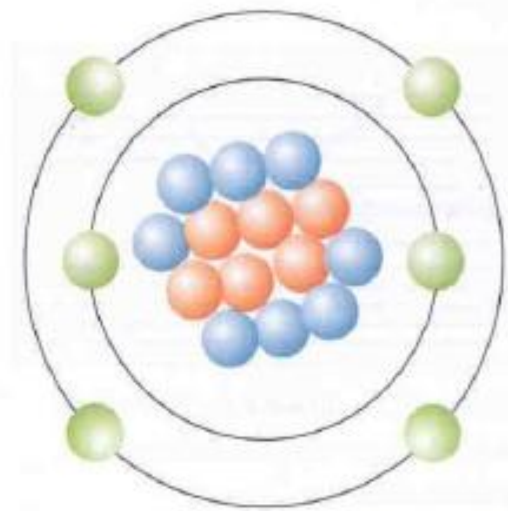
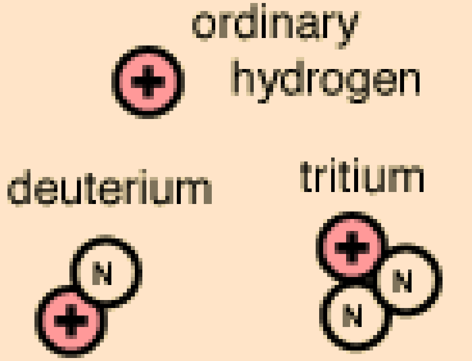


Figure 32.5 Carbon–14 has an extra two neutrons in the nucleus



Isotopes of hydrogen

$^{12}_{6}C \quad ^{13}_{6}C \quad ^{14}_{6}C$

Notation for the different isotopes of the chemical element carbon.

There are about 400 stable isotopes.

Figure 33.1 Sir Ernest Rutherford

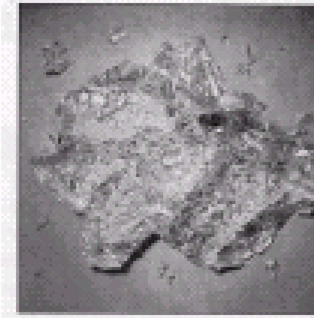


Figure 33.4 Thin gold foil

Alpha (α) particle scattering

- Geiger and Marsden arranged to fire alpha particles at thin gold foil and detect them by a screen, which gave out a flash of light whenever it was hit by an alpha particle (Figure 33.2).
- By counting the flashes, they compared the number of alpha particles passing straight through with the numbers deflected through various angles.

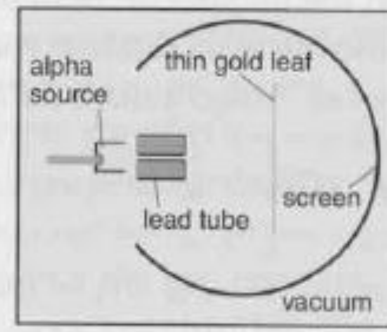


Figure 33.2 Alpha scattering apparatus

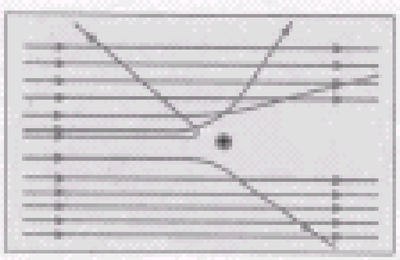


Figure 33.3 About 1 in 8000 alpha particles were deflected through greater than 90°

Thin gold foil 10^{-6} m 1 µm

This is ≈ 3000 atom thick

so each atom ≈ 0.3 nm

Nucleus is 10,000 times smaller ≈ 10^{-14} m

If gold atom → A4 page

nucleus is 100 times smaller than a full stop.

Atomic and nuclear sizes

Thin gold foil (Figure 33.4) can be typically 1/1000th mm ($= 10^{-6}$ m $= 1\ \mu$m) thick. At this thickness, the foil is about 3000 atoms thick – the diameter of a gold atom is about 0.3×10^{-9} m (= 0.3 nm). The nucleus is more than 10 000 times smaller still – less than 10^{-14} m in diameter. If the gold atom were the same size as this page, the nucleus would be 100 times smaller than a single full stop.

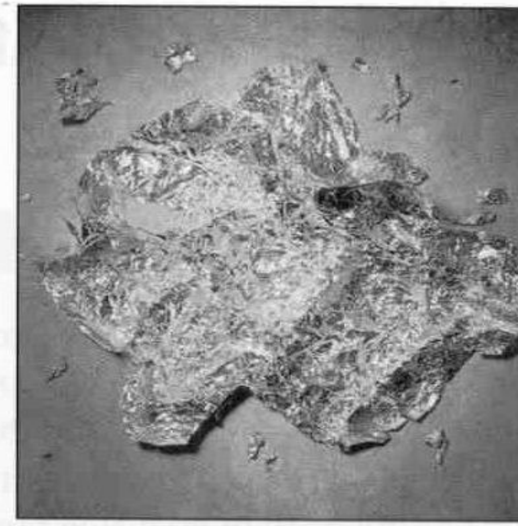


Figure 33.4 Thin gold foil

Quarks

For some time, physicists thought that protons, neutrons and electrons alone were sufficient to explain the structure of matter, but measurements of radioactive decay produce evidence of other sub-atomic particles. You can read about these particles in the Particle Physics topic section of *Electricity and Thermal Physics*.

Nowadays, physicists think that all sub-atomic particles are themselves made up of yet smaller particles called **quarks** (which rhymes with either 'pork' or 'park').

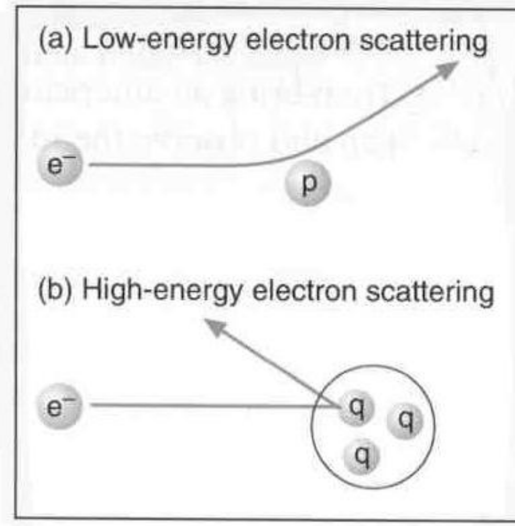


Figure 33.5 Deep inelastic scattering reveals that the proton has structure

Evidence for *quarks* comes from firing electrons at protons to probe the distribution of charge within the proton. If the charge is uniform, the electrostatic field around the proton should be uniform and the electrons should scatter elastically. Low-energy electrons do scatter in this way (Figure 33.5a) and the protons recoil as predicted. But above a particular energy, the protons deflect some electrons through large angles. This is like the nucleus scattering alpha particles. This is **deep inelastic scattering**. This scattering is *deep*; it probes deep into the structure of matter. It is also *inelastic*, because sometimes the electron loses kinetic energy (Figure 33.5b).

If protons can do this to electrons, it suggests that the charge in the protons is not uniform but split between even smaller charged particles, the quarks.

Alpha radiation

ALPHA RADIATION

Figure 34.3 Smoke detectors contain an americium source. Smoke particles stop the alpha radiation and trigger the alarm

Conducting air

- Set up the circuit of Figure 34.1. The high-voltage power supply pushes charge around the circuit, and the nanoammeter measures the current that flows. With no match present, check that no current flows through the air gap.
- Now hold a match flame underneath the air gap and observe the meter.
- Then bring an americium radioactive source to the air gap and observe the meter.

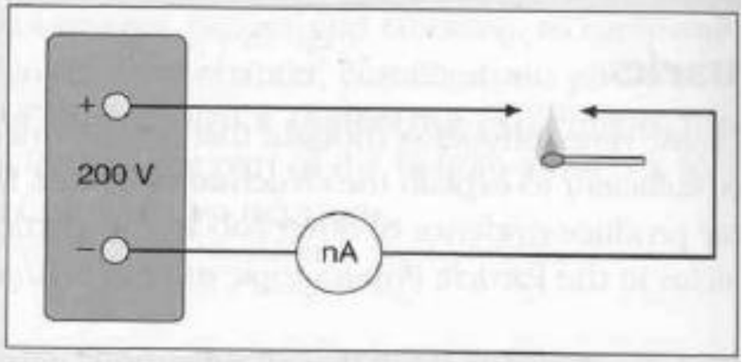
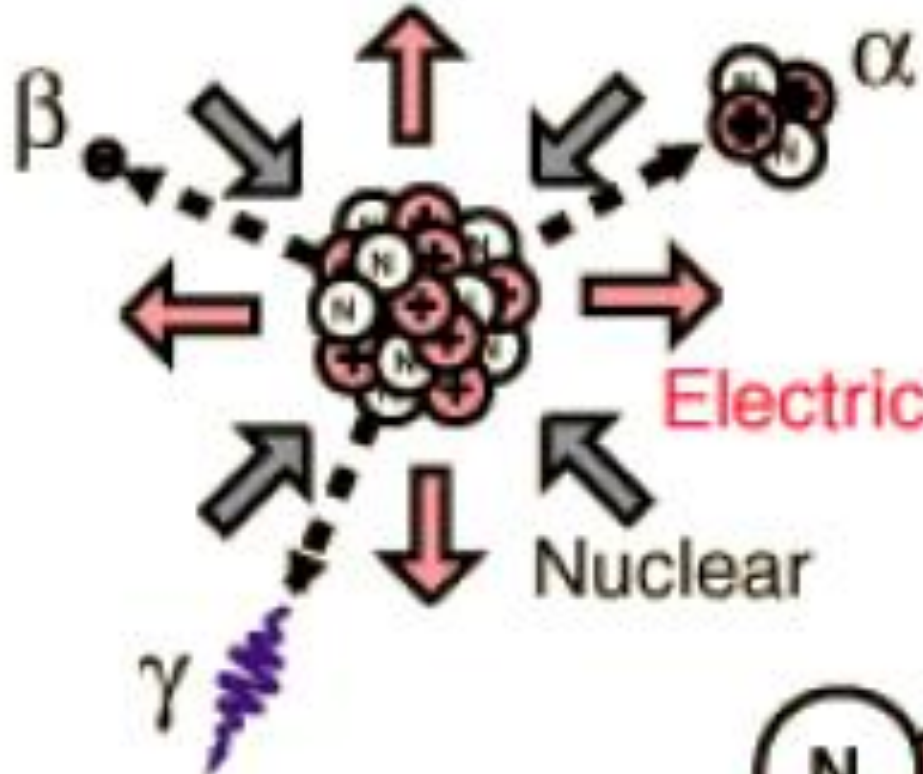
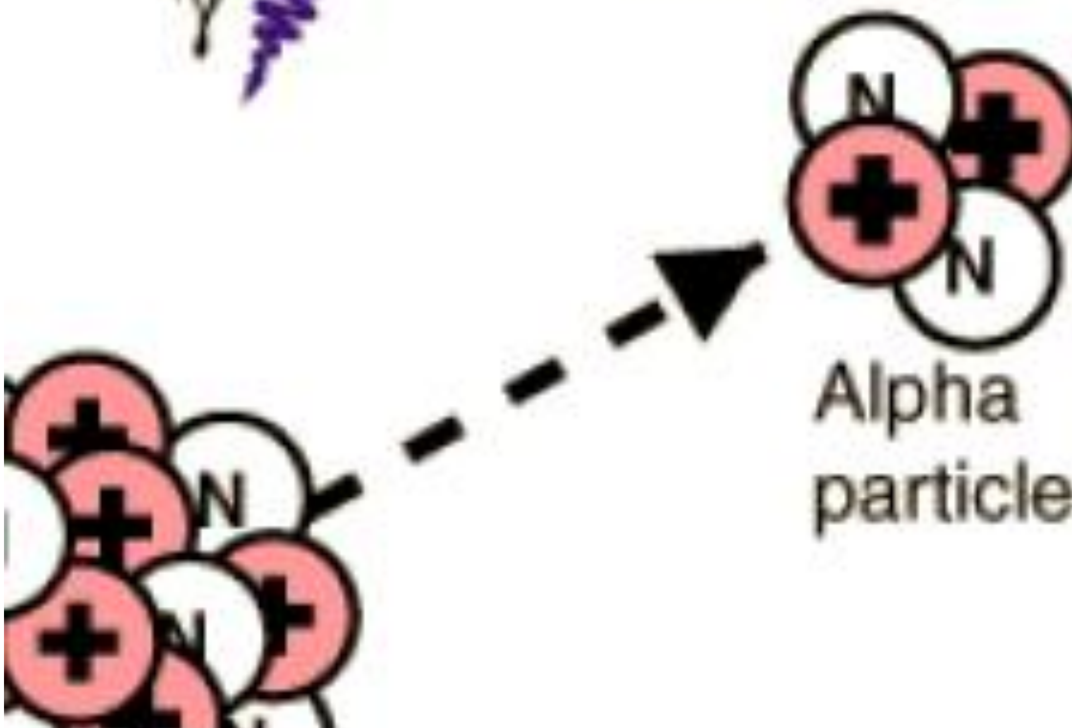


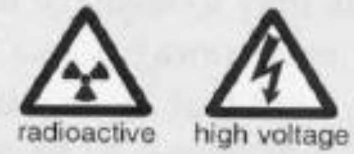
Figure 34.1 Measuring current through an air gap


β
α
Electric
Nuclear
γ


N
N
Alpha
particle

Investigating alpha (α) radiation

- The ionisation chamber is an enclosed air gap that you can use to investigate radiation. Any radiation that gets in to the chamber and ionises the air enables a current to flow and be detected by the meter.
- Check that the americium source produces an ionisation current when you hold it near the gauze (Figure 34.2). Then move the source further away from the gauze until the current stops, so that you can find the distance that the alpha radiation can travel through air.
- Next hold the source close to the gauze. Put thin pieces of paper between the source and the gauze to investigate the distance that alpha radiation can travel through paper.



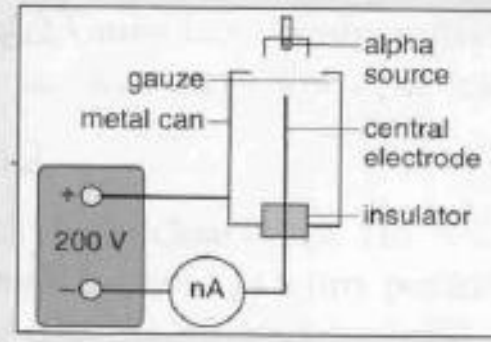


Figure 34.2 Detecting the ions produced by alpha radiation

The range of alpha radiation

Alpha radiation is heavily ionising – it produces many ions per millimetre along its path. But the range of alpha radiation is limited. It is stopped by 5 – 6 cm of air, or by thin paper. Figure 34.3 shows a smoke detector which is triggered by smoke particles stopping alpha radiation.

The mechanism of alpha decay

You read in Chapter 33 that alpha particles consist of two protons and two neutrons. This is the same as the nucleus of the helium-4 nuclide ($^{4}_{2}He$). Americium decays by emitting an alpha particle. The proton number decreases by 2 and the nucleon number decreases by 4. The atom becomes neptunium; it is no longer americium. This equation shows the decay:

$$^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^{4}_{2}\alpha$$

Neptunium decays by a further alpha decay to protactinium-233:

$$^{237}_{93}Np \rightarrow {}^{233}_{91}Pa + {}^{4}_{2}\alpha$$

When, at the end of its path, an alpha particle stops, it picks up two electrons and becomes a helium atom. Alpha decay within the Earth is responsible for the presence of helium in natural gas deposits.

Figure 34.3 Smoke detectors contain an americium source. Smoke particles stop the alpha radiation and trigger the alarm

GM tube

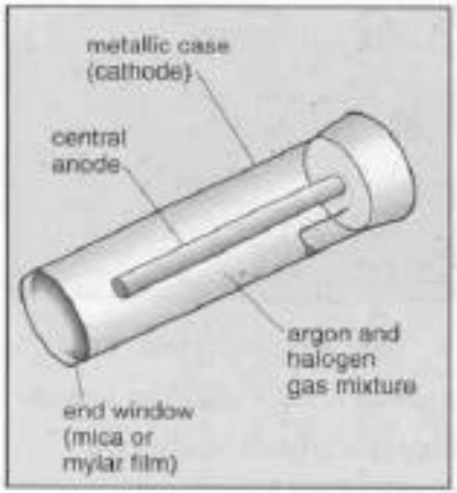
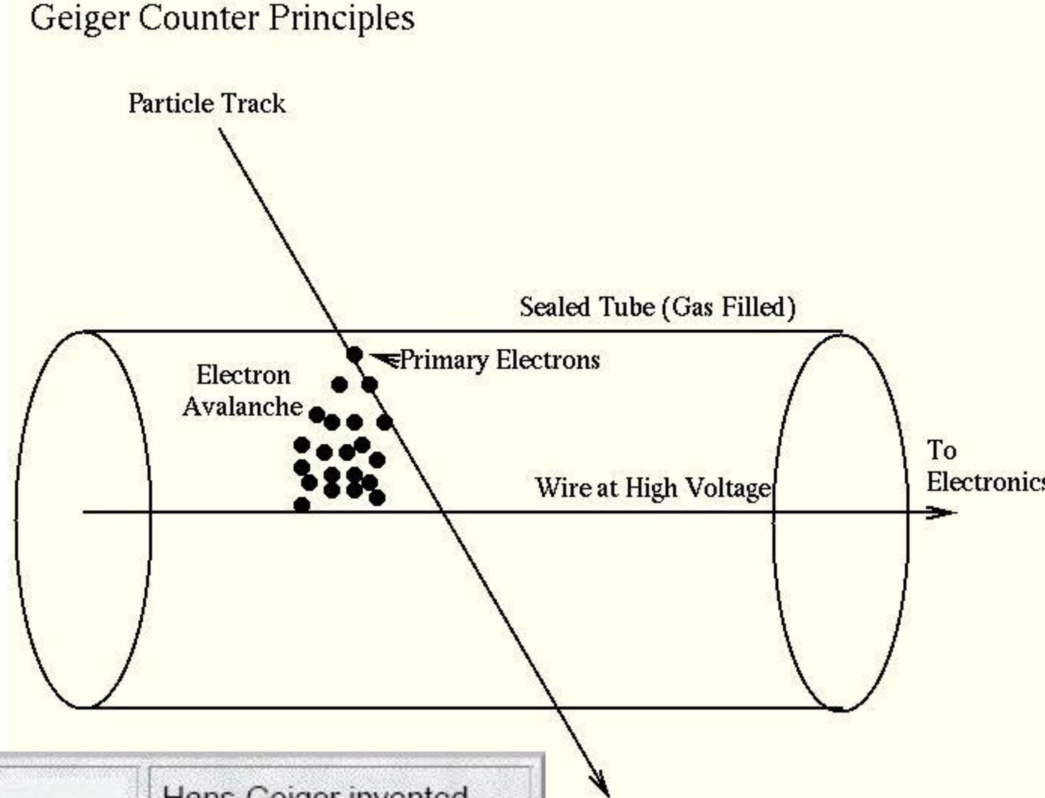
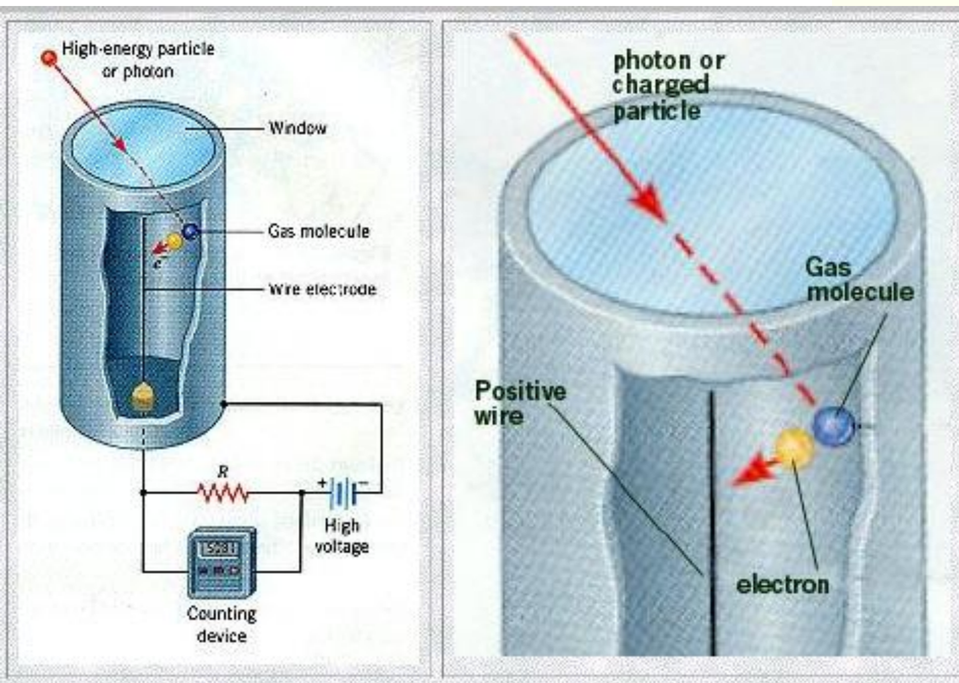


Figure 35.1 A Geiger–Müller tube





Hans Geiger invented the "Geiger counter".

It was Hans Geiger who, while working in Ernest Rutherford's lab, was the first to see the alpha particles reverse direction in the alpha particle experiment, but it was Rutherford's calculation which proved the existence of the nucleus.

Beta

Investigating beta-minus (β^-) and gamma (γ) radiations

Investigating beta-minus radiation

- Strontium-90 is a beta-minus emitter. Use a source-handling tool to mount a strontium-90 source near the GM tube and measure the count rate.
- For a range of distances from the tube, measure the count rate. Plot a graph of count rate against distance.
- Fix the beta-minus source 3 cm from the GM tube and measure the count rate (Figure 35.2).
- Insert a piece of paper between the source and the tube, and measure the new rate.
- Then insert a series of thin pieces of aluminium between the source and the tube. Plot a graph of count rate against number of pieces of aluminium.

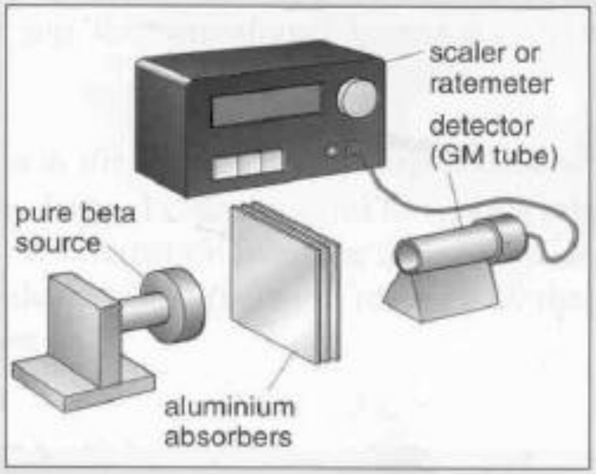


Figure 35.2 Investigating beta radiation

Investigating gamma radiation

- Use the arrangement in Figure 35.2 to measure the count rate at different distances from a cobalt-60 gamma source.
- Then use a source-handling tool to mount the source 8 cm from the tube and measure the count rate for a range of thicknesses of lead absorbers between the source and the tube.

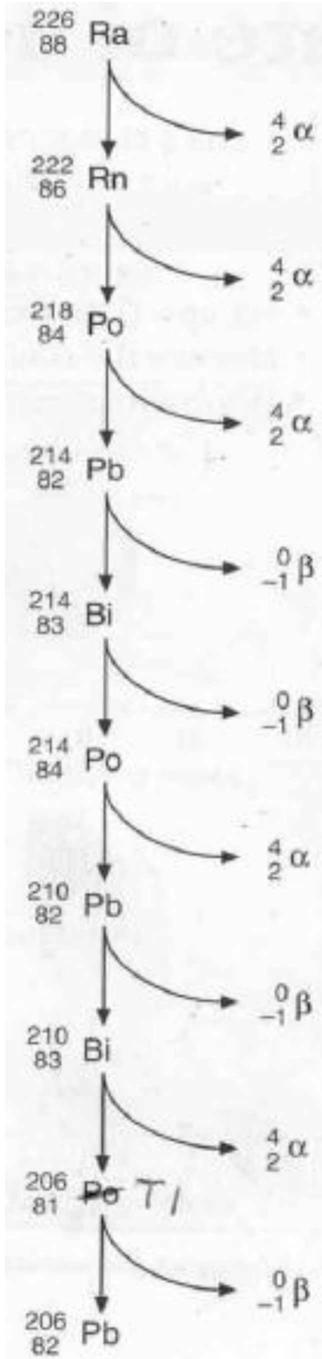
Properties of beta-minus (β^-) radiation

Beta-minus (β^-) radiation is much less heavily ionising than alpha radiation, and so is very difficult to detect with an ionisation chamber. However, beta-minus radiation will travel more than 30 cm through air and through several millimetres of aluminium.

In beta-minus decay, a neutron in the nucleus splits up into a proton plus an electron. The proton stays in the nucleus; the electron is ejected at high speed – it is a beta-minus particle. Beta-minus particles are fast electrons that have been emitted from the nucleus.

$$^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + {}^{0}_{-1}\beta^-$$

neutron → proton + electron



Proton & Neutrons
A
Protons

When beta-minus decay occurs, the number of nucleons stays the same. The number of protons goes up by 1, the number of neutrons goes down by 1 and an electron is emitted. Strontium-90 becomes yttrium-90, as the equation shows:

$$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + ^{0}_{-1}\beta^-$$

neutron → Proton + electron

Beta-plus (β^+) decay

Another type of decay, beta-plus (β^+) decay, occurs rarely in Nature, but more frequently in man-made radionuclides. In beta-plus decay, a proton in the nucleus splits up into a neutron plus a positron. The neutron remains; the beta-plus particle is ejected at high speed.

Proton → neutron + Positron

When beta-plus decay occurs, the number of nucleons stays the same. The number of neutrons goes up by 1, the number of protons goes down by 1 and a positron is emitted.

Carbon-11 decays by beta-plus decay to boron-11, as the equation shows:

$$^{11}_{6}C \rightarrow ^{11}_{5}B + ^{0}_{1}\beta^+$$

Gamma (γ) radiation

After emitting alpha or beta radiation, a nucleus may have surplus energy. Often it gives out this energy by emitting electromagnetic radiation. These photons of radiation are called **gamma (γ) rays**. You can read more about photons in *Waves and Our Universe*.

Properties of gamma radiation

The gamma radiation from a source is a stream of electromagnetic photons. The photons ionise when they react drastically with matter along the path, knocking a single electron from an atom and therefore producing a single ion pair. The ejected electron produces further ion pairs as it collides with other atoms. When a gamma photon ionises an atom, the number of photons decreases, but the remaining photons are unchanged. Gamma radiation causes relatively little ionisation per millimetre of its path. Because it interacts so little, it has a large range. High-energy gamma radiation is attenuated (reduced in strength), but not stopped, by several centimetres of lead.

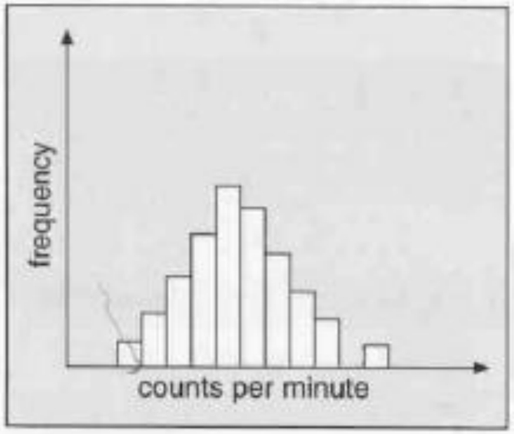
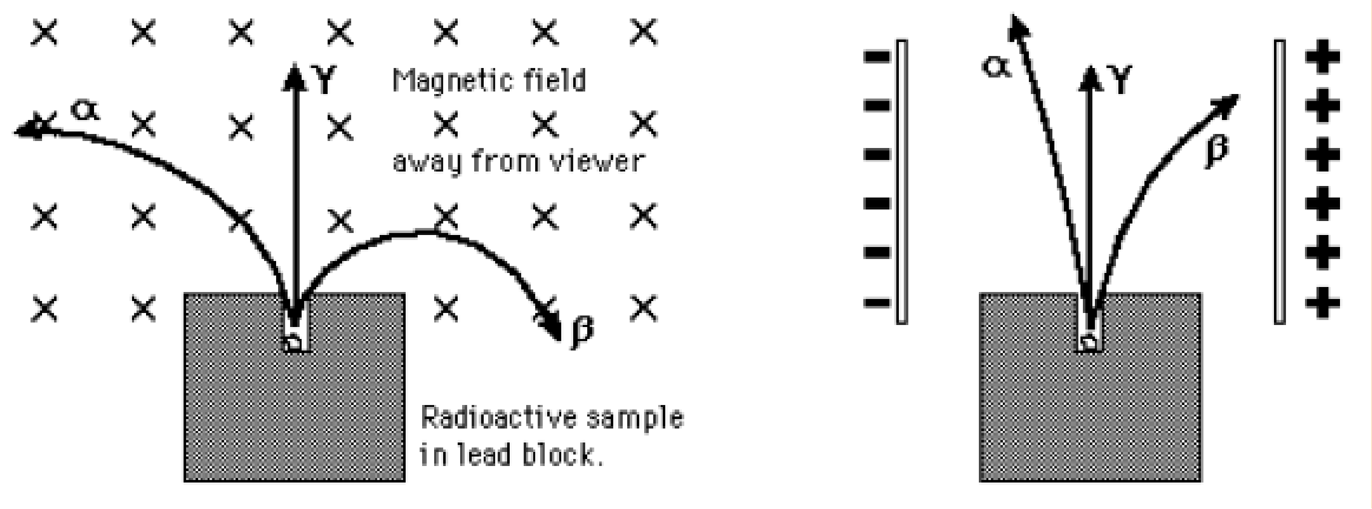


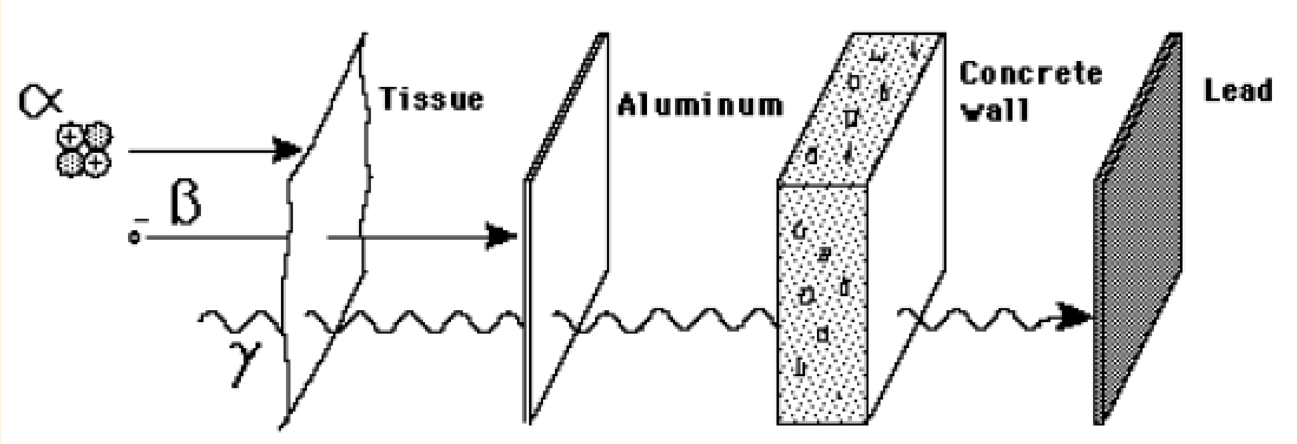
Figure 36.1 A histogram of background counts

Property	Alpha (α)	Beta-minus (β^-)	Beta-plus (β^+)	Gamma (γ)
charge	+2	−1	+1	0
rest mass	4 u	1/1800 u	1/1800 u	0
penetration	5 cm air; thin paper	30 cm air; few mm Al	annihilated on interaction with an electron	long way; keeps going through Pb
nature	helium nucleus	electron	positron	e.m. wave
ionising	heavily	light		a single ion pair on interaction

Historically, the products of radioactivity were called alpha, beta, and gamma when it was found that they could be analyzed into three distinct species by either a magnetic field or an electric field.



Though the most massive and most energetic of radioactive emissions, the alpha particle is the shortest in range because of its strong interaction with matter. The electromagnetic gamma ray is extremely penetrating, even penetrating considerable thicknesses of concrete. The electron of beta radioactivity strongly interacts with matter and has a short range.



Throwing dice

- Take 100 dice. Throw them all together and remove those which show a six. Stack these in a line.
- Then throw the remaining dice, and again remove those which show a six. Stack these in a line next to the first one. Repeat until all the dice are removed.
- Produce graphs of number remaining for each throw and number removed for each throw.

On any one occasion, the number showing a six, N_6, is proportional to the total number of dice thrown, N:

$$N_6 \propto N \qquad \text{or} \qquad N_6 = \text{constant} \times N$$

In this case the constant would be 1/6.

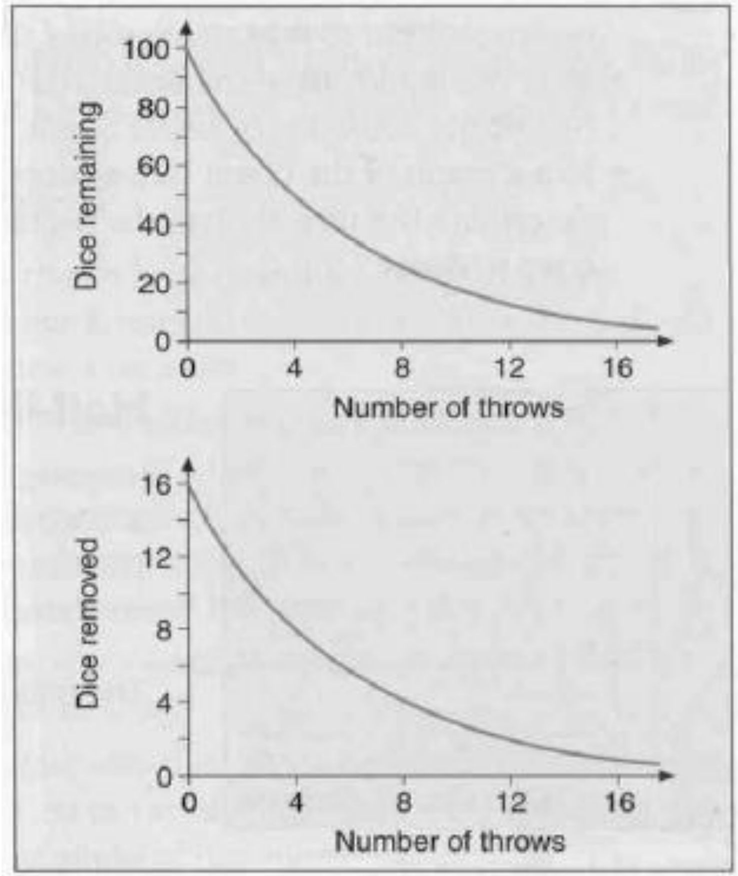


Figure 36.2 Modelling radioactive decay with 100 dice

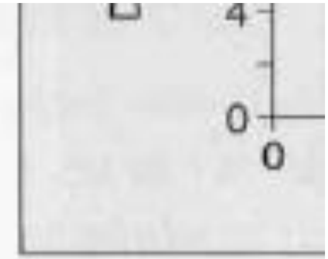


Figure 36.2 Mo

The number of atoms of a source that decay per second is called the **activity** of the source. The activity is proportional to the total number N of atoms present.

So we can write

Units $[s^{-1}] = [s^{-1}]$

$$\text{activity} = \lambda N$$

where N is the number of nuclei present at that instant and λ (the Greek letter *lambda*) is the **decay constant**; λ has units second^{-1}, and represents the proportion of N that decays in 1 s.

If the average rate of decay for 72 nuclei is 12 s^{-1}, then activity $= 12$ for $N = 72$. So

$$\text{Activity} = \lambda N$$

$$12\ \text{s}^{-1} = \lambda \times 72$$

$$\lambda = 1/6\ \text{s}^{-1}$$

Measuring half-life

- Protactinium-234 is a beta-minus emitter; a compound of it is soluble in organic solvent. It is generated in a water-based solution in the protactinium generator. Shake the generator gently to dissolve the protactinium compound from the water-based liquid, stand the generator next to the GM tube and allow the organic solvent to float to the top of the water (Figure 36.3).
- After the liquids have stabilised, start the counter and record the count every 3 s for 5 min.
- Plot a graph of the count rate against time. From this, determine the time for half the protactinium in the top layer to decay.

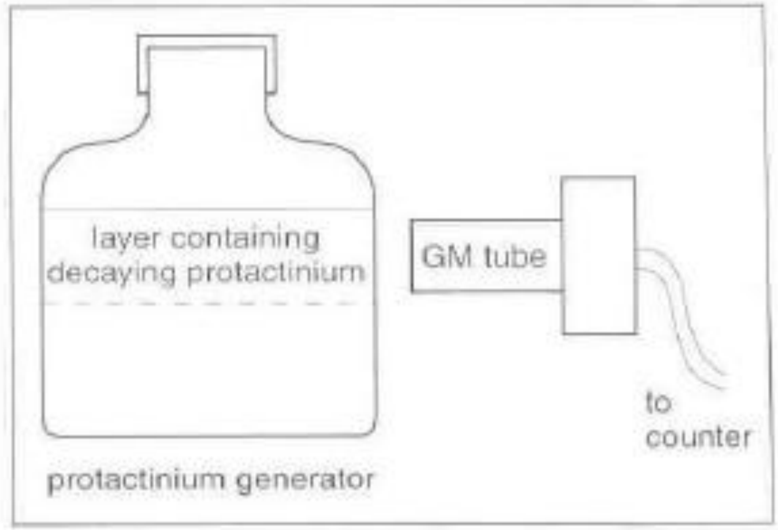


Figure 36.3 Measuring the decay of protactinium dissolved in the top liquid layer

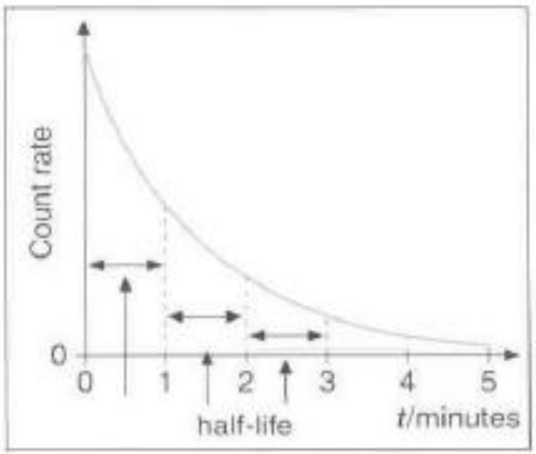


Figure 36.4 Decay graph

Half-life

However large the radioactive sample, experiment shows that for any particular isotope the average time for half of the atoms of one isotope to decay is constant. This time is called the **half-life**. The half-life of the isotope in Figure 36.4 is about one minute.

The half-life $t_{1/2}$ is connected to the decay constant λ by the equation

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

where ln 2 is 0.69.

The half-life of the isotope in Figure 36.4 is about 1 minute = 60 s.

Therefore $60\ \text{s} = \dfrac{0.69}{\lambda}$

and $\lambda = \dfrac{0.69}{60\ \text{s}}$

$= 0.012\ \text{s}^{-1}$

$$A = \lambda N$$

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

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

$$\int_{N_0}^{N} \frac{dN}{N} = -\lambda \int_0^t dt$$

$$\ln \frac{N}{N_0} = -\lambda t$$

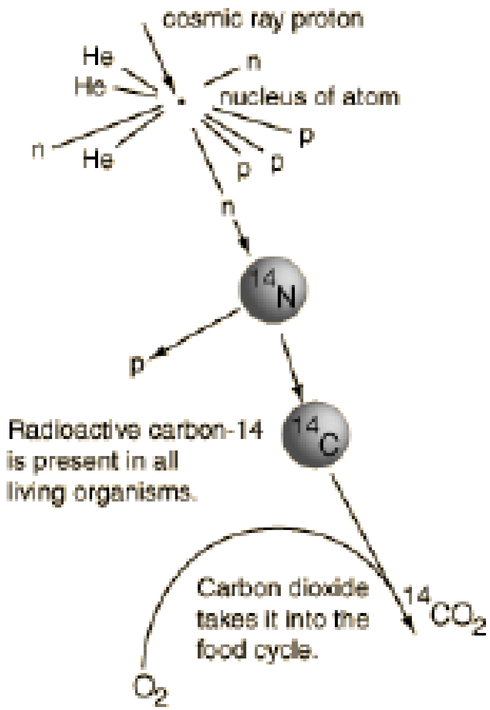
$$\frac{N}{N_0} = e^{-\lambda t}$$

$$\frac{1}{2} = e^{-\lambda t_{1/2}}$$

$$2 = e^{\lambda t_{1/2}}$$

$$\ln 2 = \lambda t_{1/2}$$

Carbon Dating

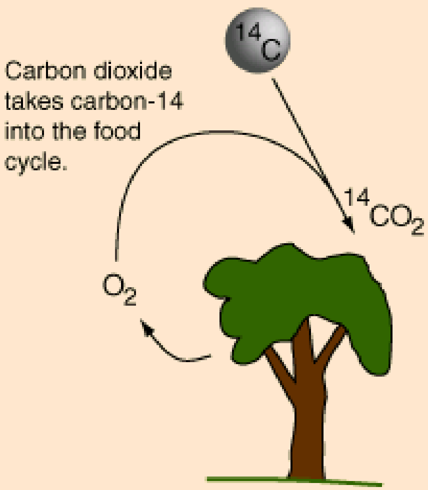


Carbon dating is a variety of radioactive dating which is applicable only to matter which was once living and presumed to be in equilibrium with the atmosphere, taking in carbon dioxide from the air for photosynthesis.

Cosmic ray protons blast nuclei in the upper atmosphere, producing neutrons which in turn bombard nitrogen, the major constituent of the atmosphere . This neutron bombardment produces the radioactive isotope carbon-14. The radioactive carbon-14 combines with oxygen to form carbon dioxide and is incorporated into the cycle of living things.

The carbon-14 forms at a rate which appears to be constant, so that by measuring the radioactive emissions from once-living matter and comparing its activity with the equilibrium level of living things, a measurement of the time elapsed can be made.

Carbon Dating

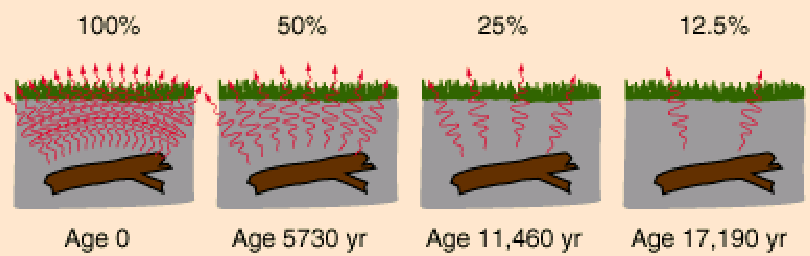


Presuming the rate of production of carbon-14 to be constant, the activity of a sample can be directly compared to the equilibrium activity of living matter and the age calculated. Various tests of reliability have confirmed the value of carbon data, and many examples provide an interesting range of application.

Carbon-14 decays with a halflife of about 5730 years by the emission of an electron of energy 0.016 MeV. This changes the atomic number of the nucleus to 7, producing a nucleus of nitrogen-14. At equilibrium with the atmosphere, a gram of carbon shows an activity of about 15 decays per minute.

The low activity of the carbon-14 limits age determinations to the order of 50,000 years by counting techniques. That can be extended to perhaps 100,000 years by accelerator techniques for counting the carbon-14 concentration.

Measurement of the beta decay activity of a buried piece of wood provides a measurement of the time elapsed since it was living and in equilibrium with the atmosphere.



Carbon-14 Equilibrium Activity

Since living organisms continually exchange carbon with the atmosphere in the form of carbon dioxide, the ratio of C-14 to C-12 approaches that of the atmosphere.

$$\frac{^{14}_{6}C}{^{12}_{6}C} \approx 1.3 \times 10^{-12}$$

From the known half-life of carbon-14 and the number of carbon atoms in a gram of carbon, you can calculate the number of radioactive decays to be about 15 decays per minute per gram of carbon in a living organism.

Radioactive carbon is being created by this process at the rate of about two atoms per second for every square centimeter of the earth's surface." Levin

The rate of production of carbon-14 in the atmosphere seems to be fairly constant. Carbon dating of ancient bristlecone pine trees of ages around 6000 years have provided general corroboration of carbon dating and have provided some corrections to the data.

Carbon has two stable, nonradioactive isotopes: carbon-12 (^{12}C), and carbon-13 (^{13}C). In addition, there are trace amounts of the unstable isotope carbon-14 (^{14}C) on Earth. Carbon-14 has a half-life of 5730 years and would have long ago vanished from Earth were it not for the unremitting cosmic ray impacts on nitrogen in the Earth's atmosphere, which create more of the isotope. The neutrons resulting from the cosmic rays interactions participate in the following nuclear reaction on the atoms of nitrogen molecules (N_2) in the atmospheric air:

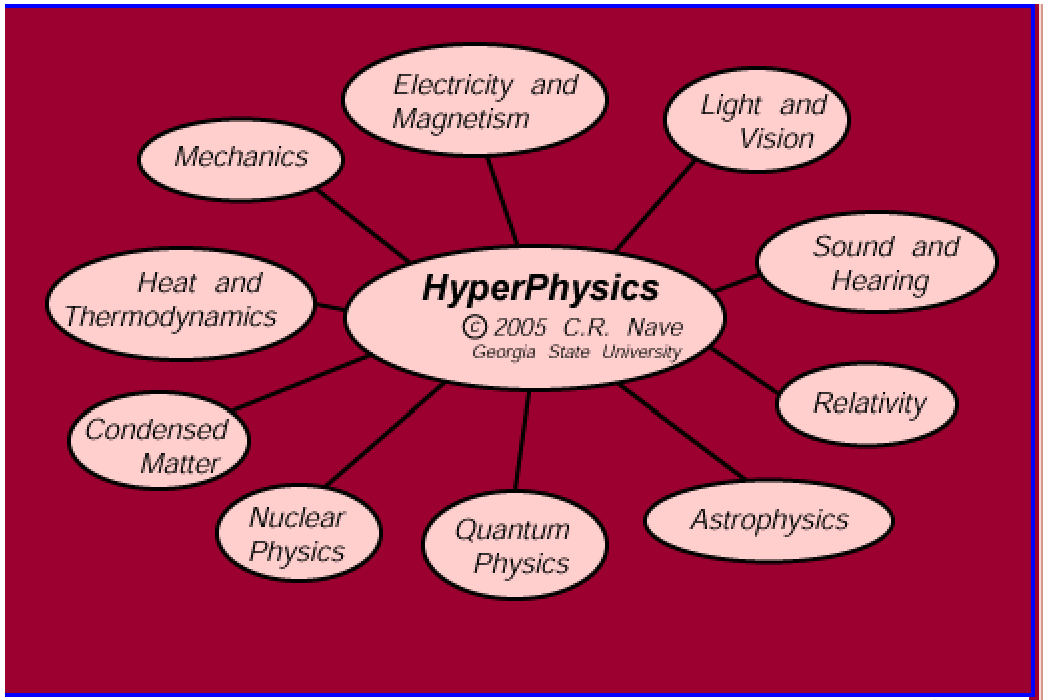
$$n + {}^{14}_{7}\mathrm{N} \rightarrow {}^{14}_{6}\mathrm{C} + p$$

For **approximate** analysis it is assumed that the cosmic ray flux is constant over long periods of time; thus carbon-14 is produced at a constant rate and **the proportion of radioactive to non-radioactive carbon is constant**: ca. 1 part per trillion (600 billion atoms/mole).

Plants take up atmospheric carbon dioxide by photosynthesis, and are ingested by animals, so every living thing is constantly exchanging carbon-14 with its environment as long as it lives. **Once it dies, however, this exchange stops, and the amount of carbon-14 gradually decreases through radioactive** beta decay.

$$^{14}_{6}\mathrm{C} \rightarrow \, ^{14}_{7}\mathrm{N} + e^{-} + \bar{\nu}_e$$

This decay can be used to measure how long ago once-living material died. This is done by looking at the ratios of radioactive and non-radioactive Carbon



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