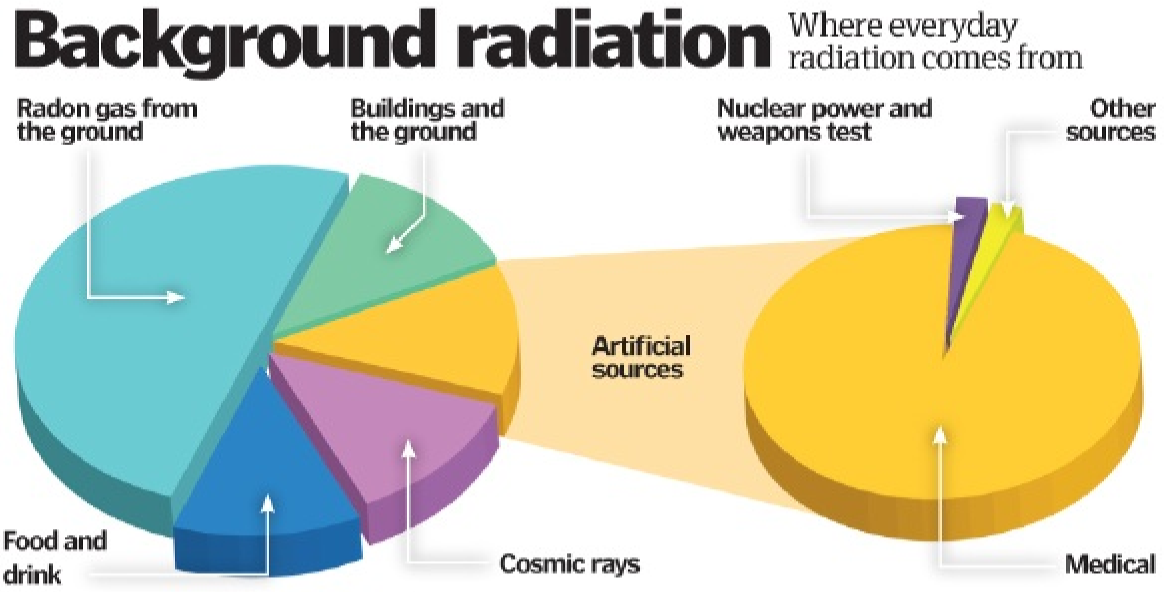
Dunman High School (Senior High Physics)

H2 Topic 20

Nuclear Physics



Content

- The nucleus
- Isotopes
- Mass defect and nuclear binding energy
- Nuclear processes
- Radioactive decay
- Biological effects of radiation

Learning Outcomes

Candidates should be able to:

(a) infer from the results of the α-particle scattering experiment the existence and small size of the nucleus.
(b) distinguish between nucleon number (mass number) and proton number (atomic number).
(c) show an understanding that an element can exist in various isotopic forms each with a different number of neutrons.
(d) use the usual notation for the representation of nuclides and represent simple nuclear reactions by nuclear equations of the form ${}^{14}_{7}\text{N}+{}^{4}_{2}\text{He}\rightarrow{}^{17}_{8}\text{O}+{}^{1}_{1}\text{H}$.
(e) show an understanding of the concept of mass defect.
(f) recall and apply the equivalence relationship between energy and mass as represented by $E = mc^2$ in problem solving.
(g) show an understanding of the concept of binding energy and its relation to mass defect.
(h) sketch the variation of binding energy per nucleon with nucleon number.
(i) explain the relevance of binding energy per nucleon to nuclear fusion and to nuclear fission.
(j) state and apply to problem solving the concept that nucleon number, proton number, energy and mass are all conserved in nuclear processes.
(k) show an understanding of the spontaneous and random nature of nuclear decay.
(l) infer the random nature of radioactive decay from the fluctuations in count rate.
(m) show an understanding of the origin and significance of background radiation.
(n) show an understanding of the nature of α, β and γ radiations.
(o) define the terms activity and decay constant and recall and solve problems using $A=\lambda N$.
(p) infer and sketch the exponential nature of radioactive decay and solve problems using the relationship $x = x_0 e^{-\lambda t}$ where x could represent activity, number of undecayed particles and received count rate.
(q) define half-life.
(r) solve problems using the relation $\lambda = \dfrac{0.693}{t_{\frac{1}{2}}}$
(s) discuss qualitatively the effects, both direct and indirect, of ionising radiation on living tissues and cells.

References:

1) *College Physics* by A. Giambattista, B.M. Richardson and R.C. Richardson

2) *Advanced Physics* by T. Duncan

3) *Physics* by J.D.Cutnell and K.W.Johnson

4) *College Physics* by Serway

5) *Physics Principles with Applications* by D.C. Giancoli

Introduction

At the same time that quantum theory was being developed and scientists were attempting to understand the structure of the atom and its electrons, investigations into the nucleus itself had also begun. In the chapter on Quantum Physics, we generally treated the nucleus as a point charge so massive that it is not affected by electrical forces on it due to the electrons. An important question for physicists was whether the nucleus had a structure and what that structure might be. It turns out that the nucleus is a complicated entity (till today, it is not fully understood) that manifests itself in radioactive decay and nuclear reactions.

1 BASICS OF NUCLEAR PHYSICS

(b) distinguish between nucleon number (mass number) and proton number (atomic number).

(c) show an understanding that an element can exist in various isotopic forms each with a different number of neutrons.

In the early 1930s, a model of the nucleus had been developed that is still useful today. According to this model, a nucleus is considered to be a bound collection of protons and neutrons (The only exception is the hydrogen nucleus which consists of a single proton). **Together, protons and neutrons are referred to as nucleons**. In describing some of the properties of the nucleus, the following terms are used:

- **Proton number** (also known as atomic number) of a nuclide is the number of protons in the nucleus. Proton number is designated by the letter *Z*.
- **Nucleon number** (also known as mass number) of a nuclide is the number of nucleons (that is, protons plus neutrons) in the nucleus. Nucleon number is designated by the letter *A*.

Nuclide is a particular species (type) of nucleus that is specified by its proton number and neutron number. We use the symbol ${}^{A}_{Z}\mathrm{X}$ to represent a nuclide where *X* represents the chemical symbol for the element, *A* is the nucleon number and *Z* is the proton number.

Worked Example 1

Determine the number of protons and neutrons in the nucleus of aluminium nuclide ${}^{27}_{13}\mathrm{Al}$.

The atomic number, Z = number of protons = 13
The mass number, A = number of protons and neutrons = 27
Thus, the number of neutrons = 27 – 13 = 14

It was once thought that all nuclei of a given element were identical. However, we now know that certain elements have *isotopes*. The **isotope** of an element is the nucleus of the same element with the same number of protons but different number of neutrons in the nucleus. For example, ${}^{12}_{6}\mathrm{C}$, ${}^{13}_{6}\mathrm{C}$ and ${}^{14}_{6}\mathrm{C}$ have virtually identical chemical properties but they have different masses. Thus, the isotopes of an element can be separated using a mass spectrometer.

1.1 *Charge and mass*

Why is *A* the *mass number*?

	Charge	**Mass**
Proton	+1.6 x 10^{-19} or +e (charge of an electron)	1.6726 x 10^{-27} kg
Neutron	0	1.6749 x 10^{-27} kg

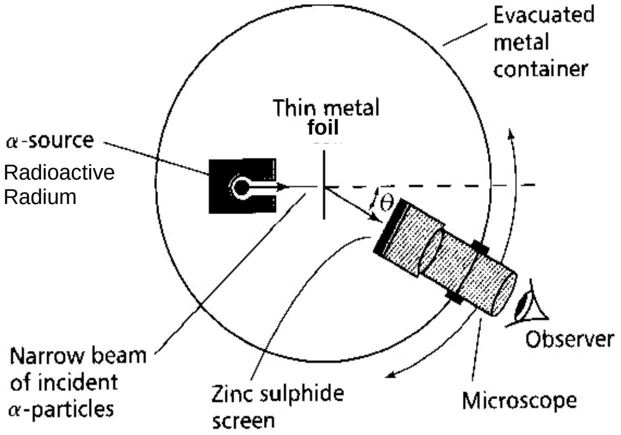
As the mass of protons and neutrons is small, it is more convenient to write the mass of a nucleus or atom in *atomic mass unit* (symbol *u*) rather than in kg. The **atomic mass unit**, *u*, is defined such that the mass of a carbon-12 atom is 12*u*. In other word, one *u* is $\frac{1}{12}$ of the mass of a carbon-12 atom, thus **1 *u* = 1.66 x 10^{-27} kg**. Thus nucleons have masses of approximately 1 u (proton mass = 1.007 u, neutron mass = 1.008 u, electron mass = 0.0005 u). Since the mass of protons and neutrons are approximately the same and the electron is much less massive (about 1840 times lighter), the mass of a nucleus (or an atom) is approximately *A* u. This is why *A* is called the *mass number*.

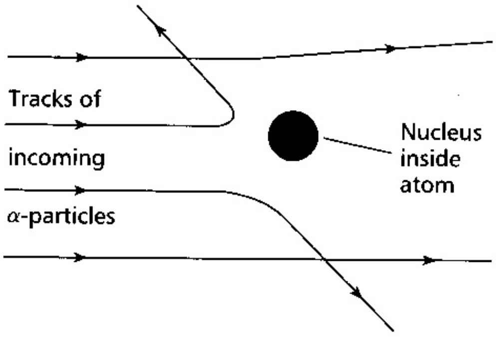
1.2 *Size of nucleus*

(a) infer from the results of the α-particle scattering experiment the existence and small size of the nucleus.

Geiger-Marsden Experiment (aka Rutherford gold foil experiment)

The approximate size of the nuclei was determined by Rutherford from the scattering of α-particles by thin gold foils (about 10^{-8} m thick)





Ernest Rutherford
Father of Nuclear Physics
Nobel Prize (Chemistry)

1. Most of the α-particles were not deflected or only deflected by small angles. They passed almost straight through the foil and behaved as if the gold foil was not there.
2. Less than 1% of the α-particles were deflected through very large angles of more than 90°. A much smaller but significant percentage of the α-particles were deflected through 180°.

Deductions about the structure of atoms:

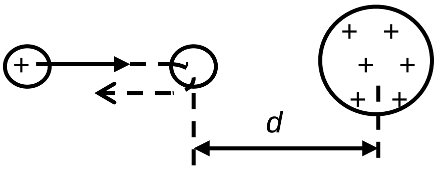
1. When α-particles are directed at the atoms of a thin gold foil, the electrons in each atom are easily pushed aside by the α-particles as α-particles are much heavier than electrons. Since most of the α-particles either passed through the foil undeflected or were scattered at small angles, this suggests

that the atom is made of mostly empty space, i.e. the electrons surround the nucleus at relatively large distances.

2 Most of the atom's mass is concentrated in its nucleus. The size of the nucleus is small compared to the atom. Forward and back scattering indicates the existence of large repulsive force (Coulomb force of repulsion between the α-particles and the positive charge in the atom). The positive charge must be concentrated in a small volume, i.e. the nucleus of the atom. Most α-particles miss the nucleus because the nucleus is so tiny inside the atom and few α-particles pass near the nucleus.

Worked Example 2

An α-particle of energy 5.4 MeV collides head-on with a gold nucleus (atomic number 79). Determine the minimum distance of separation of the α-particle and the gold nucleus, (i.e. what is the closest that the α-particle can get to the nucleus).



Concept: Conservation of Energy

KE lost by α-particle = EPE gained by α-particle

EPE of α-particle at closest distance, d = $\frac{1}{4\pi\varepsilon_O}\frac{Q_\alpha Q_{gold}}{d}$

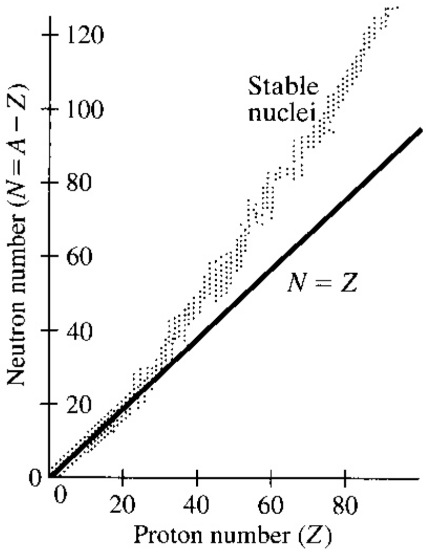
So, assuming α-particle comes from infinity such that starting EPE = 0.

EPE gained = KE lost

$$\frac{1}{4\pi\varepsilon_O}\frac{Q_\alpha Q_{gold}}{d} = 5.4 \times 10^6 (1.6 \times 10^{-19})$$

$$\frac{1}{4\pi\varepsilon_O}\frac{(2e)(79e)}{d} = 5.4 \times 10^6 (1.6 \times 10^{-19})$$

➔ d = 4.21×10^{-14} m



1.3 ***Nuclear Stability***

How is it possible that the nucleus consists of closely packed protons and neutrons? Shouldn't the very large electrostatic force of repulsion between protons cause the nucleus to fly apart?

The nucleons are actually held together by a short-range attractive force, called the ***nuclear force***. This force exists between all nucleons (that is, between two protons, between two neutrons or between a proton and a neutron), and at short distances, is strong enough to overcome the Coulomb force of repulsion. As a result, many naturally occurring atoms can have stable nuclei.

There are about 260 stable nuclei. A plot of neutron number N (= $A–Z$) against proton number Z for naturally occurring elements that have stable nuclei is shown on the left.

It can be seen that points representing stable nuclei fall on or above the reference line $N = Z$. Light nuclei are most stable if they contain equal number of protons and neutrons, that is, $N = Z$ while heavy nuclei are more stable if $N > Z$.

This can be partially understood by recognising that as the number of protons increases, the strength of the long-range Coulomb force of repulsion increases, and this tends to break the nucleus apart. As a result, more neutrons are needed to keep the nucleus stable as neutrons experience only the short-range attractive nuclear forces. However, as more protons occur in the nucleus, there comes a point where the limited short-range action of the strong nuclear force cannot compensate for the repulsive Coulomb force. The stable nucleus with the largest number of protons is that of bismuth $^{209}_{83}\text{Bi}$ which contains 83 protons and 126 neutrons. All nuclei with more than 83 protons are unstable and spontaneously disintegrate into other particles as time passes. This spontaneous disintegration is known as radioactivity or nuclear decay. We will examine radioactivity in greater detail later.

2 MASS DEFECT OF THE NUCLEUS AND NUCLEAR BINDING ENERGY

(e) show an understanding of the concept of mass defect.

(f) recall and apply the equivalence relationship between energy and mass as represented by $E = mc^2$ in problem solving.

(g) show an understanding of the concept of binding energy and its relation to mass defect.

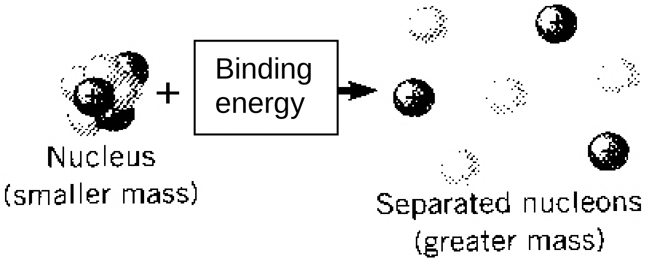
The nucleons in a stable nucleus are held tightly together by the strong nuclear force. Therefore, energy is required to separate a stable nucleus into its constituent protons and neutrons. The more stable the nucleus is, the greater is the amount of energy needed to break it apart. The minimum energy required to separate the nucleus into its constituent protons and neutrons is called the **binding energy** of the nucleus.

After successfully explaining photoelectric effect, Einstein in 1905, through his Special Theory of Relativity, went on to show that mass is a form of energy, through his now-famous equation

$$\boxed{E = m\,c^2}$$

where E = energy, m = mass and c = speed of light. Since mass is a measure of energy content, any change in mass is accompanied by a corresponding change in energy and vice versa.

Since binding energy must be supplied to separate a nucleus into its constituent protons and neutrons, the total energy of the separated protons and neutrons must be more than the energy of the bound nucleus, that is,



Energy of nucleus + Binding Energy = Total energy of *separated* protons and neutrons

Binding Energy = Total energy of *separated* protons and neutrons – energy of nucleus

Since energy and mass are equivalent, the total mass of the *separated* protons and neutrons is more than the mass of the nucleus. The difference in mass between the mass of a nucleus and the total mass of its constituent nucleons is called the **mass defect**.

Mass defect = total mass of *separated* protons and neutrons – mass of nucleus

From the above two relations, we have

$$\boxed{\text{Binding Energy} = (\text{mass defect})c^2}$$

which shows that the nuclear binding energy is related to the mass defect of the nucleus.

Example 3

Calculate (a) mass defect in kg, (b) binding energy in MeV, (c) binding energy per nucleon in MeV of the helium nucleus ${}^{4}_{2}\text{He}$ (also known as α-particle) given the following:
mass of helium nucleus = 4.00153 u, mass of proton = 1.00728 u, mass of neutron = 1.00866 u.

Mass defect = total mass of *separated* protons and neutrons – mass of nucleus
= total mass of 2 protons and 2 neutrons – mass of nucleus
= (2 x 1.00728 u + 2 x 1.00866 u) – 4.00153 u
= 4.03188u – 4.00153 u
= 0.03035u
= $0.03035 \times 1.66 \times 10^{-27}$ kg
= 5.0381×10^{-29} kg

Binding Energy = (mass defect)c^2
= $(5.0381 \times 10^{-29})(3 \times 10^{8})^2$
= 4.53429×10^{-12} J
= $\dfrac{4.53429\text{x}10^{-12}}{10^{6} \times 1.6 \times 10^{-19}}$
= 28.3 MeV

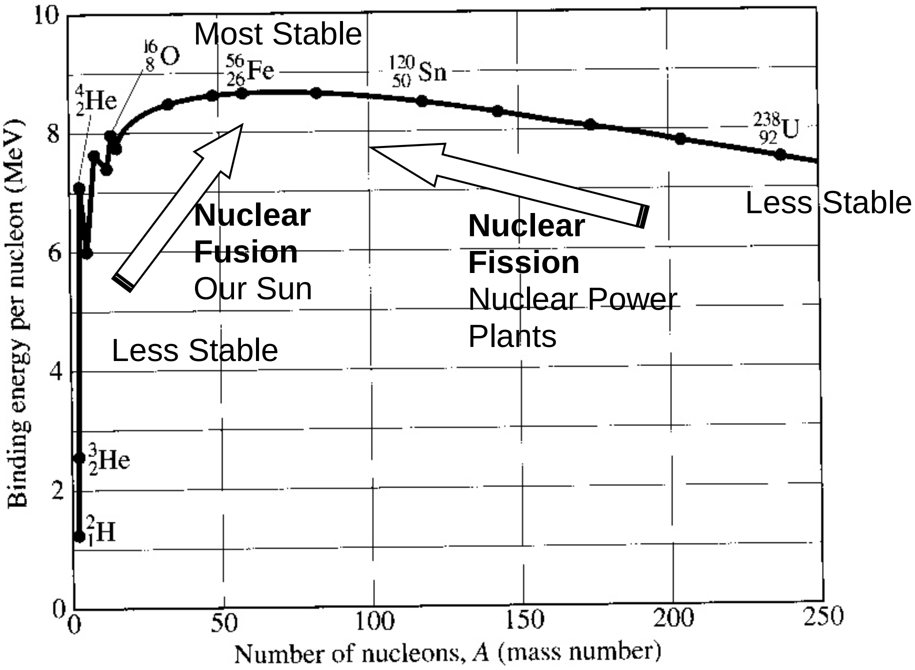
Binding Energy per nucleon = $\dfrac{\text{Binding energy}}{\text{number of nucleon}}$
= $\dfrac{28.3}{4}$
= 7.08 MeV

2.1 *Binding Energy Per Nucleon*

(h) sketch the variation of binding energy per nucleon with nucleon number.

(i) explain the relevance of binding energy per nucleon to nuclear fusion and to nuclear fission.

To examine how the nuclear binding energy varies from nucleus to nucleus, we compare the binding energy on a per-nucleon basis for each nucleus. The **binding energy per nucleon** is the binding energy of a nucleus divided by the number of nucleons in the nucleus. This value gives us an idea of how strongly bound the nucleons are within the nucleus. The greater the value, the more stable is the nucleus.



The graph shows a plot of the binding energy per nucleon (that is, $\frac{\text{B.E.}}{A}$) against the nucleon number A. The important features of the graph are:

1. The binding energy per nucleon increases rapidly for nuclei with small masses and reaches a maximum value of approximately 8.8 MeV/nucleon for a nucleus of nucleon number about 56. For greater nucleon number, the binding energy per nucleon decreases gradually until there is insufficient binding energy to hold the nucleus together.

2 The greater the binding energy per nucleon, the greater is the energy that must be supplied to remove the nucleon. So, maximum binding energy per nucleon corresponds to the most stable nuclei. The curve reaches its maximum value in the vicinity around A = 56. Iron-56, with one of the highest B.E. per nucleon, is an example of the most tightly bound nuclei. Either side of the maximum binding energy per nucleon, the easier it is to separate a nucleus into its nucleons. In other words, the nucleons are not bound so strongly and hence the nucleus is less stable.

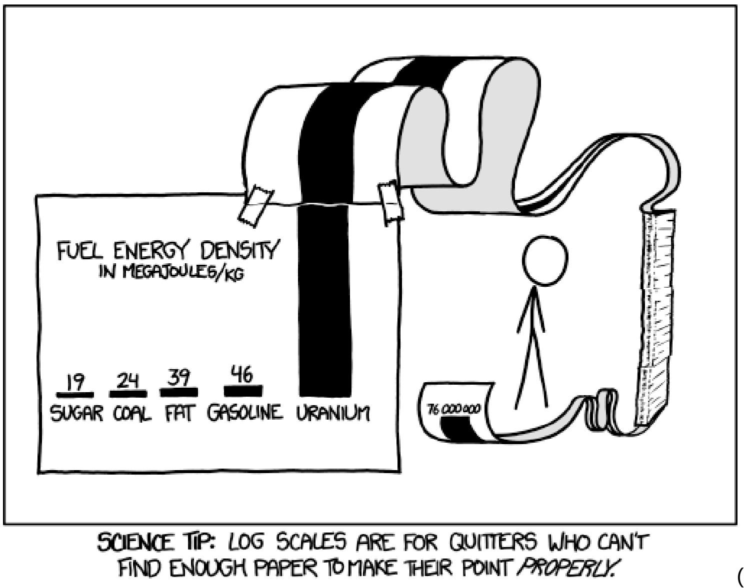
3 Nuclei with large mass number may undergo nuclear **fission**. This means that a heavy nucleus splits into two lighter daughter nuclei of *approximately the same mass* with the release of a large amount of energy and neutrons. From the graph, the daughter nuclei possess a greater binding energy per nucleon, that is, the resulting smaller nuclei are more tightly bound together. Example of fission:

$$ {}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{140}_{92}Xe + {}^{94}_{38}Sr + 2{}^{1}_{0}n + \gamma + energy $$

4 Nuclei with low mass number may undergo nuclear **fusion**. This means that two light nuclei combine to form a heavier nucleus, releasing large amount of energy. The resulting larger nucleus possesses a greater binding energy per nucleon, that is, it is more tightly bound together. Example of fusion:

$$ {}_{1}^{2}H + {}_{1}^{3}H = {}_{2}^{4}He + {}_{0}^{1}n + energy $$

In both nuclear fusion and nuclear fission, since the resulting product nucleus/nuclei are more tightly bound together, energy (equal to the increase in *total* binding energy) is released. Refer to Example 4 on next page.



(source XKCD)

3 NUCLEAR PROCESSES

(d) use the usual notation for the representation of nuclides and represent simple nuclear reactions by nuclear equations of the form ${}_{7}^{14}N + {}_{2}^{4}He \rightarrow {}_{8}^{17}O + {}_{1}^{1}H$.

(j) state and apply to problem solving the concept that nucleon number, proton number, energy and mass are all conserved in nuclear processes.

There are two types of nuclear processes

1 *Nuclear decay* in which an unstable nucleus undergoes a spontaneous nuclear reaction by emitting radiation (α, β and γ radiations). We will examine this in Section 4 later.

2 *Induced nuclear reaction* in which nuclei are bombarded with energetic particles like alpha particle, neutron, proton or γ-ray.

3.1 ***Conservation Laws in Nuclear Processes***

In all nuclear processes, whether spontaneous or not, the following quantities are conserved:

1. Atomic Number → this is because total electric charge is conserved
2. Mass Number → this is because the total number of nucleons must be conserved.
3. Momentum → the total momentum of the system is conserved.
4. Mass-energy → since mass is equivalent to energy, the total mass-energy of the system is conserved.

Example 4

Two isotopes of hydrogen ${}^{2}_{1}\mathrm{H}$ (deuterium, D) and ${}^{3}_{1}\mathrm{H}$ (tritium, T) fuse to form ${}^{4}_{2}\mathrm{He}$ and a neutron according to the following reaction:

$${}^{2}_{1}\mathrm{H}+{}^{3}_{1}\mathrm{H}\rightarrow{}^{4}_{2}\mathrm{He}+{}^{1}_{0}\mathrm{n}$$

Find the energy released in this fusion reaction.

Method 1: Given the masses: ${}^{2}_{1}\mathrm{H}$ =2.0141 u, ${}^{3}_{1}\mathrm{H}$ =3.0161 u, ${}^{4}_{2}\mathrm{He}$ =4.0026 u and ${}^{1}_{0}\mathrm{n}$ = 1.0087 u

Note: Energy released = (mass of reactant – mass of product) c^2

Mass difference,

Δm = mass of reactants – mass of products
= 2.0141 u + 3.0161 u – (4.0026 u + 1.0087 u)
= 0.0189 u

Energy released, $E = \Delta mc^2 = 0.0189\ (1.66 \times 10^{-27})\ (3.0 \times 10^{8})^2 = 2.82 \times 10^{-12}$ J = 17.6 MeV

Method 2: Given the B.E. per nucleon instead

${}^{2}_{1}H$ - 0.885 MeV
${}^{3}_{1}H$ - 2.677 MeV
${}^{4}_{2}He$ - 6.875 MeV

Note: Energy released = Total B.E. of product - Total B.E. of reactant

Refer to derivation in Annex 1

Energy released = Total B.E. of products – Total B.E. of reactants
= (6.875 x 4 + 0) – (0.885 x 2 + 2.677 x 3)
= 17.7 MeV

Note: The neutron has no binding energy.

Example 5

The ${}^{238}_{92}\mathrm{U}$ nuclide decays by emitting an α-particle as follows:

$${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + \alpha \qquad \text{(Assume U is stationary)}$$

Given the atomic mass of ${}^{238}_{92}\mathrm{U}$ = 238.0507826 u, ${}^{234}_{90}\mathrm{Th}$ = 234.0435955 u and ${}^{4}_{2}\mathrm{He}$ = 4.0026032 u, calculate the kinetic energy of the α-particle. [Ans: 4.21 MeV]

By conservation of mass-energy:

$$m_{\mathrm{U}}c^2 = (mc^2 + ½\, mv^2)_{\mathrm{Th}} + (mc^2 + ½\, mv^2)_{\mathrm{He}}$$

$$m_{\mathrm{U}}c^2 - (m_{\mathrm{Th}}c^2 + m_{\mathrm{He}}c^2) = ½\, m_{\mathrm{Th}}v_{\mathrm{Th}}{}^2 + ½\, m_{\mathrm{He}}v_{\mathrm{He}}{}^2$$

that is, energy is released in the form of KE of products

Mass difference = Δm = mass of reactants – mass of products
= 238.0507826 u – (234.0435955 u + 4.0026032 u)
= 0.0045839 u

Energy released = Δmc^2 = 0.0045839 $(1.66 \times 10^{-27})(3.0 \times 10^{8})^2 = 6.848 \times 10^{-13}$ J

Total KE = $½\, m_{\mathrm{Th}} v_{Th}^2 + ½\, m_{\mathrm{He}}\ v_{He}^2 = 6.848 \times 10^{-13}$ ---- (1)

or $$\frac{p_{Th}^2}{2m_{Th}} + \frac{p_{He}^2}{2m_{He}} = 6.848 \times 10^{-13}$$

By conservation of momentum, total initial momentum = total final momentum

$$0 = p_{\mathrm{Th}} + p_{\mathrm{He}}$$

or $p_{\mathrm{Th}} = -\, p_{\mathrm{He}}$ (that is, Th and He move in opposite directions)

Sub into Eqn (1):

$$\frac{p^2}{2m_{Th}} + \frac{p^2}{2m_{He}} = 6.848 \times 10^{-13}$$

$$\frac{p^2}{2(234.0435955x1.66x10^{-27})} + \frac{p^2}{2(4.0026032x1.66x10^{-27})} = 6.848 \times 10^{-13}$$

$$p = 9.459 \times 10^{-20} \text{ kg m s}^{-1}$$

Hence, KE of the α-particle = $\dfrac{p^2}{2m_{He}} = \dfrac{(9.459x10^{-20})^2}{2(4.0026032x1.66x10^{-27})} = 6.73 \times 10^{-13} = 4.21$ MeV

The α-particle carries most of the kinetic energy.

4 RADIOACTIVE DECAY

(k) show an understanding of the spontaneous and random nature of nuclear decay.

(n) show an understanding of the nature of α, β and γ radiations.

Radioactive decay or **radioactivity** is the *spontaneous* and *random* disintegration of the unstable nucleus from which may be emitted some or all of the following nuclear radiations: alpha particle, beta particle, gamma radiations. (other particles/types of electromagnetic radiation e.g. neutrino, antineutrino, positron are emitted too, but these are not in H2 syllabus). **Spontaneous** means that the nuclear decay occurs without the presence of any external influence e.g. no external source of energy, not affected by external pressure, temperature, electric and magnetic fields etc. **Random** means that it is impossible to predict whether any given nucleus in a given radioactive sample will be among the small number of nuclei that decay during the next second. All have the same chance.

We shall examine the properties of three different kinds of radiation (α-particle, β-particle and γ ray) emitted by radioactive nuclei.

4.1 *Nature of α, β particle & γ radiation*

α-particles

- are helium nuclei, ${}^{4}_{2}\text{He}$, consisting of two protons and two neutrons. Hence α-particles are positively charged.
- have the same energy in most cases, in the range of a few MeV. Their speed is about 0.1*c*.
- can be deflected by electric and magnetic field since they are positively charged. The deflection path for electric field is parabolic, and that for magnetic field is circular.
- have high ionising power and produce a large number of ion pairs per unit length of its path.
- have a range of about 5 cm in air. They are easily stopped by a piece of paper.
- emission occurs mainly in nuclides of mass number larger than 130.

Consider an α-particle decay

$${}^{A}_{Z}\text{X} \longrightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\text{He}$$

X is called the parent nucleus and Y the daughter nucleus.

It is found that the mass of the parent nucleus is greater than the combined mass of the daughter nucleus and the α-particle. Thus, conservation of mass-energy gives

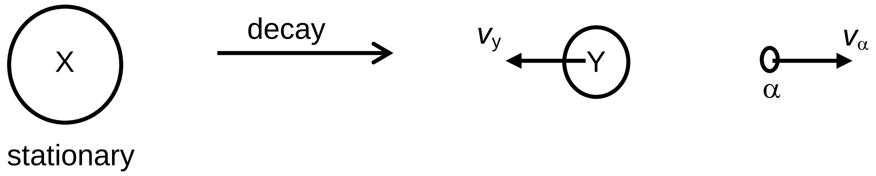
$$m_x c^2 = m_y c^2 + m_\alpha c^2 + E$$

where E is the energy released in the reaction and appears in the form of kinetic energy of the α-particle and daughter nucleus.

Conservation of momentum gives $0 = m_y v_y + m_\alpha v_\alpha$

or $v_\alpha = -\left(\dfrac{m_y}{m_\alpha}\right) v_y$

that is, the daughter nucleus and the α-particle move off in opposite direction.



Since $m_y >> m_\alpha$, the energy released in the reaction manifests itself mainly in the kinetic energy of the α-particle. Also see Example 5.

β - particles

- are either electrons (β^- decay) or positrons (β^+ decay). Positrons have the same mass as electrons but carry a charge of +*e*.
- can be electrons emitted in β^- decay. This electron does not exist within the parent nucleus and is not any of the orbital electrons in the atom. Instead, the electron originates from the nucleus through a nuclear transformation in which a neutron changes into a proton and an electron. The new proton is retained in the nucleus (proton number increases from Z to Z+1 while the nucleon number remained the same) while the electron is ejected as a β-particle.

β^- decay $${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$$

β^+ decay $${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}e$$

- are emitted with a continuous range of energies. Their speed can be as high as 0.9 *c*.
- are charged and can be deflected by electric and magnetic field. The deflection path for electric field is parabolic, and that for magnetic field is circular. β-particles will be deflected more than α-particles as they have smaller mass.
- have lower ionising power than α-particles but is more penetrating than α-particles. β-particles can be stopped by a few mm thick of aluminium sheet.

Experimental evidence found that β-particles do not account for all the energy released during β-decay and it was proposed that part of the energy released is carried by another particle emitted along with the β-particle. This particle is called the neutrino (i.e. the little neutral one) ν and its existence was verified in 1956. The neutrino has zero electric charge and its mass is a tiny fraction of the mass of the electron).

γ - radiation

- are sometimes emitted together with the emission of either α-particle or β-particle.
- (or photons) are emitted when a nucleus changes from an excited state (denoted by *) to a lower energy state. Like the orbital electrons in the atom, the nucleus exists only in discrete energy states or levels.

Example:

↳ β-decay

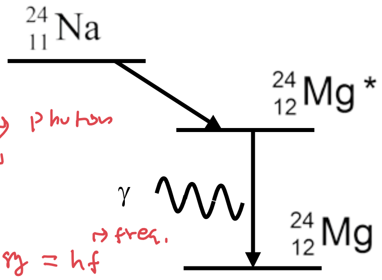
$${}^{24}_{11}\mathrm{Na} \rightarrow {}^{24}_{12}\mathrm{Mg}^* + {}^{0}_{-1}\mathrm{e}$$

$${}^{24}_{12}\mathrm{Mg}^* \rightarrow {}^{24}_{12}\mathrm{Mg} + \gamma$$

$\Rightarrow {}^{24}_{11}Na \rightarrow {}^{24}_{12}Mg + \gamma$ ↳ photon

$\Delta M = M_{Na} - M_{Mg}$

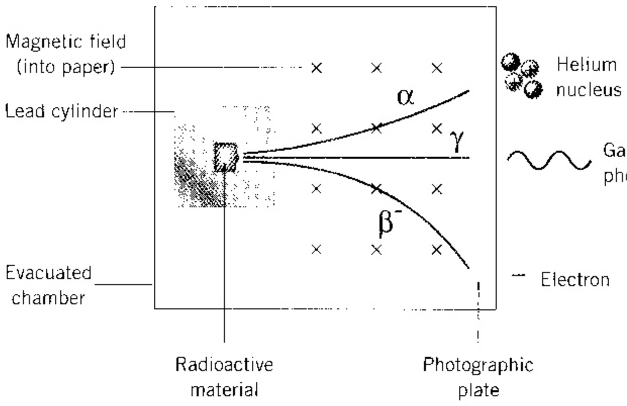
$\Delta M c^2$ = photo energy = hf ↳ freq.

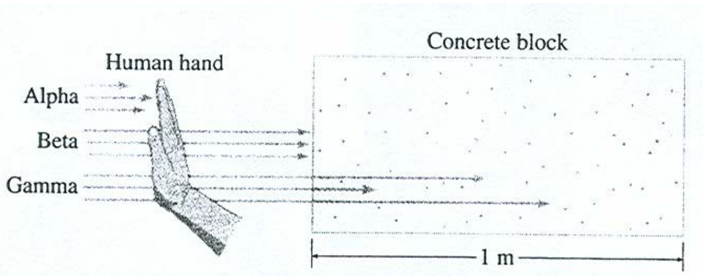


- emission does not result in any change in the proton number or mass number.
- is a packet of electromagnetic radiation and thus travels at the speed of light *c*.
- are not affected by electric and magnetic field since they carry no charge.
- have the least ionising power but are the most penetrating. γ -rays can be stopped by a few cm thick of lead.

Summary

	α-particle	**β-particle**	**γ-ray**
Nature	Helium nuclei ^4_2He (2 protons & 2 neutrons)	Electrons (β^- decay) or positrons (β^+ decay).	Electromagnetic radiation
Charge	positive	positive or negative	No charge
Energy	Few MeV	continuous range of energies	E = hf
Speed	0.1 c	As high as 0.9 c	c
Electric Field	Deflected	Deflected	Not deflected
Magnetic Field	Deflected	Deflected	Not deflected
Ionising Power	High – will produce large number of ion pairs per unit length of its path Least penetrating	Lower than α-particles but more penetrating than α-particles.	Least ionising but most penetrating.
Stopped by	5 cm of air or Piece of paper	aluminium sheet few mm thick	lead few cm thick
Emission	Occurs mainly in nuclides of mass number > 130	Can be emitted with a neutrino	Sometimes α-particle or β-particle emitted together
Decay	$^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + {}^4_2\text{He}$	β^- decay $^A_ZX \rightarrow {}^{A}_{Z+1}Y + {}^0_{-1}e$ β^+ decay $^A_ZX \rightarrow {}^{A}_{Z-1}Y + {}^0_{1}e$	nucleus changes from excited state (*) to a lower energy state, a photon (γ -ray) is emitted. E.g. $^{24}_{12}\text{Mg}^* \rightarrow {}^{24}_{12}\text{Mg} + \gamma$ (no change in proton or mass number)





Example 6

Which one of the following statements is true of both α-particles and γ-rays?

A They cause ionisation of the air when they pass through it.
B They can be detected after passing through a few millimetres of aluminium.
C They can be deflected by magnetic fields.
D They cause a change in the nuclear structure of the radioactive nucleus.

Ans: A

Example 7

ρ ↳ same Z
diff A

Which one of the following combinations of radioactive decay would result in the formation of an isotope of the original nucleus?

A α and four β
B α and two β
C α and β
D two α and β

α-decay : ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}He + \text{Energy}$

β^- : ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + {}^{0}_{-1}e + \text{Energy}$, *: A neutron transforms to 1P and 1e^-
↳ electron

β^+ : ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X + {}^{0}_{1}e + \text{Energy}$ *: A proton transforms to 1n and 1e^+.
↳ positron

Ans: B

4.4 Detection of Radiation

(l) infer the random nature of radioactive decay from the fluctuations in count rate.

(m) show an understanding of the origin and significance of background radiation.

There are a number of devices that can be used to detect the particles emitted when a radioactive nucleus decays (Annex 2). Such devices detect the ionisation that these particles cause as they pass through matter.

4.4.1 Fluctuations in count-rate

Radioactive decay is a random process so the readings obtained from the activity of a source under exactly the same conditions may be different. Demonstrations of the random nature of the decay can be carried out with a Geiger-Muller tube connected to a rate-meter or counter. The rate-meter measures the rate of arrival of particles on a micro-ammeter calibrated in counters per second while the counter counts the particle arrivals. Both the wavering of the rate-meter needle and the irregular fluctuations in the count rate from the counter are clear testimony to the random nature of radioactive decay.

Although fluctuations in count rate is expected, statistical fluctuations show that if the total count recorded from a source is C, the variability of repeated measurements is of the order $\sqrt{C}$. In other words, there is a statistical error of $\pm\sqrt{C}$. If the count rate is 10,000, the possible error in the count is $\pm\sqrt{10{,}000} = \pm 100$ and the percentage error is 1%. If large counts are taken, the percentage error (that is $\sqrt{C}/C \times 100 = 100/\sqrt{C}$) in the count is smaller. Large number of counts can be obtained by

(i) increasing the size of the radioactive sample used,
(ii) increasing the duration during which the counts are taken

4.4.2 Background Radiation

Background radiation is the radiation detected by a radiation counter when no radioactive source is nearby. It is the unavoidable radiation arising from natural resources, e.g. cosmic rays, radioactive substances in rocks and the atmosphere. It is typically about 20 – 30 counts per minute, but can be higher in some parts of the world, and lower in other parts (see Annex 3 for more information). The intensity of this radiation was found not to vary by day or night or time of the year, nor to depend on direction. It comes from all directions with equal intensity. Therefore,

Reading for count of radioactive source = count from source alone + background radiation count

Where the count from a source is high, the background count may be neglected without much error. Alternatively, the background count can be measured in the absence of the radioactive source and subtracted from the observed reading in the presence of the source.
E.g. If reading = 100 counts/min, background count = 30 counts/min, therefore actual count = 70 counts/min

4.5 ***Rate of Decay***

(o) define the terms activity and decay constant and recall and solve problems using $A=\lambda N$.

(p) infer and sketch the exponential nature of radioactive decay and solve problems using the relationship $x = x_o e^{-\lambda t}$ where x could represent activity, number of undecayed particles and received count rate.

What determines when an unstable nucleus decays? Radioactive decay is a quantum-mechanical process that can be described in terms of probability. Given a radioactive sample consisting of a vast number of nuclei, they do not all decay at the same time and there is no way to predict which one decays when. However, we can determine, on a probabilistic basis, the number of nuclei in a sample that will decay over a given time period by assuming that each nucleus has the same probability of decaying in each second that it exists. That is to say that the probability of decay for one nucleus is independent of its past history and of other nuclei. Each radioactive nuclide has a certain decay probability per unit time. **Decay constant**, λ, of a radioactive nuclide represents the probability of decay per unit time of the nucleus of that particular radioactive nuclide.

$$\boxed{\lambda = \frac{\textit{probability of decay}}{\textit{time}}}$$

(SI unit: s^{-1})

The probability that a nucleus decays during a short time interval Δt is $\lambda\Delta t$.

Then in a large number N of identical radioactive nuclei, the average number that decay ΔN during a short time interval Δt is just N times the probability that any one nucleus decays, that is,

$$\Delta N = -N\lambda\Delta t \qquad \text{--- (1)}$$

The negative sign is necessary because as nuclei decay, the number of nuclei that remain decreases, so the change in N $(N_f - N_i)$ is negative. Equation (1) gives the average number that is expected to decay during time Δt. Since radioactive decay is a probabilistic process, we may not observe exactly that number of decays. However, if N is sufficiently large, then we expect Equation (1) to be very close to what we observe. For small N, deviations from the expected number can be significant.

The **activity,** A**,** of the radioactive nuclide is the number of nuclear disintegrations per unit time of the nuclei of that particular radioactive nuclide. *It is also called the rate of nuclear disintegration*.

The SI unit for activity is the Bq (Becquerel) where 1 Bq = 1 decay per sec = 1 s^{-1}
Another unit of activity is the Ci (Curie) where 1 Ci = 3.7×10^{10} Bq.

If the number of decays during a short time interval Δt is ΔN, then the activity A, from definition, is

$$- \quad \boxed{A = \frac{\textit{number of decays}}{\textit{time taken}} = \frac{-\Delta N}{\Delta t} = \frac{-(-N\lambda\Delta t)}{\Delta t} = \lambda N} \quad \text{-- (2)}$$

Since activity is also the rate of decay, Equation (2) can be written as a first-order differential equation

$\frac{dN}{dt} = \lambda N$ and can be solved to give

$$\boxed{N = N_o e^{-\lambda t}} \qquad \text{--- (3)}$$

where N_o: number of nuclei remaining at time $t = 0$
N : number of nuclei remaining after time t

Thus, according to equation (3), the number of parent nuclei in a sample decreases exponentially with time. Since activity is proportional to number of nuclei present, activity also decays exponentially:

$$\boxed{A = A_o e^{-\lambda t}} \qquad \text{--- (4)}$$

where A_o: activity at time $t = 0$
A : activity at time after time t

The count rate is the rate at which emissions from a radioactive source are detected. The count rate received by a detector should be proportional to the activity of the nuclide,

$$\boxed{C = C_o e^{-\lambda t}}$$

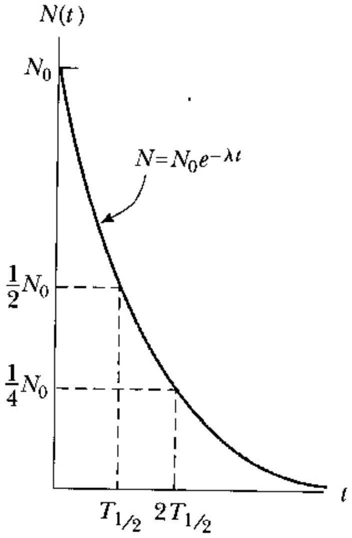
where C_o: count rate at time $t = 0$
C : count rate after time t

4.6 Half-life

(q) define half-life.

(r) solve problems using the relation $\lambda = \dfrac{0.693}{t_{\frac{1}{2}}}$

The rate of decay or activity of any radioactive sample is often specified by giving its half-life rather than the decay constant λ. The **half-life,** $t_{\frac{1}{2}}$, of a radioactive nuclide is the *average* time taken for the number of nuclei of *that particular radioactive nuclide* to decay to half of its original value. After two half-lives, $\frac{1}{4}$ of the parent nuclei remains, after three half-lives, $\frac{1}{8}$ of the parent nuclei remain. Generalizing, after n half-lives, the fraction of parent nuclei remaining



--- (5)

$$\boxed{\frac{N}{N_o} = \left(\frac{1}{2}\right)^n}$$

From equation (3) and using the definition of half-life,

$$N = N_o e^{-\lambda t}$$

When t = $t_{\frac{1}{2}}$, N = $\frac{1}{2}$ N_o,

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

Taking ln on both sides: $\ln \frac{1}{2} = -\lambda t_{\frac{1}{2}}$

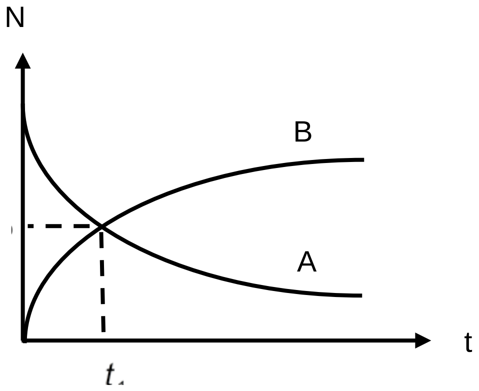
$$\boxed{\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}}$$ --- (6)

Example 8

Given A → B + α-particle

Draw, using the same axes for A and B,
a graph of number of nuclei of A and B against time.
State the assumption for your graph.

Assumption: B is not radioactive.



Example 9

The activity from a radioactive source is found to fall by 0.875 of its initial activity in 210 s. What is the half-life of the source? [70 s]

Activity of source after 210 s = $A_0 - 0.875\,A_0 = 0.125\,A_0$

$A = A_0 e^{-\lambda t}$ ➔ $0.125\,A_0 = A_0 e^{-\lambda(210)}$ ➔ $\lambda = 9.902 \times 10^{-3}\ \mathrm{s}^{-1}$

$t_{½} = \ln 2 / \lambda = 70$ s

Alternatively,
$0.125 = {}^{1}/_{8} = (½)^3$
So, $3\,t_{½} = 210$ s
➔ $t_{½} = 70$ s

Example 10

A lab has 1.49 μg of pure $^{13}\mathrm{N}$ which has a half-life of 10.0 min. (a) How many nuclei are present initially? [Hint: ^{13}N means there are 13 nucleons in the nuclide.] (b) What is the initial activity? (c) What is the activity after an hour? (d) After how long will the activity drop to less than one per second? [6.90×10^{16}, 7.97×10^{13}, 1.25×10^{12}, 7.69 hours]

a) N = no. of moles x N_A = $(1.49 \times 10^{-6} / 13)(6.02 \times 10^{23}) = 6.90 \times 10^{16}$

b) $A_0 = \lambda N_0 = \dfrac{\ln 2}{t_{½}} N_0 = \dfrac{\ln 2}{10.0 \times 60}(6.90 \times 10^{16}) = 7.97 \times 10^{13}$ Bq

c) $A = A_0\, e^{-\lambda t} = 7.97 \times 10^{13} e^{-\left[\frac{\ln 2}{(10.0 \times 60)}(3600)\right]} = 1.25 \times 10^{12}$ Bq

d) $A = A_0\, e^{-\lambda t}$ ➔ $1 = 7.97 \times 10^{13} e^{-\left[\frac{(\ln 2)}{t_{½}} t\right]}$ ➔ $t = 2.77 \times 10^{4}$ s = 7.69 hr

Example 11 (*Radioactive dating* - Annex 4)

A 50 g sample of carbon is taken from the pelvis bone of a skeleton and is found to have a $^{14}\mathrm{C}$ decay rate of 200 decays per min. It is known that carbon from 1 g of a living organism has a decay rate of 15.0 decays per min. Given that the half-life of $^{14}\mathrm{C}$ is 5730 years, what is the age of the skeleton? [10926 years]

50 g of living organism would have decay rate of
15.0 x 50 = 750 decays per min

$A = A_0 e^{-\lambda t}$ ➔ $200 = 750\, e^{-\lambda t}$ where $\lambda = \dfrac{\ln 2}{t_{\frac{1}{2}}}$

t = 10926 years

Alternatively, use

$\dfrac{A}{A_o} = \left(\dfrac{1}{2}\right)^n$ ➔ $n = 1.91$

t = 1.91 x 5730 = 10926 years

5 BIOLOGICAL EFFECTS OF RADIATION

(s) discuss qualitatively the effects, both direct and indirect, of ionising radiation on living tissues and cells.

Ionising radiation is radiation with enough energy to ionise an atom or molecule – typically between 1 eV and a few tens of eV. An α-particle, β-particle or γ-ray with a typical energy of about 1 MeV can potentially ionise tens of thousands of molecules.

The radiation damage produced in biological organisms is due primarily to ionisation produced in cells. Ionising radiation causes atoms and molecules to become ionised or excited and may break the chemical bonds. The normal functions of a cell may be disrupted when highly reactive ions or radicals are formed as a result of ionising radiation. In addition, ionising radiation may also damage molecules that regulate vital cell processes (e.g. DNA, RNA, proteins) or produce new chemical bonds and cross-linkages between macromolecules.

The cells can normally repair certain levels of cell damage. At low doses e.g. that received from background radiation, cellular damage is rapidly repaired. However, large doses of radiation may damage so many molecules that new cells cannot be made quickly enough such that cell death results and the tissue fails to function. On the other hand, cells that do survive the radiation may become defective. It may go on dividing and producing many more defective cells, to the detriment of the whole organism. Thus radiation can cause cancer – the rapid uncontrolled production of defective cells.

Radiation damage to biological organisms is often separated into categories. Somatic damage refers to any part of the body except the reproductive organs. The effect of radiation depends on the nature of the radiation, the part of the body irradiated and the dose received. Radiation can cause immediate damage to tissues resulting in radiation burns (redness of skin leading to sores and blisters which may take a long time to heal), radiation sickness (characterised by nausea, fatigue, loss of body hair) or even death. Delayed effects such as cancer, leukaemia and eye cataracts may appear many years later. Genetic damage refers to damage to reproductive cells, causing mutations which may lead to hereditary defects in succeeding generations. Thus, the possible damage done by the medical use of X-rays and other radiation must be balanced against the medical benefits and prolongation of life as a result of their diagnostic use in radiotherapy.

See Annex 5 for more details on health problems caused by radiation.

The End - This is the last topic of the H2 Physics syllabus.

Annex 1

Finding the energy released for a nuclear reaction.

e.g. nuclear fusion in the Sun: $^{2}_{1}X + ^{3}_{1}Y \rightarrow ^{4}_{2}Z + ^{1}_{0}n + E_R$

Method 1: Given the masses

Conservation of Mass-energy:

$$E_X + E_Y = E_Z + E_n + E_R$$

or

$$m_Xc^2 + m_Yc^2 = m_Zc^2 + m_nc^2 + E_R$$

$$E_R = [(m_X + m_Y) - (m_Z + m_n)]c^2$$

Energy released = [mass of reactant – mass of product] c^2

Method 2: Given the binding energies

$$E_X + BE_X = E_p + E_n \quad \Rightarrow \quad E_X = E_p + E_n - BE_X$$

$$E_Y + BE_Y = E_p + 2E_n \quad \Rightarrow \quad E_Y = E_p + 2E_n - BE_Y$$

$$E_Z + BE_Z = 2E_p + 2E_n \quad \Rightarrow \quad E_Z = 2E_p + 2E_n - BE_Z$$

Conservation of Mass-energy:

$$E_X + E_Y = E_Z + E_n + E_R$$

$$(E_p + E_n - BE_X) + (E_p + 2E_n - BE_Y) = (2E_p + 2E_n - BE_Z) + E_n + E_R$$

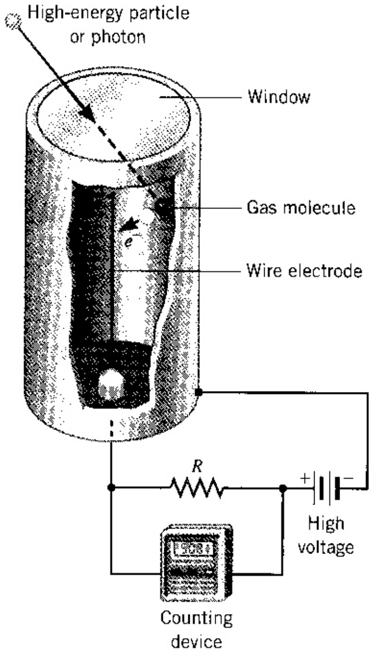
$$E_R = BE_Z - (BE_X + BE_Y)$$

Energy released = BE of product – BE of reactant

Annex 2

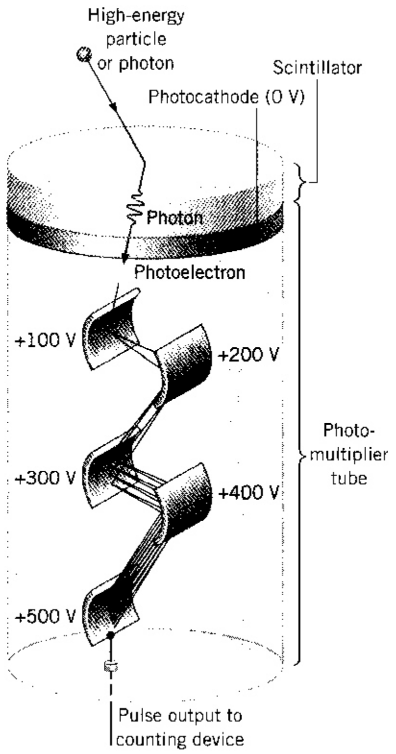
Detection of Radiation

1 Geiger-Muller counter



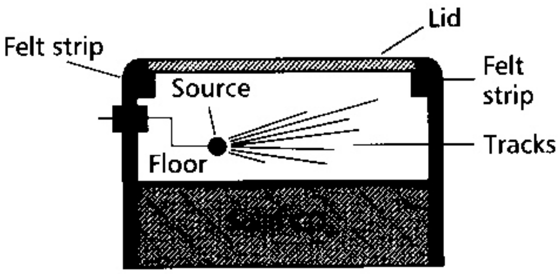
The Geiger-Muller counter consists of a gas-filled metal. The α-particles, β-particles or γ rays enter the cylinder through a thin window at one end. A wire electrode runs along the centre of the tube and is kept at a high positive voltage (1000 – 3000 V) relative to the outer cylinder. When the decay particles or γ photons enter the cylinder, they collide with and ionise the gas molecules. The electrons produced from the gas molecules accelerate toward the positive wire, ionising other molecules in its path. Additional electrons are formed and an avalanche of electrons rushes towards the wire, leading to a pulse of current through the resistor *R*. This pulse can be counted or made to produce a “click” in a loudspeaker. The number of counts or clicks is related to the number of disintegrations that produced the particles or photons.

2 Scintillation counter

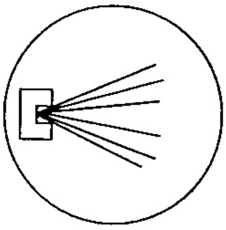


This consists of a scintillator mounted on a photomultiplier tube. Very often, the scintillator is a crystal containing a small amount of impurity. In response to ionising radiation, the scintillator emits a flash of visible light. The photons of the flash then strike the photocathode of the photomultiplier tube. The photocathode tube is made of a material that emits electrons because of photoelectric effect. These photoelectrons are then attracted to a special electrode kept at a voltage of about +100 V relative to the photocathode. The electrode is coated with a substance that emits several additional electrons for every electron striking it. The additional electrons are attracted to a second similar electrode (voltage +200 V) where they generate even more electrons. Commercial photomultiplier tubes contain as many as 15 of these special electrodes, so photoelectrons resulting from the light flash of the scintillator lead to a cascade of electrons and a pulse of current. As in a Geiger-Muller tube, the current pulses can be counted.

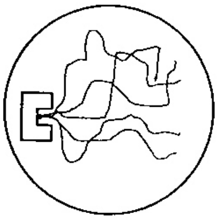
3 Wilson cloud chamber



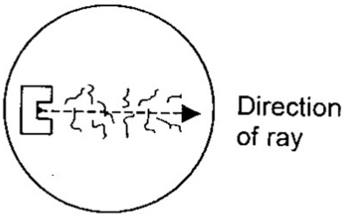
In a cloud chamber, a gas is cooled to a temperature slightly below its usual condensation point (super-cooled) and gas molecules condense on any ionised molecules present. Ions produced when a charged particle passes through serve as centres on which tiny droplets form. Light scatters more from these droplets than from the gas background, so a photo of the cloud chamber at the right moment shows the track of that particle. The paths revealed in a cloud chamber can be photographed to provide a permanent record of the event. α-particles give bright, straight tracks as they cause intense ionisation. β-particles give longer but thinner and straggly tracks. γ rays give short track branches off from the direction of radiation.



α - particle tracks



β - particle tracks



γ -ray tracks

4 Solid-state (Semiconductor) detectors

A semiconductor detector consists of a reverse-biased *pn* junction diode. A particle passing through the junction can excite electrons into the conduction band, leaving holes in the valence band. The freed charges produce a short electrical pulse that can be counted just as for Geiger and scintillation counters.

Annex 3

Background Radiation

Natural background radiation

Natural background radiation comes from two primary sources: cosmic radiation and terrestrial sources. The worldwide average background dose for a human being is about 2.4 millisievert (mSv) per year. This exposure is mostly from cosmic radiation and natural isotopes in the Earth. This is far greater than human-caused background radiation exposure, which in the year 2000 amounted to an average of about 5 μSv per year from historical nuclear weapons testing, nuclear power accidents and nuclear industry operation combined, and is greater than the average exposure from medical tests, which ranges from 0.04 to 1 mSv per year. Older coal-fired power plants without effective fly ash capture are one of the largest sources of human-caused background radiation exposure.

The level of natural background radiation varies depending on location, and in some areas the level is significantly higher than average. Such areas include Ramsar in Iran, Guarapari in Brazil, Kerala in India, the northern Flinders Ranges in Australia and Yangjiang in China. In Ramsar a peak yearly dose of 260 mSv has been reported.

Cosmic radiation

The Earth, and all living things on it, are constantly bombarded by radiation from outer space. This radiation primarily consists of positively charged ions from protons to iron nuclei derived from the sun and from other sources outside our solar system. This radiation interacts with atoms in the atmosphere to create secondary radiation, including X-rays, muons, protons, alpha particles, pions, electrons, and neutrons. The immediate dose from cosmic radiation is largely from muons, neutrons, and electrons, and this dose varies in different parts of the world based largely on the geomagnetic field and altitude. This radiation is much more intense in the upper troposphere, around 10 km altitude, and is thus of particular concern for airline crews and frequent passengers, who spend many hours per year in this environment. Similarly, cosmic ray causes higher background exposure in astronauts than in humans on the surface of Earth. Astronauts in low orbits, such as in the International Space Station or the Space Shuttle, are partially shielded by the magnetic field of the Earth, but also suffer from the Van Allen radiation belt which accumulates cosmic rays and results from the earth’s magnetic field. Outside low Earth orbit, as experienced by the Apollo astronauts who traveled to the Moon, this background radiation is much more intense, and represents a considerable obstacle to potential future long term human exploration of the moon or Mars.

Cosmic rays also cause elemental transmutation in the atmosphere, in which secondary radiation generated by the cosmic rays combines with atomic nuclei in the atmosphere to generate different radioactive nuclides. Many so-called cosmogenic nuclides can be produced, but probably the most notable is carbon-14, which is produced by interactions with nitrogen atoms. These cosmogenic nuclides eventually reach the Earth's surface and can be incorporated into living organisms. The production of these nuclides varies slightly with short-term variations in solar cosmic ray flux, but is considered practically constant over long scales of thousands to millions of years. The constant production, incorporation into organisms and relatively short half-life of carbon-14 are the principles used in radiocarbon dating of ancient biological materials such as wooden artifacts or human remains.

Terrestrial sources

Radioactive material is found throughout nature. It occurs naturally in the soil, rocks, water, air, and vegetation. The major radionuclides of concern for terrestrial radiation are common elements with low-abundance radioactive isotopes, like potassium and carbon, or rare but intensely radioactive elements like uranium, thorium, radium and radon. Most of these sources have been decreasing, due to radioactive decay since the formation of the Earth, because there is no significant amount currently transported to the Earth. Thus, the present activity on earth from uranium-238 is only half as much as it originally was because of its 4.5 billion year half-life, and potassium-40 (half life 1.25 billion years) is only at about 8% of original activity. The effects on humans of the actual diminishment (due to decay) of these isotopes is minimal however. This is because humans evolved too recently for the difference in activity over a fraction of a half-life to be significant. Put another way, human history is so short in comparison to a half life of a billion years that the activity of these long-lived isotopes has been effectively constant throughout our time on this planet.

In addition, many shorter half-life and thus more intensely radioactive isotopes have not decayed out of the terrestrial environment, however, because of natural on-going production of them. Examples of these are carbon-14 (cosmogenic), radium-226 (decay product of uranium-238) and radon-222 (a decay product of radium-226).

Annex 4

Radioactive Dating

This refers to the technique at which the age of ancient materials can be determined. The age of any object made from once-living matter e.g. wood can be determined using the radioactivity of ^{14}C. All living plants absorb carbon dioxide from the air and use it to synthesize organic molecules. The vast majority of these carbon atoms are ^{12}C but a small fraction (about 1.3 x 10^{-12}) is the radioactive isotope ^{14}C. The ratio of ^{14}C to ^{12}C in the atmosphere has remained roughly constant over many thousands of years, in spite of the fact that ^{14}C decays with a half-life of about 5730 years. This is due to the cosmic radiation (consists of highly energetic charged particles and impinges on the Earth from outer space) which strike nuclei of atoms in the atmosphere and releases a shower of secondary particles which includes a large number of neutrons. These neutrons can collide with nitrogen nuclei in the atmosphere to produce the form ^{14}C:

$$^{1}_{0}n + ^{14}_{7}N \rightarrow ^{14}_{6}C + ^{1}_{1}p$$

This continual production of ^{14}C in the atmosphere roughly balances the loss of ^{14}C by radioactive decay. As long as a plant or tree is alive, it continually uses the carbon from carbon dioxide in the air to build new tissue to replace the old. Animals eat plants, so they too are continually receiving a fresh supply of carbon for their tissues.

When an organism is alive, carbon is exchanged with the environment and since the ratio of ^{14}C to ^{12}C in the atmosphere remains nearly constant, so the organism maintains the same relative abundance of the two isotopes as the environment. When the organism dies however, carbon dioxide is no longer absorbed and carbon exchange with the environment stops. As the ^{14}C present in the organism decays, the ratio of ^{14}C to ^{12}C decreases. The ratio of ^{14}C to ^{12}C in a sample can be measured and used to determine the age of the sample. One way to do this is to measure the ^{14}C activity per gram of carbon.

Annex 5

Exposure to Ionising Radiation

Cell Damage Expressed as a Health Problem

An example to show the connection between cell damage and observable illness in the person exposed might help in understanding the problems posed by radionuclide (radioactive chemical) uptake, i.e. their ingestion, inhalation or absorption with food, air and water, into human bodies, with subsequent cell damage. The thyroid gland contains cells which produce thyroid hormone, which when released into the bloodstream causes the body functions such as breathing, digesting and reacting to stress to proceed at a certain rate. If the thyroid is `overactive', one might notice in the person increased pulse rate, nervousness, excitability, loss of body weight and, in females, more frequent menstruation. Such a person is often called `hyperactive' (hyper-thyroidism). A normal amount of thyroid hormone in the blood produces a normally active individual. An `underactive' or `hypoactive' thyroid can result in sluggishness, listlessness, weight gain and irregular and/or infrequent menstrual flow in women (hypothyroidism).

If radioactive iodine (I-131 or I-129) is ingested with food it will enter the blood and tend to accumulate in the thyroid. Radioactive iodine emits high-energy gamma radiation which can destroy thyroid cells, thus reducing total thyroid hormone production in the individual so affected. A small amount of radioactive iodine would probably kill only a few cells and have little or no noticeable effect on health. However, if many cells are destroyed or altered, the hormone level would noticeably drop or the hormone itself would be slightly changed. The individual would become lethargic and gain weight. If properly diagnosed and severe enough to require medical intervention, this hypoactive thyroid condition can be controlled with artificially ingested thyroid hormone. A mild exposure experienced by a large population could cause a decrease in average thyroid hormone levels and an increase in average body weight, such as is occurring now in the North American population. The USA has been polluted with nuclear industries since 1943 and with radioactive iodine from weapon testing since 1951. Radioactive iodine is routinely released in small quantities by nuclear power plants and in large quantities by nuclear reprocessing plants. It is not part of the natural human environment. The connection between this pollution and the overweight problem has, unfortunately, never been seriously researched. There is no evidence to confirm or deny the hypothesis, but weight increase is a well-known biological response to radioactive iodine. The hypothesis is certainly plausible under the circumstances.

It is possible for thyroid cells to be altered but not killed by the radiation. The cellular growth mechanism may be damaged, allowing a runaway proliferation of cells. This results in a thyroid tumour, either cancerous (malignant), or non-cancerous (benign). Other possible radiation damage includes changes in the chemical composition of the individual's thyroid hormone, altering its action in the body and causing clinically observable symptoms not easily diagnosed or corrected. Damage to the thyroid of a developing foetus can cause mental retardation and other severe developmental anomalies.

Other radionuclides will lodge in other parts of the body. If the trachea, bronchus or lung are exposed, the damage eventually causes speech or respiratory problems. If radioactive particles lodge in the stomach or digestive tract, the heart, liver, pancreas or other internal organs or tissues, the health problems will be correspondingly different and characteristic of the organ damaged. Radionuclides which lodge in the bone marrow can cause leukaemia, depression of the immune system or blood diseases of various kinds.

If the radiation dose is high, there is extensive cell damage and health effects are seen immediately. Penetrating radiation doses at 1,000 rad or more cause `frying of the brain' with immediate brain death and paralysis of the central nervous system. This is why no one dared to enter the crippled Three Mile Island nuclear reactor building during the 1979 accident. An average of 30,000 roentgens (or rads) per hour were being reported by instruments within the containment building. This would convert to a 1,000 rad exposure for two minutes spent inside the building. Such a dose to the whole body is invariably fatal.

The radiation dose at which half the exposed group of people would be expected to die, i.e. the 50 percent lethal dose, is 250 rad. The estimate is somewhat higher if only young men in excellent health (e.g. soldiers) are exposed. Between 250 and 1,000 rad, death is usually due to gross damage to the stomach and gut. Below 250 rad death is principally due to gross damage to the bone marrow and blood vessels. A dose of about 200 rad to a foetus in the womb is almost invariably fatal.

Penetrating radiation in doses above 100 rad inflicts severe skin burns. Lower doses produce burns in some people. Vomiting and diarrhoea are caused by doses above about 50 rad. There are some individuals who are more sensitive to radiation, however, showing typical vomiting and diarrhoea radiation sickness patterns with doses as low as 5 rad. An individual may react differently at different times of life or under different circumstances. Below 30 rad, for most individuals, the effects from external penetrating radiation are not immediately felt. The mechanism of cell damage is similar to that described for minute quantities of radioactive chemicals which lodge within the body itself, and our bodies are incapable of `feeling' damage to or death of cells. Only when enough cells are damaged to interfere with the function of an organ or a body system does the individual become conscious of the problem.

By sharpening our perceptions more subtle radiation effects can often become observable where once they went unnoticed. For example, a series of X-rays received by a young child may cause temporary depression of the white blood cells, and ten days to two weeks after the exposure the child will get influenza or some other infectious disease. Ordinarily the parent views the two events as unconnected.

Sometimes one can observe a mutation in a person who has experienced loss of hair after radiation therapy to kill tumour cells: hair that was formerly very straight can be curly when it grows again. A plant whose flowers are normally white with red tips but which begins to form uniformly red flowers has mutated. Such an event has been observed by persons living in the vicinity of Sellafield in the United Kingdom.

The use of radiation therapy to destroy malignant cells also has observable results. It is rather like surgery in that it is deliberately used to kill the unwanted tumour cells.

Probable Health Effects resulting from Exposure to Ionising Radiation

Dose in rems (whole body)	**Immediate Health Effects**	**Delayed Health Effects**
1,000 or more	Immediate death. `Frying of the brain'.	None
600-1,000	Weakness, nausea, vomiting and diarrhoea followed by apparent improvement. After several days: fever, diarrhoea, blood discharge from the bowels, haemorrhage of the larynx, trachea, bronchi or lungs, vomiting of blood and blood in the urine.	Death in about 10 days. Autopsy shows destruction of hematopoietic tissues, including bone marrow, lymph nodes and spleen; swelling and degeneration of epithelial cells of the intestines, genital organs and endocrine glands.
250-600	Nausea, vomiting, diarrhoea, epilation (loss of hair), weakness, malaise, vomiting of blood, bloody discharge from the bowels or kidneys, nose bleeding, bleeding from gums and genitals, subcutaneous bleeding, fever, inflammation of the pharynx and stomach, and menstrual abnormalities. Marked destruction of bone marrow, lymph nodes and spleen causes decrease in blood cells especially granulocytes and thrombocytes.	Radiation-induced atrophy of the endocrine glands including the pituitary, thyroid and adrenal glands. From the third to fifth week after exposure, death is closely correlated with degree of leukocytopenia. More than 50% die in this time period. Survivors experience keloids, ophthalmological disorders, blood dyscrasis, malignant tumours, and psychoneurological disturbances.

150-250	Nausea and vomiting on the first day. Diarrhoea and probable skin burns. Apparent improvement for about two weeks thereafter. Foetal or embryonic death if pregnant.	Symptoms of malaise as indicated above. Persons in poor health prior to exposure, or those who develop a serious infection, may not survive. The healthy adult recovers to somewhat normal health in about three months. He or she may have permanent health damage, may develop cancer or benign tumours, and will probably have a shortened lifespan. Genetic and teratogenic effects.
50-150	Acute radiation sickness and burns are less severe than at the higher exposure dose. Spontaneous abortion or stillbirth.	Tissue damage effects are less severe. Reduction in lymphocytes and neutrophils leaves the individual temporarily very vulnerable to infection. There may be genetic damage to offspring, benign or malignant tumours, premature ageing and shortened lifespan. Genetic and teratogenic effects.
10-50	Most persons experience little or no immediate reaction. Sensitive individuals may experience radiation sickness.	Transient effects in lymphocytes and neutrophils. Premature ageing, genetic effects and some risk of tumours.
0-10	None	Premature ageing, mild mutations in offspring, some risk of excess tumours. Genetic and teratogenic effects.

Annex 6

How tenacity, a wall saved a Japanese nuclear plant from meltdown after tsunami

http://www.oregonlive.com/opinion/index.ssf/2012/08/how_tenacity_a_wall_saved_a_ja.html

The Onagawa nuclear plant survived last year's earthquake and tsunami virtually intact, largely thanks to Yanosuke Hirai, who insisted that the plant exceed design requirements. *(Rich Read/The Oregonian)*

United Nations inspectors marveled this month that the nuclear plant closest to the epicenter of Japan's massive earthquake survived virtually intact, averting a Fukushima-style meltdown.

"With the earthquake of this magnitude, we would have expected the plant to have more damage," said Sujit Samaddar, leader of a U.N. nuclear watchdog team, at a Tokyo news conference. "This indicated there were significant margins in the designs."

Why would the plant in Onagawa, Japan, endure the same tsunami and stronger ground shaking while Fukushima Dai-ichi reactors melted down in the world's worst nuclear accident since Chernobyl?

According to a retired civil engineer I interviewed in March, there's one man to thank for averting a catastrophe worse than Fukushima, which spewed radiation across an area where 100,000 people still can't return home.

He is Yanosuke Hirai, who died 26 years ago, too soon to witness the disaster and too early to become a national hero. But the story of this tenacious man is inspiring, especially because he bucked convention in a society known for pounding the nail that sticks up. Hirai's example transcends the nuclear arena, where Japanese regulators coddled powerful companies, to offer lessons on corporate excesses and safety problems everywhere.

While reporting in Japan last spring, a year after the tsunami that killed as many as 20,000, I noticed an article about Hirai in the Mainichi Shimbun, a national newspaper. It quoted his understudy, Tatsuji Oshima, the retired president of a Tohoku Electric Power Co. subsidiary, still very much alive at 82.

My fixer/interpreter, Kayo Matsushita, managed to find Oshima, using her skills as a former foreign correspondent. We drove a couple of hours to meet him over hotel-lobby coffee in his hometown of Sendai, another city hit by the tsunami.

Oshima is a throwback to the World War II generation, a vanishing breed that I encountered sometimes during six years based in Tokyo. An earnest man with a white comb-over and big bifocals, he wore a dark blue suit with a Rotary International lapel pin and tie clip. He asked whether he could smoke.

Oshima used to choose sites for nuclear plants. He opened a sheaf of faded newspaper clippings and family photographs. He showed us pictures of his mentor, Hirai, a stern, straight-lipped man born in 1902 on the coast near Fukushima.

Hirai died at 84. He never forgot visiting a shrine as a boy and learning that it had been clobbered by the Jogan tsunami in the year 869. In 1968, after retiring as vice president of Tohoku Electric Power, he joined a committee planning construction of the company's plant in Onagawa. The plant would be built in a more populous area than Fukushima Dai-ichi, fronting the Pacific Ocean at Onagawa, a fishing town of 10,000.

Hirai said the plant should be built almost 50 feet above sea level. He called for a unique cooling system that would provide water even if a receding tsunami temporarily left the plant high and dry. And Hirai said the plant should be protected by a seawall 49 feet high, not 10 feet as originally designed.

PAM MARTIN/THE OREGONIAN

Colleagues told Tohoku Electric's president that 39 feet would be sufficient. But Hirai, trained by the formidable Yasuzaemon Matsunaga, known as Japan's king of electric power, disagreed.

"Matsunaga-san hated bureaucrats," Oshima said. "He said they are like human trash. In your country, too, there are probably bureaucrats or officials who never take final responsibility.

"So Matsunaga's attitude was that you've got to go beyond the regulations," Oshima said. "If you just follow the regulations, you end up with what happened at Fukushima Dai-ichi. That's what Matsunaga told Hirai, and Hirai taught me."

Defying authority took courage, especially four decades ago in Japan, even for an expert such as Hirai who advised the utility after retiring. Even today, despite a gloss of anime and independence, Japan remains a place of hierarchy and convention. The nuclear lobby was particularly powerful, swaying politicians and placating the public.

Finally, Oshima said, Tohoku's president agreed to spend more for the higher wall -- before resigning to take responsibility for an electricity rate increase. The wall ended up at 46 feet, according to the team's recent inspection.

Not so at Fukushima Dai-ichi, whose reactors came on line during the 1970s. That plant's seawall was built to withstand a tsunami of less than 19 feet, the inspectors said.

On March 11, 2011, the Great East Japan Earthquake rocked the country, merely flooding a basement at the Onagawa plant. The 9-magnitude quake unleashed a 43-foot tsunami that traveled 44 miles from the epicenter to slam into Hirai's seawall. It held.

The plant shut down so safely that it served as an evacuation center in Onagawa, where 827 died. The fishing town, where I spent a few days reporting after the tsunami, escaped a far worse fate, thanks to Hirai.

The tsunami traveled 112 miles before overcoming Fukushima Dai-ichi's seawall. It knocked out power, causing meltdowns, explosions and the radioactivity releases.

Oshima said Fukushima Dai-ichi's designers at Tokyo Electric Power Co. built it to respond to a spike in electricity demand and to pressure for lower power rates.

"They thought that was their final responsibility," Oshima said of demand and price. "If you don't look at it that way, you'd be too harsh on Tepco."

Experts such as the team studying Onagawa will sift evidence for decades. Already workers have raised the Onagawa seawall to 56 feet.

Nuclear opponents cite Japan's disaster as a compelling reason for a ban. Oshima sees it as a mistake the country can learn from while still improving nuclear technology, which he regards as one of the world's great inventions behind only alcohol and go, an Asian board game.

"Corporate ethics is different from compliance," Oshima said, echoing Hirai. "Just being 'not guilty' is not enough.

Other good reading material:

Health costs of Coal-fired power plants
http://www.psr.org/assets/pdfs/coal-fired-power-plants.pdf

Poster on Standard Model of Particle Physics (Really Advanced Stuff)
http://www.pha.jhu.edu/~dfehling/particle.gif

H2 Physics (9646)
Topic 20: Nuclear Physics
Tutorial

Given the masses: proton = 1.007825 u, neutron = 1.008665 u.

Self-Attempt Questions

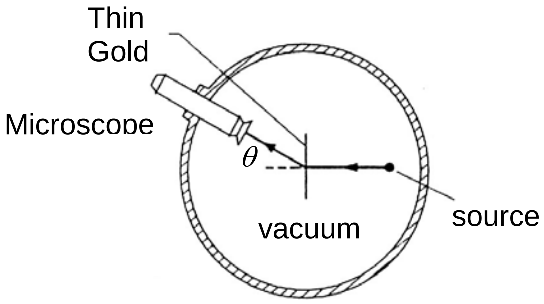
1 Give the number of protons, neutrons and nucleons for the following atoms / particles

Atoms	Notation	Protons	Neutrons	Nucleons
Hydrogen	${}^{1}_{1}H$			
Helium (Alpha Particles)	${}^{4}_{2}He$			
Carbon –12	${}^{12}_{6}C$			
Carbon –14	${}^{14}_{6}C$			

2 The isotopic mass of ${}^{20}\text{Ne}$ is 19.99244 u. Find its mass in kg. (3.32×10^{-26} kg)

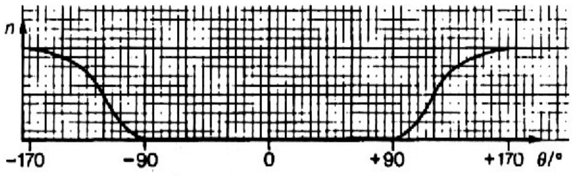
3 The specific heat capacity of water is 4.2 kJ kg^{-1} K^{-1}.
(a) How much energy is needed to raise the temperature of 5.0 kg of water from 20^{o} C to 70^{o} C? (1.05×10^{6} J)
(b) Estimate the increase in the mass of water when the temperature is raised by this amount. (1.2×10^{-11} kg)

4 The experimental setup for Rutherford's alpha-particle scattering experiment is as shown.
Answer the following questions.
(a) What kind of source must be used?
(b) Why is vacuum inside the apparatus necessary?
(c) Why is the foil used thin and why is gold suitable?



(d) The microscope, held at various angular positions θ, is used to determine *n*, the number of α-particles incident per unit time.
Which graph best represents the variation of *n* with θ?

A



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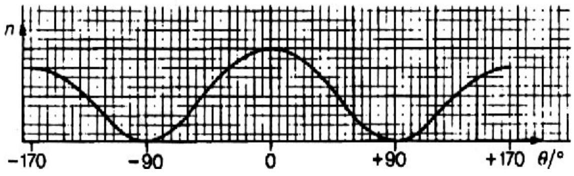

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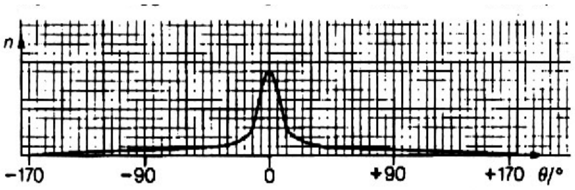

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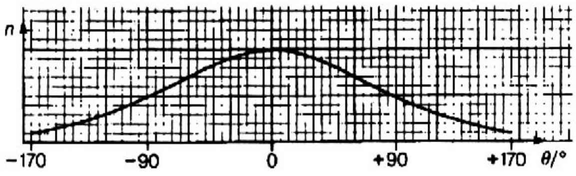


(e) Draw sketch diagrams to illustrate the path of an α-particle, the original path of which

(i) is directly towards the nucleus of a gold atom,
(ii) passes close to the nucleus of a gold atom,
(iii) passes some distance from the nucleus

(f) Describe and explain how the α-particle scattering experiment gives evidence for the existence and small size of the nucleus

5 Explain the terms *mass defect* and *nuclear binding energy*? What determines the stability of an atom?

Given the following data, calculate the binding energy and mass defect for the following atom

Mass of 1 proton	= 1.673×10^{-27} kg
Mass of 1 neutron	= 1.675×10^{-27} kg
Speed of light	= 2.998×10^{8} ms^{-1}

		Mass of Atom / kg	Mass defect / kg	Binding Energy / J	Binding Energy per nucleon / J
Helium	${}^{4}_{2}He$	6.644×10^{-27}			
Carbon	${}^{12}_{6}C$	1.992×10^{-26}			
Uranium	${}^{238}_{92}U$	3.951×10^{-25}			

Of these 3, which nuclide is the most stable?

6 Find the energy equivalent (in MeV) of 1 u (934 MeV)

7 For the nuclear reaction: ${}^{13}_{6}\text{C} + {}^{1}_{1}\text{p} \rightarrow \text{X} + {}^{13}_{7}\text{N}$

(a) Deduce what is X.

(b) Deduce if the above reaction can occur when ${}^{13}_{6}\text{C}$ is bombarded with 2.0 MeV protons.

Given the masses: ${}^{13}_{6}\text{C}$=13.003355 u, ${}^{13}_{7}\text{N}$=13.005738 u.

8 A radioactive sample contains 3.50 μg of pure ^{11}C which has a half-life of 20.4 min. (a) How many moles of ^{11}C is present initially? (b) Determine the number of nuclei present and its initial activity (c) What is its activity after 8 hours? (3.18×10^{-7}, 1.92×10^{17}, 1.09×10^{14} Bq, 9.08×10^{6} Bq)

9 A certain radioactive nuclide has a half-life of 200 s. A sample containing just this radioactive nuclide has an initial activity of 80 000 s^{-1} (a) What is the activity 600 s later? (b) How many nuclei were there initially? (c) What is the probability per second that any one of the nuclei decays? (10 000 Bq, 2.31×10^{7}, 3.47×10^{-3} s^{-1})

10 An α-particle produced in a radioactive alpha decay has a kinetic energy of typically about 6 MeV. When an α-particle passes through matter (such as biological tissue), it makes ionizing collisions with molecules, giving up some of its kinetic energy to supply the ionising energy of the electron that is removed. If a typical ionization energy for a molecule in the body is around 20 eV, how many molecules can the α-particle ionize before coming to rest? (3×10^{5} molecules)

Discussion Questions

11 The approximate relationship between the radius R of a nucleus and its mass number A is

$$R = 1.2 \times 10^{-15} A^{1/3}$$

Calculate (a) the number density of nucleons within a nucleus (that is, the number of nucleons in unit volume of nuclear matter), (b) the approximate density of a nucleus

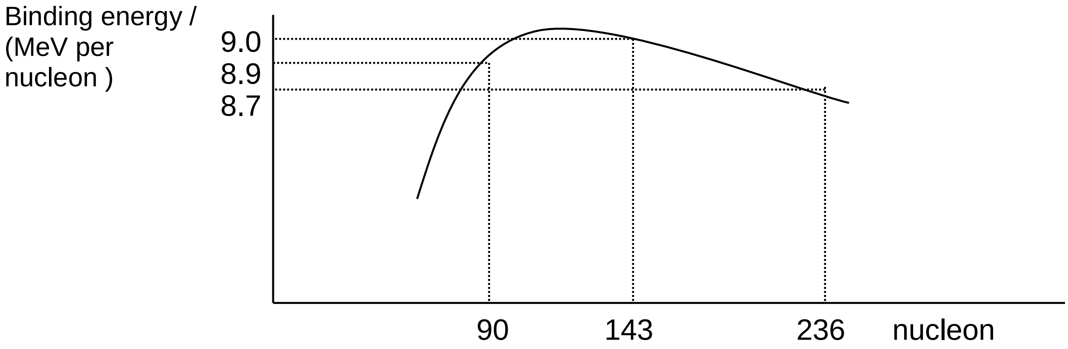
12 In order to achieve a fusion reaction between two deuterium $^{2}_{1}\mathrm{H}$ nuclei, temperatures of the order of 1.0×10^{7} K must be attained. Estimate the root-mean-square speed of the deuterium nuclei at this temperature. Mass of deuterium = 2.01410 u.

13 Estimate the energy released in a fission reaction:

$$^{1}_{0}\mathrm{n} + ^{235}_{92}\mathrm{U} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$$

Given the binding energy per nucleon: $^{235}_{92}\mathrm{U} = 7.6$ MeV, $^{141}_{56}\mathrm{Ba} = 8.25$ MeV, $^{92}_{36}\mathrm{Kr} = 8.75$ MeV

14 The binding energy per nucleon varies with nucleon number in the way shown below.



During one particular fission process, a Uranium-236 nucleus gives, among its fission products, a Strontium-90 ($^{90}_{38}Sr$) nucleus and a Xenon-143 ($^{143}_{54}\mathrm{X}e$) nucleus.

(i) Use the value on the graph to calculate the energy released during this fission process.
(ii) What other fission particles are produced by this process? Why do these particles not have to be taken into account in the calculation in (i)?
(iii) Why does a release of energy occur when there is an *increase* in the binding energy?

15 A small volume of solution containing a radioactive isotope of sodium, of half-life 15 hours, had an activity of 204 Bq when it was injected into a blood vessel of a patient. After 30 hours, the activity of 1 cm^{3} was found to be 8.5×10^{-3} Bq. Estimate the volume of blood in the patient.

16 The backup power of a certain satellite is provided by the heat generated by a radioactive source. Calculate the mass of $^{226}_{88}\text{Ra}$ that will generate 50 W of power. Given that the half-life of $^{226}_{88}\text{Ra}$ is 1620 years and it emits 4.78 MeV α-particles.

17 In a radioactive decay, the number n of atoms undecayed at time t is given by

$$n = n_o\text{expt}(-\lambda t),$$

where n_o is the number of atoms present at the start of the decay and λ is the decay constant.

(a) Sketch, on the axes below, a graph which shows qualitatively how number of undecayed atoms varies with time.

(b) For a particular radioactive source, $\lambda = 1.83 \times 10^{-9}\ \text{s}^{-1}$ and $n_o = 3.72 \times 10^{21}$.

(i) Calculate the number of undecayed atoms when $t = 3.16 \times 10^7$ s (1 year).

(ii) Calculate the half-life of the source.

(iii) Calculate the activity of the source at the start of the decay ($t = 0$)

18 By what percentage does the ^{14}C activity of a non-living sample decrease in a year? Given that the half-life of ^{14}C is 5730 years. (0.012%) (Implication: The tiny change in activity illustrates one reason why we do not expect ^{14}C dating to give dates precise to a specific year.)