NUCLEAR PHYSICS

DR ROY SEBASTIAN K

ASSOCIATE PROFESSOR

ST JOSEPH'S COLLEGE

MOOLAMATTOM

DEDICATED TO MY DAUGHTER **ASHLY ROY**

CHPTER 1

NUCLEAR MODELS

ISOTOPES

Using a mass spectrograph, Aston has shown that chlorine is a mixture of two kinds of atoms of atomic weights 35 and 37. These two kinds of atoms are called isotopes of chlorine. The relative proportions of these two isotopes in chlorine give a value of 35.46 to the atomic weight of chlorine. Similarly the atomic weight of neon (20.2) has been explained to be due to two isotopes of atomic weights 20 and 22. The study of the various elements using different kinds of mass spectrograph showed the presence of 297 isotopes.

Isotope is a set of chemically identical species of atoms which have the same atomic number but different mass numbers.

Eg: Hydrogen $_1H^1$; $_1H^2$; $_1H^3$

Oxygen $_8O^{16}$; $_8O^{17}$; $_8O^{18}$

Chlorine $_{17}Cl^{35}$; $_{17}Cl^{37}$

PROBLEM: The relative abundance of isotopes of magnesium was determined in a mass spectrometer. The values are 77.4% of Mg^{24}, 11.5% of Mg^{25} and 11.1% of Mg^{26}. Calculate the mean atomic weight of magnesium.

$$mean\ atomic\ weight = \frac{77.4\ x\ 24 + 11.5\ x\ 25 + 11.1\ x\ 26}{100} = 24.337$$

ISOBAR

Isobars are nuclei having the same mass number but different atomic number.

Eg. Isotopes of thorium (Z=90), protactinium (Z=91) and uranium (Z=92) all have mass numbers of 234.

ISOTONE

Isotones are nucleus of different elements having the same neutron number.

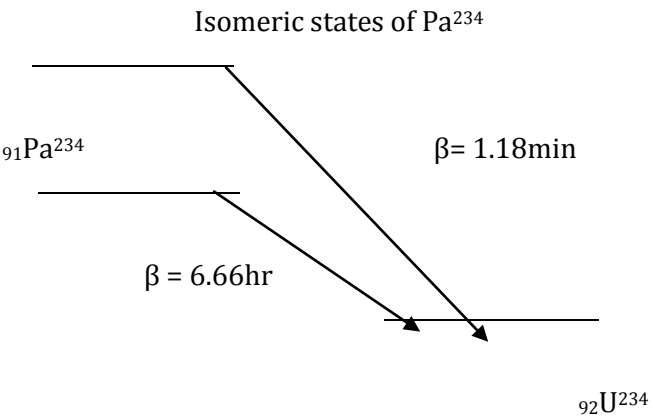
Eg: The nuclides of $_{85}At^{213}$ and $_{84}Po^{212}$, which have 128 neutrons

NUCLEAR ISOMERS

In the early study of radioactive isotopes it was common to assign a separate isotope to a particular half-life. Thus if two half-lives were observed in a given sample, it was assumed that

they were due to two different isotopes, each decaying with a particular half-life. For example, consider the decay:

$_{90}Th^{234} \rightarrow {}_{91}Pa^{234} + {}_{-1}e^{0} + \overline{\nu}$



$_{91}Pa^{234}$ (Protactinium) was found to decay by emission of β-particles of two different half-lives, one of 1.18min and the other of 6.66hr. In the early days it was assumed that these two half – lives were due to two different isotopes. In 1921 Hahn showed that these two half-lives of β-decay are due to different energy states (excited) of the same nucleus. Such long-lived excited states of the same nucleus are called isomeric states or nuclear isomers.

GENERAL PROPERTIES OF NUCLEUS

Nuclear size – Radius, volume, mass and density

The nuclear charge is spread uniformly over a sphere of radius R. The radius R can be obtained from experiments on nuclear reactions. More accurate value can be obtained from mirror nuclei. The volume of the nucleus $V \propto A$, the number of nucleons. The radius may be expressed by the relation

$$R = R_0 A^{1/3}$$

Where $R_0 = (1.28 \pm 0.05) \times 10^{-15}$m. Therefore

$$V = \left(\frac{4}{3}\right)\pi R^3 = \left(\frac{4}{3}\right)\pi R_0^3 A$$

Mass of the nucleus, M = mass of the proton x A = Mp x A

Density of the nucleus = Mass of the nucleus /volume of the nucleus

$$= M/V = (Mp\ A)/[\left(\frac{4}{3}\right)\pi R_0^3 A\ ] = 3Mp/4\pi\ R_0^3$$

$$=3x1.672x10^{-27}/4\pi \times (1.5 \times 10^{-15})^3 = 10^5 \text{ tons/mm}^3$$

RADIUS OF THE NUCLEUS

The information of the nucleus is first provided by Rutherford's α-particle scattering experiments which showed that the positive charge in an atom is confined to a very small region. On grounds of symmetry this positive region is assumed to be spherical in shape and located at the centre of the atom. It was called the nucleus. The distance of closest approach at which anomalous scattering begins was identified as the first measure of the nuclear radius. There is no single précised definition of nuclear radius which can be applied to all nuclear situations. The size of the nucleus is determined by shooting probing particles and measuring the effects produced. The wavelength of the probing particles must be of the order of the size of the nucleus or smaller.

Electromagnetic radius and Nuclear force radius

The neutron cross section in neutron scattering experiment gives the radial distance at which the nuclear forces begin to be effective. Neutrons of 100MeV and de-Broglie wavelength of the order of 10^{-15}m is used for the measurement of total scattering cross section

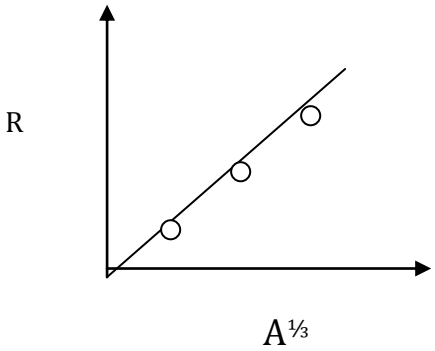
$$\sigma_t = 2\pi(R + \lambda)^2$$

Where, R = radius of the nucleus
λ = de-Broglie wavelength

Many experiments have been carried out to measure the absorption of high energy neutrons by a variety of targets. The nuclear radius R is plotted against $A^{⅓}$

The nature of the graph verifies the empirical relation $R = R_0A^{⅓}$ of the constant density model.

$$R = (1.28 \pm .05) \times 10^{-15}\text{m } A^{⅓}$$



Nuclear radii could also be estimated from X-rays emitted by mesonic atoms during their energy transition. Since μ-mesons have a mass 207 times the mass of electron, their orbital radii are extremely close to their nuclear surface. These mesons make transitions to lower energy and in the process X-rays are emitted.

The X-ray energies can be accurately measured with a spectrometer and the nuclear radii can be determined.

$R = (1.2 \pm 0.1) \times 10^{-15} A^{1/3} m$

NUCLEAR SPIN

Each proton and each neutron in the nucleus has an angular momentum due to the spinning motion of the nucleus about an axis through its centre of mass. The magnitude of this spin angular momentum is ½h/2π. The wave mechanical properties of an angular momentum of this kind are such that its orientation in space can be described only by two states: the spin axis is either 'parallel' or 'anti-parallel' to any given direction, say the z-axis, is either ½h/2π or -½h/2π. In addition, each nucleon may be pictured as having an angular momentum associated with orbital motion within the nucleus. According to quantum theory, the orbital angular momentum is a vector whose greatest possible component in any given direction is an integral multiple of h/2π. Each nucleon has a total angular momentum 'i' about a given direction, with

$$i = \ell \pm s$$

where 'ℓ' is the orbital angular momentum and s is the spin angular momentum. The spin of any single nucleon can add or subtract ½h/2π depending on its orientation with respect to the axis of reference, and 'i' is therefore half-integral. For nuclei containing more than one particle, it is customary to write corresponding relationship between the momentum and spin in capitals; the resultant total angular momentum of the nucleus is then

$$I = L \pm S$$

Where 'L' is the total orbital angular momentum, and 'S' is the total spin angular momentum. The total angular momentum is actually a vector, denoted by 'I', and the scalar quantity 'I' is defined as the maximum possible component of 'I' in any given direction. The orbital angular momentum L is an integral multiple of h/2π; S is an even half-integral multiple of h/2π if the number of nuclear particles is even, and an odd half-integral multiple if the number of particles is odd. Hence, I is an integral multiple of h/2π when A is even, and an odd half integral multiple when A is odd.

The term "spin" is often used for the total angular momentum of a nucleus rather than for the spin S alone.

MAGNETIC DIPOLE MOMENT OF THE NUCLEUS

A moving charged particle produces a magnetic field. The spin angular momentum and the orbital angular momentum of the protons produce nuclear magnetic field. This can be described in terms of a resultant magnetic dipole moment located at the centre of the nucleus. The magnetic moment is given by Dirac' equation

$$\mu_p = e\hbar/2mpC$$

This is 1836 times smaller than a Bohr magneton. However a proton has a magnetic moment μp=2.7927 nuclear magneton(n.m.) and a neutron has a magnetic moment μn=-1.913n.m. Hence protons and neutrons do not obey Dirac equation is respect of their magnetic moment.

This anomaly can be resolved if we consider the proton and neutron to be surrounded by a cloud of mesonic charges. A proton exist as $P \longrightarrow n + \pi^+$ meson for a part of its time and a neutron exist as $n \longrightarrow P + \pi^-$ meson for a part of its time. The π meson be a lighter particle gives a major contribution towards the nuclear magnetism. Due to this inherent structure of the nucleons the actual magnetic moment is a

vector sum of the new state. The nuclear magnetism therefore is an anomalous value. The nuclear magnetic moment of any nucleus is related to the nuclear spin **I** as

$\mu_I = g_I \frac{e}{2mpc} \hbar I = \gamma \hbar I$

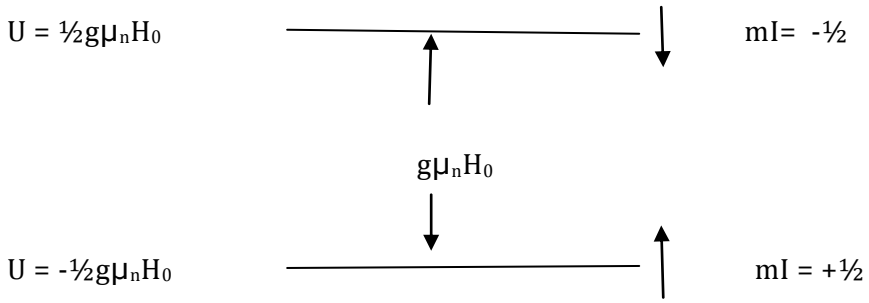
where $\gamma = gI[\frac{e}{2mpc}]$ is the nuclear gyromagnetic ratio and g_I is the nuclear g factor.

In the presence of an external field H the nuclear magnetic moment in the z-direction
$\mu_I(z) = \gamma m_I \hbar$ where m_I can take values from +I to –I.
magnetic energy of interaction
$U = -\mu_I H = -\mu_I(z) H_0$ [where Hx=Hy=0 and Hz=H_0]
Therefore $U = -\gamma m_I \hbar H_0$

$$\gamma = g[\frac{e}{2mpc}]$$

$$\gamma\hbar = g[\frac{e\hbar}{2mpc}] = g\mu_n$$

Therefore $U = -m_I g \mu_n H_0$



In the case of proton mI=+½ and -½

Selection rule for transition is $\Delta I = \pm 1$. Proton has only two orientations upward and downward. We can only change these directions by applying a magnetic field which produces resonance. If ħω denote the energy difference between the two levels

$\hbar\omega = g\mu_n H_0 = g\left[\frac{e\hbar}{2mpc}\right]H_0$

$\omega = \gamma H_0$ where $\gamma = \omega/2\pi$

γ(KHz) = $4.258H_0$ (H_0 in gauss)

γ(MHz) = $4.258H_0$ (H_0 in Kilogauss)

NUCLEAR ELECTRIC QUADRUPOLE MOMENT

The electric quadrupole moment is a measure of the deviation from spherical symmetry of a nucleus and is defined by the equation

$$Q = (\frac{1}{e}) \int \rho(3z^2 - r^2) d^3r \qquad (1)$$

Where $r^2 = x^2 + y^2 + z^2$ and 'e' is the electronic charge, ρ is the density distribution of the charge is the nucleus and z is the direction coincide with the spin axis. The electric quadrupole moment is usually measured in unit of electronic charge (eQ). It is clear from Equ.(1) that for a spherically symmetric charge distribution the average value of$3z^2$ is equal to the average value of $r^2 = x^2 + y^2 + z^2$, then the quadrupole moment 'Q' becomes zero. Therefore the nuclear electric quadrupole moment is a measure of the departure of nuclear charge distribution from spherical symmetry. Further if the nuclear charge distribution is elongated (prolate) along the nuclear spin axis 'Q' is positive and if it is flattened out (oblate) along the spin axis 'Q' is negative. Q has the dimensions of area and of the order of magnitude equal to the square of the nuclear radius $(10^{-24}cm^2)$

Prolate spheroid (Q>0) Oblate spheroid (Q<0)

The quadrupole moment also can be expressed as

$$eQ = C\,[I(2I - 1)] \qquad (2)$$

where C is a constant and I the nuclear spin. It is clear from Equ.(2) that nuclei with spin $\mathbf{I < 1}$ cannot have electric quadrupole moment. A nucleus with spin I = 0 has no preferred nuclear orientation and the one with $\mathbf{I = ½}$ differs only by reversal of the spin direction and thus corresponds to the same effective nuclear charge distribution. Hence for $\mathbf{I = 0}$ and $\mathbf{I = ½}$ there cannot be any meaningful orientation dependent electrostatic interaction.

The non-spherical charge distribution around the nucleus can be described in terms of electric field gradient (EFG). The electric field gradient 'eq' is mainly determined by the unfilled shells of electronic orbitals. The largest contribution is that of the electrons in the nearest unfilled p shells. The fully occupied p orbitals do not contribute to the EFG and the same holds for the s electrons. The contribution from electrons in the unfilled d shells is much less as they are further off from the nucleus.

Nuclear quadrupole resonance (NQR) deals with the electrostatic interaction between the nuclear electric quadrupole moment and electric field gradient at the nucleus due to the surrounding charges.

ATOMIC MASS UNIT AND BINDING ENERGY

Atomic mass unit (amu) is the common unit of mass and energy in nuclear physics. Previous to 1960, one amu is the one-sixteenth the mass of the isotope of oxygen $_8O^{16}$. But in 1960, the General Assembly of the International Union of Pure and Applied Physics adopted carbon $_6C^{12}$ as the reference for the atomic mass unit. Now one atomic mass unit is taken as one-twelfth of the mass of carbon atom $_6C^{12}$. The masses of protons, neutrons etc. are expressed in amu . Carbon of atomic weight 12 and atomic number 6 has a mass equal to 12 amu.

Accordingly, 1amu = 1.66038×10^{-27}kg

The mass of all particles and atoms have been found in terms of amu.

The mass of proton = 1.007277 amu

The mass of neutron = 1.008665 amu

It is found that the mass of a nucleus is less than the sum of the masses of the constituent particles in the free state. According to Einstein, the decrease in mass is due to the release of energy when the particles combine to form a nucleus. The energy released is given by the relation $E = \Delta mc^2$, where 'Δm' is the decrease in mass and 'c' the velocity of light.

The difference in mass 'Δm' is called the **mass defect**. It is the amount of mass which would be converted into energy if a particular atom were to be assembled from the requisite numbers of protons, neutrons and electrons. The same amount of energy would be needed to break the atom into its constituent particles. The energy equivalent of the mass defect is therefore a measure of the binding energy of the nucleus. If the binding energy is large, the nucleus is stable.

It is convenient to calculate energy in joule of electron volt, when a mass equal to 1 amu is converted into energy.

$E = mc^2$

$m = 1$ amu $= 1.66 \times 10^{-27}$kg

$c = 3 \times 10^8$m/s

$\mathbf{E} = (1.66 \times 10^{-27})(3 \times 10^8)^2$

$\mathbf{= 1.49 \times 10^{-10}}$**Joules** (1)

But 1 eV of energy = 1.6×10^{-19}Joule

$\mathbf{E} = 1.49 \times 10^{-10} / 1.60 \times 10^{-19}$

$= 931 \times 10^6$ eV

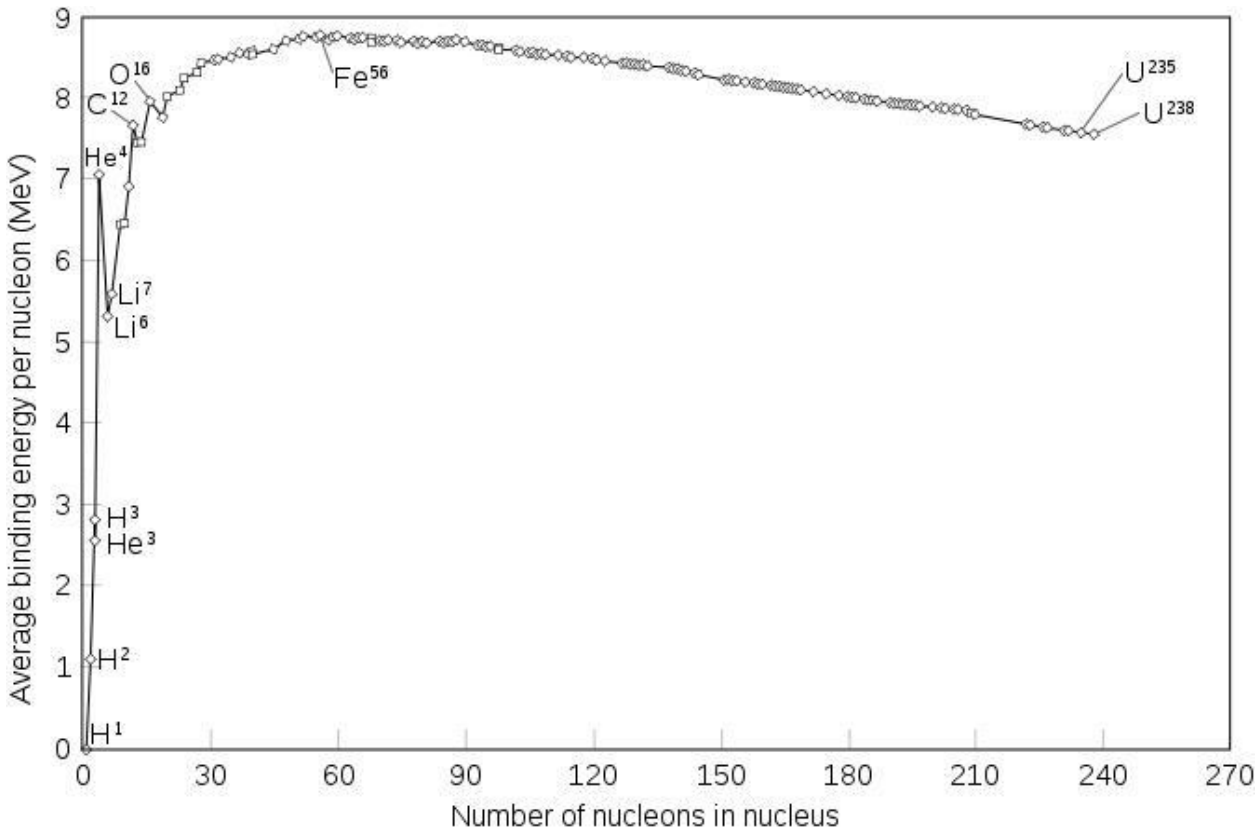
= 931 MeV (2)

The relation (2) represents the conversion of amu into MeV and vice-versa. Thus as nucleus of mass M is 1 amu is equivalent to 931 million electron volt of energy.

The mass of the constituent particles in a nucleus is the sum of Z proton masses and (A-Z) neutron masses. The proton and electron masses can be combined into the mass of Z hydrogen atoms because the minute change in mass which may accompany the formation of a hydrogen atom from a proton and electron is negligible.

The average B.E. per nucleon is obtained by dividing the total B.E. of the nucleus by the mass number **A**

Nucleus	B.E. per nucleon (MeV)
H^2	1.113
He^4	7.07
Li^7	5.61
Be^9	6.46
O^{16}	7.97
Ne^{20}	8.03
Si^{28}	8.45
Cl^{35}	8.52
Fe^{56}	8.79
Cu^{63}	8.75
Sn^{116}	8.52
Nd^{150}	8.25
U^{238}	7.58



Binding energy per nucleon as a function of mass number

Mass Defect

The difference in mass between the sum of masses of protons and neutrons in a nucleus and the nuclear mass is called the **mass defect (**Δm). The mass of the nucleus will be always less than the sum of the masses of protons and neutrons in the nucleus. It is the amount of mass which would be converted into energy if a particular atom were to be assembled from the requisite numbers of protons and neutrons. The same amount of energy would be needed to break the nucleus into its constituent particles.

The mass defect Δm can be written as

$$\Delta m = Zm_H + (A-Z)m_n - M(A,Z)$$

Where m_H, mass of H_2 atom = 1.0081437 amu

m_n, mass of neutron = 1.0089830 amu and

M(A,Z) - the mass of the atom

The mass of electron in the H_2 atom will be cancelled by substrating the mass of atom.

Since 1 amu is equivalent to 931 MeV, the Binding energy (B.E.) of the nucleus is given by

$$\Delta E\ (MeV) = 931\ [1.0081437\ Z + 1.0089830(A-Z) - M(A,Z)]$$

PACKING FRACTION

The packing fraction p is the mass defect per elementary particle in the nucleus.

$$p = \frac{\Delta m}{A} = \frac{M - A}{A}$$

A graph drawn between packing fraction p and mass number A is shown below

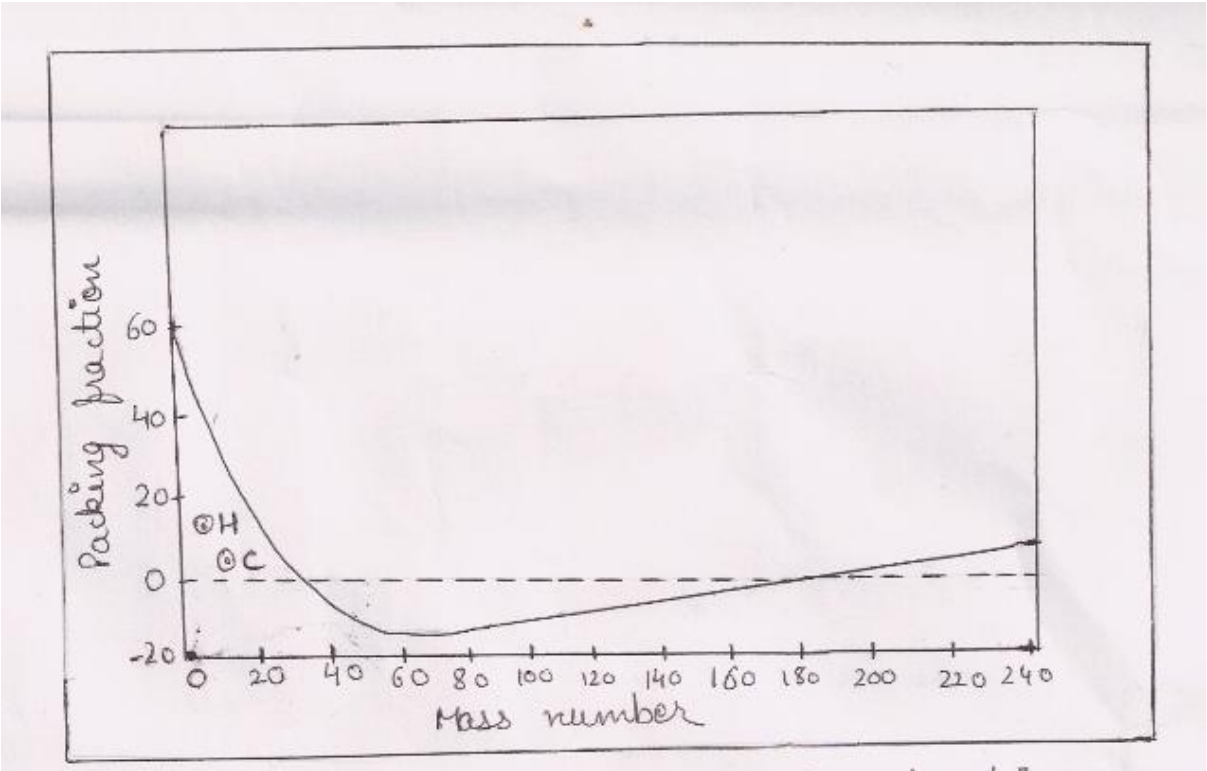


Fig.1 Variation of packing fraction with mass number.

It can be seen that

1. The packing fraction is positive for elements having mass number below 20.
2. The packing fraction is negative for elements having mass number between 20 and 200.
3. The packing fraction is positive for elements having mass number greater than 200.
   The packing fraction is zero for carbon A=12 and Z=6. This does not mean that its B.E. is zero. The mass defect and packing fraction only show their relations with respect to carbon. A nucleus having positive packing fraction has its mass M greater than its mass number A. It means that the loss of mass due to B.E. arrangement in this nucleus is less than for carbon.

NUCLEAR FORCES

The nucleus consists of protons and neutrons, they are together known as nucleons. Since neutrons are uncharged there is no electrostatic force between them or between a proton and a neutron. There is electrostatic repulsion between protons. Yet the nucleons remain close together inside the nucleus as a very stable unit. So there must be some attractive force between them.

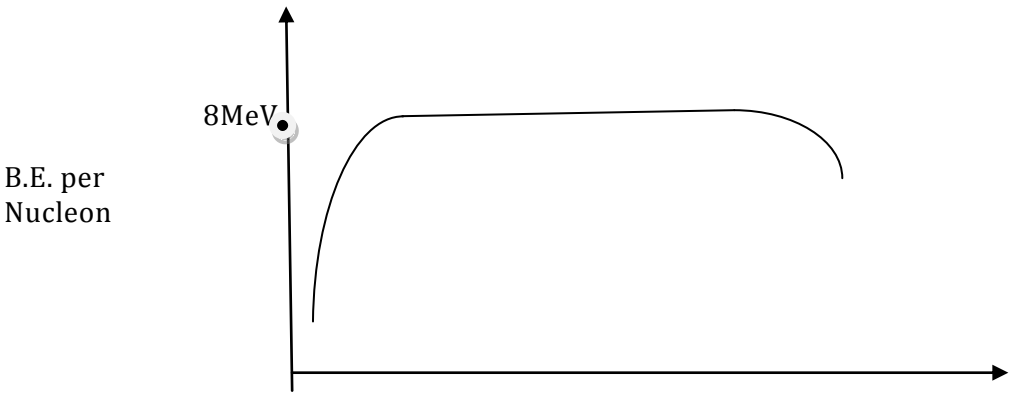
The gravitational force is negligible in all atomic and nuclear phenomena. The nucleus has some magnetic moment but it is considerably less than the electrostatic repulsion. So there must be some new forces that give the nucleons together, we shall call it the nuclear force.

First upon we can see the well known characteristic of nuclear forces.

GENERAL NATURE OF NUCLEAR FORCES

1. STRENGTH

Evidently the nuclear force must be stronger than the electrostatic force. Consider the binding energy curve given below



For almost all elements in the periodic table the B.E. per nucleon is about 8MeV except at the ends. But the B.E. of an electron in an atom is only a few electron volts. The electron is bound to the nucleus by the electrostatic force and the nucleon is bound to the nucleus by the nuclear forces. The binding energies in the two cases indicate the nuclear force is far stronger than the electrostatic force.

Another indication of the strength of the nuclear force is that huge density of the nucleus. The volume of the nucleus $V \propto A$, the number of nucleons. Therefore

Radius $R \propto A^{1/3}$

Or $R = R_0 A^{1/3}$

Experimentally R_0 is about 1.5×10^{-15}m

Therefore $V = \frac{4}{3}\pi R^3$

$= \frac{4}{3}\pi R_0^3 A$

Mass of the nucleus, M = mass of the proton x A = $m_p A$

Therefore, density = $\frac{M}{V} = (M_p A)/(\frac{4}{3}\pi R_0^3 A) = 3M_p/4\pi R_0^3 = 10^5$tons/mm^3

This huge density indicates the nucleons are very thickly packed inside the nucleus which in turn indicates the tremendous strength of nuclear forces. Because of this huge nuclear force not even a single attempt to break the nucleus with enormous temperatures, fantastic pressures or vigorous chemical reaction has succeeded even though all these weapons can easily remove the electronic structure outside the nucleus. The nuclear force is stronger than any non nuclear force; it is the strongest of all known forces.

2. RANGE

Gravitational and electrostatic forces operate between two particles whatever be their separation, we say their range is infinite but the nuclear force has only a short range.

In hydrogen molecule the inter proton distance is about 0.1nm. This is an indication that the range of nuclear force is less than 0.1nm. Scattering experiments indicate that the range of the nuclear force is far less about 2×10^{-15}m (1 Fermi = 10^{-15}m). Because of this very short range the nuclear force never display its action outside the nucleus.

As in the case of gravitational and electrostatic forces we shall assume that the nuclear force also is derivable from a potential. Since the force low is not known the potential cannot be calculated. Therefore various potentials have been suggested. The important among them are

1. $V = -V_0 e^{-r/b}$ where V_0 and b are constants and r is the distance. This is known as the exponential potential.
2. $V = -V_0 e^{-\left(\frac{r}{b}\right)2}$ known as the Gaussian potential.
3. $V = -V_0 \frac{e^{-r/b}}{r/b}$ known as the Yukawa potential.
4. $V = -V_0 \frac{e^{-r/b}}{1-e^{-r/b}}$ known as the Hulten potential.
5. $V = 0 \begin{cases} -V0 & r \leq b \\ r > b & \end{cases}$ known as the square well potential.

The peculiarity of all this expression is that V has a large value where r<b and a negligibly small value when r>b. The force is obtained as the –ve gradient of the potential. In general $V = -V_0 f(r/b)$

Gaussian and square well are called short tailed potential and the others long tailed potential. The constant V_0 represent the depth of the potential well which is the measure of the strength of the force. The constant '**b**' is the range of the nuclear force.

3. SATURATION

The electrostatic force operate whatever be the number of charges present in a region we say electrostatic force is unsaturated. Gravitational force is also unsaturated.

Consider the CH_4 molecule the 4 H_2 atoms establish force links with a carbon atom. A fifth H_2 atom brought near the carbon atom will not be linked with the molecule. So molecular forces are saturated. Thus there are two types of forces saturated and unsaturated and the nuclear force belongs to the saturated type. i.e. each nucleon establishes a force only with a few of its neighbours and not with all other nucleons.

Consider a nucleus having 'A ' particles. If there is no saturation the number of force bonds among them will be AC_2.

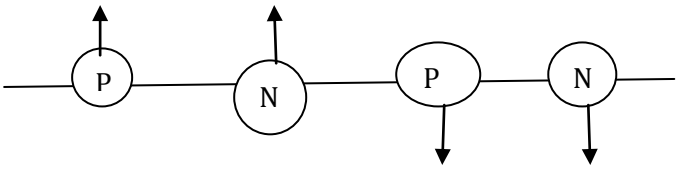
$AC_2 = \frac{A!}{2!(A-2)!} = \frac{A(A-1)}{2} \approx \frac{A^2}{2}$

If E is the energy of one bond, total B.E. = $\frac{A^2}{2} \times E$

Therefore B.E. per nucleon = $\frac{AE}{2}$

Therefore B.E. per nucleon is proportional to A. If the nuclear force is saturated each nucleon interact with only a few others say 'n' of them, then the number of force bond is $\frac{An}{2}$ Total B.E. = $\frac{AnE}{2}$. Therefore B.E. per nucleon = $\frac{nE}{2}$ = constant.

Experimentally the B.E. per nucleon is almost a constant – 8MeV, so the nuclear force must be saturated. During radio activity two protons and two neutrons come together out of the nucleus as the α-particle. This fact leads some scientist to suggest that the α-particle is the saturation unit. The Paul's exclusion principle support the above conclusion if you assumed that nucleons interacts very strongly only when they are in the same orbital state.



Saturation is supposed to be the reason for the inhospitable behavior of the He nucleus. In other words there is no nucleus with mass number 5 because nuclear force is saturated with four nucleons. The constant density of nucleus is another indication of a saturated nuclear force.

The saturation of molecular forces can be easily explained on the basis of electron exchange. But no such easy explanation is available in the case of nuclear force.

4. CHARGE INDEPENDENCE

If a force depends upon charge, it is said to be charge independent. Otherwise it is charge dependent. The electrostatic force is charge dependent. The gravitational force is charge independent. The nuclear force does not care about the charge of the nucleons. It operates just as well between a proton and a neutron as between a pair of protons or a pair of neutrons. In other words the force between a neutron and a proton is equal to force between two protons is equal to the force between two neutrons. This equality of the nuclear force between all pairs of nucleons is known as the hypothesis of charge independence.

Consider T^3 and He^3

The B.E. of T^3 is 8.48 and that of He^3 is 7.72MeV. If E_{PN} is the energy of a proton -neutron force and E_{NN} that of a neutron-neutron force.

$2E_{PN} + E_{NN} = 8.48MeV$ and

$2E_{PN} + E_{PP} = 7.72\ MeV$

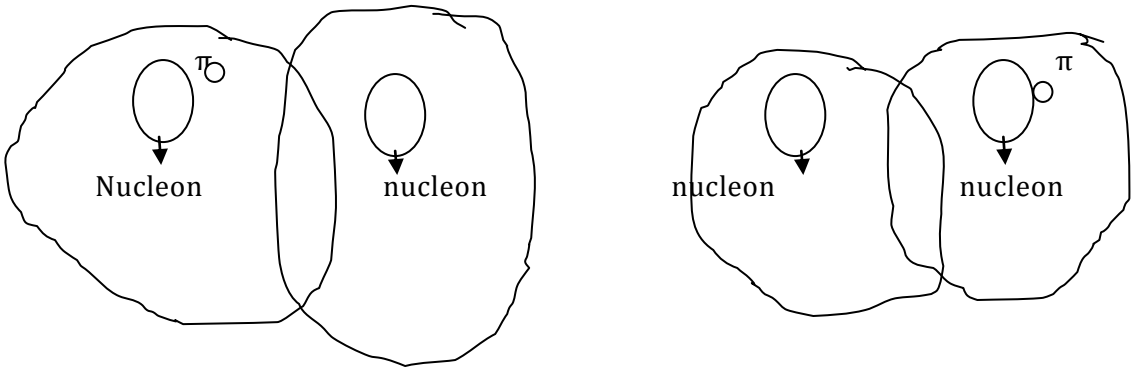
Subtracting $E_{NN} - E_{PP} = 0.76MeV$

From this it may appear that the neutron-neutron force is greater than the proton-proton force. But if we take into account the coulombs repulsion between the protons, the forces in the two cases are equal. This equality of the force between two neutrons and that between two protons is known as the charge symmetry of nuclear force.

MESON THEORY OF NUCLEAR FORCE

Yukawa in 1935 proposed that a nucleon frequently emit a particle with an appreciable rest mass, called the π meson or pion. This particle hovers near the nucleon in the so called π meson field for a very short time and then is absorbed by the nucleon. During the process the nucleon maintain its normal rest mass and while the process takes place there is a violation of mass-energy conservation. This is because there is more rest mass than before the π meson is emitted or absorbed. The energy time uncertainty principle shows, however, that such a violation is possible if it lasts for a sufficiently short time. The π meson cannot permanently escape the nucleon and then the mass-energy would be permanently violated. Such a pion is called a virtual particle because of its short existence and limited by its violation of mass energy conservation.

If two nucleons are close enough for their fields to overlap, it is possible for a π meson to leave one field and join the other without permanently changing the total energy of the system of two nucleons. Such an interaction between the fields is pictured crudely in the figure.



In the interaction the momentum carried by the π meson is transferred from one field to the other and therefore from one nucleon to the other. But if momentum is transferred, the effect is the same as if a force is acting between the nucleons. Thus the exchange of a virtual pion between two nucleons leads to the nuclear force acting between them, according to Yukawa.

In making his proposal, Yukawa was guided by two analogies available to him at that time. One is the covalent binding in the H2 molecule and the other organic molecule. In this process, a force arises from the sharing or exchange of an electron between two atoms. An even closer analogy is the Coulomb force acting between two charged particles. According to the very successful theory of quantum electrodynamics, surrounding each charge is a field photons and the Coulomb force actually results from an exchange of a virtual photon between the fields.

Quantum electrodynamics shows that the long range of the Coulomb force is a consequence of the fact that photons have zero rest mass. Yukawa adopted the theory to the case of two nucleons, interacting with a short range nuclear force, by assuming that the particle exchanged has a non zero rest mass. When he made his proposal pions had not yet been detected. But Yukawa was able to estimate the rest mass that would lead to the observed range by performing a calculation similar to the one in the following example.

Use energy conservation as modified by the energy-time uncertainty principle to establish a relation between the range r^1 of the nuclear force and the rest mass m_π of the π meson whose exchange produces the force. Then use the relation to estimate the value of m_π, assuming $r^1 = 2F$.

The range of the nuclear force is of the order of the radius r^1 of the π meson field surrounding a nucleon, since two nucleons experience that force only when their meson fields overlap. To estimate the radius of the field, consider a process in which a nucleon emits a meson of rest mass m_π , which travels out to the limits of the field, and then returns to the nucleon where it is absorbed. In this process the π meson travels a distance of the order of r^l (r^l is the nuclear radius). While it is happening there is a violation of the conservation of mass-energy. The reason is that the total energy of the system equals one nucleon rest mass energy before and after the process, and one nucleon rest mass energy plus at least one π meson rest mass energy during the process. But the energy-time uncertainty principle shows that a violation of energy conservation by an amount

$$\Delta E \sim m_\pi c^2$$

Is possible if it does not happen to a time longer than Δt, where $\Delta E \Delta t \sim \hbar$. Since the speed of the pion cannot be greater than C, the time required for it to travel a distance of the order of r1 is at least $\Delta t = \frac{r^1}{C}$. These three relations give

$m_\pi C^2 \sim \frac{\hbar}{\Delta t} \sim \frac{\hbar C}{r^1}$

or $m_\pi \sim \frac{\hbar}{cr^1}$

If we take $r^1 = 2F$

$m_\pi \sim \frac{\hbar}{cr^1} \sim 1x10^{-34}/2x10^{-15}x3x10^8 = 2x10^{-28}kg$

This can also be written as $m_\pi = 200me = 100MeV/c^2$ where me is the rest mass of an electron which has the value $me = 0.511MeV/c^2$

A meson of rest mass $m_\pi \sim \frac{\hbar}{cr^1}$ can have a nuclear force of range r^1. But a photon has zero rest mass and thus Coulomb force have long range.

The π+ mesons have a positive charge equal in magnitude to that of the electron and the π- mesons have a negative charge of the same magnitude. Measurements show that the π+ and π- mesons have the same rest mass equal to $140MeV/c^2$. Neutral π^0 mesons with rest mass equal to $135MeV/c^2$ were also observed.

Experimental evidence for the exchange of pions between two interacting nucleons is found in n-p scattering. The scattering cross section implies that for half the scattering the neutron changes into a proton and the proton changes to a neutron.

This is given by the set of reactions

$n \rightarrow p + \pi^-$ then $\pi^- + p \rightarrow n$

The neutron emits a negatively charged π^- meson into its field and become a proton. The π^- meson joins the field of the proton and is absorbed giving a neutron. The scattering process can also be taking place by the following set of reactions.

$P \rightarrow n + \pi^+$ then $\pi^+ + n \rightarrow p$

In this case a π^+ meson is emitted and then absorbed to give back the proton. Similarly

$n \rightarrow n + \pi^0$ then $\pi^0 + n \rightarrow n$ and

$p \rightarrow p + \pi^0$ then $\pi^0 + p \rightarrow p$

MAGIC NUMBERS

If the proton number or the neutron number of any isobar is 2, 8, 20, 50, 82 or 126, it will lay 1 to 2 MeV below the value predicted by the smoothly varying mass

formula. These numbers are known as 'magic' numbers. If Z or N is a magic number, those elements have exceptional stability. The heaviest stable isotope is $_{83}Bi^{209}$, note that its neutron number is 126 and all other Bismuth isotopes are unstable. The nuclear electric quadrupole moment is zero for a nucleus with Z or N having a magic number. These nucleuses have spherical symmetry.

NUCLEAR SHELL MODEL (Independent particle model)

It is well known that an electron in an atom move in single particle orbits of various energy levels with the coulomb potential set up by the nucleons. These energy levels occur in groups and the levels of each group form a shell. The levels are filled from the bottom according to Pauli's exclusion principle. The chemical properties of the atom depend upon the number of electrons in the outermost shell.

The shell model of the nucleus suggests that the nucleons in a nucleus are also arranged in a definite pattern similar to the electron shell structure of the atom. Since each nucleon behaves independently, this model is also known as independent particle model. The following evidences show that nuclear shells are caused with 2, 8, 20, 50, 82 and 126 nucleons.

1. The end product of 3 main radio -active changes is Lead with Z=82. The most abundant Lead isotope is $_{82}Pb^{208}$ has 126 neutrons. The Neptunium series end with Bi^{209} which also have 126 neutrons.
2. Helium with 2 protons and 2 neutrons and Oxygen with 8 protons and 8 neutrons are particularly stable as seen from the B.E. curve.
3. Tin has 10 isotopes larger than any other element. Z=50 for Tin. Calcium with Z=20 has 6 isotopes.
4. The biggest group of isotones (number of neutrons same) is at N=82 and the next are at N=50 and N=20.
5. It is found that some isotopes are spontaneous neutron emitters. When excited by a preceding β-decay they are O^{17}, Kr^{87} and Xe^{137} with neutron numbers 9, 51 and 83 respectively. Note that neutron numbers are one above the next magic numbers.

From this and other accumulated evidences the numbers 2, 8, 20, 50, 82 and 126 for either Z or N is associated with high stability and that is why they are called magic numbers.

Difference Between Electronic Shells and Nuclear Shells

1. The electrons are bound to the atom by electrostatic force but the nucleons are bound to the nucleus by the nuclear force.
2. Atomic shells have a core which is the nucleus of the atom. There is no such core in the case of nuclear shells.
3. Electronic shells are filled with one type of particles i.e. the electrons. The nuclear shells are filled with two types of particles, the protons and the neutrons.

Because of these differences the order of filling the nuclear shells is different from that of electronic shells.

The shell model is on the basis of ideas suggested by Quantum mechanics. Assuming the potential to be of the harmonic oscillator term, the energy

Ex = (nx + ½)ħω

Where nx = 0, 1, 2, -------

In three dimensions

$E = (\lambda + \frac{3}{2})\hbar\omega$

Where λ = nx +ny + nz

λ is called the total quantum number. In spherical polar co-ordinates

$\lambda = 2n + \ell$

where 'n' is the radial quantum number and 'ℓ' is the orbital quantum number. Therefore corresponding to each energy level there are different sublevels. For example for the energy level λ = 2 there can be two sublevels one with n=0 and ℓ=2 and the other n=1 and ℓ=0. Corresponding to each sublevel there are (2ℓ+1) sub states because of the projection of orbital quantum numbers 'mℓ' can take (2ℓ+1) values. Corresponding to each value of 'mℓ', the spin quantum numbers 'ms' can take two values ± ½. So the Paul's exclusion principle allows 2(2ℓ+1) nucleons in each shell to go to a sub-shell.

According to this theory the number of nucleons in each shell will be as follows

				No. of nucleons	Total No.
λ = 0 →	n = 0,	ℓ= 0 →	(0s)	2	2
λ = 1 →	n = 0,	ℓ= 1 →	(0p)	6	8
λ = 2 →	n = 0,	ℓ= 2 →	(0d)	10	
	n = 1,	ℓ = 0 →	(1s)	2	20
λ = 3 →	n = 0,	ℓ = 3 →	(0f)	14	
	n = 1,	ℓ = 1 →	(1p)	6	40

Note that the number of nucleons in both shells does not give magic numbers.

Mayer and Jenson suggested spin-orbit coupling, where spin and orbital momentum combine to get total angular momentum quantum number j = ℓ±½.

For the same 'ℓ' the energies (ℓ+½) and (ℓ-½) states may be quite different. According to quantum mechanics energy of the (ℓ+½) is below the (ℓ-½) state and the difference in energy is proportional to (2 ℓ +1).

Therefore, the difference between the energies increases with increasing 'ℓ'. Consequently when ℓ =4 or more the energy separation is so great that the nucleons occupying (ℓ-½) level are actually in a different shell from those of (ℓ+½).

After the introduction of the spin-orbit coupling each sublevel will be fitted with (2j+1) nucleon of each kind because the quantum number 'm' can take (2j+1) values.

As you have seen $\boldsymbol{\lambda=2n+\ell}$;

For the first shell $\boldsymbol{\lambda=0}$, then n=0, ℓ=0 and j=0+½. Therefore (2j+1) =2

Therefore 2 nucleons of each type can be accommodated in the lowest shell.

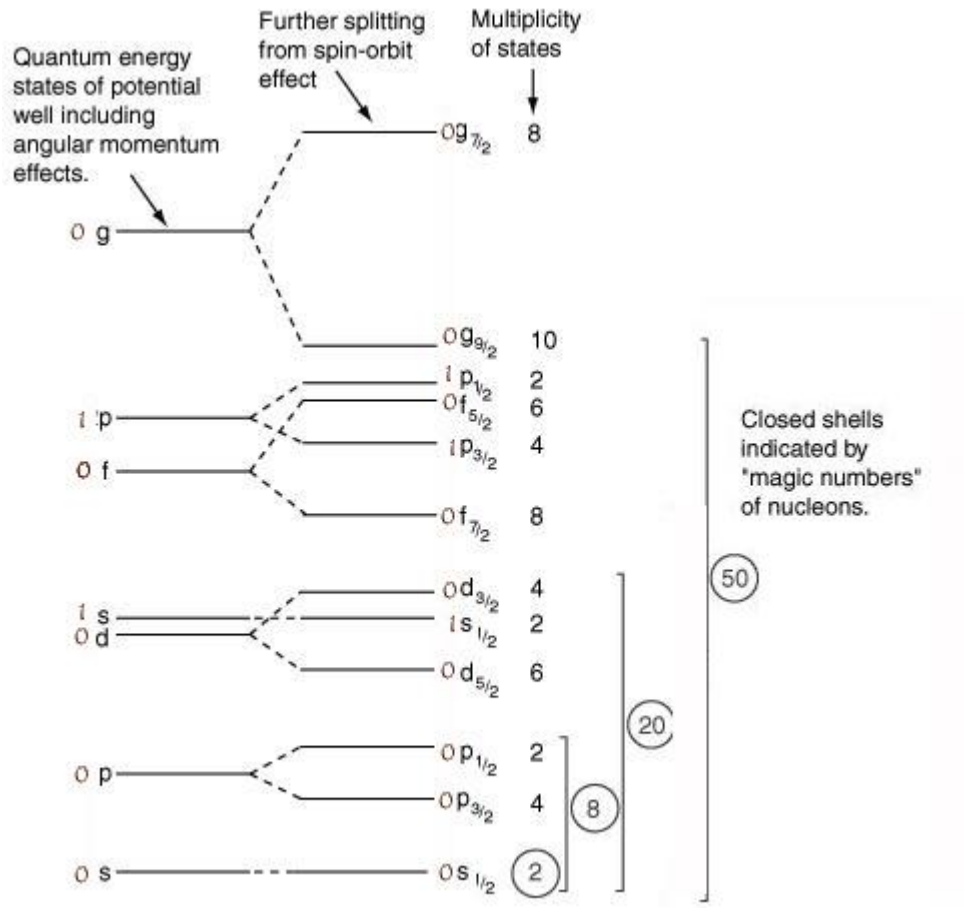
For the next shell $\boldsymbol{\lambda=1}$, n=0, ℓ=1 and j=$\frac{3}{2}$ or $\frac{1}{2}$. Therefore (2j+1) = 4 or 2

For the next shell $\boldsymbol{\lambda=2}$, n=0, ℓ=2 or n=1, ℓ=0 and j=$\frac{5}{2}$, $\frac{3}{2}$ or j= $\frac{1}{2}$

The 0d level has two j values 5/2 and 3/2, j=5/2 is the (ℓ+½) state so it is below $0d_{3/2}$ level. The $0d_{5/2}$ level can accommodate 6 particles. Because (2j+1) =2x $\frac{5}{2}$ +1 = 6. Similarly $0d_{3/2}$ can accommodate 4 particles. The second possibility n=1 and ℓ=0 give rise to the 1s½ level which can accommodate two particles. Therefore altogether there are 12 particles in this shell making the total number 20.

Important changes start taking place from $\boldsymbol{\lambda=3}$, in this case the two possibilities are n=0, ℓ=3 or n=1, ℓ=1. The first possibility gives rise to 0f level and the second 1p level. The 0f level has j= 7/2, 5/2 and has two sublevels with 8 particles in one level and 6 in the other. Similarly the 1p level has two sublevels $1p_{3/2}$ containing 4 nucleons and $1p_{1/2}$ containing 2 nucleons. Since the splitting is larger for 'f' state, so the $0f_{7/2}$ is the lowest state next comes $1p_{3/2}$ then $0f_{5/2}$ and $1p_{1/2}$. The total number of nucleons is 40 which is a semi magic number.

The next level is $\boldsymbol{\lambda=4}$, in this case there are three possibilities n=0, ℓ=4 or n=1, ℓ=2 or n=2, ℓ=0. For n=0, ℓ=4; 'j' can have values 9/2 and7/2. The lowest level in λ=4 is $0g_{9/2}$ which contains 10 particles. The spin orbit splitting of 'g' state is so large that $0g_{9/2}$ level is pushed down to the vicinity of the levels containing λ=3, producing the magic number 50. Thus the spin orbit coupling radically changes the concept of a shell. Very often the expression major shell is used to describe the new shell. Similarly the spin orbit splitting can be applied to the sublevels in λ=5, 6 etc. for the explanation of the remaining magic numbers.



["*spuds if pug dish of pig*". This means: (eat) potatoes if the pork is bad. Deletion of all vowels, except the last yield "spdsfpgdshfpig". This is the ordering of 'ℓ' for all the unsplit levels.]

Miner discontinuvities are there when the number of particles are 14, 28 and 40. They are called semi magic numbers.

$_{2}He^{4}$, $_{8}O^{16}$, $_{20}Ca^{40}$ and $_{82}Pb^{208}$ are doubly magic because both proton number and neutron number are magic numbers. If either proton number or the neutron number is a magic number it is called a single closed shell nucleus. The Antimony isotopes with Z=50 belong to this category.

Upto $_{20}Ca^{40}$ both neutron and proton fill up the same shell model level. Beyond that there is a neutron excess and the excess neutron go the levels above those of protons.

In shell model the colsed shells are treated as an inert core. The nucleons in the outermost partially filled sublevels determined the nuclear properties.

One of the physical properties easily explained by the shell model is the ground state spin (i.e. total angular momentum) of the nucleus. A nucleus with closed shell structure has zero spin. If there is one nucleon outside a closed shell its spin will be the spin of the nucleus. For example $_{51}Sb^{123}$ (Antimony) has one proton beyond the closed shell of 50 and its spin is 7/2. So the spin of the nucleus is 7/2, same is the case of $_{40}Zr^{91}$ (Zirconium) which has 51 neutrons. For $_{49}In^{113}$ (Indium) the spin is 9/2 which is the j value of the vacancy of the 50^{th} proton.

But there are a number of instances where the sublevels are not filled in the order indicated by the spectrum. This is especially true when j is greater than 9/2.

The shell model aslo provides a qualitative interpretation of magnetic moment of the nucleus. The magnetic moment $\mu = \mu_l + \mu_s$, where μ_l is the magnetic moment due to orbital motion and μ_s that due to spin motion.
$\mu_l = g_l \mathbf{l}$ and $\mu_s = g_s \mathbf{s}$ where gl and gs are the gyromagnetic ration, they are given by

$g_l = \begin{cases} 1 \text{ for proton} \\ 0 \text{ for neutron} \end{cases}$

$g_s = \begin{cases} 5.58 \text{ for proton} \\ -3.83 \text{ for neutron} \end{cases}$

This gives $\mu = \begin{cases} j\text{-}½ + ½gs \text{ for proton} \\ ½gs \text{ for neutron} \end{cases}$ in the ℓ +½ state

And $\mu = \begin{cases} \frac{j}{j+1}(j + \frac{3}{2} - ½gs) \text{ for protons} \\ \frac{-j}{j+1} x\ ½gs \text{ for neutron} \end{cases}$ in the ℓ -½ state

As an example for $_{49}In^{113}$, the 49th proton is in the $0g_{9/2}$ level which is an l+½ state. Therefore the magnetic moment is 5.79. The experimental value is 5.49.

According to shell model closed shell nuclei have spherical symmetry and consequently zero quadrupole moment. This is in agreement with the experiment. For a nuclei just beyond the closed shell the quadrupole moment is –ve. As the nucleon number increases the quadrupole moment increases and becomes +ve reaching a maximum value midway between closed shells. Thereafter it decreases again and becomes zero when the next shell is completed. In this manner the shell model prediction is covered but in some other situations the prediction fails. For example the quadrupole moment due to an odd proton is not much different from that due to an odd neutron but the shell model predict a larger quadrupole moment due to proton.

BAINBRIDGE MASS SPECTROGRAPH

In 1933 K.T.Bainbridge, the American physicist, designed a mass spectrograph in which a velocity selector was used to produce a monovelocity ion-beam and a transverse magnetic field was employed to discriminate between ions of different masses.

Principle

The Bainbridge mass spectrograph is based on the principle that a uniform magnetic field acting normal to the path of ions having the same velocity, deflect the ions of different masses from a straight path into several circular of different radii, the radius of each circular path being linerly related to the mass of the ion describing the circular path.

Construction

Figure (1) shows the schematic of the Bainbridge mass spectrograph. It is essentially a vacuum champer placed in a uniform magnetic field acting perpendicular to its larger surface. Slit S1 collimate the incoming ion beam. The deflection plates are placed next to the slits. The electric field produced by the charged deflection plates and the transverse magnetic field constitute a velocity filter. Beyond the velocity filter, another slit S2 is arranged to further collimate the narrow monovelocity ion beam. A photographic plate is mounted in the analyzing chamber in line with slit S2.

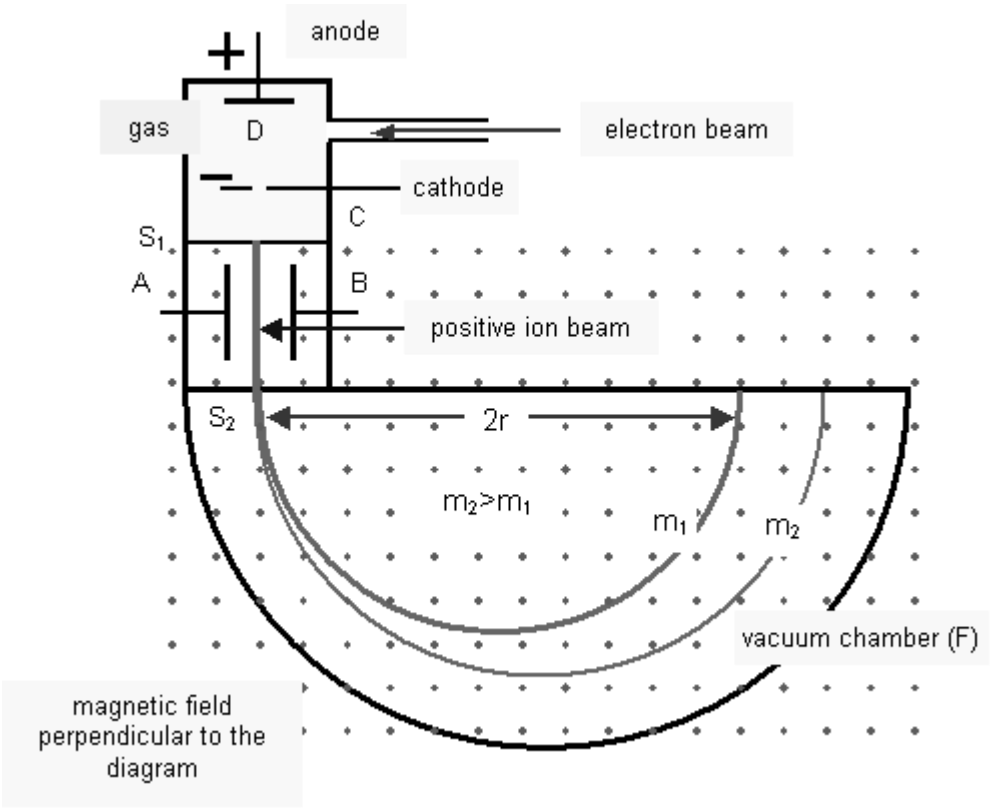


Figure 1: The schematic of the Bainbridge mass spectrograph

Working

The element under study is taken in the form of gas and introduced into a discharge tube. When a potential difference of about 20KV is applied across the electrodes, the gas is ionized and positive ions are accelerated and conducted into the mass spectrometer through slit S1. The ions in the beam have a wide range of velocities and they pass through the velocity filter. The electric field strength E and magnetic field strength are adjusted such that the ion experience an equal and opposite electric and magnetic forces.

i.e. $qE = qvB$

or $v = \frac{E}{B}$ (1)

Thus the electric field strength is adjusted such that ions having a velocity v = E/B emerge out of the filter without diflection and pass through slit S2. Ions having velocities different from v get deflected away and are absorbed by the walls of the chamber. The beam passing through S2 consist of ions all having a single velocity v. In the analysing chamber A, the ions are deflected by the transverse magnetic field Bl, and describe circular paths. The ions are recorded on the photographic plates mounted in line with slit S2. The transverse

magnetic field acting on the analying chamber constitutes a momentum selector and separates out ions of different masses. The different isotopes produce a multiple number of lines on the photographic plate. The visual record of ions in the form of vertical lines on the photographic plate is called the mass spectrum. Figure (2) shows the mass spectrum of germanium isotopes.

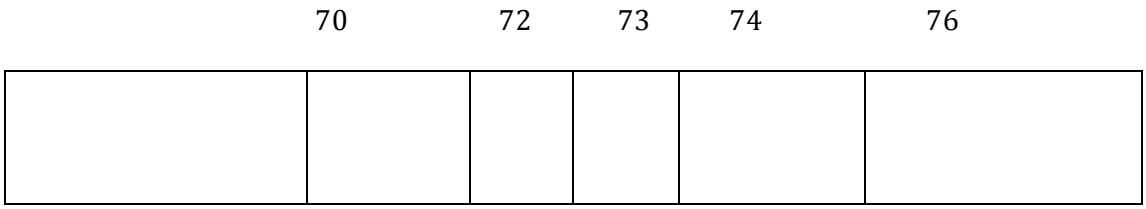


Figure 2: Mass spectrum of Germanium isotope

The positive ions entering into the analyzing chamber are subjected to the strong uniform magnetic field of strength B^l perpendicular to their path. The force acting on each ion is qvBl and transverse circular paths of radius R given by

$$\frac{Mv^2}{R} = qvB^l$$

Or $R = \frac{Mv}{qB^l}$ (2)

From equation (1) we have

$R = \frac{ME}{qBB^l}$

Consider a single ionized ion (q = +ve) with a mass M entering the magnetic field Bl with velocity v. It is deflected along the circular path of radius R, given by

$R = \frac{Mv}{qB^l} = \frac{ME}{qBB^l}$

As E, q, B and Bl are all fixed

$R \propto M$ (3)

Or R = kM (4)

Where, k = E/qBBl is a constant

Therefore, ions with different mass values are focussed at different positions on the photograghic plate. The distance of any line on the photographic plate can be measured from the centre of slit S2. Let it be designed as x. Obviously x is the diameter of the circular path of the ion. Thus

X = 2R (5)

From the relations (2) and (5), it is seen that

$M = \frac{qB^l}{2E}x$ (6)

As the relation between M and x is a linear relation, the mass of the ion is obtained from the measurement of E, B and x by proper calibration of the photographic plate. The relative masses of two isotopes involve only measurement of x and so can be obtained with high precision. If M1 and M2 are the masses of two isotopes and if x1 and x2 respectively are the distances from S2, the line separation is given by

$\Delta x = (x2 - x1) = \frac{2E}{qB^2}(M2 - M1)$ (7)

In practice, one kind of ion is employed as a standard of mass and the mass of the ion under investigation is compared with it by means of equation (7).

THE PROTON-ELECTRON HYPOTHESIS

The emission of α and β particles by radioactive nuclei suggested that a model of the nucleus might be constructed by starting with α and β particles as building blocks. Such a model would make it easy to see, for example, how a number of α particle could be emitted, in succession, in a radio- active series. But not all nuclei are radioactive, nor do all nuclei have masses that are multiples of the a-particle mass. For example, the nucleus of an atom of the lightest element, hydrogen, with an atomic mass of one unit (two units in the case of the heavy isotope), is too light to contain an α particle; so is the light isotope of helium, He^3.

A positively charged particle with mass of one unit would seem to be more satisfactory as a nuclear building block. Such a particle does indeed exist: the nucleus of the common isotope of hydrogen, H^1. This particle has been named the proton, from the Greek word protos for "first." Following the Rutherford–Bohr theory of atomic structure, the hydrogen atom thus consists of a proton with a single electron revolving around it.

The atomic masses of the nuclides are very close to whole numbers; hence, the nuclides are written in symbols with whole number values for A. This result, together with the properties of the proton (e.g., its single positive charge) made it appear possible that all atomic nuclei are made up of pro-tons. Could a nucleus of mass number A consist of A protons? If this were the case, the charge of the nucleus would be A units, but, except for hydrogen, the nuclear charge Z is found to be always less than A, usually less than $1/2\,A$. To get around this difficulty, it was assumed early that in addition to the protons, atomic nuclei contain just enough electrons to cancel the positive charge of the extra protons; that is, they were supposed to contain $(A - Z)$ electrons. After all, nuclei emitted electrons in decay, so, it appeared, electrons must exist within the nucleus. These electrons would contribute only a small amount to the mass of the nucleus, but together with the protons they would make the net charge equal to $+Z$ units, as required.

It seemed plausible to consider the atom as consisting of a nucleus made up of A protons and $A - Z$ electrons, with Z additional electrons outside the nucleus to make the entire atom electrically neutral. For example, an atom of O^{16} would have a nucleus with 16 protons and 8 electrons, with 8 additional electrons outside the nucleus. This model of the nucleus is known as the *proton–electron hypothesis* of nuclear composition.

The proton–electron hypothesis seemed to be consistent with the emission of α and β *particles* by atoms of radioactive substances. Since it was assumed that the nucleus contained electrons, explanation of β decay was no problem. When the nucleus is in an appropriate state, it may simply eject one of its electrons. It also seemed reasonable that an α particle could be formed, in the nucleus, by the combination of four protons and two electrons. (An α particle might exist, already formed in the nucleus, or it might be formed at the instant of emission.)

The proton–electron hypothesis is similar to an earlier idea suggested by the English physician William Prout in 1815. On the basis of the small number of atomic masses then known, Prout proposed that all atomic masses are multiples of the atomic mass of hydrogen and that therefore all the elements might be built up of hydrogen. Prout's hypothesis was discarded when, later in the nineteenth century, the atomic masses of some elements were found to be fractional, in particular, those of chlorine (35.46 units) and copper (63.54 units). With the discovery of isotopes, however, it was realized that the fractional atomic masses of chlorine and copper, like that of neon, arise because these elements are *mixtures of* isotopes, with each separate isotope having an atomic mass close to a whole number.

Although the proton–electron hypothesis was satisfactory in some respects, it led to serious difficulties and had to be given up. One of the most serious difficulties arose from

Heisenberg's uncertainty principle in quantum mechanics. As we noted the confinement of an electron to a space as small as the nucleus would result in the circumstance that at times the electron's speed would be greater than the speed of light, which is not possible according to special relativity theory.

How could scientists account for the circumstance that electrons cannot be confined within the nucleus, yet they emerge from the nucleus in β decay? As he recalled later, Heisenberg and his assistants were contemplating this problem one day while sitting in a café across from a building housing a swimming pool. Heisenberg suggested a possible approach to the problem. "You see people going into the building fully dressed," he said. "And you see them coming out fully dressed. But does that mean that they also swim fully dressed?" In short, you see electrons coming out of the nucleus, and occasionally being captured by the nucleus, but that does not mean that they remain electrons while in the nucleus. Perhaps the electrons are created in the process of emission from the nucleus.

The Proton- Neutron Model

The discovery of the neutron, with an atomic mass close to one unit and with no electric charge, confirmed Rutherford's suggestion that the atomic nucleus is made up of protons and neutrons. This hypothesis was soon used as the basis of a detailed theory of the nucleus by Heisenberg in 1932. His work represented another triumph of quantum mechanics.

According to the *proton–neutron model* that arose from the new theory, the nucleus of an atom having atomic number Z and mass number A consists of Z protons and $A–Z$ neutrons. The nuclei of the isotopes of a given element differ only in the number of neutrons they contain. Thus, the nucleus of the hydrogen isotope of mass number 1 contains one proton; the nucleus of the hydrogen isotope of mass number 2 contains one proton and one neutron. (That nucleus is called a deuteron.) The nucleus of the neon isotope Ne^{20} contains 10 protons and 10 neutrons, while that of Ne^{22} contains 10 protons and 12 neutrons. The atomic number Z identified with the charge on the nucleus, is the number of protons in the nucleus. The mass number A is the total number of protons and neutrons.

The term *nucleons* refer to both kinds of nuclear particles. *So atomic mass number A turns out to be simply the number of nucleons in the nucleus!* According to the proton–neutron model, one proton alone forms the common isotope of hydrogen, ^{1}H. One proton and one neutron yield H^2, called a deuteron, and the resulting atom is called deuterium. When two deuterium atoms combine with oxygen, they form "heavy water." The atom formed from the rare isotope H^3 is called tritium, a radioactive substance.

Is the proton–neutron hypothesis for the structure of nuclei fully consistent with the facts of radioactivity, such as α and β emission and the transformation rules? If two protons and two neutrons could combine, the resulting particle would have $Z = 2$ and $A = 4$, just the properties of the α particle. The emission of two protons and two neutrons (in the combined form of an α particle) would be consistent with the first transformation rule of radioactivity. (The α particle might exist as such in the nucleus, or it might be formed at the instant of emission; the latter possibility is now considered more likely.)

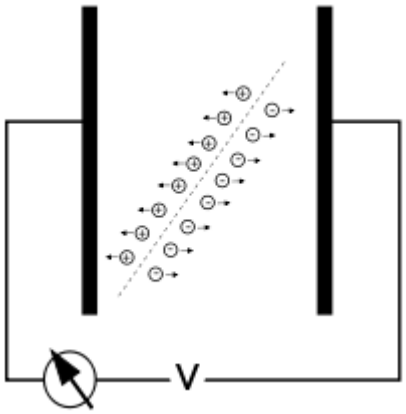
The neutron–proton hypothesis raised a new question: if the nucleus consists of protons and neutrons, where could a β *particle* come from in decay? This question is more difficult to answer than that of the origin of an α particle. The second transformation rule of radioactivity provides a clue: When a nucleus emits a β particle, its charge Z

increases by one unit while its mass number A remains unchanged. This would happen if a neutron were to change into a proton and a β *particle*.

This idea was not a return to the proton–electron hypothesis discussed earlier. Physicists had already come to the conclusion that electrons are not present in the nucleus, so decay was not considered to be a simple separation of a proton and electron; it would have to be a *transformation* of a neutron that *created* a proton and electron. However, there were additional experimental data that raised difficulties for such a simple transformation idea.

IONIZATION CHANBER

Construction and operation



Ion chamber, showing drift of ions. Incident radiation is the dotted line.

An ionization chamber is an instrument constructed to measure charge from the number of ions within a medium (which we will consider to be gaseous, but can also be solid or liquid). It usually consists of a gas filled enclosure between two conducting electrodes (the anode and cathode). The electrodes may be in the form of parallel plates (Parallel Plate Ionization Chambers: PPIC), or coaxial cylinders to form a convenient portable detector; in some cases one of the electrodes may be the wall of the vessel itself.

When gas between the electrodes is ionized by any means, such as by alpha particles, beta particles, X-rays, or other radioactive emission, the ions and dissociated electrons move to the electrodes of the opposite polarity, thus creating an ionization current which may be measured by a galvanometer or electrometer. Each ion essentially deposits or removes a small electric charge to or from an electrode, such that the accumulated charge is proportional to the number of like-charged ions. A voltage potential that can have a wide range from a few volts to many kilovolts, depending on the application, can be applied between the electrodes. The applied voltage allows the device to work continuously by mopping up electrons and preventing the device from becoming saturated. The current that originates is called a bias current, and prevents the device from reaching a point where no more ions can be collected.

Practical Considerations

Because of the very low currents generated (in the order of nanoamperes), the stray leakage current between anode and cathode must be kept to a minimum. Hygroscopic moisture effects on the surface of chamber connection insulators can be sufficient to cause leakage

currents which will swamp any radiation-induced ion current. For higher voltage ion chambers this requires scrupulous cleaning and avoidance of moisture at the chamber connections and at both ends of any cabling. Often in industrial applications the chamber is housed in an outer chamber which contains a desiccant to remove airborne moisture. Guard rings are often used to reduce leakage through or along the surface of connection insulators. Ion chambers are sometimes micro phonic due to their high impedance, and non-ion related charges can be set up inside due to the piezoelectric effect. To overcome this in practice, where the chamber is a long distance from the measuring electronics, a local converter module is often used to translate the very low ion chamber currents to a pulse train having a frequency related to the incident radiation.

Applications

1. Nuclear industry

Ionization chambers are widely used in the nuclear industry as they provide an output that is proportional to radiation dose and have a greater operating lifetime than standard Geiger tubes; in Geiger-Müller tubes the gas eventually breaks down due to incident radiation.

2.Smoke detectors

The ionization chamber has found wide and beneficial use in smoke detectors. In a smoke detector, the gap between the plates is exposed to the open air. The chamber contains a small amount of americium-241, which is an emitter of alpha particles. These alpha particles carry a substantial amount of energy, and when they collide with gas in the ionization chamber (mostly nitrogen and oxygen) the momentum transferred ionizes the gas molecules—that is, the uncharged gas molecules will lose one or more electrons and become charged ions.

Since the plates are at different voltages (in a typical smoke detector, the voltage difference is a few volts) the ions and electrons will be attracted to the plates. This small flow of ions between the plates represents a measurable electric current. If smoke enters the detector, it disrupts this current because ions strike smoke particles and is neutralized. This drop in current triggers the alarm.

3. Medical radiation measurement

In medical physics and radiotherapy, ionization chambers are used to ensure that the dose delivered from a therapy unit or radiopharmaceutical is what is intended. Such devices are called "radioisotope dose calibrators". Ionization chambers are connected to electrometers, and they typically report a collected charge in nanocoulombs. A correction factor is then required to convert this reading into a meaningful dose. Often, a chamber will have a factor established by a national standards laboratory such as the NPL in the UK, or will have a factor determined by comparison against a standards-calibrated

G-M counter

Introduction:

Geiger-Müller (GM) counters were invented by H. Geiger and E.W. Müller in 1928, and are used to detect radioactive particles. A typical GM Counter consists of a GM tube having a thin end window (e.g. made of mica), a high voltage supply for the tube, a scalar to record the number of particles detected by the tube, and a timer which will stop the action of the scalar at the end of a preset interval.

The sensitivity of the GM tube is such that any particle capable of ionizing a single atom of the filling gas of the tube will initiate an avalanche of electrons and ions in the tube. The collection of the charge thus produced results in the formation of a pulse of voltage at the output of the tube. The amplitude of this pulse, on the order of a volt or so, is sufficient to operate the scalar circuit with little or no further amplification. The pulse amplitude is largely independent of the properties of the particle detected, and gives therefore little information as to the nature of
the particle. Even so, the GM Counter is a versatile device which may be used for counting alpha particles, beta particles, and gamma rays, albeit with varying degrees of efficiency.

Principle of the Method

All nuclear radiations, whether they are charged particles or gamma rays, it will ionize atoms/molecules while passing through a gaseous medium. This ionizing property of a nuclear radiation is utilized for its detection. Geiger-Muller counter, commonly called as GM counter or simply as Geiger tube is one of the oldest and widely used radiation detectors. It consists of a metallic tube with a thin wire mounted along its axis. The wire is insulated from the tube using a ceramic feed-through (Fig. 1). The central wire (anode) is kept at a positive potential of a few hundreds of volt or more with respect to the metallic tube, which is grounded. The tube is filled with argon gas mixed with 5-10% of ethyl alcohol or halogens (chlorine or bromine).

When an ionizing radiation enters the Geiger tube some of the energy of the radiation may get transferred to a gas molecule within the tube. This absorption of energy results in ionization, producing an electron-ion pair (primary ions). The liberated electrons move towards the central wire and positive ions towards the negatively charged cylinder. The electrons now cause further ionization by virtue of the acceleration due to the intense electric field. These secondary ions may produce other ions and these in turn still other ions before reaching the electrodes. This cascading effect produces an avalanche of ions. In an avalanche created by a single original electron many excited gas molecules are formed by electron collisions in addition to secondary ions. In a very short time of few nanoseconds these excited molecules return to ground state through emission of photons in the visible or ultraviolet region.

These photons are the key element in the propagation of the chain reaction that makes up the Giger discharge. If one of these photons interacts by photoelectric absorption in some other region of the tube a new electron is liberated creating an avalanche at a different location in the tube. The arrival of these avalanches at the anode causes a drop in the potential between the central wire and the cylinder. This process gives rise to a very large pulse with an amplitude independent of the type and energy of the incident radiation. The pulse is communicated to the amplifier through an appropriate RC circuit, and then to a counter which is called as scaler. Suitable arrangements are made to measure the counts for a preset time interval. The schematic diagram of the G-M tube and the associated electronic components is given in the figure.

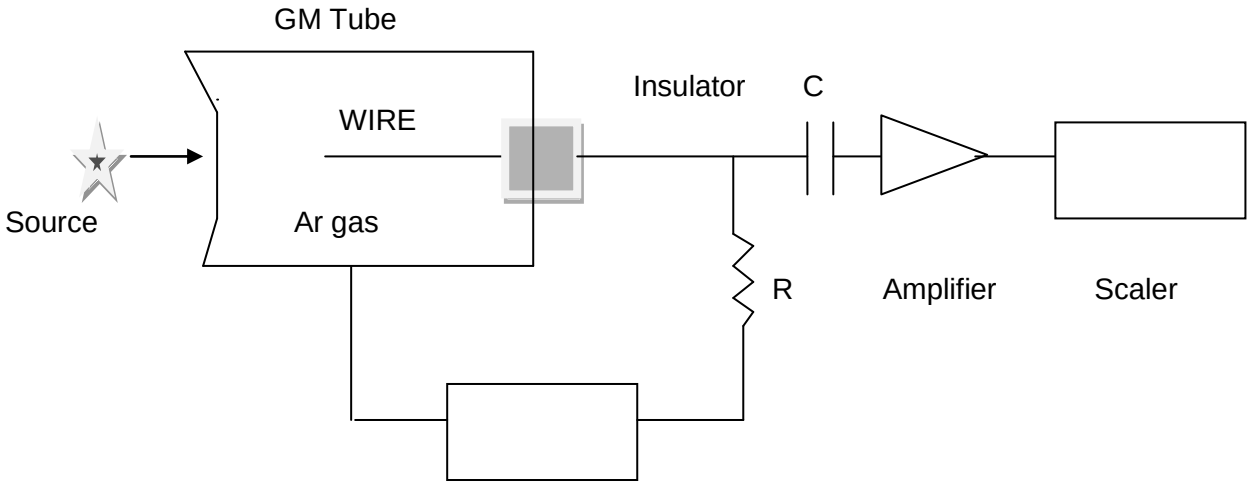


Figure: Schematic diagram of the G-M tube and the associated electronics

2 Dead-time of the GM counter

There is an interval of time following the production of a pulse in the GM tube during which no other pulse can be recorded. This interval is called the dead-time of the system.

If this time is known it can be used to make a correction to the observed count rate to yield the true count rate. The procedure below can give a good estimate of the dead-time.

(a) Obtain a dead-time source (a "split source") from the instructor.
This source is split into two parts. Remove one half of the source and set it aside.

(b) Place the carrier containing one part on the second shelf of the counting chamber and make a trial count of 1 minute duration. Get the maximum count rate you can. This should be more than 20,000 counts per minute, but if not use what you can get.

(c) Make a 2-minute count and record the counts, N_1.

(d) Put the two parts of the source back together, taking care not to disturb the position of the first part. Make a 2-minute count of the combined parts and record as N_c.

(e) Remove the part initially counted and make a 2 minute count on the second part -- record counts as N_2.

(f) Calculate the dead-time of the GM counter using the relation:

$$\tau = \frac{N_1 + N_2 - N_c}{2N_1N_2} T$$

Nuclear Stability

What is the nuclear stability? Nuclear stability means that nucleus is stable meaning that it does not spontaneously emit any kind of radioactivity (radiation). On the other hand, if the nucleus is unstable (not stable), it has the tendency of emitting some kind of radiation, i.e., it is radioactive. Therefore the radioactivity is associated with unstable nucleus:

Stable nucleus – non-radioactive

Unstable nucleus – radioactive

Keep in mind that less stable means more radioactive and more stable means less radioactive.

We want to know why there is a radioactivity. What makes the nucleus a stable one? There are no concrete theories to explain this, but there are only general observations based on the available stable isotopes. It appears that neutron to proton (n/p) ratio is the dominant factor in nuclear stability. This ratio is close to 1 for atoms of elements with low atomic number and increases as the atomic number increases. Then how do we predict the nuclear stability? One of the simplest ways of predicting the nuclear stability is based on whether nucleus contains odd/even number of protons and neutrons:

Protons	Neutrons	Number of Stable Nuclides	Stability
Odd	Odd	4	least stable
Odd	Even	50	↓
Even	Odd	57	↓
Even	Even	168	most stable

Nuclides containing odd numbers of both protons and neutrons are the least stable means more radioactive.

Nuclides containing even numbers of both protons and neutrons are most stable means less radioactive.

Nuclides contain odd numbers of protons and even numbers of neutrons are less stable than nuclides containing even numbers of protons and odd numbers of neutrons.

In general, nuclear stability is greater for nuclides containing even numbers of protons and neutrons or both.

Example

Based on the even-odd rule presented above, predict which one would you expect to be radioactive in each pair?

(a) ${}_{8}O^{16}$ and ${}_{8}O^{17}$

(b) ${}_{17}Cl^{35}$ and ${}_{17}Cl^{36}$

(c) ${}_{10}Ne^{20}$ and ${}_{10}Ne^{17}$

(d) ${}_{20}Ca^{40}$ and ${}_{20}Ca^{45}$

(e) ${}_{80}Hg^{195}$ and ${}_{80}Hg^{196}$

Answer

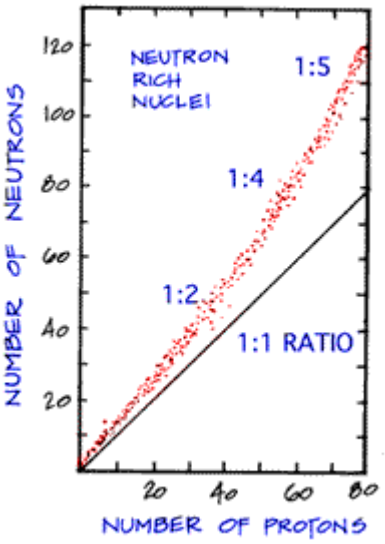
(a) The ${}_{8}O^{16}$ contains 8 protons and 8 neutrons (even-even) and the ${}_{8}O^{17}$ contains 8 protons and 9 neutrons (even-odd). Therefore, ${}_{8}O^{17}$ is radioactive.

(b) The ${}_{17}Cl^{35}$l has 17 protons and 18 neutrons (odd-even) and the ${}_{17}Cl^{36}$ has 17 protons and 19 neutrons (odd-odd). Hence, ${}_{17}Cl^{36}$ is radioactive.

(c) The ${}_{10}Ne^{20}$ contains 10 protons and 10 neutrons (even-even) and the ${}_{10}Ne^{17}$ contains 10 protons and 7 neutrons (even-odd). Therefore, ${}_{10}Ne^{17}$ is radioactive.

(d) The ${}_{20}Ca^{40}$ has even-even situation and ${}_{20}Ca^{45}$ has even-odd situation. Thus, ${}_{20}Ca^{45}$ is radioactive.

(d) The $_{80}Hg^{195}$ has even number of protons and odd number of neutrons and the $_{80}Hg^{196}$ has even number of protons and even number of neutrons. Therefore, $_{80}Hg^{195}$ is radioactive.



Nuclides which have "magic numbers" of protons or neutrons are especially stable. Nuclides with a number of protons and neutrons equal to 2, 8, 20, 50, 82 or 126 are unusually stable. For example there are 10 stable isotopes of Sn with atomic number 50 and only 2 stable isotopes of Sb with atomic number 51. These magic numbers have a significance in nuclear stability similar to the number of electrons associated with the very stable noble gases. A plot of the number of neutrons versus the number of protons in various isotopes is shown below. Stable nuclei are located in an area of the graph known as the belt of stability. Most radioactive nuclei lie outside this belt.

A quantitative measure of the nuclear stability is the nuclear binding energy, which is the energy required to break up a nucleus into its components protons and neutrons. It has been observed that the mass of an atom is always less than the sum of the masses of its subatomic particles. The difference between these two masses is called the mass defect (Δm). This means that mass defect is the difference between the sum of masses of electrons, protons and neutrons (calculated mass) and the actual mass of the atom.

CHAPTER 2

RADIO ACTIVITY

In 1896 Henry Becquerel discovered that crystals of a Uranium salt emitted highly penetrating rays that could affect a photographic plate. Becquerel's discovery was followed by the identification by the Curies (1898) of two other radioactive elements, polonium and radium. There are three kinds of radiations from naturally occurring radioactive substances. In this experiment a collimated beam of rays is supplied by a small piece of radioactive material at the bottom of a long groove in a lead block.

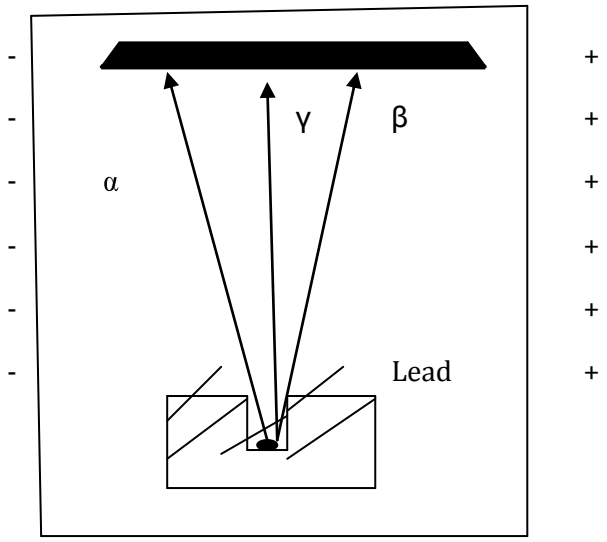


Figure 1

Under the action of the electric field a component bent towards the left, a component bent towards the right and a component came undeviated. A magnetic field also exhibits the same effect. Thus it is clearly proved that the radioactive radiations are made up of three distinct components. Paths bending to left indicate positively charged particles called α-rays, those bending to the right indicate negatively charged particles called β-rays and those going straight ahead indicate no charge and are called γ-rays.

PROPERTIES

I. α- Particles

1. They can produce fluorescence. The fluorescent disc does not show emission of light uniformly, but only of a series of scintillations, showing that α-rays consist of particles which can be counted.

2. They are positively charged particles. By determining their e/m value and charge, one finds that each α-particle is a composite body consisting of two protons and two neutrons and therefore, identical with the helium nucleus.

3. Alpha particles ionize heavily the gases through which they travel.

4. They are easily absorbed by matter. A 0.1cm thick aluminium foil or ordinary thickness of paper is enough to absorb an α-particle.

5. They are scattered while passing through metal sheets.

6. They can produce artificial disintegration of an atom.

7. The velocity of emission of α-particle is characteristic of the isotope from which they emanate, and is about c/20. Because of their large mass they possess considerable momentum and are used as bullets for bombarding atomic nuclei and for artificial disintegration of elements.

8. Alpha particles are characterized by the fact that after they have proceeded a certain distance in air, they are no longer able to ionize the air. This shows that α-particles have a well defined range. The range R is related with the velocity 'v' of the α-particles by the relation

$$V^3 = kR$$

I I. β-Particles

1. β-Particles are negatively charged particles. Their specific charge shows that they consist of very fast moving electrons.
2. They are emitted with a range of velocities whose maximum is characteristic of the isotope from which they emanate and may be as high as 99/100c.
3. They have a smaller energy than α-particles of the same velocity hence they possess smaller ionizing power.
4. They are similar to cathode rays of very high energy except that they originate from the nuclei rather than the outer structure of atoms.
5. It is believed that when β-Particle strikes against the outer electrons of the atom γ-rays are produced.
6. These particles do not show any definite range in air and they follow an irregular path unlike α-particles which go through straight in air.
7. Their penetrating power is greater than that of α-particles but still they are absorbed by an aluminium foil 0.5cm thick.

I I I. Gamma Rays

1. Gamma rays are electromagnetic waves of very short wavelength and are not charged particles.
2. Gamma rays often emitted in conjunction with β-Particles. It is believed that they are produced by the sudden stoppage of β-Particles within the radioactive material.
3. They produce fluorescence and affect a photographic plate.
4. They are reflected from the surface of a crystal.
5. They ionize gases very slightly.
6. When they fall on a substance they are absorbed according to the exponential law

$$I = I_0 e^{-Pt}$$

Where' I_0 ' is the original intensity of γ-rays, 'I' their intensity after they have passed through a substance of thickness 't' and 'P' is the absorption coefficient.

7. By placing lead absorbers of various thicknesses between a source and a detector, it can be shown that γ-rays have a much greater penetrating power than either alpha or β-Particles.

RADIOACTIVE TRANSFORMATION

Rutherford and Soddy proposed a theory to explain the characteristics of the radioactive transformation. According to them a radioactive disintegration occurs with the emission of either a α-particle or a β-Particle. The original nucleus is called parent and the new nucleus formed after the emission of an α-particle or a β-Particle is known as daughter. Rutherford and Soddy gave two rules from which the nature of daughter could be inferred from the nature of the parent and the particle emitted. These rules are

1. The algebraic sum of the charges before the disintegration must equal to the total charge after the disintegration.
2. The sum of the mass numbers of the initial particles must equal the sum of the mass numbers of the final particles.

These rules imply that the emission of an α-particle from an atom must reduce its atomic number by 2 and mass number by 4. Also with the emission of a β-Particle the atomic number of the daughter must be one unit higher than that of the parent while its mass number remains unchanged. Thus, we can represent the transformation involving α and β emission by the following equations

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

$$_{Z}P^{A} \longrightarrow {}_{Z+1}Q^{A} + {}_{-1}e^{0}\ (\beta)$$

Another important feature of Rutherford and Soddy theory is that a daughter atom from a given parent is also usually radioactive. This further decays with the emission of an α and β forming a new radioactive daughter. Thus the disintegration continues as a chain reaction until a stable element is formed. Such a chain of radioactive changes constitute a

radioactive series. In nature there exist four main radioactive series: the uranium, thorium actinium and neptunium series. Each of the series starts with a long lived parent radioactive element. It decays with the successive emissions of α and β-particles forming a series of radioactive elements. This continues until the series terminates at a stable element – usually a stable isotope of lead.

LAWS OF RADIOACTIVE DISINTEGRATION

It can be seen that every radioactive disintegration is accompanied by the emission of an α and β-particle. As a result the original nucleus changes and thus the number of atoms of original kind progressively decrease. The disintegrations occur in a random manner and therefore the phenomenon can only be described statistically.

Consider a radioactive element having N_0 atoms at the instant t = 0. Let 'λ' represent the probability that one of these atoms will disintegrate in a unit time. Let at any time't' later the number of atoms remaining be N. Then the probable number of atoms that disintegrate in a unit time is λN. It is also represented by –(dN/dt). The –ve sign indicate the disintegration reduces the original number of atom.

$$\frac{dN}{dt} = -\lambda N \qquad (1)$$

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

Integrating the above equation we get

$$\ln N = -\lambda t + C \qquad (2)$$

Where C is a constant of integration which can be determined from the condition that at t = 0, N = N_0.

Using this condition in Equ. (2) we get

$$\ln N_0 = 0 + C$$

or $C = \ln N_0$

Substituting the value of C we get

$$\ln N = -\lambda t + \ln N_0$$

or $\ln\left(\frac{N}{N0}\right) = -\lambda t$

or $N = N_0 \exp(-\lambda t)$ (3) [or $N=N_0 e^{-\lambda t}$]

It can be seen from Equ. (3) that the radioactive disintegration follows an exponential law. This is illustrated in the figure 2.

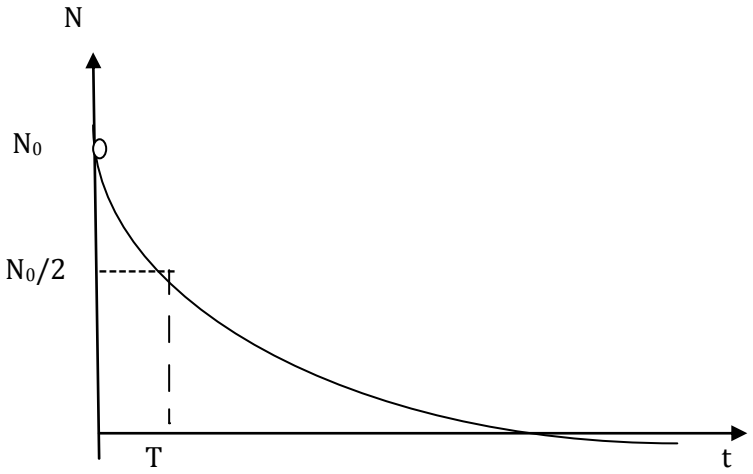


Figure 2

The constant λ is known as transformation or disintegration constant. λ is a characteristic of a particular transformation. A convenient way to obtain λ from experimental data is to plot logN against 't'. The graph would be a straight line whose slope would be –λ.

HALF LIFE PERIOD

The half-life period of a radioactive substance is defined as the time required for one-half of the radioactive substance to disintegrate. The half-life period is different for different substances and depends upon the radioactive constant of the substance.

Suppose half-life period = T, from Eqn.3

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

$$\frac{N}{N0} = e^{-\lambda t}$$

When N = $N0/2$ at t = T

Then $\frac{1}{2} = e^{-\lambda T}$

or $e^{\lambda T} = 2$

$$\lambda T = \log_e 2 = 0.693$$

or $$\boldsymbol{T = 0.693/\lambda}$$

AVERAGE LIFE PERIOD

The actual life of individual atoms lying between zero and infinity. The average or mean life period of the atom can be calculated by adding the life periods of all the atoms and then by dividing it by the total number of atoms present at the beginning.

Suppose the number of atoms at the beginning is equal to N_0. At time't', the number of atoms = N, and dN atoms disintegrate between't' and (t + dt). It means that (-dN) atoms have lived for a time't'. Therefore, total life of (-dN) atoms = (-dN) t. Since all the atoms disintegrate in time from zero to infinity, the sum of the life periods of all the atoms = $\int_0^\infty (-dN)t$

$$The\ average\ life\ period, Ta = \frac{Sum\ of\ the\ life\ periods\ of\ all\ the\ atoms}{Total\ number\ of\ atoms}$$

$$= \int_0^\infty (-dN)t/No$$

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

$dN = -\lambda Ndt = -\lambda Noe^{-\lambda t}dt$ because $N = N_0e^{-\lambda t}$

$$Ta = \int_0^\infty \lambda Noe^{-\lambda t}\, dt.t/No$$

i.e. $$Ta = \lambda \int_0^\infty te^{-\lambda t}dt$$

Integrating by parts

$$Ta = \lambda[\left(\frac{te^{-\lambda t}}{-\lambda}\right) - \frac{\int_0^\infty (e^{-\lambda t}dt)}{-\lambda}]_0^\infty$$

$$= [te^{-\lambda t} - \frac{e^{-\lambda t}}{\lambda}]_0^\infty$$

i.e. **$Ta = 1/\lambda$**

Thus the average life period of a radioactive atom is the reciprocal of the radioactive constant.

$$\boldsymbol{T = \frac{0.693}{\lambda} = 0.693Ta}$$

The average life and half-life period of the radioactive substance are different for different substance. It has been found that the half-life period of Uranium is about 4.5×10^9 years and that of Thorium is 1.34×10^{10} years. These substances have very long half-life period. On the other hand, there are certain substances that disintegrate in a short time. Thorium C^I has a half-life period of 10^{-11} second and Radium C^I disintegrate in 10^{-6} second. It is not possible to change in any way the rate of disintegration of the radioactive substance. The average life period and half-life period of the radioactive substance are independent of pressure and temperature.

RADIOACTIVE DECAY SERIES

The heavy radioactive elements may be grouped into four decay series. The common radioactive elements Thorium, Uranium and Actinium occur naturally and belong to three different series named after them. They are the parent member of their respective series and have the longest half-periods. They decay by a series of α and β emissions and produce radioactive elements which are successively more stable until finally a stable isotope is reached. All three series terminate with element with atomic number 82 (Lead). Following the discovery of the artificial post uranium elements, the Neptunium series has been added, which ends with bismuth, the element number 83.

Thorium (4n) series $_{90}Th^{232}$ 1.39×10^{10} years

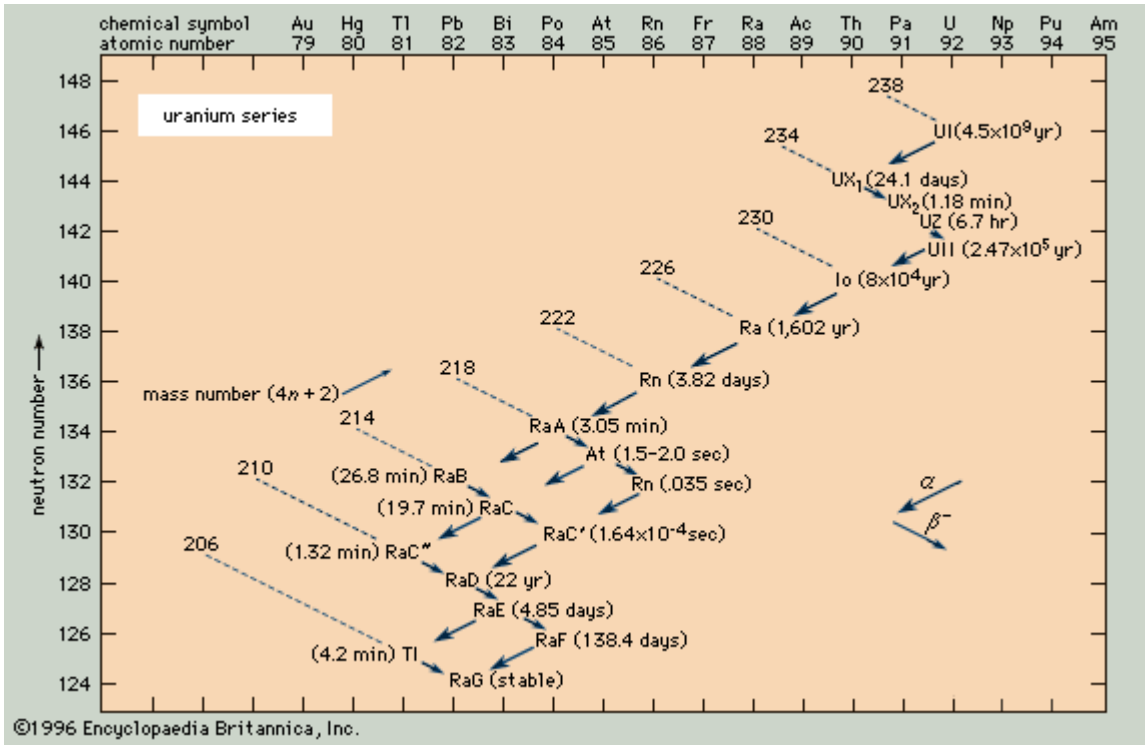
Neptunium (4n+1) series $_{93}Np^{233}$ 2.25×10^6 years

Uranium (4n+2) series $_{92}U^{238}$ 4.51×10^9 years

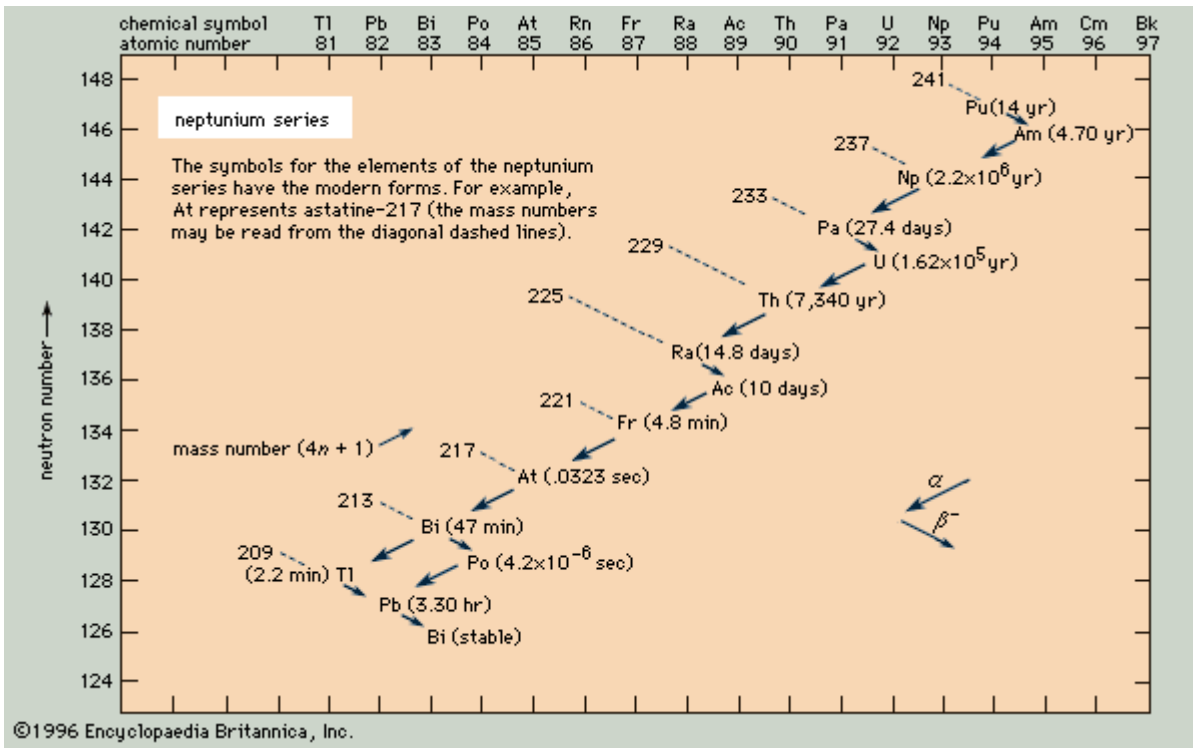
Actinium (4n+3) series $_{92}U^{235}$ 7.07×10^8 years

The numbers indicate that the parent and all the members of a particular series have mass numbers exactly divisible by four, or divisible by four with a remainder of one, two or three. There is no natural cross-linking between the four series, although this can be performed artificially.

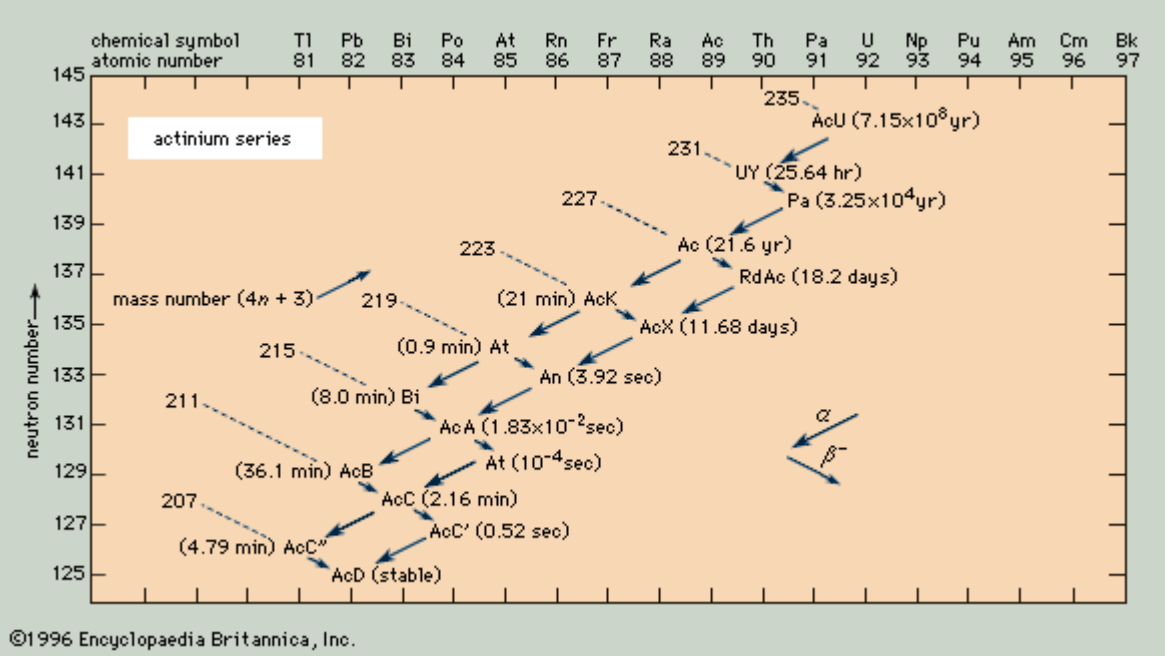
Certain elements, such as Thorium C, disintegrate in two ways; one mode is accompanied by the emission of an alpha particle and the other by a beta particle. Such disintegrations are called branched disintegration which occurs once, at least, in each case. In Thorium C the two types of disintegration always occur in a definite proportion in any given case, thus 33.7%of the Thorium C atoms give off alpha particles to form Thorium C^{II}, where as the other 66.3% emit beta particles and become converted into atoms of Thorium C^I. It will be noted that upon subsequent disintegration, both Thorium C^I and C^{II} yield the same product, namely, Thorium D.



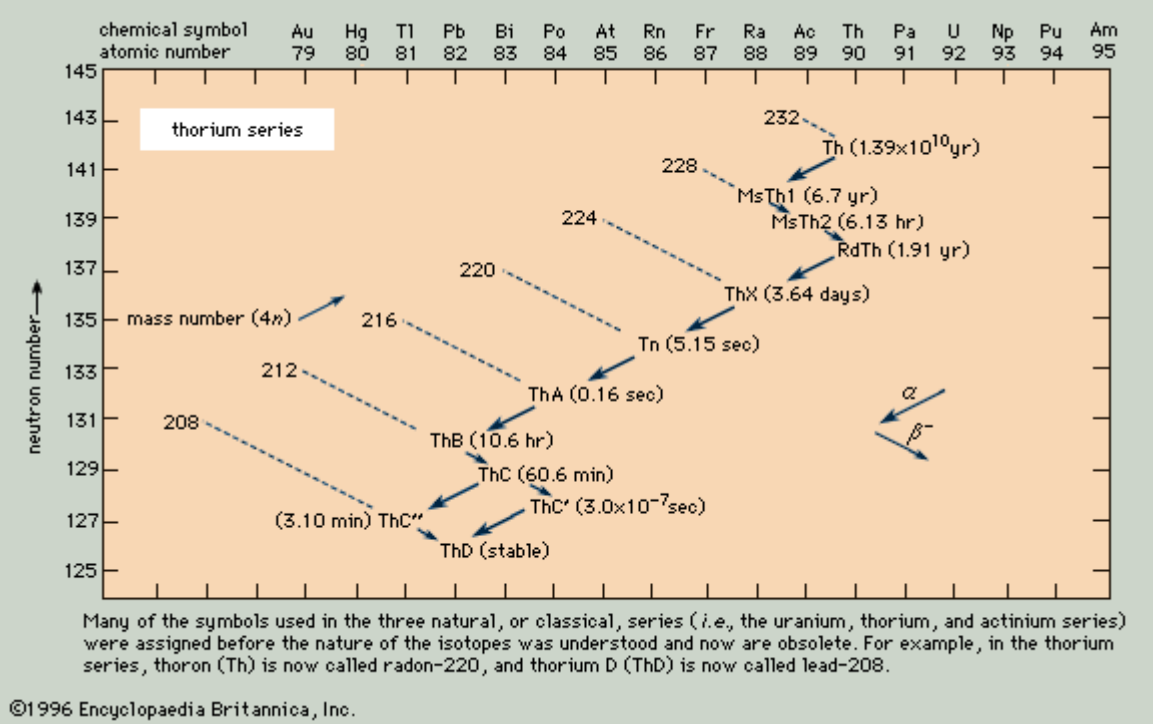
In this case the parent element is Uranium with mass number 238. The series ends with Pb^{206}.



This series is known as Neptunium series because the nuclide in it with the longest half-life period is Neptunium with mass number 237. The series ends with stable Bi^{209}.



The parent element of this series is Uranium with mass number 235. The series ends with stable Lead with mass number 207.



The parent element of this series is Thorium with mass number 232. The series ends with stable Lead with mass number 208.

ISOTOPIC DATING IN GEOLOGY AND COSMOLOGY

The age of a rock or mineral containing Uranium can be determined from the known half life of the parent and the amount of Uranium and the end product present in that rock. Consider the radioactive decay equation

$N=N_0 e^{-\lambda t}$ (1)

Where N_0 ⟶ the amount of U^{238} originally present in a rock at the time it was formed

N ⟶ the amount still left after a time't'

t ⟶ the age of the rock.

The U^{238} decayed has been converted into Pb^{206}. The amount of Pb^{206} will be equal to (N0 –N). Equation (1) becomes

$U^{238} = (U^{238} + Pb^{206})$

Where the symbols U^{238} and Pb^{206} refer to the amount of the respective nuclides existing at present in a given piece of rock. These quantities can be determined by experiment and λ the decay constant of U^{238} is known, hence the age of the rock can be calculated.

A similar expression will hold for the relationship between U^{235}, the parent of the Actinium series, and its end product Pb^{207}.

$U^{235} = (U^{235} + Pb^{207})$

Where λ' is the decay constant of U^{235}. Thus two sets of measurement on a uranium mineral, containing both isotopes, will serve as a check on one another.

[Minerals containing Rubidium may be dated by making use of the fact that Rubidium- 87 present in nature undergoes beta decay and forms Strontium -87. It follows therefore that

$Rb^{87} = (Rb^{87} + Sr^{87})$

The Potassium- 40 decay technique has found particular application in dating stony meteorites. The maximum age of these extraterrestrial objects has been found to be about 4.6×10^9 years.]

RADIO CARBON DATING (Biological)

For more recent objects, especially those of animal or vegetable origin, the radio carbon method is used to determine its age. Carbon in living matter contains a definite proportion of the long lived C^{14} isotope. It is formed by ${}_7N^{14}$ (n, p) ${}_6C^{14}$ reaction between atmospheric nitrogen and neutrons from cosmic rays.

Any radio carbon formed in this way will soon be converted into CO_2. Plants take up these CO_2 during photosynthesis and converted into carbohydrates. Animals consumed these carbohydrates and return a part to the atmosphere during respiration. As a result of this plant – animal carbon cycle equilibrium is established and the carbon present in living matter will contain a constant equilibrium concentration of C^{14} isotope. This amount will be

determined by the rate of formation from the cosmic ray neutrons and the natural decay of C^{14} back to nitrogen-14.

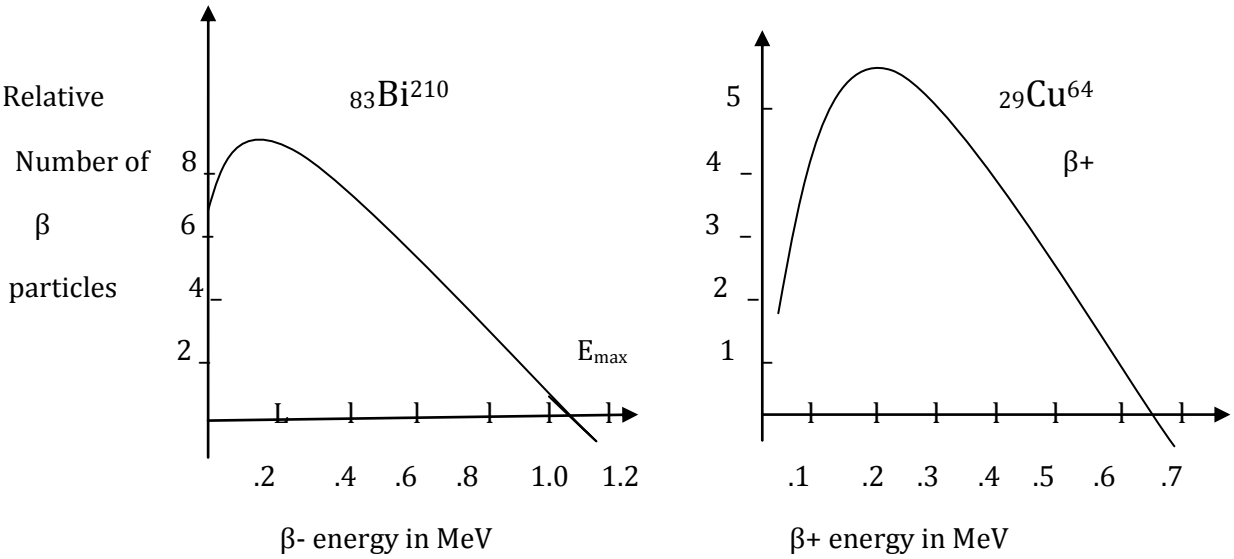
Once the animal (plant) has been separated from equilibrium with the plant-animal cycle, it is expected that the C^{14} will decay, with its normal half-life of 5730 years. It is assumed that at the time of death, the animal (plant) should have the same amount of C^{14} compared to the present living animal (plant). In the decay equation $N=N_0$ the value of N_0 is taken as 15.3 disintegrations per minute per gram of carbon, N is the corresponding number of disintegrations as determined at present i.e. at the age of 't', and λ the decay constant for C^{14}. Since the half-life of C^{14} is 5730 years, λ is 0.693/5730 in reciprocal years. Hence if the number of disintegrations per minute per gram of old carbon is determined, its age can be readily calculated.

The validity of radio carbon dating depends on the postulate that when originally formed, the dated materials had the same content of C^{14} as new material has now. Since this isotope results from the capture of neutrons from cosmic rays, a basic assumption is that the intensity of cosmic rays has not changed appreciably during the course of the past 50,000 years.

BETA (β) DECAY

In certain nuclear transformations electrons are emitted from the nucleus. Some nuclei emit positrons. Also sometimes the nucleus captures one of the orbital electrons, mostly from the shell closest to it, the K-shell. All three of these processes are closely related and are known as β-decay.

The β-ray spectrum is continuous, implying that electrons emitted in β-decay process do not have the same K.E. This continuous nature of the β-ray spectrum is unexpected, since β-transition connects two states of definite energy. Most of the electrons are emitted with only about ⅓rd of the maximum energy E_{max}.



From the figure it should be clear that the continuous β-spectrum has a definite upper energy limit, E_{max}. This energy E_{max}, called the end – point energy is found to be the total energy available for disintegration by β-decay process. For the two cases shown in Figure it is found out that the mass-energy of the nuclear reactions is exactly balanced if we make the Q-value equal to E_{max}, the upper limit of kinetic energy of the β-particles. The nuclear reactions are

$$_{83}Bi^{210} \longrightarrow {}_{84}Po^{210} + {}_{-1}e^{0} + Q \text{ and}$$
$$_{29}Cu^{64} \longrightarrow {}_{28}Ni^{64} + {}_{+1}e^{0} + Q \qquad \text{----(1)}$$

Another series difficulty presented by the continuous nature of the β-rays spectrum is that it appears to violate not only the principle of conservation of energy but also the principle of conservation of angular momentum. This is well brought out by the case of tritium which is a β-emitter. The nuclear reaction is

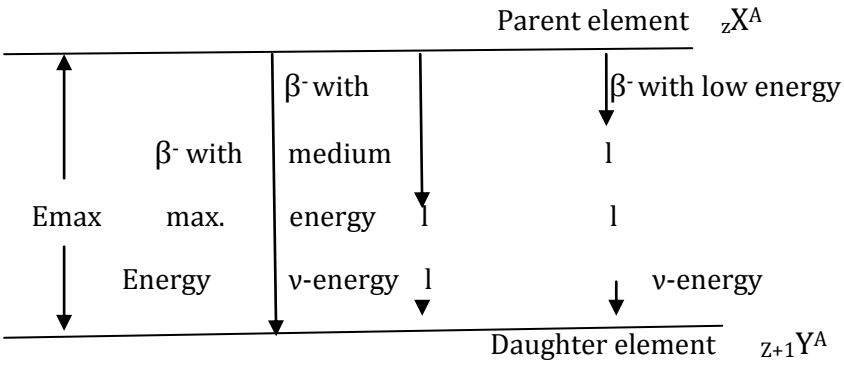
$$_{1}H^{3} \longrightarrow {}_{2}He^{3} + {}_{-1}e^{0} \qquad (2)$$

Clearly the charge and mass numbers are conserved. However angular momentum of $_1H^3$ is ½ and that of $_2He^3$ + e is 0 or 1 from their spins, since both $_2He^3$ and 'e' are fermions and the sum of their spins is either 0 or 1. In addition to this $_2He^3$ + e may have an integral angular momentum because of a possible orbital motion. Thus, the angular momentum of L.H.S. is half-integral while that of R.H.S. is integral and the law of conservation of angular momentum seems to be in question. Further $_1H^3$ is a fermions and the system ($_2He^3$ + e) is a boson. All these difficulties were overcome by the introduction of the neutrino hypothesis.

Pauli's Neutrino Hypothesis

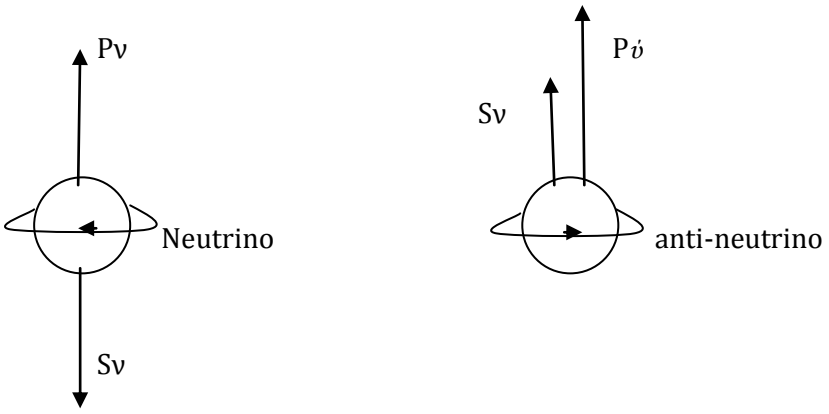
According to Pauli, an additional particle called a neutrino, denoted by ν, is emitted in the process of β-decay. This particle carries away an amount of energy equal to the difference between the observed energy for a particular β-particle and the maximum energy Emax of the continuous β-spectrum. The principle of conservation of energy is thus upheld. To

satisfy the principle of conservation of angular momentum and of charge and nuclear statistic the neutrino must be assigned the following properties.



1. <u>It must have zero charge,</u> because in a β-decay process the charge is conserved without the neutrino. Also if neutrino is charged it would produce ionization which certainly would have been detected zero charge in turn implies negligible magnetic moment.
2. <u>It must have zero or almost zero mass.</u> The mass energy balance of β-decay process like those given by the reactions in Equs. (1) and (2) shows that the neutrino rest mass is negligible (of the order of a few hundred eV)
3. <u>It must have a spin of ½.</u> This will satisfy the law of conservation of angular momentum in β-decay process. Eg. The transformation given by Equ.(2). In this case giving the neutrino a spin 1/2, makes both the LHS and RHS of Equ. (2) have half-integral angular momentum. Further, the neutrino must be fermions so that nuclear statistical requirements are fulfilled. Eg. In the case of Equ (2) both LHS and RHS are fermions systems.

All these properties are assigned to the neutrino in order to preserve important conservation laws in β-decay process. We know that the anti-particle of the electron is the positron. Similarly, neutrino 'ν' has an anti-particle called an anti-neutrino '$\dot{\nu}$'. An anti-neutrino has zero mass, zero charge and a spin of ½. A neutrino 'ν' has its spin Sν always anti-parallel to its momentum Pν while spin S$\dot{\nu}$ of an anti-neutrino $\dot{\nu}$ is always parallel to its momentum P$\dot{\nu}$. In other words, ν is left handed particle while $\dot{\nu}$ is a right handed particle.



(1) For neutrino Sν is anti-parallel to Pν (2) For anti-neutrino S$\dot{\upsilon}$ is parallel to P$\dot{\upsilon}$

By definition, the neutrino (ν) is the particle emitted in β+ decay and the anti-neutrino ($\dot{\upsilon}$) is the particle emitted in β- decay. Incorporating the neutrino hypothesis we may write the equation for beta decay as

$$\left.\begin{array}{l} {}_{Z}X^{A} \longrightarrow {}_{Z+1}Y^{A} + {}_{-1}e^{0} + \dot{\upsilon} \text{ for } \beta\text{- decay} \\ {}_{Z}X^{A} \longrightarrow {}_{Z-1}Y^{A} + {}_{+1}e^{0} + \nu \text{ for } \beta\text{+ decay and} \\ {}_{Z}X^{A} + {}_{-1}e^{0} \longrightarrow {}_{Z-1}Y^{A} + \nu \text{ for electron capture} \end{array}\right\} \quad \text{----(3)}$$

Thus the correct nuclear reactions corresponding to the β decay given in Equs. (1) and (2) are

$$\left.\begin{array}{l} {}_{83}Bi^{210} \longrightarrow {}_{84}Po^{210} + {}_{-1}e^{0} + \dot{\upsilon} \\ {}_{29}Cu^{64} \longrightarrow {}_{28}Ni^{64} + {}_{+1}e^{0} + \nu \text{ and} \\ {}_{1}H^{3} \longrightarrow {}_{2}He^{3} + {}_{-1}e^{0} + \dot{\upsilon} \end{array}\right\} \quad \text{-----(4)}$$

A simple and interesting example of β decay is the disintegration of the free neutron with a half life of about 12 minutes. The neutron is slightly heavier than the proton. This extra mass gives the energy required for β decay of neutron. The decay process can be represented as

$${}_{0}n^{1} \longrightarrow {}_{1}p^{1} + {}_{-1}e^{0} + \dot{\upsilon} \quad \text{-------(5)}$$

Clearly charge, mass number and spin (also statistic) are all conserved. The mass difference between n and p is about 1.3MeV. Thus subtracting the electron rest mass, 0.511MeV, we have about 0.8MeV left. This energy of 0.8MeV is available for sharing between the electron and the anti-neutrino.

Fermi proposed the following basic nuclear transformations which lead to the beta decay process.

$${}_{0}n^{1} \longrightarrow {}_{1}p^{1} + {}_{-1}e^{0} + \dot{\upsilon} \text{ for } \beta\text{- decay}$$

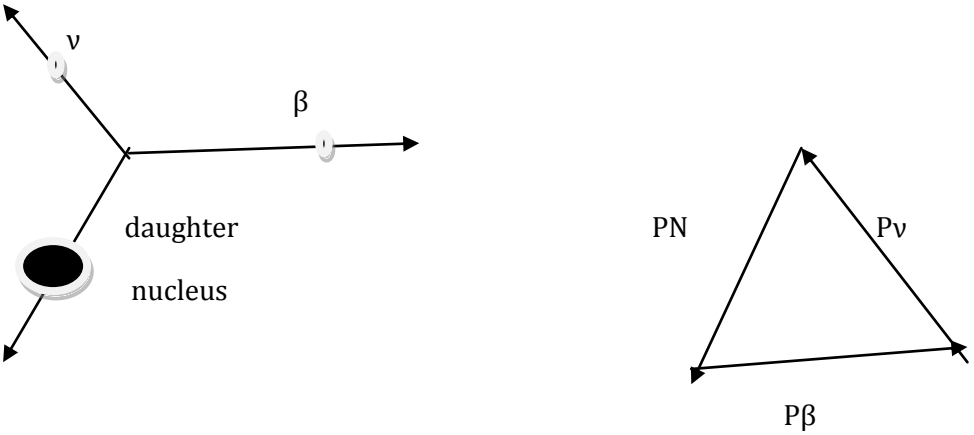
$${}_{1}p^{1} \longrightarrow {}_{0}n^{1} + {}_{+1}e^{0} + \nu \text{ for } \beta\text{+ decay and}$$

$${}_{1}p^{1} + {}_{-1}e^{0} \longrightarrow {}_{0}n^{1} + \nu \text{ for electron capture}$$

The detection of neutrino

The zero charge and the zero rest mass make the neutrino the most difficult particle to detect. It is clear from equ. (5) that beta decay is a three body problem (alpha decay is a two body problem). Conservation of momentum therefore demands that after emission of a β particle and neutrino, the daughter nucleus recoils in a direction not exactly

opposite to the emitted β particle. If this recoil of the daughter can be detected, then it would form an indirect evidence of neutrino existence. Figure indicates this recoil of the daughter and the momentum triangle for the β particle, the daughter nucleus and the neutrino.



PN ⟶ daughter nucleus momentum

Pν ⟶ neutrino momentum

Pβ ⟶ β particle momentum

An estimate of the recoil energy can be made for the daughter nucleus. If the neutrino carries all the energy in the β decay then its momentum is

Pν (max) =

Where Eν (max) will corresponds to end point energy of the β spectrum. For a light nucleus like O^{14} which β decays by the process

$$_8O^{14} \longrightarrow {}_7N^{14} + \beta^+ + \nu$$

The end point energy is Emax = Eν(max) = 1.812MeV

Therefore Pν(max) = = PN by momentum conservation

Where PN = momentum of daughter nucleus

Clearly this momentum corresponds to daughter recoil energy, $EN = (PN)^2/2M$, where M is the mass of the daughter N^{14}.

$EN = [(1.812MeV)^2/C^2]/[(26087.73MeV)^2/C^2] = 125eV$

Thus we see that even for a very favourable case of a light nucleus the recoil energy is about 125eV. This makes experimental measurements on daughter recoil extremely difficult.

The recoil experiments have been performed with several β emitters. A cloud chamber photograph reveals that the daughter nucleus recoils in a direction not opposite to the path of the emitted β particle. This clearly demonstrates that the β decay is a three body problem and gives indirect proof of the existence of the neutrino.

Gamma (γ) decay

When a nucleus is in an excited state, it emits γ–rays and the nucleus is eventually brought to the ground state. Usually when a nucleus decays by α – emission or β emission, it is left in an excited state. If it is energetically impossible for this nucleus to emit another particle, or if the decay by emission of another particle is slow, then the nucleus decays by electromagnetic interaction. Let, Ei be the energy of an excited state of a nucleus. When there is a transition to a lower state (or ground state) of energy Ef, we have the release of energy

$\Delta E = Ei - Ef$

This energy ΔE is emitted by one of the following three electromagnetic interactions.

(i) γ-ray emission
(ii) Internal conversion
(iii) Internal pair production

The last process of internal pair production occurs much less frequently than others. To create an electron-positron pair, ΔE must be at least 1.02MeV. The gamma emission and internal conversion are much more frequent.

γ -ray emission – Selection Rule

The gamma ray spectra would correspond to discrete energies. Or in other words, a γ-ray spectrum consists of sharp lines. If we neglect the small recoil energy of the γ–emitter nucleus, the energy of the γ-ray is given by

$hf = \Delta E = Ei - Ef$

where f is the frequency of the γ–photon.

If the spin to the initial state of the nucleus is Ii and that of the final state is If then, L, the angular momentum carried off by the γ –photon is

$L = Ii - If = \Delta I$

In other words we have

$|Ii - If| \leq L \leq |Ii - If|$

We have the following selection rules for γ –decay

(i) The γ–photon must carry away at least one unit of angular momentum and
(ii) In γ –decay, parity is always conserved.

In this discussion, ΔI represent the vector change in angular momentum which must be distinguished from the change in the magnitude of the angular momentum ΔI = |Ii ± If|. It is ΔI that is conserved during a γ – emission, though ΔI is what is easily obtained if spins of the initial and final states are known. As an example let us consider a case in which the nuclear spin changes from 4 to 2 during a transition. Clearly ΔI is simply the scalar difference 2. However |ΔI| can have values 2,3,4,5 or 6 since any integral value from 4-2 to 4+2 is possible.

Obviously ΔI for a γ- transition cannot be zero, because the intrinsic spin of the photon is one.

Internal conversion

Internal conversion is a process which enables an excited nuclear state to come down to some lower state without the emission of a γ- photon. The energy ΔE involved in this nuclear transition gets transformed directly to a bound electron of the atom. Such an electron gets knocked out of the atom. Electrons like this are called conversion electrons and the process is called internal conversion.

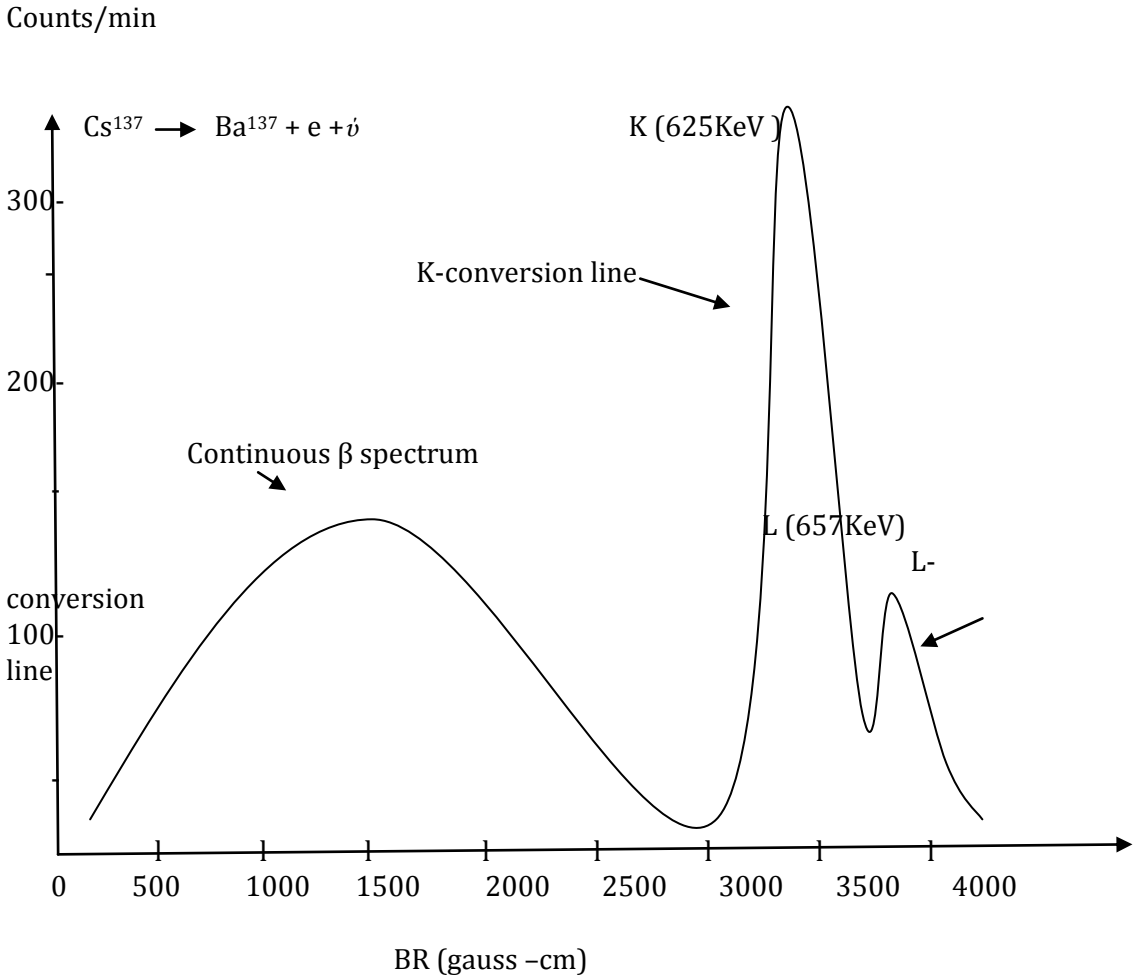
Wave mechanically; an atomic electron spends part of its time inside a nucleus. This probability is highest for the K-shell electrons which are closest to the nucleus. For such a case, the nucleus may de-excite not by γ- emission but by giving the excitation energy ΔE directly to a K-shell electron. Internal conversion is also possible (though less, as compared to the K-shell) for higher atomic shells, L, M etc.

The K.E. of the converted electron Ke is

Ke =ΔE – Be

Where Be is the atomic binding energy of the electron, and ΔE = Ei – Ef = Nuclear excitation energy between initial state i (higher) and final state f (lower).

Usually the continuous β spectra are superimposed by discrete lines due to conversion electrons. Figure shows two internal conversion lines from Cs^{137}. The continuous β distribution is also shown.



Continuous β spectrum of Cs^{137} showing K and L internal conversion lines.

If a radioactive source emits Nγ γ -rays and Ne conversion electrons during the same interval of time then the conversion coefficient α is defined as

The value of α is found to depend on transition energy, multipole character of transition and the atomic number Z.

Problem

1. $T\ell^{203}$ atom resulting from β decay of Hg^{203} atom emits 4 groups of conversion electrons with kinetic energies of 266.3, 264.2, 263.6 and 193.3KeV. To what shell of Tℓ atom, K L1, L2 and L3 does each group correspond? The electron binding energies in the shells are 87.7, 15.4, 14.8 and 12.7 KeV respectively. Calculate the energies of γ -quanta concurrent with that decay.

We know that Ke = ΔE –Be

Clearly the maximum kinetic energy group corresponds to L3 conversion electrons as they are least tightly bound

266.3KeV = ΔE -12.7KeV

Therefore ΔE = 279KeV

Similarly 264.2KeV = ΔE – 14.8KeV

263.6KeV = ΔE – 15.4KeV

193.3KeV = ΔE – 87.7KeV for the K Shell

For all these, ΔE = 279KeV. Thus the γ - energy concurrent with the β decay is 279KeV.

ALPHA DECAY

Alpha decay, commonly occur in nuclei with atomic number greater than 82. It involves the decay of an unstable parent nucleus into its daughter nucleus by the emission of an α-particle, the nucleus $_2He^4$. The process takes place spontaneously because it is energetically favored. The mass of the parent nucleus formed would be greater than the mass of the daughter nucleus plus the mass of the α-particle. The energy made available in the decay is the energy equivalent of the mass difference. This decay energy is carried away by the α-particle as K.E..

GAMOWS THEORY OF α-DECAY

The facts explained by the theory are the following

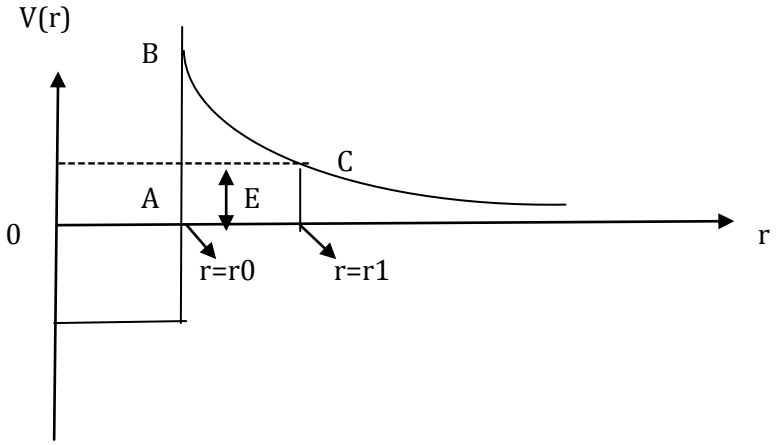
1. Starting with N radioactive atoms Nλdt disintegrate in a time dt.
2. Value of λ varies over a wide range.
3. According to Geiger and Nuttal's law there is an approximately linear relation between log λ and E, where E is the energy with which α-particles are emitted from the nucleus.

In Gamow's theory an alpha particle is assumed to be pre-formed inside the parent nucleus. The force field in which α-particle moves is determined by the daughter nucleus.

Consider a nucleus of mass number A and atomic number Z. During α-decay energy is released and a α-particle is removed from it to form the daughter nucleus (A-4, Z-2). E is the energy released due to emission of α-particle. The P.E. V(r) of a α-particle at a distance 'r' from the daughter atom (A-4, Z-2) is expressed as

$$V(r) = \frac{2(Z-2)e^2}{r}$$ for large values of r (1)

At distances comparable with nuclear radius the potential function V(r) must take a shape corresponding to an attractive force field. This has to be so because α-particle is held inside the nucleus for a considerably long time. Gamow assumed the potential function to be as shown in Figure. This is usually referred to as square well potential approximation



An – particle escaping from nucleus with energy E is visualized as having same energy E inside the nucleus. This α-particle is visualized as separated from outside by a potential barrier ABC. According to classical physics any α-particle reaching r = r0 must reverse its path and cannot escape from nucleus unless given additional energy. However, in quantum mechanical model the α-particle has a finite probability of being able to cross the potential hill. The decay constant λ, in this model, is a measure of the probability of escape of α-particle per unit time. Therefore

$\lambda = np$ (2)

where 'n' is the number of α-particle reaches the potential barrier per unit time and 'p' is the probability of its crossing potential barrier. If d0 stands for diameter of nucleus and 'v' speed of a α-particle then $n \sim \frac{v}{d_0}$. The probability 'p' can be calculated quantum mechanically using WKB perturbation theory.

$$P = \exp\left[-\frac{2}{\hbar}\int_A^C \sqrt{\{2m(V(r) - E)\}}dr\right] \equiv e^{-G} \quad \text{--------(3)}$$

Here m stands for mass of α particle and the limits of integration corresponds A(r = r0) to C(r=r1). The square well potential V(r) is expressed mathematically as

$V(r) \approx 2(Z-2)e^2/r$ for $r > r0$
$= \text{constant}$ for $r < r0$ } ------(4)

Where ro is of the order of nuclear radius. The distance r1 is measured from the fact that at r=r1, V(r) = E, therefore

$E = 2(Z-2)e^2/r1$ or

$r1 = 2(Z-2)e^2/E$ ----------(5)

Equ.(3) can be rewritten as

$$G = \frac{2}{\hbar}\int_{r0}^{r1}\left[2m\left\{\frac{2(Z-2)}{r}e^2 - E\right\}\right]^{1/2}dr$$

$$= \frac{2}{\hbar}\int_{r0}^{r1}\left[2m\left\{\frac{Er1}{r} - E\right\}\right]^{1/2}dr \quad \text{using equ. (5)}$$

$$= \frac{2}{\hbar}(2mE)^{1/2} \int_{r0}^{r1} \left(\frac{r1}{r} - 1\right)^{1/2} dr \quad \text{----------(6)}$$

To evaluate the integral put $(\frac{r1}{r} - 1) = u^2$ or $r = r1/(1+u^2)$

Therefore $dr = -2udur1/(1+u^2)^2$

Hence $G = \frac{-2}{\hbar}(2mE)^{1/2} \int_{\sqrt{(\frac{r1}{r0}-1)}}^{0} [r1u2udu/(1+u^2)^2]$

$= \frac{4}{\hbar} mvr1 \int_{0}^{\sqrt{(\frac{r1}{r0}-1)}} [u^2 du/(1+u^2)^2$ because $E = \frac{1}{2} mv^2$

$= \frac{4}{\hbar} mvr1.\ \frac{1}{2} \Big[\tan^{-1}u - u/(1+u^2) \Big]_{0}^{(r1/r0-1)^{1/2}}$ -------(7)

Let $ro/r1 = \cos^2 W$ -------7(a) so that

$(r1/r0 -1)^{1/2} = (\sec^2 W -1)^{1/2} = \tan W$ $\tan W$

Therefore $G = \frac{2mvr1}{\hbar} \Big[\tan^{-1}u - u/(1+u^2) \Big]_{0}^{\tan W}$

$= \frac{2mvr1}{\hbar} [W - \tan W/(1+\tan^2 W)]$

$= \frac{mvr1}{\hbar} [2W - 2\tan W \cos^2 W]$

$= \frac{mvr1}{\hbar} [2W - 2\sin W \cos W]$

$= \frac{mvr1}{\hbar} [2W - \sin 2W]$

$= \frac{mv}{\hbar} \frac{2(Z-2)}{r0} e^2 [2W - \sin 2W]$ ---------(8)

Let us introduce a quantity B defined as

$B = \frac{2(Z-2)}{r0} e^2 = E \frac{r1}{r0}$ -------(9)

It is obvious that B is equal to Coulomb potential of daughter atom at r = r0. It is interpreted as the "potential barrier height". Combining Equs(7a) and (9) we get

$\cos^2 W = E/B$

Or $W = \cos^{-1}\sqrt{(E/B)} = \pi/2 - \sqrt{(E/B)}$ for $E \ll B$

Therefore $2W - \sin 2W = (\pi - 2\sqrt{(E/B)}) - \sin(\pi - 2\sqrt{(E/B)})$

$= \pi - 2\sqrt{(E/B)} - \sin 2\sqrt{(E/B)}$

$= \pi - 2\sqrt{(E/B)} - 2\sqrt{(E/B)}$

$= \pi - 4\sqrt{(E/B)}$

Since $E \ll B$, as a crude approximation we may write

$2W - \sin 2W = \pi$ -------(10)

Using this approximation Equ. (8) reduces to

$$G = \frac{\sqrt{(2mE)}}{\hbar} 2\frac{(Z-2)}{E} e^2 \pi \qquad \text{(Where } m^2v^2 = 2mE\text{)}$$

$$= [\frac{2\pi}{\hbar}\sqrt{2m}\ (Z-2)e^2]\ E^{1/2} \quad \text{------(11)}$$

We can write decay constant λ as

$$\lambda = np = ne^{-G}$$

$$\ell n\lambda = \ell_n n - G$$

$$= \ell_n n - \frac{2\pi}{\hbar}\sqrt{2m}\,(Z-2)e^2E^{-1/2}$$

$$= a - b(Z-2)E^{-1/2} \text{ -------(12)}$$

Where $a = \ell n\ n$ and $b = \frac{2\pi}{\hbar}\sqrt{(2m)e^2}$

Equ. (12) can be rewritten in terms of speed of α particle as

$\ell n\lambda = a - b(Z-2)/v$ -----(13)

This equation represent the Geiger and Nuttal's law. Equation (13) also tells that the decay constant varies exponentially with the energy of α-particle, since dependence of λ on G is an exponential one, it shows variations are large. The Gamow theory, therefore explains qualitatively the essential features of α-decay.

The main drawback of Gamow's theory is the assumption of pre-existence of a α-particle in the present nucleus, which is not likely to be correct.

Electron–positron annihilation

Electron–positron annihilation occurs when an electron (e^-) and a positron (e^+, the electron's antiparticle) collide. The result of the collision is the annihilation of the electron and positron, and the creation of gamma ray photons or, at higher energies, other particles:

$$e^- + e^+ \rightarrow \gamma + \gamma$$

The process must satisfy a number of conservation laws, including:

- Conservation of electric charge. The net charge before and after is zero.
- Conservation of linear momentum and total energy. This forbids the creation of a single gamma ray. However, in quantum field theory this process is allowed; see examples of annihilation.
- Conservation of angular momentum.

As with any two charged objects, electrons and positrons may also interact with each other without annihilating, in general by elastic scattering.

Low energy case

There are only a very limited set of possibilities for the final state. The most possible is the creation of two or more gamma ray photons. Conservation of energy and linear momentum forbid the creation of only one photon. (An exception to this rule can occur for tightly bound atomic electrons.) In the most common case, two photons are created, each with energy equal to the rest energy of the electron or positron (511 keV). A convenient frame of reference is that in which the system has no net linear momentum before the annihilation; thus, after collision, the gamma rays are emitted in opposite directions. It is also common for three to be created, since in some angular momentum states, this is necessary to conserve C parity. It is also possible to create any larger number of photons, but the probability becomes lower with each additional photon because these more complex processes have lower probability amplitudes.

Since neutrinos also have a smaller mass than electrons, it is also possible—but exceedingly unlikely—for the annihilation to produce one or more neutrino–antineutrino pairs. The same would be true for any other particles, which are as light, as long as they share at least one fundamental interaction with electrons and no conservation laws forbid it. However, no other such particles are known.

High energy case

If either the electron or positron, or both, have appreciable kinetic energies, other heavier particles can also be produced (such as D mesons), since there is enough kinetic energy in the relative velocities to provide the rest energies of those particles. It is still possible to produce photons and other light particles, but they will emerge with higher energies.

At energies near and beyond the mass of the carriers of the weak force, the W and Z bosons, the strength of the weak force becomes comparable with electromagnetism. This means that it becomes much easier to produce particles such as neutrinos that interact only weakly.

The heaviest particle pairs yet produced by electron–positron annihilation in particle accelerators are W+ –W− pairs. The heaviest single particle is the Z boson. The driving motivation for constructing the International Linear Collider is to produce Higgs bosons in this way.

Artificial Radioactivity

Artificial or induced radioactivity was discovered by Curie and Joliot in 1934. They were studying the disintegration of light elements by α-particles. When boron and aluminium were bombarded with α-particles, the target continued to emit radiations even after the source of α-particles had been removed. With the help of magnetic deflection experiments the ionization measurements it was found that the radiations consisted of particles having a positive charge and mass equal to electrons. These particles are known as positrons. Curie and Joliot explained the phenomenon as follows: When the above elements are bombarded by α-particles, an unstable nucleus was formed and this nucleus disintegrated spontaneously. In the case of boron, the nuclear reactions are

$${}_5B^{10} + {}_2He^4 \longrightarrow {}_7N^{13} + {}_0n^1$$

The nitrogen is radioactive and decays with a half-life of 10.1 minutes into a stable isotope of carbon with the emission of a positron.

$${}_7N^{13} \longrightarrow {}_6C^{13} + {}_1e^0$$

In the case of aluminium,

$${}_{13}Al^{27} + {}_2He^4 \longrightarrow {}_{15}P^{31} \longrightarrow {}_{15}P^{30} + {}_0n^1$$

P^{30} is radioactive. The half-life period of radiophosphorus is about 3 minutes and it disintegrates producing a stable isotope of silicon and ejecting a positron.

$${}_{15}P^{30} \longrightarrow {}_{14}Si^{30} + {}_1e^0$$

Curie and Joliot verified their explanation by chemical analysis. In the boron reaction, the target used was boron nitride (BN). After irradiation with α-particles for a few minutes, it was heated with caustic soda. One of the products of this chemical reaction was gaseous ammonia NH3. When the various products were tested for positron activity, it was found that only NH3 had it. This indicated that nitrogen was the radioelement produced in the experiment. Its half-life was found to be the same as that produced in other irradiated boron targets.

This phenomenon, by which even light elements could be made artificially radioactive, is called induced radioactivity. The artificial radioactivity follows the same laws of decay as natural radioactivity. Unlike natural radioactive substances, which emit α, β and -rays, artificial radioactive substances emit electrons, neutrons, positrons or -rays.

Practically all elements can be made artificially radioactive by bombarding them with various particles. It is found that electron emission takes place in artificial radioelements produced by (n, p), (n, α), (d, p) and (n,) reactions.

Examples

(1) $_{7}N^{14} + {}_{0}n^{1} \longrightarrow (_{7}N^{15}) \longrightarrow {}_{6}C^{14*} + {}_{1}H^{1}$

$_{6}C^{14*} \longrightarrow {}_{7}N^{14} + {}_{-1}e^{0}$

(2) $_{13}Al^{27} + {}_{0}n^{1} \longrightarrow (_{13}Al^{28}) \longrightarrow {}_{11}Na^{24*} + {}_{2}He^{4}$

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

(3) $_{15}P^{31} + {}_{1}H^{2} \longrightarrow (_{16}S^{33}) \longrightarrow {}_{15}P^{32*} + {}_{1}H^{1}$

$_{15}P^{32*} \longrightarrow {}_{16}S^{32} + {}_{-1}e^{0}$

(4) $_{49}In^{115} + {}_{0}n^{1} \longrightarrow (_{49}In^{116}) \longrightarrow {}_{49}In^{116*} +$

$_{49}In^{116*} \longrightarrow {}_{50}Sn^{116} + {}_{-1}e^{0}$

Positron emission takes place in artificial radio-elements produced by (p,), (p, n), (α,n) and (, n) reactions.

Example

$_{6}C^{12} + {}_{1}H^{1} \longrightarrow (_{7}N^{13}) \longrightarrow {}_{7}N^{13*} +$

$_{7}N^{13*} \longrightarrow {}_{6}C^{13} + {}_{1}e^{0}$

Preparation of Radio-elements

(1) Artificially radioactive elements are now being produced by placing the elements in nuclear reactors. The large number of neutrons available in the nuclear reactor bombarded with these elements. Thus radio-phosphorus can be obtained by neutron bombardment of P^{31}. A large number of isotopes are obtained from nuclear reactors by the neutron radiative capture (n, process.

$_{15}P^{31} + {}_{0}n^{1} \longrightarrow {}_{15}P^{32} +$

$_{27}Co^{59} + {}_{0}n^{1} \longrightarrow {}_{27}Co^{60} +$

The most important radioisotopes so produced are Tritium ($_{1}H^{3}$), Radio-sodium ($_{11}Na^{24}$), Radio-Phosphorus ($_{15}P^{32}$), Radio-cobalt ($_{27}Co^{60}$), Radio-carbon ($_{6}C^{14}$), Radio-iodine (I^{131}) and Radio-sulphur (S^{35}).

(2) Another method of preparing a radio-element is to bombard the element with deuterons from a cyclotron. Radio-sodium can be obtained by bombarding Mg^{24} with deuterons. The reaction in this case is (d, α) reaction. The half-life of the radio-isotopes ranges from a fraction of a second to several thousand years.

Applications of Radio-isotopes

As tracers, radio isotopes have found wide application in agriculture, medicine, industry and research. To study the dynamics of a particular system, a radio-isotope is added and the course of the isotope is studied to understand the whole system. For instance, $_8O^{15}$ mixed with normal air breathed by a patient, enables radio-detection of the path of inhaled oxygen in the lungs. Phosphorus uptake by plants from the soil is studied using a phosphate fertilizer containing the radio-isotope P^{32}. Brain and thyroid tumours are detected using I^{131}.

Transuranium elements

The most fruitful source of artificial radionuclides is the radiative capture of neutrons, the (n,) reaction, which usually yields an electron emitting product. In 1934, Fermi suggested the possibility that the bombardment of uranium with neutrons might result in the production of elements with nuclear charge greater than 92. If U^{238} were to capture a neutron, the following reaction should occur:

$$_{92}U^{238} + {}_0n^1 \longrightarrow {}_{92}U^{239*} \longrightarrow {}_{92}U^{239} +$$

If the U^{239} were then to decay by electron emission, the result would be a nuclide with Z=93, an isotope of a hitherto unknown element. Early experiments showed that when uranium was bombarded with neutrons, four different β activities were detected, one of which was presumably associated with $_{92}U^{239}$. It was also considered possible that the new element with Z= 93 might decay by electron emission to form an isotope of another new element with Z=94. Any element which might have values of Z greater than 92 were called transuranium element because they would lie beyond uranium in the periodic table. Between 1934 and 1939, many attempts were made to make and identify transuranium elements. The research on these elements led to the discovery of nuclear fission.

The following is the list of transuranic elements.

Neptunium ($_{93}$Np), Plutonium ($_{94}$Pu), Americium ($_{95}$Am), Curium ($_{96}$Cm), Berkelium ($_{97}$Bk), Californium ($_{98}$Cf), Einsteinium ($_{99}$Es), Fermium ($_{100}$Fm), Mendelevium ($_{101}$Md), Nobelium (102No), Lawrencium ($_{103}$Lw), Kurchatovium ($_{104}$Xv) etc.

Electron–positron annihilation

Electron–positron annihilation occurs when an electron (e^-) and a positron (e^+, the electron's antiparticle) collide. The result of the collision is the annihilation of the electron and positron, and the creation of gamma ray photons or, at higher energies, other particles:

$$e^- + e^+ \rightarrow \gamma + \gamma$$

The process must satisfy a number of conservation laws, including:

- Conservation of electric charge. The net charge before and after is zero.
- Conservation of linear momentum and total energy. This forbids the creation of a single gamma ray. However, in quantum field theory this process is allowed; see examples of annihilation.
- Conservation of angular momentum.

As with any two charged objects, electrons and positrons may also interact with each other without annihilating, in general by elastic scattering.

Low energy case

There are only a very limited set of possibilities for the final state. The most possible is the creation of two or more gamma ray photons. Conservation of energy and linear momentum forbid the creation of only one photon. (An exception to this rule can occur for tightly bound atomic electrons.) In the most common case, two photons are created, each with energy equal to the rest energy of the electron or positron (511 keV). A convenient frame of reference is that in which the system has no net linear momentum before the annihilation; thus, after collision, the gamma rays are emitted in opposite directions. It is also common for three to be created, since in some angular momentum states, this is necessary to conserve C parity. It is also possible to create any larger number of photons, but the probability becomes lower with each additional photon because these more complex processes have lower probability amplitudes.

Since neutrinos also have a smaller mass than electrons, it is also possible—but exceedingly unlikely—for the annihilation to produce one or more neutrino–antineutrino pairs. The same would be true for any other particles, which are as light, as long as they share at least one fundamental interaction with electrons and no conservation laws forbid it. However, no other such particles are known.

High energy case

If either the electron or positron, or both, have appreciable kinetic energies, other heavier particles can also be produced (such as D mesons), since there is enough kinetic energy in the relative velocities to provide the rest energies of those particles. It is still possible to produce photons and other light particles, but they will emerge with higher energies.

At energies near and beyond the mass of the carriers of the weak force, the W and Z bosons, the strength of the weak force becomes comparable with electromagnetism. This means that it becomes much easier to produce particles such as neutrinos that interact only weakly.

The heaviest particle pairs yet produced by electron–positron annihilation in particle accelerators are $W^+ W^-$ pairs. The heaviest single particle is the Z boson. The driving motivation for constructing the International Linear Collider is to produce Higgs bosons in this way.

Artificial Radioactivity

Artificial or induced radioactivity was discovered by Curie and Joliot in 1934. They were studying the disintegration of light elements by α-particles. When boron and aluminium were bombarded with α-particles, the target continued to emit radiations even after the source of α-particles had been removed. With the help of magnetic deflection experiments the ionization measurements it was found that the radiations consisted of particles having a positive charge and mass equal to electrons. These particles are known as positrons. Curie and Joliot explained the phenomenon as follows: When the above elements are bombarded by α-particles, an unstable nucleus was formed and this nucleus disintegrated spontaneously. In the case of boron, the nuclear reactions are

$$_5B^{10} + {}_2He^4 \longrightarrow {}_7N^{13} + {}_0n^1$$

The nitrogen is radioactive and decays with a half-life of 10.1 minutes into a stable isotope of carbon with the emission of a positron.

$$_7N^{13} \longrightarrow {}_6C^{13} + {}_1e^0$$

In the case of aluminium,

$$_{13}Al^{27} + {}_2He^4 \longrightarrow {}_{15}P^{31} \longrightarrow {}_{15}P^{30} + {}_0n^1$$

P^{30} is radioactive. The half-life period of radiophosphorus is about 3 minutes and it disintegrates producing a stable isotope of silicon and ejecting a positron.

$$_{15}P^{30} \longrightarrow {}_{14}Si^{30} + {}_1e^0$$

Curie and Joliot verified their explanation by chemical analysis. In the boron reaction, the target used was boron nitride (BN). After irradiation with α-particles for a few minutes, it was heated with caustic soda. One of the products of this chemical reaction was gaseous ammonia NH3. When the various products were tested for positron activity, it was found that only NH3 had it. This indicated that nitrogen was the radioelement produced in the experiment. Its half-life was found to be the same as that produced in other irradiated boron targets.

This phenomenon, by which even light elements could be made artificially radioactive, is called induced radioactivity. The artificial radioactivity follows the same laws of decay as natural radioactivity. Unlike natural radioactive substances, which emit α, β and γ-rays, artificial radioactive substances emit electrons, neutrons, positrons or γ-rays.

Practically all elements can be made artificially radioactive by bombarding them with various particles. It is found that electron emission takes place in artificial radioelements produced by (n, p), (n, α), (d, p) and (n, γ) reactions.

Examples

(5) $$_7N^{14} + {}_0n^1 \longrightarrow ({}_7N^{15}) \longrightarrow {}_6C^{14*} + {}_1H^1$$

$_6C^{14*} \longrightarrow {}_7N^{14} + {}_{-1}e^0$

(6) $_{13}Al^{27} + {}_0n^1 \longrightarrow (_{13}Al^{28}) \longrightarrow {}_{11}Na^{24*} + {}_2He^4$

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

(7) $_{15}P^{31} + {}_1H^2 \longrightarrow (_{16}S^{33}) \longrightarrow {}_{15}P^{32*} + {}_1H^1$

$_{15}P^{32*} \longrightarrow {}_{16}S^{32} + {}_{-1}e^0$

(8) $_{49}In^{115} + {}_0n^1 \longrightarrow (_{49}In^{116}) \longrightarrow {}_{49}In^{116*} + \gamma$

$_{49}In^{116*} \longrightarrow {}_{50}Sn^{116} + {}_{-1}e^0$

Positron emission takes place in artificial radio-elements produced by (p, γ), (p, n), (α,n) and (γ, n) reactions.

Example

$_6C^{12} + {}_1H^1 \longrightarrow (_7N^{13}) \longrightarrow {}_7N^{13*} + \gamma$

$_7N^{13*} \longrightarrow {}_6C^{13} + {}_1e^0$

Preparation of Radio-elements

(3) Artificially radioactive elements are now being produced by placing the elements in nuclear reactors. The large number of neutrons available in the nuclear reactor bombarded with these elements. Thus radio-phosphorus can be obtained by neutron bombardment of P^{31}. A large number of isotopes are obtained from nuclear reactors by the neutron radiative capture (n, γ)process.

$_{15}P^{31} + {}_0n^1 \longrightarrow {}_{15}P^{32} + \gamma$

$_{27}Co^{59} + {}_0n^1 \longrightarrow {}_{27}Co^{60} + \gamma$

The most important radioisotopes so produced are Tritium ($_1H^3$), Radio-sodium ($_{11}Na^{24}$), Radio-Phosphorus ($_{15}P^{32}$), Radio-cobalt ($_{27}Co^{60}$), Radio-carbon ($_6C^{14}$), Radio-iodine (I^{131}) and Radio-sulphur (S^{35}).

(4) Another method of preparing a radio-element is to bombard the element with deuterons from a cyclotron. Radio-sodium can be obtained by bombarding Mg^{24} with deuterons. The reaction in this case is (d, α) reaction. The half-life of the radio-isotopes ranges from a fraction of a second to several thousand years.

Applications of Radio-isotopes

As tracers, radio isotopes have found wide application in agriculture, medicine, industry and research. To study the dynamics of a particular system, a radio-isotope is added and the course of the isotope is studied to understand the whole system. For instance, $_8O^{15}$ mixed with normal air breathed by a patient, enables radio-detection of the path of inhaled oxygen in the lungs. Phosphorus uptake by plants from the soil is studied using a phosphate fertilizer containing the radio-isotope P^{32}. Brain and thyroid tumours are detected using I^{131}.

Transuranium elements

The most fruitful source of artificial radionuclides is the radiative capture of neutrons, the (n, γ) reaction, which usually yields an electron emitting product. In 1934, Fermi suggested the possibility that the bombardment of uranium with neutrons might result in the production of elements with nuclear charge greater than 92. If U^{238} were to capture a neutron, the following reaction should occur:

$$_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239*} \longrightarrow {}_{92}U^{239} + \gamma$$

If the U^{239} were then to decay by electron emission, the result would be a nuclide with Z=93, an isotope of a hitherto unknown element. Early experiments showed that when uranium was bombarded with neutrons, four different β activities were detected, one of which was presumably associated with $_{92}U^{239}$. It was also considered possible that the new element with Z= 93 might decay by electron emission to form an isotope of another new element with Z=94. Any element which might have values of Z greater than 92 were called transuranium element because they would lie beyond uranium in the periodic table. Between 1934 and 1939, many attempts were made to make and identify transuranium elements. The research on these elements led to the discovery of nuclear fission.

The following is the list of transuranic elements.

Neptunium ($_{93}$Np), Plutonium ($_{94}$Pu), Americium ($_{95}$Am), Curium ($_{96}$Cm), Berkelium ($_{97}$Bk), Californium ($_{98}$Cf), Einsteinium ($_{99}$Es), Fermium ($_{100}$Fm), Mendelevium ($_{101}$Md), Nobelium (102No), Lawrencium ($_{103}$Lw), Kurchatovium ($_{104}$Xv) etc.

Nuclear Fission

Discovery

In experiments performed by Enrico Fermi, in 1934, the bombardment of uranium by neutrons produced several β ray activities with different half-lives. Since uranium decays by α-particle emission with a very long half-life, it was assumed that transuranic elements (Z>92) were being formed. However, in 1938, Hahn and Strassman showed by very careful chemical analysis that one of the radioactive elements produced when uranium is bombarded by neutrons is an isotope of barium, Z=56 ($_{56}Ba^{141}$). They found that barium was accompanied by a radioactive isotope of the gas krypton (Z=36). The atomic numbers of these two nuclides add up to 92, the atomic number of uranium. Hence, Meitner and Frisch suggested that on neutron bombardment, the uranium nucleus splits up into two lighter nuclei (Ba and Kr). The phenomenon was called fission, since it resembled division of cells in biology.

Fission and its products

The process of breaking up of the nucleus of a heavy atom into two, more or less equal fragments with the release of a large amount of energy is known as fission.

When uranium is bombarded with neutrons, a uranium nucleus captures a slow neutron, forming an unstable compound nucleus. The compound nucleus splits into two nearly equal parts. Some neutrons are also released in this process. The schematic equation for the fission is

$$_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{92}U^{236*} \longrightarrow X + Y + \text{neutrons} \qquad (1)$$

$_{92}U^{236*}$ is highly unstable isotope, and X and Y are the fission fragments. The fragments are not uniquely determined, because there are various combinations of fragments possible and a number of neutrons are given off. Typical fission reactions are

$$_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{92}U^{236*} \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_{0}n^{1} + Q \quad (2)$$

$$_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{92}U^{236*} \longrightarrow {}_{54}Xe^{140} + {}_{38}Sr^{94} + 2{}_{0}n^{1} + Q \quad (3)$$

Where Q is the energy released in the reaction.

Energy Released in Fission

We know that in the process of nuclear fission a large amount of energy is released. This energy is produced because the original mass of the nucleus is greater than the sum of the masses of the products produced after fission. The difference between these masses before and after fission is converted into energy according to Einstein's equation $E=mc^2$.

The energy liberated per fission can be calculated as follows: Let us consider the fission of 92U235. The fission reaction is

$$_{92}U^{235} + {}_{0}n^{1} \longrightarrow {}_{92}U^{236*} \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3{}_{0}n^{1} + Q$$

Let us estimate the actual masses before and after the fission reaction.

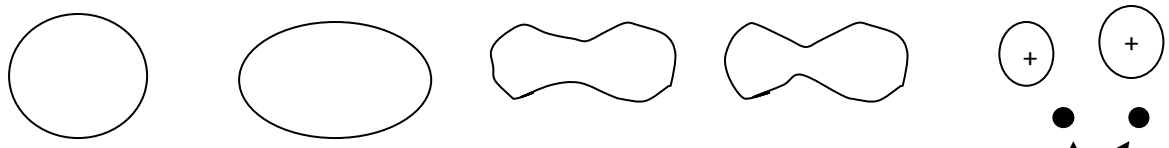
Mass of $_{92}U^{235}$	= 235.045733u
Mass of $_{0}n^{1}$	= 1.008665u
Total mass	= 236.054398u
Mass of $_{56}Ba^{141}$	= 140.9177u
Mass of $_{36}Kr^{92}$	= 91.8854u
Mass of 3 neutrons	= 3.025995u
Total final mass	= 235.829095u

Decrease in mass = 236.054398 – 235.829095 = 0.2253u
This decrease in mass is converted into energy
Energy released = 0.2253 x 931 = 209.8MeV
Thus in the process of fission of one nucleus of uranium, about 200MeV energy is released.

Bohr and Wheeler's theory of nuclear fission

Bohr and Wheeler successfully explained the phenomenon of nuclear fission on the basis of liquid drop model. A liquid drop has a spherical shape due to surface tension. According to their theory, an excited liquid drop may oscillate in a number of ways. On applying a large external force, the nucleus may change its spherical shape to an ellipsoid. If the external force is sufficiently large, the ellipsoid may change into a dump-bell shape and may even break at the narrow end into two portions.

Spherical compound nucleus Ellipsoidal Dump-bell Critical state Nuclear separation



A B C D neutrons

E

The analogy may be extended to a nucleus which behaves like a liquid drop. When a nucleus absorbs a neutron, it forms a compound nucleus which is highly energetic. The extra energy possessed by it comes mostly from the binding energy of the neutron absorbed by it. The extra energy may set up a series of rapid oscillations in the spherical compound nucleus shown as A in figure. As a result of these oscillations, the shape of the nucleus may change at times from spherical to ellipsoidal shown as B. If the extra energy is large, oscillations may be so violent that stage C and ultimately stage D may be approached. The nucleus is now dumbbell shaped. Each bell of the dumb-bell has now a positive charge and one repels the other. This results in a fission (stage E).

The nuclei that result from fission are called fission fragments. Usually fission fragments are of unequal size. A heavy nucleus undergoes fission when it acquires enough excitation energy to oscillate violently. Certain nuclei, notably $_{92}U^{235}$ are sufficiently excited by the mere absorption of an individual neutron. Other nuclei, notably $_{92}U^{238}$ require more excitation energy for fission than the binding energy released when another neutron is absorbed. $_{92}U^{238}$ undergoes fission only by reaction with fast neutrons whose kinetic energies exceed about 1MeV.

Chain Reaction

A chain reaction is a self-propagating process in which number of neutrons goes on multiplying rapidly almost in geometrical progression during fission till whole of fissile material is disintegrated.

Suppose a single neutron causing fission in a uranium nucleus produces 3 prompt neutrons. The three neutrons in turn may cause fission in three uranium nuclei producing 9 neutrons. These nine neutrons in turn may cause fission in nine uranium nuclei producing 27 neutrons and so on. The number of neutrons produced in n such generations is 3^n. The ratio of secondary neutrons produced to the original neutrons is called the multiplication factor (k).

Consider 1 kg of $_{92}U^{235}$ which contains $6.023 \times 10^{26}/235$ atoms. Suppose a stray neutron causes fission in a uranium nucleus. Each fission will release on the average 2.5 neutrons. The velocity of a neutron among the uranium atoms is such that a fission capture of a thermal neutron by the $_{92}U^{235}$ nuclei takes place in about 10^{-8}s. Each of these fissions, in turn, will release 2.5 neutrons. Let us assume that all these neutrons are available for inducing further fission reactions. Let n be the number of stages of fission captures required to disrupt the entire mass of 1 kg of $_{92}U^{235}$. Then

$(2.5)^n = 25 \times 10^{23}$ for n = 60

The time required for 60 fissions to take place = 60×10^{-8}s = 0.6μs.

Since each fission releases about 200MeV of energy, this means that a total of $200 \times 25 \times 10^{23} = 5 \times 10^{26}$MeV of energy is released in 0.6μs. The release of this tremendous amount of energy in such a short time interval leads to a violent explosion. This results in powerful air blasts and high temperature of the order of 10^7K or more, besides intense radioactivity. The self-propagating process described here is called a chain reaction. Two types of chain reaction are possible. In one, the chain reaction is first accelerated so that the neutrons are built up to a certain level and thereafter the number of fission producing neutrons is kept constant. This is called controlled chain reaction. Such a controlled chain reaction is used in nuclear reactors. In the other type of chain reaction, the number of neutrons is allowed to multiply indefinitely and the entire energy is released all at once. This type of reaction takes place in atom bombs.

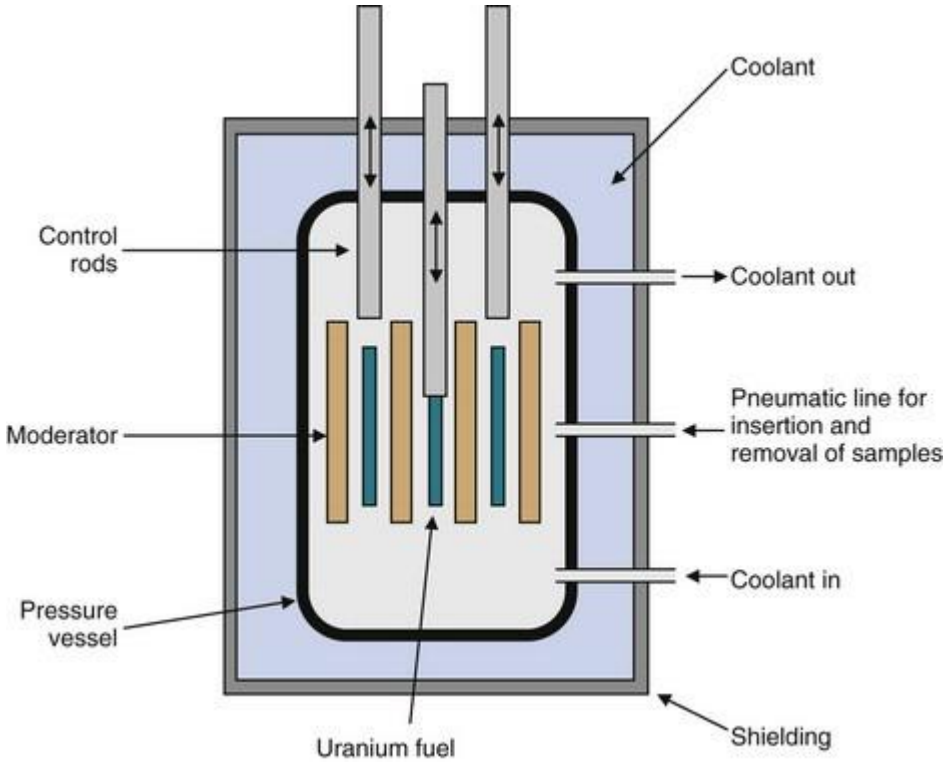
Multiplication factor(k)

The ratio of secondary neutrons produced to the original neutrons is called the multiplication factor. It is defined as

$$K=\frac{Number\ of\ neutrons\ in\ any\ one\ generation}{Number\ of\ neutrons\ in\ the\ preceding\ generation}$$

The fission chain reaction will be "critical" or steady when k = 1, it will be building up or "supercritical" when k > 1 and it will be dying down or "subcritical when k < 1.

Nuclear Reactor



We know that during the fission of U^{235} a large amount of energy is released. In a nuclear reactor the chain reaction is brought about under controlled conditions. If the chain reaction is put under control, after some time a steady state is established. Under a steady state, the rate of energy production also attains a constant level. Such a device in which energy is released at a given rate is known as a nuclear reactor. Nuclear reactors consist of five main elements:

1. The fissionable material called fuel
2. Moderator
3. Neutron reflector
4. Cooling system and
5. The safety and control systems

(1) **The fissionable substance**

The commonly used fissionable materials are the uranium isotopes U^{233}, U^{235}, the thorium isotope Th^{232}, and the plutonium isotopes Pu^{239}, Pu^{240} and Pu^{241}.

(2) **Moderator**

The function of the moderator is to slow down the highly energetic neutrons produced in the process of fission of U^{235} to thermal energies. Heavy water (D_2O), graphite, beryllium etc. are used as moderators. Ideally, moderators have low atomic weight and low absorption cross sections for neutrons.

(3) **Neutron reflector**

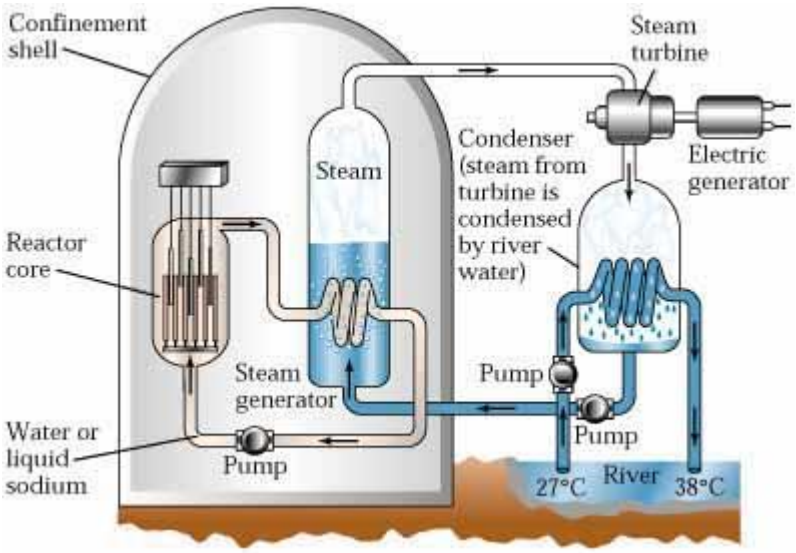
By the use of reflectors on the surface of reactors, leakage of neutrons can be very much reduced and the neutron flux in the interior can be increased. Materials of high scattering cross-section and low absorption cross-section are good reflectors.

(4) **Cooling system**

The cooling system removes the heat evolved in the reactor core. This heat is evolved from the K.E. of the fission fragments when they are slowed down in the fissionable substance and moderator. The coolant or heat transfer agent (water, steam, He, CO_2, air and certain molten metals and alloys) is pumped through the reactor core. Then through a heat exchanger, the coolant transfers heat to the secondary thermal system of the reactor.

(5) **Control and safety system**

The control systems enable the chain reaction to be controlled and prevent it from spontaneously running away. This is accomplished by pushing control rods into the reactor core. These rods are of a material (boron or cadmium) having a large neutron absorption cross-section. These rods absorb the neutrons and hence cut down the reactivity. By pushing in the rods, the operation of the reactor can be made to die down, by pulling them out to build up. The safety systems protect the space surrounding the reactor against intensive neutron flux and gamma rays existing in the reactor core. This is achieved by surrounding the reactor with massive walls of concrete and lead which would absorb neutrons and gamma rays.



Breeder reactor

If a thermal reactor core with U^{235} fuel is surrounded by a blanket of a fertile material like U^{238}, Th^{232} can be converted into fissile fuel. Reactors of this type are called fuel producing reactors. The reactions are as follows:

$_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} + \gamma$

This is followed by $_{92}U^{239} \longrightarrow {}_{93}Np^{239} + \beta^{-}$

$_{93}Np^{239}$ is also radioactive. It emits a β particle to form plutonium.

$_{93}Np^{239} \longrightarrow {}_{94}Pu^{239} + \beta^{-} + \gamma$

<u>This process of producing one type of fissionable material (Pu^{239}) from a non-fissionable material (U^{238}) is called breeding and the reactor a breeder reactor</u>.

The breeding reactions for the fertile material $_{90}Th^{232}$ are

$$_{90}Th^{232} + {}_{0}n^{1} \longrightarrow {}_{90}Th^{233*} \xrightarrow{\beta^{-}} {}_{91}Pa^{233} \xrightarrow{\beta^{-}} {}_{92}U^{233}$$

($T_{½}$=1.6x10^{5}yrs)

22 min 27days

Nuclear Fusion

<u>In this process, two or more light nuclei combine together to form a single heavy nucleus</u>. For example, when four hydrogen nuclei are fused together, a helium nucleus is formed. The mass of the single nucleus formed is always less than the sum of the masses of the individual light nuclei. The difference in mass is converted into energy according to Einstein's equation $E=mc^2$.

Example: Consider a single helium nucleus formed by the fusion of two deuterium nuclei. Mass of $_{1}H^{2}$ = 2.014102u; mass of $_{2}He^{4}$ = 4.002604u.

The initial mass of two deuterium atoms = 2 x 2.014102 = 4.028204u

Mass of helium atom = 4.002604u

Decrease in mass = 4.02820 – 4.002604 = 0.025600u

Therefore energy released = 0.0256 x 931.3 MeV = 23.84MeV

Thus the energy released in fusion is **23.84MeV.**

Source of stellar energy

The temperatures of the stars are very high and they radiate tremendous amount of energy. The sun radiates 3.8×10^{26}Joules of energy each second. The origin of such a tremendous amount of energy is neither chemical nor gravitational. The fusion of protons is supposed to release the energy in the sun and in other stars. Bethe suggested the following carbon-nitrogen cycle as one of the most important nuclear reactions for release of energy by fusion.

Carbon-Nitrogen cycle

The cycle is as follows:

$${}_6C^{12} + {}_1H^1 \longrightarrow {}_7N^{13*} + \gamma \qquad (1)$$

$${}_7N^{13*} \longrightarrow {}_6C^{13} + {}_1e^0 + \nu \qquad (2)$$

$${}_6C^{13} + {}_1H^1 \longrightarrow {}_7N^{14} + \gamma \qquad (3)$$

$${}_7N^{14} + {}_1H^1 \longrightarrow {}_8O^{15*} + \gamma \qquad (4)$$

$${}_8O^{15*} \longrightarrow {}_7N^{15} + {}_1e^0 + \nu \qquad (5)$$

$${}_7N^{15} + {}_1H^1 \longrightarrow {}_6C^{12} + {}_2He^4 \qquad (6)$$

In this cycle C^{12} acts like a catalyst. The reaction cycle is essentially the reaction

$$4\,{}_1H^1 \longrightarrow {}_2He^4 + 2\,{}_1e^0 + 2\nu + Q$$

The loss in mass is calculated as follows:

$4\,{}_1H^1 = 4.0313$; ${}_2He^4 = 4.002603$ and $2\,{}_1e^0 = 0.001098$

Therefore loss in mass = 0.02756u

Therefore energy released = 0.02756 x 931 = 25.7MeV

It is found that in one million years the sun loses about 10^{-7} of its mass by the above process. Taking mass of the sun as 2×10^{30}kg and its present age as 10^{10}years, it is estimated that the C-N cycle may keep going for another 30 billion years.

Proton-Proton cycle

Recent modification of the estimate of the temperature of the sun' core now favour the proton-proton chain. In the p-p chain, two protons first fuse to produce a deuterium nucleus which combines with another proton to yield He^3. Two He^3 nuclei interact and form He^4 and two protons. These reactions can be represented by the equations

$${}_1H^1 + {}_1H^1 \longrightarrow 2He^{2*} \longrightarrow {}_1H^2 + {}_1e^0 + \nu + 0.42MeV$$

$$_1H^2 + {}_1H^1 \longrightarrow 2He^{3*} \longrightarrow {}_2He^3 + \gamma + 5.5MeV$$

$$_2He^3 + {}_2He^3 \longrightarrow {}_4Be^{6*} \longrightarrow {}_2He^4 + {}_1H^1 + {}_1H^1 + 12.8MeV$$

$$4\,{}_1H^1 \longrightarrow {}_2He^4 + 2\,{}_{+1}e^0 + 2\nu + 2\,\gamma + 26.7MeV$$

Controlled thermonuclear reactions

A large amount of energy is released in a fraction of a second in a hydrogen bomb. If the thermonuclear reaction could be controlled to take place more slowly, the energy released can be used for constructive purpose. We know that very high temperatures are needed to bring about a nuclear fusion process. The main problem is to produce such a high temperature. At this temperature the gas is highly ionized and is called plasma. One of the severe engineering problems is the design of a "container" in which very hot plasma can be contained under high pressure to initiate a fusion reaction. Since almost any container would melt in the presence of plasma, attempts are being made to contain and control plasmas trapped in a specially shaped magnetic field. By increasing the field and changing the shape of the field, it is hoped that the plasma in this "magnetic bottle" can be raised to the required temperature and pressure for fusion reactions.

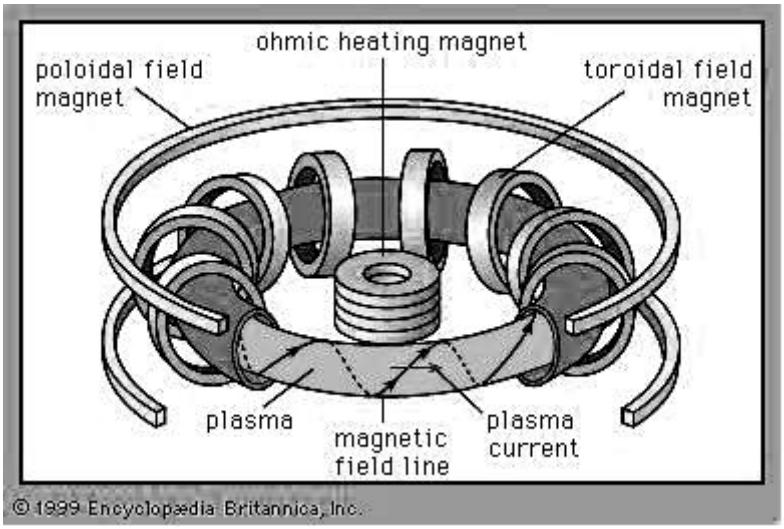
Nuclear fusion as an energy source will be a boom to humanity because of the following reasons:

1. Hydrogen is available everywhere on this planet in various forms.
2. The lightness of the reactant nuclei makes the energy yield per unit mass of the reacting material much greater than that in nuclear fission process.
3. A fusion reactor does not leave behind as in fission reactor radioactive waste, the disposal of which poses a tremendous problem.

Toroidal confinement

The most extensively investigated toroidal confinement concept is the tokamak. The tokamak (an acronym derived from the Russian words for "toroidal magnetic confinement") was introduced in the mid-1960s by Soviet plasma physicists. The magnetic lines of force are helixes that spiral around the torus. The helical magnetic field has two components: (1) a toroidal component, which points the long way around the torus, and (2) a poloidal component directed the short way around the machine. Both components are necessary for the plasma to be in stable equilibrium. If the poloidal field were zero, so that the field lines were simply circles wrapped about the torus, then the plasma would not be in equilibrium. The particles would not strictly follow the field lines but would drift to the walls. The addition of the poloidal field provides particle orbits that are contained within the device. If the toroidal field were zero, so that the magnetic field lines were directed only the short way around the torus, the plasma would be in equilibrium, but it would be unstable. The plasma column would develop growing distortions, or kinks, which would carry the plasma into the wall.

The toroidal field is produced by coils that surround the toroidal vacuum chamber containing the plasma. (The plasma must be situated within an evacuated chamber to prevent it from being cooled by interactions with air molecules.) In order to minimize power losses in the coils, designs involving superconducting coils have begun to replace copper coils. The plasma in a tokamak fusion reactor would have a major diameter in the range of 10 meters (33 feet) and a minor diameter of roughly 2 to 3 meters. The plasma current would likely be on the order of tens of millions of amperes, and the flex density of the toroidal magnetic field would measure several teslas. In order to help guide research and development, scientists frequently perform conceptual designs of fusion reactors. This device in theory would generate 1 gigawatt (1 billion watts) of electric power—sufficient to meet the electricity needs of a large city.



Radioactive wastes

Radioactive wastes are wastes that contain radioactive material. Radioactive wastes are usually by-products of nuclear power generation and other applications of nuclear fission or nuclear technology, such as research and medicine. Radioactive waste is hazardous to most forms of life and the environment, and is regulated by government agencies in order to protect human health and the environment.

Radioactivity diminishes over time, so waste is typically isolated and stored for a period of time until it no longer poses a hazard. The period of time waste must be stored depends on the type of waste. Low-level waste with low levels of radioactivity per mass or volume (such as some common medical or industrial radioactive wastes) may need to be stored for only hours, days, or months, while high-level wastes (such as spent nuclear fuel or by-products of nuclear reprocessing) must be stored for thousands of years. Current major approaches to managing radioactive waste have been segregation and storage for short-lived wastes, near-surface disposal for low and some intermediate level wastes, and deep burial or transmutation for the long-lived, high-level wastes.

CLASSIFICATION OF RADIOACTIVE WASTE

Classifications of nuclear waste vary by country. The IAEA, which publishes the Radioactive Waste Safety Standards (RADWASS), also plays a significant role.

URANIUM TAILINGS

Uranium tailings are waste by-product materials left over from the rough processing of uranium-bearing ore. They are not significantly radioactive. Mill tailings are sometimes referred to as **11(e) 2 wastes**, from the section of the Atomic Energy Act of 1946 that defines them. Uranium mill tailings typically also contain chemically hazardous heavy metal such as lead and arsenic. Vast mounds of uranium mill tailings are left at many old mining sites, especially in Colorado, New Mexico, and Utah.

LOW-LEVEL WASTE

Low level waste (**LLW**) is generated from hospitals and industry, as well as the nuclear fuel cycle. Low-level wastes include paper, rags, tools, clothing, filters, and other materials which contain small amounts of mostly short-lived radioactivity. Materials that originate from any region of an Active Area are commonly designated as LLW as a precautionary measure even if there is with only a remote possibility of being contaminated with radioactive materials. Such LLW typically exhibits no higher radioactivity than one would expect from the same material disposed of in a non-active area, such as a normal office block.

Some high-activity LLW requires shielding during handling and transport but most LLW is suitable for shallow land burial. To reduce its volume, it is often compacted or incinerated before disposal. Low-level waste is divided into four classes: **class A**, **class B**, **class C**, and **Greater Than Class C** (**GTCC**).

INTERMEDIATE-LEVEL WASTE

Spent Fuel Flasks are transported by railway in the United Kingdom. Each flask is constructed of 14 in (360 mm) thick solid steel and weighs in excess of 50 tons

Intermediate-level waste (**ILW**) contains higher amounts of radioactivity and in some cases requires shielding. Intermediate-level wastes includes resins, chemical sludge and metal reactor nuclear fuel cladding, as well as contaminated materials from reactor decommissioning. It may be solidified in concrete or bitumen for disposal. As a general rule, short-lived waste (mainly non-fuel materials from reactors) is buried in shallow repositories, while long-lived waste (from fuel and fuel reprocessing) is deposited in geological repository. U.S. regulations do not define this category of waste; the term is used in Europe and elsewhere.

HIGH-LEVEL WASTE

High-level waste (**HLW**) is produced by nuclear reactors. It contains fission products and transuranic elements generated in the reactor core. It is highly radioactive and often thermally hot. HLW accounts for over 95 percent of the total radioactivity produced in the process of nuclear electricity generation. The amount of HLW worldwide is currently increasing by about 12,000 metric tons every year, which is the equivalent to about 100 double-decker buses or a two-story structure with a footprint the size of a basketball court. A 1000-MW nuclear power plant produces about 27 tones of spent nuclear fuel (unreprocessed) every year.

TRANSURANIC WASTE

Transuranic waste (**TRUW**) as defined by U.S. regulations is, without regard to form or origin, waste that is contaminated with alpha-emitting transuranic radionuclides with half-lives greater than 20 years and concentrations greater than 100 nCi/g (3.7 MBq/kg), excluding high-level waste. Elements that have an atomic number greater than uranium are called transuranic ("beyond uranium"). Because of their long half-lives, TRUW is disposed more cautiously than either low- or intermediate-level waste. In the U.S., it arises mainly from weapons production, and consists of clothing, tools, rags, residues, debris and other items contaminated with small amounts of radioactive elements (mainly plutonium).

Under U.S. law, transuranic waste is further categorized into "contact-handled" (CH) and "remote-handled" (RH) on the basis of radiation dose measured at the surface of the waste container. CH TRUW has a surface dose rate not greater than 200 Roentgen equivalent man

per hour (to millisievert/hr), whereas RH TRUW has a surface dose rate of 200 Rontgen equivalent man per hour (2 mSv/h) or greater. CH TRUW does not have the very high radioactivity of high-level waste, nor its high heat generation, but RH TRUW can be highly radioactive, with surface dose rates up to 1000000 Rontgen equivalent men per hour (10000 mSv/h). The U.S. currently disposes of TRUW generated from military facilities at the Waste Isolation Pilot Plant.

PREVENTION OF WASTE

The only way of preventing the accumulation of radioactive waste is the phasing out of nuclear power generation, and replacing it renewable energy sources such as wind power, solar power, Wave power and geothermal power. Germany is the first major industrialized country to adopt this policy.

A theoretical way to reduce waste accumulation is to phase out current reactors in favour of Generation IV Reactors or Liquid Fluoride Thorium Reactors, which output less waste per power generated. Fast reactors can theoretically consume some existing waste, but the UK's Nuclear Decommissioning Authority described this technology as immature and commercially unproven, and unlikely to start before 2050.

Effects of nuclear explosion

An American nuclear test.

Nuclear weapons

•

The energy released from a nuclear weapon detonated in the troposphere can be divided into four basic categories:

- Blast—40-50% of total energy
- Thermal radiation—30-50% of total energy
- Ionizing radiation—5% of total energy (more in a neutron bomb)

- Residual radiation—5-10% of total energy

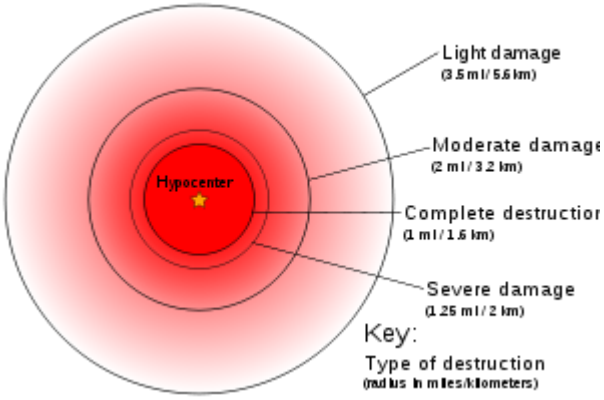
However, depending on the design of the weapon and the environment in which it is detonated the energy distributed to these categories can be increased or decreased. The blast effect is created by the coupling of immense amounts of energy, spanning the electromagnetic spectrum, with the surroundings. Locations such as submarine, surface, airburst, or exo-atmospheric determine how much energy is produced at blast and how much as radiation. In general, denser media around the bomb, like water, absorb more energy, and create more powerful shockwaves while at the same time limiting the area of its effect.

The dominant effects of a nuclear weapon where people are likely to be affected (blast and thermal radiation) are identical physical damage mechanisms to conventional explosives. However, the energy produced by a nuclear explosive is millions of times more powerful per gram and the temperatures reached are briefly in the tens of millions of degrees.

Energy from a nuclear explosive is initially released in several forms of penetrating radiation. When there is a surrounding material such as air, rock, or water, this radiation interacts with and rapidly heats it to an equilibrium temperature (i.e. so that the matter is at the same temperature as the atomic bomb's matter). This causes vaporization of surrounding material resulting in its rapid expansion. Kinetic energy created by this expansion contributes to the formation of a shockwave. When a nuclear detonation occurs in air near sea level, much of the released energy interacts with the atmosphere and creates a shockwave which expands spherically from the hypocenter. Intense thermal radiation at the hypocenter forms a fireball and if the burst is low enough, it's often associated mushroom cloud. In a burst at high altitudes, where the air density is low, more energy is released as ionizing gamma radiation and x-rays than an atmosphere-displacing shockwave.

In 1942 there was some initial speculation among the scientists developing the first nuclear weapons that there might be a possibility of igniting the Earth's atmosphere with a large enough nuclear explosion. This would concern a nuclear reaction of two nitrogen atoms forming a carbon and an oxygen atom, with release of energy. This energy would heat up the remaining nitrogen enough to keep the reaction going until all nitrogen atoms were consumed. This was, however, quickly shown to be impossible, due to inverse Compton Effect cooling of the fireball. Nevertheless, the notion has persisted as a rumour for many years.

Overpressure ranges from 1 to 50 psi (6.9 to 345 kilopascals) of a 1 kiloton of TNT air burst as a function of burst height. The thin black curve indicates the optimum burst height for a given ground range.



and the thickness and moisture content of the target. Near ground zero where the energy flux exceeds 125 J/cm^2, what can burn, will. Farther away, only the most easily ignited materials will flame. Incendiary effects are compounded by secondary fires started by the blast wave effects such as from upset stoves and furnaces.

In Hiroshima, a tremendous firestorm developed within 20 minutes after detonation and destroyed many more buildings and homes. A firestorm has gale force winds blowing in towards the center of the fire from all points of the compass. It is not, however, a phenomenon peculiar to nuclear explosions, having been observed frequently in large forest fires and following incendiary raids during World War II.

Because thermal radiation travels more or less in a straight line from the fireball (unless scattered) any opaque object will produce a protective shadow. If fog or haze scatters the light, it will heat things from all directions and shielding will be less effective, but fog or haze would also diminish the range of these effectsAn estimate of the size of the damage caused by the Atomic bombings of Hiroshima and Nagasaki. A modern hydrogen bomb would be tens of times more powerful and cause similar levels of damage at 2-5 times the distance.

The high temperatures and radiation cause gas to move outward radially in a thin, dense shell called "the hydrodynamic front." The front acts like a piston that pushes against and compresses the surrounding medium to make a spherically expanding shock wave. At first, this shock wave is inside the surface of the developing fireball, which is created in a volume of air by the X-rays. However, within a fraction of a second the dense shock front obscures the fireball, causing the characteristic double pulse of light seen from a nuclear detonation. For air bursts at or near sea-level, between 50-60% of the explosion's energy goes into the blast wave, depending on the size and the yield of the bomb. As a general rule, the blast fraction is higher for low yield weapons. Furthermore, it decreases at high altitudes because there is less air mass to absorb radiation energy and convert it into blast. This effect is most important for altitudes above 30 km, corresponding to <1 per cent of sea-level air density.

Much of the destruction caused by a nuclear explosion is due to blast effects. Most buildings, except reinforced or blast-resistant structures, will suffer moderate to severe damage when subjected to overpressures of only 35.5 kilopascals (kPa) (5.15 pounds-force per square inch or 0.35 atm).

The blast wind may exceed one thousand km/h. The range for blast effects increases with the explosive yield of the weapon and also depends on the burst altitude. Contrary to what one might expect from geometry the blast range is not maximal for surface or low altitude blasts but increases with altitude up to an "optimum burst altitude" and then decreases rapidly for higher altitudes. This is due to the nonlinear behaviour of shock waves.[*clarification needed*] If the blast wave reaches the ground it is reflected. Below a certain reflection angle the reflected wave and the direct wave merge and form a reinforced horizontal wave, the so-called Mach stem (named after Ernst Mach). For each goal overpressure there is a certain optimum burst height at which the blast range is maximized. In a typical air burst, where the blast range is maximized for 5 to 20 psi (34 to 140 kPa), these values of overpressure and wind velocity noted above will prevail at a range of 0.7 km for 1 kiloton (kt) of TNT yield; 3.2 km for 100 kt; and 15.0 km for 10 megatons (Mt) of TNT.

Two distinct, simultaneous phenomena are associated with the blast wave in air:

- **Static overpressure**, i.e., the sharp increase in pressure exerted by the shock wave. The overpressure at any given point is directly proportional to the density of the air in the wave.
- **Dynamic pressures**, i.e., drag exerted by the blast winds required to form the blast wave. These winds push, tumble and tear objects.

Most of the material damage caused by a nuclear air burst is caused by a combination of the high static overpressures and the blast winds. The long compression of the blast wave weakens structures, which are then torn apart by the blast winds. The compression, vacuum and drag phases together may last several seconds or longer, and exert forces many times greater than the strongest hurricane.

Acting on the human body, the shock waves cause pressure waves through the tissues. These waves mostly damage junctions between tissues of different densities (bone and muscle) or the interface between tissue and air. Lungs and the abdominal cavity, which contain air, are particularly injured. The damage causes severe hemorrhaging or air embolisms, either of which can be rapidly fatal. The overpressure estimated to damage lungs is about 70 kPa. Some eardrums would probably rupture around 22 kPa (0.2 atm) and half would rupture between 90 and 130 kPa (0.9 to 1.2 atm).

Blast Winds: The drag energies of the blast winds are proportional to the cubes of their velocities multiplied by the durations. These winds may reach several hundred kilometers per hour.

Nuclear weapons emit large amounts of thermal radiation as visible, infrared, and ultraviolet light. This is known as "Flash". The chief hazards are burns and eye injuries. On clear days, these injuries can occur well beyond blast ranges. The light is so powerful that it can start fires that spread rapidly in the debris left by a blast. However, the high winds following the blast wave will put out almost all such fires, unless the yield is very high. This is because the intensity of the blast effects drops off with the third power of distance from the explosion, while the intensity of radiation effects drops off with the second power of distance. However, in urban areas, the extinguishing of fires ignited by thermal radiation matters little, as fires will be started anyway by electrical shorts, gas pilot lights, overturned stoves, and other

ignition sources. The range of thermal effects increases markedly with weapon yield. Thermal radiation accounts for between 35-45% of the energy released in the explosion, depending on the yield of the device.

There are two types of eye injuries from the thermal radiation of a weapon:

Flash blindness is caused by the initial brilliant flash of light produced by the nuclear detonation. More light energy is received on the retina than can be tolerated, but less than is required for irreversible injury. The retina is particularly susceptible to visible and short wavelength infrared light, since this part of the electromagnetic spectrum is focused by the lens on the retina. The result is bleaching of the visual pigments and temporary blindness for up to 40 minutes.

Burns visible on a woman in Hiroshima during the blast. Darker colors of her kimono at the time of detonation correspond to clearly visible burns on skin touching parts of the garment exposed to thermal radiation. Since kimonos are not form fitting attire, some parts not directly touching her skin are visible as breaks in the pattern, and the tighter fitting areas approaching the waistline have a much more well-defined pattern.

A retinal burn resulting in permanent damage from scarring is also caused by the concentration of direct thermal energy on the retina by the lens. It will occur only when the fireball is actually in the individual's field of vision and would be a relatively uncommon injury. Retinal burns, however, may be sustained at considerable distances from the explosion. The apparent size of the fireball, a function of yield and range will determine the degree and extent of retinal scarring. A scar in the central visual field would be more debilitating. Generally, a limited visual field defect, which will be barely noticeable, is all that is likely to occur.

When thermal radiation strikes an object, part will be reflected, part transmitted, and the rest absorbed. The fraction that is absorbed depends on the nature and color of the material. A thin material may transmit a lot. A light colored object may reflect much of the incident radiation and thus escape damage like anti-flash white paint. The absorbed thermal radiation raises the temperature of the surface and results in scorching, charring, and burning of wood, paper, fabrics, etc. If the material is a poor thermal conductor, the heat is confined to the surface of the material.

Actual ignition of materials depends on how long the thermal pulse lasts.

ELECTROMAGNETIC PULSE

Main articles: Electromagnetic pulse and Geomagnetically induced current

Gamma rays from a nuclear explosion produce high energy electrons through Compton scattering. For high altitude nuclear explosions, these electrons are captured in the Earth's magnetic field at altitudes between twenty and forty kilometers where they interact with the Earth's magnetic field to produce a coherent electromagnetic pulse (EMP) which lasts about one millisecond. Secondary effects may last for more than a second.

The pulse is powerful enough to cause moderately long metal objects (such as cables) to act as antennas and generate high voltages due to interactions with the electromagnetic pulse. These voltages can destroy unshielded electronics. There are no known biological effects of EMP. The ionized air also disrupts radio traffic that would normally bounce off the ionosphere.

Electronics can be shielded by wrapping them completely in conductive material such as aluminum foil; however, the effectiveness of the shielding may be less than perfect. Proper shielding is a complex subject due to the large number of variables involved. Semiconductors, especially integrated circuits, are extremely susceptible to the effects of EMP due to the close proximity of the PN junctions, but this is not the case with thermionic tubes (or valves) which are relatively immune to EMP. A Faraday cage doesn't offer protection from the effects of EMP unless the mesh is designed to have holes no bigger than the smallest wavelength emitted from a nuclear explosion.

Large nuclear weapons detonated at high-altitudes also cause geomagnetically induced current in very long electrical conductors. The mechanism by which these geomagnetically induced currents are generated is entirely different from the gamma ray induced pulse produced by Compton electrons.

IONIZING RADIATION

About 5% of the energy released in a nuclear air burst is in the form of ionizing radiation: neutrons, gamma rays, alpha particles, and electrons moving at speeds up to the speed of light. Gamma rays are high energy electromagnetic radiation; the others are particles that move slower than light. The neutrons result almost exclusively from the fission and fusion reactions, while the initial gamma radiation includes that arising from these reactions as well as that resulting from the decay of short-lived fission products.

The intensity of initial nuclear radiation decreases rapidly with distance from the point of burst because the radiation spreads over a larger area as it travels away from the explosion. It is also reduced by atmospheric absorption and scattering.

The character of the radiation received at a given location also varies with distance from the explosion. Near the point of the explosion, the neutron intensity is greater than the gamma intensity, but with increasing distance the neutron-gamma ratio decreases. Ultimately, the neutron component of initial radiation becomes negligible in comparison with the gamma component. The range for significant levels of initial radiation does not increase markedly with weapon yield and, as a result, the initial radiation becomes less of a hazard with increasing yield. With larger weapons, above 50 kT (200 TJ), blast and thermal effects are so much greater in importance that prompt radiation effects can be ignored.

The neutron radiation serves to transmute the surrounding matter, often rendering it radioactive. When added to the dust of radioactive material released by the bomb itself, a large amount of radioactive material is released into the environment. This form of radioactive contamination is known as nuclear fallout and poses the primary risk of exposure to ionizing radiation for a large nuclear weapon.

Details of nuclear weapon design also affect neutron emission: the gun-type assembly Hiroshima bomb leaked far more neutrons than the implosion type 21 kt Nagasaki bomb

because the light hydrogen nuclei (protons) predominating in the exploded TNT molecules (surrounding the core of the Nagasaki bomb) slowed down neutrons very efficiently while the heavier iron atoms in the steel nose forging of the Hiroshima bomb scattered neutrons without absorbing much neutron energy.

EARTHQUAKE

The pressure wave from an underground explosion will propagate through the ground and cause a minor earthquake. Theory suggests that a nuclear explosion could trigger fault rupture and cause a major quake at distances within a few tens of kilometers from the shot point.

RADIATION DOSAGES

Ionizing radiation comes from natural and artificial sources. The energy absorbed from exposure to radiation is called a **dose**. Absorption of a dose changes the state of a device, and the changes provide measures of the dosages received. Such devices are called **dosimeters**. Physical, chemical, and biological changes are used as the bases for dosimeters.

Units in Source, Absorption, and Dosage

Process	Type	Unit
Source ♣ ♦ ♥ ♠ ↓ ↓ ↓ ↓	α, β, γ neutron (n) nuclei	Becquerel, (Bq) curie (Ci)
Energy exposure ↓ ↓ ↓ ↓	Energy transmitted	joul (J) erg
Energy absorbed ↓ ↓ ↓ ↓	Absorbed dose	Gray (Gy) roetgen (R) or rad
Relative biological effectiveness ♣ ♦ ♥ ♠ ↓ ↓ ↓ ↓	X-, β–, γ– rays thermal n Fast n, α, p Recoil nuclei	rbe = 1 rbe = 3, rbe = 10 rbe = 20
Radiation effects in human	Effective dose	Sievert (Sv) Sv = Gy*rbe Rem = rad*rbe

However, radiation effects depend on the type of radiation, and various units are used for dosages.

RADIATION SOURCES

Radioactive sources emit alpha, beta, or gamma rays. Each type has a unique effect on health of living beings. Strengths of sources are measured in the SI unit Bq (becquerel), which is the number of disintegration per second, disintegration or decay rate. However, the cgs unit curie (=3.700x10^{10} Bq), is still used in medical and technical practices. For convenience, modifiers have been used for the unit Ci. Decay rates say nothing about energies or type of particles emitted.

When neutron and other particles are the sources, the intensity is either expressed as the total number of particles per unit time or the number of particles per unit time per unit area. However, these numbers do not contain information on energy of the beam.

For electromagnetic radiation such as laser, the rate of energy emission (watt) of the beam is often specified. No particular unit is used for intensity of X-rays, but the rate of photon emission is similar to the rate of gamma ray emission.

ENERGY EXPOSURE AND ABSORBED DOSE

The radiation effect depends on the amount of energy and the type of radiation a person is exposed to. The amount of energy a subject exposed to differ from that absorbed. However, to tell them apart is very difficult. In practice, the reading from a dosimeter represents the amount of energy exposure and absorption.

The amount of radiation energy exposed to or absorbed by a subject is called a **dose**.

A **roentgen (R)** is the dose of X- or gamma-rays that produce 1 esu (negative and positive each) charge in 1.0 L (at standard temperature and pressure, STP, 298 K and 1 atmosphere) of air. This dose is equivalent to 0.12 erg absorbed by 0.00123 g of mass, or approximately 100 erg in 1.0 g.

For other particles, absorption of 100 erg per gram is called a **rad**. Rad and reontgen are equivalent, (1 R = 1 rad).

The SI dose unit is gray (Gy), which is the absorption of 1.0 J per kg of mass. Thus,

1 Gy = 100 R or rad

THE QUALITY FACTOR AND ROETGEN EQUIVALENT MAN (REM)

The absorbed dosage contains neither information on the type of particles nor the degree of damage.

The study of radiation victims indicated that receiving the same dosage from gamma radiation suffered much less harm than from alpha particles. Alpha particles cause 3 times more damage than do gamma rays or beta particles.

Radiations	*Q* or rbe
β, γ and X-rays	1
Thermal neutrons (n)	3
Fast n, a, and protons	10
Heavy and recoil nuclei	20

The study of radiation victims indicated that receiving the same dosage from gamma radiation suffered much less harm than from alpha particles. Alpha particles cause 3 times more damage than gamma rays or beta particles. Thus, **quality factor (*Q*)** or **relative biological effectiveness** is introduced to reflect the relative harmfulness of the four types of radiation.

Multiplication of the absorbed dose (in rad or Gy) by the *Q* factor converted it to an effective dosage equivalent to that of X-ray or gama-ray. The cgs unit used for the dose equivalent is **roentgen equivalent man (rem)** whereas the SI unit for it is the **sievert**, (Sv). The relationship between Sv and rem is:

$$1\ \text{Sv} = 100\ \text{rem}$$

Thus, the rem is the dose from any radiation that produces biological effects in man equivalent to one rad or R of X-ray, gamma- or beta rays.

Multiplying the absorbed dose in Gy or rad by the *Q* factor converted it to a radiation effective dose in sievert (Sv) and roentgen equivalent man (rem) respectively. Thus, the dose in Gy is also the effective dose in Sv for of X-ray, gamma or beta rays; similarly, the value remains the same in rad, R or rem for this class of radiation. For other types of radiation, their values differ by a factor *Q*. Dosages are usually given in rem or Sv.

A unit for total energy absorbed by a particular organ called integral dose is **gram-rad or g-rad**.

Similar to g-rad, the unit **g-rem** is used for the integral dose of an organ (used in medicine) when other radiation than X-rays, gamma rays, or beta particles are in question.

DOSIMETER

A **dosimeter** is a device for the measurement of exposed dose. There are many different types of dosimeters: film badges, electroscopes, ionization chambers, chemical dosimeters, biological dosimeters, and sophisticated computer-controlled instruments.

Dosimeters are commercially available from various manufactures. Their choice depends on the need of the work place. Shelf life, lineality of dose response, stability, simplicity in their handling procedure, easy-to-read meters, independence of dose rate and equal responses to X-rays, gamma rays and beta particles are some of factors on the quality of dosimeters.

Radiation causes chemical and biological changes. If the changes are quantitatively related to the absorbed dose, they are dosage indicators. Their applications lead to chemical and biological dosimeters.

RADIATION EXPOSURE

Exposure Levels:

- Low dosage - less than 1 sv (100 rem)
- Medium low dosage - 1-2 sv (100 - 200 rem)
- Medium high dosage exposure 2-5 sv (200-450 rem)
- High dosage exposure more than 5 sv (500 rem and more)

Radiation Hazards

One thing we can all agree on is that radiation is bad for you, right? Well . . . . First we have to be careful to define what we mean by "radiation." Your fireplace *radiates* in the infrared (heat) and visible (light) parts of the electromagnetic (*EM*) spectrum; these forms of radiation are certainly beneficial as long as they don't get out of control. On the other hand, visible light in the form of a high-power laser can inflict damage, as can excessive heat or even microwave *EM* radiation. On the shorter-wavelength side of the *EM* spectrum, ultraviolet light can cause sunburn to the skin, while X-rays penetrate deeper and can do the same sort of microscopic damage as the still shorter-wavelength gamma (γ) rays emitted by ^{60}Co (cobalt) radioisotopes. Can we make general statements about all of these? Perhaps, "A little is good, but a lot is bad!" Sorry, nothing so simple. It is certainly true that we cannot maintain health without both heat and light, and a certain amount of "near ultraviolet" may be required for natural vitamin D production in the skin, but we probably have no biological need for microwave or radio frequency radiation; and all *EM* radiation from "far ultraviolet" upward in frequency (downward in wavelength) is exclusively and unambiguously bad for the individual.[2]

Why the big qualitative difference? What do ultraviolet, X-rays and γ-rays do that visible and infrared light don't? At last, a question to which there is a simple answer! They cause *ionization* of atoms and molecules inside cells, leaving behind a variety of free radicals - types of molecules that quickly react chemically with other nearby molecules. If the free radicals react with the DNA molecules in which are encoded all the instructions to our cells for how to act and how to reproduce, some of these instructions can get scrambled.

Surprisingly, this does not always happen. The simplest detectable damage to a DNA molecule is a "single-strand break," in which one of the strands of the double helix is broken by a chemical reaction with a radical. It is a testimony to the robustness of DNA that it is usually able to repair its own single-strand breaks in a few hours![3] If, however, the DNA molecule with a single-strand break is subjected to further damage before it has a chance to "heal itself" then it may sustain a "double-strand break" (two breaks in the same strand), which it seems to be far less able to repair. Before we go on to discuss the consequences of permanent DNA damage, it is important to note that the irreparable damage usually takes place only after a large fraction of DNA molecules have already sustained temporary damage - and that the temporary damage is mostly repaired in a fairly short time. This explains why a given "dose" of radiation is less harmful when accumulated over a long time than when delivered in the space of a few hours.[4]

What sorts of bad things are liable to happen when a DNA molecule sustains irreparable damage, scrambling some part of the instruction manual for the operation of the cell it inhabits?

- **Cell Reproductive Death** [most common] - The cell containing the defective DNA may be unable to reproduce itself, so that although it may be able to function normally for its remaining natural lifetime, when it dies a natural death it will not have a new cell to replace it. Whether this causes a problem or not depends upon whether many other nearby cells have the same malady (one by itself will never be missed!) and

upon the natural lifetime of that type of cell - which ranges from a few days for hair follicles, skin and mucous membrane cells to "forever" for brain cells. Obviously, the loss of reproductive capacity is meaningless for a cell that never reproduces!

- **Genetic Mutation** [most subtle] - If the cell in question happens to be a *gamete* destined for fusion with a member of the opposite sex, the resulting individual will have some scrambled instructions in the construction manual and will probably not grow up normally. In almost every case this will be fatal to the fœtus, and in almost all the remaining cases it will be detrimental to the survival of the individual, although such mutations have presumably played a rôle in evolution to date. Note however that it is strictly impossible for any individual's genetic makeup to be *retroactively* altered by radiation (like the Hulk or Spiderman or any number of cheap sci-fi horrors), as this would require the *same* accidental scrambling to take place independently in every DNA strand in the victim's body!

  For men, there are two types of genetic damage: the sperm cells themselves have an active lifetime of only a few days, after which a new generation takes over; but the sperm-producing cells are never replaced and so can never repair damage to themselves. The latter applies also to women: the female gametes (eggs) are all produced early in life and, once damaged, cannot be repaired. If the altered cell is "just any old cell" then usually the change is harmless - either the cell merely fails to do its part in the body until it dies or else the affected part of the DNA is irrelevant to the functioning of that cell in the first place - but occasionally the change is related to cell division itself, and then there can be real trouble.

- **Cancer** [most unpleasant] - Sometimes (very rarely) a damaged DNA molecule instructs a cell to mobilize all its resources and the resources of all its neighbours to reproduce as many copies of itself as possible. The offspring preserve the mandate, and a chain reaction takes place that "crashes the system." This runaway reproductive zeal of a misguided cell is what we know as CANCER, and it is the worst hazard of radiation exposure. As far as anyone knows, *any* exposure to ionizing radiation increases one's chances of developing cancer, and so we can unambiguously say that **ionizing radiation is bad for you.**

Before we go on, it is interesting to note that *all* of the most potent therapies for *treating* cancer involve either ionizing radiation or chemical reactions that cause similar DNA damage; the strategy for these "interventions" is always to cause such overwhelming DNA damage to the cancer cells that *every single cancer cell* suffers "cell reproductive death" as described above. Although there are various techniques for making the cancer cells more susceptible to the radiation or harsh chemicals than normal cells, there are inevitably many casualties among the latter. It is not unusual, for instance, to kill off (in the sense of "reproductive death") as many as 90% of the normal cells in the tissues surrounding a tumour, relying upon the fantastic healing capacity of normal tissue to bounce back from this insult. Remember, the idea is to kill 100% (!) of the cancer cells.