KARPAGAM ACADEMY OF HIGHER EDUCATION

SEMESTER – II

			L T P C
19PHP203	**NUCLEAR PHYSICS**	**4 - - 4**	

Scope: Nuclear physics is one of the fundamental subjects of physics. It is important to know about the physics of nuclei and the different energies involved in the nuclear processes. Nuclear energy is one of the major sources of energy, which, with proper careful usage, can solve the energy crisis to a large extent.

Objectives: This paper is intended to give an insight into the different nuclear processes and the fundamental particles, which are the real building blocks of the universe.

UNIT - I

Nuclear mass and charge: Distribution of nuclear charge - Nuclear mass and binding energy of a nucleus – semi-empirical mass formula – Nature of nuclear force – form of nucleon-nucleon potential – charge independence and charge symmetry of nuclear forces - Bound states of two nucleons-Ground state of Deuterium - Wave mechanics of ground state of Deuterium-Spin states –Pauli's exclusion principle -Tensor force - Exchange force - Low energy Nucleon - Nucleon scattering

UNIT - II

Radioactivity: Alpha decay: Properties of α particles - Velocity and energy of α particles - Gamow's theory of α particles- Geiger - Nuttall law- α ray energies and fine structure of α rays - α disintegration energy-Low range α particles

Beta decay: Properties of β particles - General features of β ray spectrum – Pauli's hypothesis - Fermi's theory of β particles - Forms of interaction and selection rules - Fermi's and Gamow teller transition

Gamma decay: The absorption of γ rays by matter - Interaction of γ rays with matter - Measurement of γ ray energies - Dumont bent crystal spectrometer method-internal conversion – Applications.

UNIT -III

Nuclear models: Liquid drop model - Bhor Wheeler theory of fission - Condition for spontaneous fission - Activation energy-Seaborg's expression - Shell model: Explanation for magic numbers - Prediction of shell model -Prediction of spin and parity - Nuclear statistics - Magnetic moment of nuclei - Schmidt lines-Nuclear isomerism - Collective model: Explanation of Quadrupole moments - Prediction of sign of electric quadrupole moments. Optical model: Nilsson model - Elementary ideas

UNIT - IV

Nuclear reactions: Nuclear fission and fusion - Kinds of reaction and conservation laws - energetics of nuclear reaction – Applications of Nuclear Energy – Nuclear Reactors - Isospin - Reaction cross section-Continuum theory of nuclear reaction - Resonance - Briet Wigner Dispersion formula - Stages of nuclear reaction - Statistical theory of nuclear reaction -

Evaporation probability and cross section – Kinematics of stopping and pickup reaction - Surface reaction

UNIT -V

High energy physics : Types of interaction in nature-typical strengths and time-scales, conservation laws, charge-conjugation, Parity and Time reversal, CPT theorem, GellMann-Nishijima formula, intrinsic parity of pions, resonances, symmetry classification of elementary particles, quark hypothesis, charm, beauty and truth, gluons, quark confinement, asymptotic freedom.

TEXT BOOKS:

1. Pandya. M.L. and R. P. S. Yadav, 2004, Elements of Nuclear Physics, 1^{st} edition KedarNath Ram Nath, Meerut.
2. D.C Tayal , 4^{th} edition 2011, Nuclear Physics, Himalaya Publishing House, New Delhi.

REFERENCES:

1. Kenneth S.Karne, , 1^{st} edition, 2008, Introducing Nuclear Physics, John Wiley and Sons, New York.
2. Sharma. D.C 2004, Nuclear Physics, - K. Nath& Co, Meerut.
3. Bernard L. Cohen, , 1^{st} edition, 2011, Concept of Nuclear Physics, Tata McGraw Hill, New Delhi.
4. Devanathan V.,2^{nd}edition, 2008, Nuclear Physics, Narosa Book Distributers Pvt. Ltd., New Delhi.
5. Kaplan Irving, 2002, Nuclear Physics, 2^{nd} Edition, Narosa Book Distributers Pvt. Ltd., New Delhi.

KARPAGAM ACADEMY OF HIGHER EDUCATION

(Deemed to be University Established Under Section 3 of UGC Act 1956)

Coimbatore – 641 021.

LECTURE PLAN
DEPARTMENT OF PHYSICS

STAFF NAME: B. JANARTHANANSUBJECT NAME: NUCLEAR PHYSICS
SUB.CODE:19PHP203SEMESTER: II CLASS: IM.Sc (PHY)

S.No	Lecture Duration Period	Topics to be Covered	Support Material/Page Nos
		UNIT-I	
1	1	Distribution of nuclear charge, Nuclear mass and binding energy of a nucleus	T1:109-110
2	1	Semi-empirical mass formula, Nature of nuclear forces	T1:133-135
3	1	Form of nucleon-nucleon potential	T1:135-136
4	1	Charge independence and charge symmetry of nuclear forces	T1:168-169
5	1	Bound states of two nucleons, Ground state of deuterium	T1:157-158, T1:159-160
6	1	Wave mechanics of ground state of deuterium – spin states	T1:160-161
7	1	Pauli's exclusion principle, Tensor forces, Exchange forces, Low energy nucleon, Nuclear scattering	T1:163, T1:164-165, T1:212-213, T1:213-214
8	1	Revision	
	Total No of Hours Planned For Unit 1= 8		

Textbook

T1 - Pandya M.L. and R.P.S. Yadav, 2004. Elements of nuclear physics, Ist Edition, Kedarnath /Ramnath, Meerut
T2 - Dayal. D.C., 4^{th} Edition, 2011. Nuclear Physics, Himalaya Publishing House, New Delhi

		UNIT-II	
1	1	Properties of α-particles – Velocity and energy of α-particles	T1:274-275
2	1	Gamow's theory of α-decay, Geiger-Nuttal law	T1:285-287
3	1	α-ray energies and fine structure of α-rays	T1:288-289
4	1	α-disintegration energy, Low energy α-particles	T1:290, T1:291
5	1	Properties of β-particles- General features of β-ray spectrum, Pauli's hypothesis, Fermi's theory of β-particles	T1:301-303, T1:304, T1:305-307
6	1	Form of interaction and selection rules, Fermi's and Gamow Teller transition	T1:309-310, T1:311
7	1	Absorption of γ-rays by matter, Interaction of γ-rays with matter, Measurement of γ-ray energies, Internal conversion – applications	T1:320, T1:321-322, T1:328-329, T1:331-332, T1:334-335
8	1	Revision	
	Total number of hours planned for Unit-II = 8		

Textbook

T1 - Pandya M.L. and R.P.S. Yadav, 2004. Elements of nuclear physics, Ist Edition, Kedarnath /Ramnath, Meerut
T2 - Dayal. D.C., 4th Edition, 2011. Nuclear Physics, Himalaya Publishing House, New Delhi

		UNIT-III	
1	1	Liquid drop model, Bohr-Wheeler theory of fission, Condition for spontaneous fission	T2:418-419, T2:419-420
2	1	Activation energy, Seaborg's expression	T2:420-421
3	1	Shell model, Explanation of magic numbers, Prediction of shell model	T2:421-423
4	1	Prediction of spin and parity, Nuclear statistics	T2:423, T2:424
5	1	Magnetic moments of nuclei, Schmidtt lines, Nuclear isomerism	T2:424-425, T2:426, T2:426
6	1	Collective model, Explanation of quadrapole moments, Prediction of sign of electric quadrapole moments	T2:433-434, T2:435
7	1	Optical model, Nilson model, Elementary ideas	T2:435-436, T2:437-438
8	1	Revision	
	Total No of Hours Planned For Unit III=8		

Textbook

T1 - Pandya M.L. and R.P.S. Yadav, 2004. Elements of nuclear physics, Ist Edition, Kedarnath /Ramnath, Meerut

T2 - Dayal. D.C., 4th Edition, 2011. Nuclear Physics, Himalaya Publishing House, New Delhi

		UNIT-IV	
1	1	Nuclear fission and fusion	T2:518
2	1	Kinds of nuclear reaction and conservation laws	T2:519-520
3	1	Energetic of nuclear reaction, Applications of nuclear energy	T2:521-522
4	1	Nuclear reactors, Isospin	T2:322-323
5	1	Reaction cross-section, Continum theory of nuclear reaction	T2:404-405
6	1	Resonance, Breit-Wigner dispersion formula, Stages of nuclear reaction	T2:498-499, T2:415-416
7	1	Statistical theory of nuclear reaction, Evaporation probability, Cross-section for evaporation probability, Kinematics of stopping and pickup reaction, Surface reaction	T2:417-418, T2:483-484, T2:375-377, T2:378
8	1	Revision	
	Total No of Hours Planned For Unit IV=8		

Textbook

T1 - Pandya M.L. and R.P.S. Yadav, 2004. Elements of nuclear physics, Ist Edition, Kedarnath /Ramnath, Meerut

T2 - Dayal. D.C., 4th Edition, 2011. Nuclear Physics, Himalaya Publishing House, New Delhi

		UNIT-V	
1	1	Types of interaction in nature, typical strengths and time-scales, conservation laws	T1:545, T1:546-547
2	1	Charge-conjugation, parity and time reversal	T1:548-549
3	1	CPT theorem, Gell-Mann Nishijima formula	T1:550, T1:551
4	1	Intrinsic parity of pions, resonance, Symmetry, Classification of elementary particles	T1:554, T1:555, T1:525-526
5	1	Quark hypothesis, Charm, beauty and truth, gluons, Quark confinement, Asymptotic freedom	T1:580-581, T1:581-852, T1:583, T1:584
6	1	Revision	
7	1	Previous year ESE question paper discussion	
8	1	Previous year ESE question paper discussion	
	Total No of Hours Planned for unit V = 8		
Total Planned Hours	**40**		

Textbook

T1 - Pandya M.L. and R.P.S. Yadav, 2004. Elements of nuclear physics, Ist Edition, Kedarnath /Ramnath, Meerut

T2 - Dayal. D.C., 4th Edition, 2011. Nuclear Physics, Himalaya Publishing House, New Delhi

UNIT-

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Nuclear mass and charge: Distribution of nuclear charge - Nuclear mass and binding energy of a nucleus – semi-empirical mass formula – Nature of nuclear force – form of nucleon-nucleon potential – charge independence and charge symmetry of nuclear forces - Bound states of two nucleons-Ground state of Deuterium - Wave mechanics of ground state of Deuterium-Spin states – Pauli’s exclusion principle -Tensor force - Exchange force - Low energy Nucleon - Nucleon scattering

NUCLEAR CHARGE DISTRIBUTIONS:

The early theorists, without access to computers, had strong reasons to use analytical descriptions of charge distributions and potentials, that enabled series expansions of analytical solutions of the wave functions within and close to the nucleus. A common choice was the homogeneous charge distribution inside a radius $R = R_0A^{1/3}$, where A is the mass number of nucleus. The most important parameter for many properties is the expectation value r^2 which has the value $3R^2/5$ for the homogeneous nucleus. Already this simple distribution gives the correct analytical behavior of the electronic wave functions at $r = 0$ and has been used in many early analyses, These expansions are also useful for a general understanding of the effects involved.

Experimental information:

Experimental information about charge distributions are derived from many sources, including electron scattering. The experimental data indicate that R_0 1.2 fm gives areasonable
C
approximationforthehomogeneousdistribution.Clearly,thetailofarealnucleusislesssharp than indicated by the homogeneous distributions. It is often described in terms of a “skin thickness”
t, defined as the distance in which the charge density falls from 90% of its central value to 10%. Experiments indicate that$t$ is about 2.3 fm for most nuclei.

The primary data from electron scattering experiments are expressed in terms of a

“Fourier-Bessel expansion”. It is possible to use these data directly, using a numerical approach.

Tabulations often give values relating to additional parameterizations, in particular the two and three-parameter Fermi distributions, as well as Gaussian expansions (de Vries, de Jager & de Vries 1987, Fricke, Bernhardt, Heilig, Schaller, Schellenberg, Schera & de Jager 1995), that are discussed in more detail below.

Another source are muonic X-ray energies. These probe somewhat different moments, the"Barrettmoments",ofthenucleardistribution.Nevertheless,theresultsarequotedalsoin terms of r^2 (Engfer, Schneuwly, Vuilleu- mier, Walter & Zehnder 1974).

Optical isotope shifts provide an important source of complementary information, in particular for chains of radioactive isotopes. It is found that the changes in charge radius along an isotope chain are, in general, smaller than indicated by the textbook formula above. The isotope shifts also reveal an"odd-even staggering" of the r^2 values, providing evidence of nuclear shell structure (Aufmuth, Heilig & Steudel 1987*b*, Otten 1989). A spectacular recent application is the precision determination of the "deuteron structure radius" from the hydrogen-deuterim isotope shift of the 1s – 2s two-photon resonance (Huber, Udem, Gross, Reichert, Kourogi, Pachucki, Weitz&Hänsch1998).

Nuclear mass and binding energy:

A nucleus consists of Z protons and N neutrons. Let the mass of the nucleus be M (Z, N). If a nucleus is assumed to be a simple collection of Z protons and N neutrons, the mass of the nucleus would be just the sum of the masses of these constituent nucleons, i.e. $ZM_p + NM_n$ where M_p is the mass of proton and M_n is that ofneutron.

However, a nucleus is not a simple collection of protons and neutrons (nucleons), but they strongly combine with each other through a strong interaction named the nuclear force.

Mass defect

In general, if two or more particles interact to combine together, then the total mass of the system would decrease to be less thanthe sum of the masses of the individual particles. The stronger the interaction becomes, the more the mass decreases. This decrease of the mass of the system is called the mass defect. The mass defect of a nucleus of proton number Z and neutron number N is defined by mass defect = $(ZM_p + NM_n) - M(Z,N)$.

Semi-empirical Mass Formula:

$$E_b(MeV) = a_V A - a_S A^{\frac{2}{3}} - a_C \frac{Z^2}{A^{\frac{1}{3}}} - a_A \frac{(A-2Z)^2}{A} \pm \delta(A,Z)$$

$$\delta(A,Z) = \begin{matrix} +\delta_0 \; for\, Z, N\, even \\ 0 \\ -\delta_0 \; for\, Z, N\, odd \end{matrix}$$

This formula is called the Weizsaecker Formula (or the semi-empirical mass formula). The physical meaning of this equation can be discussed term by term.

Volume term :– a_V.A. The first two terms describe a spherical liquid drop of an incompressible fluid with a contribution from the volume scaling with A and from the surface, scaling with $A^{2/3}$. The first positive term a_V.A is known as the volume term and it is caused by the attracting strong forces between the nucleons. The strong force has a very limited range and a given nucleon may only interact with its direct neighbors. Therefore this term is proportional to A, instead of A2. The coefficient a_V is usually about ~ 16MeV.

Surface term – $a_{sf}.A^{2/3}$. The surface term is also based on the strong force, it is, in fact, a correction to the volume term. The point is that particles at the surface of the nucleus are not completely surrounded by other particles. In the volume term, it is suggested that each nucleon interacts with a constant number of nucleons, independent of A. This assumption is very nearly true for nucleons deep within the nucleus, but causes an overestimation of the binding energy on the surface. By analogy with a liquid drop this effect is indicated as the surface tension effect. If the volume of the nucleus is proportional to A, then the geometrical radius should be proportional to $A^{1/3}$ and therefore the surface term must be proportional to the surface area i.e. proportional to$A^{2/3}$.

Coulomb term – $a_C.Z^2.A^{-1/3}$. This term describes the Coulomb repulsion between the uniformly distributed protons and is proportional to the number of proton pairs Z^2/R, whereby R is proportional to $A^{1/3}$. This effect lowers the binding energy because of the repulsion between charges of equal sign.

Asymmetry term – $a_A.(A-2Z)^2/A$. This term cannot be described as 'classically' as the first three. This effect is not based on any of the fundamental forces, this effect is based only on the Pauli exclusion principle (no two fermions can occupy exactly the same quantum state in an atom). The heavier nuclei contain more neutrons than protons. These extra neutrons are necessaryforstabilityoftheheaviernuclei.Theyprovide(viatheattractiveforcesbetweenthe neutrons and protons) some compensation for the repulsion between the protons. On the other hand, if there are significantly more neutrons than protons in a nucleus, some of the neutrons will be higher in energy level in the nucleus. This is the basis for a correction factor, the so-called symmetry term.

Pairing term – δ(A,Z). The last term is the pairing term δ(A,Z). This term captures the effect of spin-coupling. Nuclei with an even number of protons and an even number of neutrons are (due to Pauli exclusion principle) very stable thanks to the occurrence of 'paired spin'. On the other hand, nuclei with an odd number of protons and neutrons are mostly unstable.

Nature of nuclear force:

The strong forces of attraction which firmly hold the nucleons in the nucleus are known as nuclear forces. The forces holding the nucleus together must be extremely strong. This is clear from the fact that the positively charged protons remain confined to the small volume of the nucleus. If the nuclear forces are weak, the electrostatic repulsion of the positively charged protons would tend to break the nucleus apart or at the very least, the nucleus would occupy a much larger volume. These forces exist between the nucleons i.e. between a neutron and a proton, between two protons and between two neutrons. The stability of the nucleus is accounted for due to the presence of theseforces.

Some important properties of nuclear forces are

- They are attractive incharacter
- They exert attractive forces on the nucleons. Hence they are also called cohesiveforces.
- They are chargeindependent
- They are the same between p and n or between p and p or between n and n. These forces do not depend upon the charge on thenucleons.
- They are short rangeforces
- It has been found that they are quite strong for an inter nucleon distance of the order of 10-15 m but become zero at an inter nucleon distance of 10 -14 m. Nuclear forces change with distance between thenucleons.
- They have saturationcharacter

- They abruptly become zero as the inter-nucleon distance is increased to a certain value. Therefore, nuclear forces do not increase with the increase in the number ofnucleons.
- They are extremely strong:
- Their magnitude is so high that a huge energy is required to divide a nucleus into its constituents. The relative strengths of gravitational (FG), electrostatic (Fe) and nuclear (FB) forces acting in the nucleus is given below, FG : Fe : FB = 1 : 1036 :1038
- The nuclear forces are dependent on the spin of thenuclei.
- Nuclear forces are non-centralforces
- The force between two nucleons does not act along the line joining their centers. This shows that nucleons in the nucleus are not sphericallysymmetric.

Form of Nucleon-Nucleon potential:

Let us discuss in some more detail the interaction between nucleons. In the past there has been a tremendous experimental effort devoted to scattering protons on protons and neutrons on protons. Since the neutron target is not available, the neutron-neutron scattering was inferred mostly from the scattering of protons on deuterons. All this effort led to a large database of cross-sections and phase shifts that provide the most extensive information on the binary interactions on nucleons. There have also been numerous attempts to model the interaction between nucleons by different kinds of potentials.

The electromagnetic part contains not only the standard Coulomb interaction between protons, but also various other terms like the two-photon Coulomb terms, vacuum polarization terms, and magnetic-moment interactions.

Charge independence and charge symmetry:

The neutron and the proton are regarded as two different states of the same entity, called the nucleon, differing only in their electrical charge. These are strong evidences to show that the basic force between two neutrons, as also between two protons, within the nuclei, is the same. This of course does not take into account the electrostatic repulsion between theprotons.

Symbolically, we can express this fact by writing

$$(n\text{-}n) = (p\text{-}p)$$

This is known as the charge symmetry of the nuclear force.

In addition the force between the neutron and the proton in s state is also equal to the above two forces, a fact known as the charge independence of the nuclear force.

(n-n) = (p-p) =(p-n)

Thus there is a basic symmetry of the nuclear forces which is broken only by the electromagnetic interaction due to the charge on the proton.

Ground state of deuterium: (Wave mechanics of ground state of deuterium)

The gravitational potential energy for the Deuteron nucleus is found to be

$$V(r) = -\frac{g^2 \hbar c}{M_0^2}\frac{m_p m_n}{r}, \quad (1.1)$$

where,

$$g^2 = \frac{e^2}{0.2254} = 0.032384 . \quad (1.2)$$

In theaboveexpression $e^2 = \frac{1}{137}$ isthefinestructureconstantand0.2254istheWeinberg mixing parameter. The parameter M_0^2 is different for each nucleus. For the Deuteron nucleus it is givenby,

$$M_0^2 = 0.931826 \times 10^{-48}\ \mathrm{gm}^2 . \quad (1.3)$$

The time independent Schrödinger equation for the deuteron is given by,

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(r)\right]\Psi(r,\vartheta,\phi) = E\Psi(r,\vartheta,\phi) . \quad (1.4)$$

Here the reduced mass μ is givenby,

$$\mu = \frac{m_p m_n}{m_p + m_n} = 0.836883 \times 10^{-24}\ \mathrm{gm} . \quad (1.5)$$

The spherically symmetric potential leads to the solution

$$\Psi(r,\vartheta,\phi) = R_{n\ell}(r)Y_{\ell m}(\vartheta,\phi), \qquad (1.6)$$

Where the quantum numbers n, ℓ and m have the following values as in the case of the hydrogenatom:

$$n = 1,2,3\cdots \text{ and } \ell = 0,1,2,\cdots,n-1,$$
$$\text{and } m = -\ell,-\ell+1,,\cdots,+\ell$$

The radial wave function is given by,

$$R_{n\ell} = A\mathrm{e}^{-\frac{\rho}{2}}\rho^{\ell}L_{n+\ell}^{2\ell+1}(\rho). \qquad (1.7)$$

Thedimensionlessparameter ρ in Equation (1.7) is given by,

$\rho = \dfrac{2r}{na_0}$, where n is the principalquantum number. (1.8)

Here,

$$a_0 = \frac{\hbar^2}{\mu}\frac{M_0^2}{g^2\hbar c m_p m_n} = 4.31734\times10^{-13}\text{ cm}. \qquad (1.9)$$

The energy spectrum for this case is given by,

$$E_{n\ell} = -\frac{\mu}{2\hbar^2}\frac{1}{n^2}\left(\frac{g^2\hbar c m_p m_n}{M_0^2}\right)^2 = -\frac{2.2251}{n^2}\text{ MeV}. \qquad (1.10)$$

The normalization constant A in Equation (1.7) is given by,

$$A = \sqrt{\left(\frac{2}{na_0}\right)^3\frac{1}{2n}\frac{(n-\ell-1)!}{\left[(n+\ell)!\right]^3}}. \qquad (1.11)$$

All the above results are obtained by a simple transcription of the hydrogen atom results with an appropriate change of variable. The ground state energy of the deuteron nucleus is givenby −2.2251 Mev. This is an excellent result. The radius of the deuteron nucleus is half of Equation (1.9) whereas Equation (1.9) gives the distance between the two nucleons. The radius is the distance of either of the nucleons from the center of mass. This result also agrees pretty wellwith the experiment. There are excited energy levels but these are a blessing in disguise. These will be necessary to explain the quadrupole moment of the deuteron nucleus as we show in the next section.

Paulis exclusion principle

The Pauli Exclusion Principle states that, in an atom or molecule, no two electrons can have the same four electronic quantum numbers. As an orbital can contain a maximum of only two electrons, the two electrons must have opposing spins. This means if one is assigned an up-spin (+1/2), the other must be down-spin (-1/2).

Electrons in the same orbital have the same first three quantum numbers, e.g., n=1n=1, l=0l=0, ml=0ml=0 for the 1s sub shell. Only two electrons can have these numbers, so that their spin moments must be either ms=−1/2ms=−1/2 or ms=+1/2ms=+1/2. If the 1s orbital contains only one electron, we have one ms value and the electron configuration is written as 1s1 (corresponding to hydrogen). If it is fully occupied, we have two ms values, and the electron configuration is 1s2 (corresponding tohelium).

The 1s and 2s sub shells for beryllium atoms can hold only two electrons and when filled, the electrons must have opposite spins. Otherwise they will have the same four quantum numbers, in violation of the Pauli Exclusion Principle.

Nuclear Magnetic Moments

Associated with each nuclear spin is a magnetic moment which is associated with the angular momentum of the nucleus. It is common practice to express these magnetic moments in terms of the nuclear spin in a manner parallel to the treatment of the magnetic moments of electron spin and electron orbital angularmomentum.

For the electron spin and orbital cases, the magnetic moments are expressed in terms of a unit called a Bohr magneton which arises naturally in the treatment of quantized angular momentum

Exchange force:

Modern field theory is based on a model in which fundamental forces are transmitted by the exchange of bosons (integer spin). The most obvious example is the electromagnetic interaction which is transmitted by photons. Most nuclear processes however can be understood in terms of what we have referred to as the 'left over' nuclear force. There is no need to deal directly with the fundamental strong force between quarks. Nevertheless in working with the nuclear force it is still possible to use the concept of exchange and in fact one of the earliest applications of such a concept was made in this area. At low energies, only the outer part of the force field which surrounds the nucleon is involved and this is dominated by single pion exchange. The pion is the lightest meson, it has zero intrinsic spin and belongs to an isospin triplet t = 1 with t3 = +1 (pi-plus), 0 (pi-zero), -1 (pi-minus). As stated above the electromagnetic interaction is transmitted by the photon and this has zero rest mass. In the case where the exchanged boson has non-zero rest mass we can examine what effect this has on the shape of the field around a source, by drawing a parallel with electrostatics. For a field transmitted by a particle with mass we start with the relativistic expression relating energy and momentum in this case $E_2 = p_2c_2+m_2c_4$

This is called the Yukawa potential since the original proposal that nuclear binding forces were due to particle exchange was made by the Hideki Yukawa in 1935, and from knowledge of the range of the force he was able to predict the mass of the particle using the sort of argument we have described above. Cecil Powell discovered the pion in 1947 in cosmic rays. Yukawa was awarded the Nobel prize in 1949 and Powell was awarded it in 1950.

We now examine what might be the result of exchange between two nucleons in terms of their spin and isospin. This is illustrated simply below. The red disks represent protons and the blue disks are neutrons with spin states indicated by the attached arrows.

The effect of the exchange of a quantity between two particles can be represented by an operator P which operates on the wave function describing the two particle state. In this case the effective potential is written V(r)P where V(r) is a normal attractive central potential. Although such a potential has little meaning in classical mechanics it causes no difficulty in quantum mechanics since it is just incorporated into the Schrödinger equation.

We will look at the effect of P in each case illustrated above to get some idea of the different components of the nuclear potential. This is clearly much more complicated than the Coulomb potential of an atom. If we include the tensor force then we have a simple physical argument for considering a two nucleon interaction made up of at least six component potentials. This is not all since we should also include velocity dependent forces which are important in scattering processes but which also show effects in nuclei - for example the spin-orbitforce.

Finally, as we have mentioned above, the nuclear force has a repulsive core which prevents the nuclei from collapsing in on themselves. We conclude this section with a crude sketch of the nucleon-nucleon potential illustrating some of the types of particle exchange which are thought tocontribute.

Tensor force:

Deuteron spends about 96% of its time in an l=0; 1s state and the remaining 4% of its time in an l=2 , 1d state. For both l=0 and l=2 we haves=1.

Thus one can account for the observed dipole and qudrapole moments of the deuteron by considering an admixture of l=2 value in to l=0 value in the corresponding wave function what is the physical effect of changing the angular momentum of the system from l=0 to l=2. Obviously a torque must be considered to act. This torque is related to thepotential.

We thus see that a change in the angular momentum implies that the potential v is not. Just a function of r as assumed previously, but is function of angle also. the force responsible for this is dependent not on r alone as in the case of a pure central force. It also depends on angle, the angle between the spin angular momentum direction and the line joining the nucleons. This force is clearly a non-central force and it is called the tensorforce.

The value of the tensor force depends on the angle which is measured from the direction of the spin vector S. therefore the tensor force is a function of s.r. the tensor force is similar to the force law for two magnets, which depend on the way they areoriented.

Neutron-Proton scattering

Consider low energy neutron proton scattering. The deuteron, the bound state of neutron and proton tellsus something about the interaction. The deuteron is the only bound state of neutron and proton. It has $J = 1$, binding energy of 2.23MeV. It has a quadrupole moment. As there is no $J = 0$ bound state, the interaction depends on spin. The most general state with spin 1 is

$$\Psi = a|\,^3S_1\rangle + b|\,^3P_1\rangle + c|\,^1P_1\rangle + d|\,^3D_1\rangle.$$

The magnetic moment of the deuteron is roughtly $\mu_n + \mu_p$. The contribution from $l = 1$ would be much larger so there can not be much $l = 1$ in the wave function. If the interaction is parity invariant then either $b = c = 0$ or $a = d = 0$. Must be that $b = c = 0$ in view of the small magnetic moment and $|D| \lll |a|$. Since there is a quadrupole moment, and we know that $l = 0$ is speherically symmetric, it must be that $|d| \neq 0$. The expectation value of the quadrupole meomtn will be

$$\langle Q\rangle = d\,\langle ^3S_1 \mid Q \mid ^3D_1\rangle + c.c. + O(d^2).$$

As there are both $l = 0$ and $l = 2$ contributions to the wave functions, the interatino does not conserve orbital angular moemntum, only total.

Write an interaction potential that distinguishes $l = 0$.

$$V = V_s(r)P_s + V_t(r)P_t,$$

where P_s and P_s are the singlet and triplet projection operators.

$$P_s = \frac{1}{4}(1 - \sigma_{\mathbf{n}} \cdot \sigma_{\mathbf{p}}), \qquad P_t = \frac{1}{4}(3 + \sigma_{\mathbf{n}} \cdot \sigma_{\mathbf{p}}) \tag{1}$$

Then

$$M(\mathbf{k}_f, \mathbf{k}_i) = f_s(k,\theta)P_s + f_t(k,\theta)P_t \tag{2}$$

For the unpolarizedbeam, the initial spin density matrix is $\phi_i = \frac{1}{4}$. The differentiual cross section is

$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\mathrm{Tr}(P_s|f_s|^2 + P_t|f_t|^2) \tag{3}$$

$$= \frac{1}{4}(|f_s|^2 + 3P_t|f_t|^2) \tag{4}$$

After scattering the most general spin-density matrix is

$$\rho = \frac{1}{4}\left(1 + \sigma_{\mathbf{n}} \cdot \mathbf{P_n} + \sigma_{\mathbf{p}} \cdot \mathbf{P_p} + \sum_{i,j=1}^{3} \sigma_{n,i}\sigma_{p,j}C_{ij}\right) \tag{5}$$

We find if the initial spin state is random

$$\rho_f = \frac{1}{4}\frac{|f_s|^2P_s + |f_t|^2P_t}{d\sigma/d\Omega} = \frac{d\sigma/d\Omega + \frac{1}{4}\sigma_{\mathbf{n}} \cdot \sigma_{\mathbf{p}}(|f_t|^2 - |f_s|^2)}{4(d\sigma/d\Omega)} \tag{6}$$

and

$$C_{ij} = \delta_{ij}\frac{|f_t|^2 - |f_s|^2}{4(d\sigma/d\Omega)}$$

Low energy Scattering

Consider s-wave scattering from a square well potential with $V = V_0$ for $r < R$ and zero otherwise. The general solution for a free particle (outside the potential) for each partial wave

$$A_l(r) = e^{i\delta_l}[\cos\delta_l j_l(kr) - \sin\delta_l n_l(kr)] \tag{7}$$

and for s-wave

$$A_0(r) = e^{i\delta_0}[\cos\delta_0 j_0(kr) - \sin\delta_0 n_0(kr)] = e^{i\delta_0}\sin(kr+\delta_0) \tag{8}$$

At $r < R$, with the requirement that $u(0) = 0$, solutions to the Schrodinger equation

$$-\frac{\hbar^2}{2m}\frac{d^2u}{dr^2} + V_0 = E \tag{9}$$

are $u(r) = A\sin k'r$ with $k' = \sqrt{2m(E-V_0)}/\hbar$. Then match logarithmic derivative at the boundary $r = R$.

$$\begin{aligned} k'\cot k'R &= k\cot(kR+\delta_0) && (10)\\ \to k'\tan(kR+\delta_0) &= k\tan k'R && (11)\\ \to \delta_0 &= \tan^{-1}(\frac{k}{k'}\tan(k'R)) - kR && (12) \end{aligned}$$

Since the scattering amplitude for $l = 0$ is

$$f(\theta) = \frac{1}{2ik}e^{i\delta_0}\sin\delta_0 \tag{13}$$

the differential cross section becomes

$$\frac{d\sigma}{d\Omega} = \frac{1}{4k^2}\sin^2\delta_0$$

If the potential is attractive, $V_0 = -|V_0|$, the cross section will reach a maximum whenever $\delta_0 = (n+\frac{1}{2})\pi$. If the potential is attractive, $V_0 < 0$, and $k' < k$, then as we increase the energy from zero, the cross section will go through resonances as δ_0 goes through $(n+\frac{1}{2})\pi$.

For very low energy, $k \to 0$, from Equation 12 we get

$$\begin{aligned} \delta_0 + kR &\sim \frac{k}{k'}\tan(k'R)\\ k(-a+R) &\sim \frac{k}{k'}\tan(k'R)\\ \to a &\sim R - \frac{\tan k'R}{k'} \end{aligned}$$

Then the cross section is independent of energy and

$$\sigma = 4\pi\frac{1}{k^2}\sin\delta_0^2 = 4\pi a^2 \tag{14}$$

If $k'R \sim \pi/2$ then the cross section can be very large at very low energy.

KARPAGAM ACADEMY OF HIGHER EDUCATION,COIMBATORE-21
DEPARTMENT OF PHYSICS
CLASS:I MSC PHYSICS
NUCLEAR PHYSICS (19PHP203)
MULIPLE CHOICE QUESTIONS

QUESTI(	**opt1**	**opt2**	**opt3**	**opt4**	**opt5**	**opt6**	**answer**
Unit - I							
The atomi	The numb	The numb	The numb	The number of –particles in th			The number of protons in the atom
The atomi	The numb	The numb	The numb	The number of –particles in th			The number of nucleons in the atom
Which of	Proton	Electron	Neutron	Nucleus			Electron
Which of	It is evenl	It is evenl	It is conce	It is concentrated in the nucleus			It is concentrated in the nucleus
Neutrons l	1639 time	1739 time	1839 time	1939 times of an electron			1839 times of an electron
Which of	N = A –Z	N = Z – A	N=Z +A	N = Z			N = A –Z
What law	Conservat	Conservat	Conservat	Conservation of energy			Conservation of energy
Why are n	Nuclear en	Nuclear en	Nuclear en	Electron energy levels depend o			Nuclear energy levels depend on attractive and repulsive forces
Which of	It is an att	It is an att	It is much	It is a strong, short-range, attrac			It is a strong, short-range, attractive force between the nucleons
Isotopes o	have the s	have the s	have diffe	have different number of electro			have the same number of protons and electrons, but a different number of neutrons
Binding en	the amour	the amour	the amour	the amount of energy released v			the amount of energy required to break a nucleus apart into protons and neutrons
When nuc	created fro	destroyed	transform	released as high energy photons			released as high energy photons or particles
An isotope	will decay	is very un	is very sta	has very few electrons			is very stable
Why do h	to add mo	to provide	to provide	to provide more attractive strong			to provide more attractive strong nuclear force to balance the repulsive electromagnetic force
The fact th	short rang	long range	weak	strong			short range
Nucleus "a	8R	R	2R	1.4R			2R
The partic	Electrons	Neutrons	Protons	None of the above			Neutrons
The mass	Always le	Always eq	Always m	Sometimes more than & someti			Sometimes more than & sometimes equal to its atomic number
Barlett for	The excha	The excha	An exchar	None of the above			The exchange of the spin coordinates
Forces inv	Nuclear fo	Coulomb	Nuclear as	Electromagnetic forces			Nuclear as well as coulomb repulsive forces
Which one	The nuclea	The nuclea	The nuclea	None of the above			The nuclear forces between n-p, n-n and p-p are equal
Which of	e-e, e-o, o	e-o, e-e, o	o-o, e-o, e	None of the above			o-o, e-o, e-e nuclei
The energ	933.17Me	93.3 MeV	9331MeV	None of these			933.17MeV
Nucleus c	p=n=e	p=e=n	p=e=n	n=p-1=e			p=e=n
Stability c	Mass defe	Binding en	Neutron-p	Ionisation potential			Ionisation potential
In stable n	1	>1	<1	None of these			1
The asymi	Non-spher	Non-zero	Unequal n	Odd number of protons inside t			Unequal number of protons and neutrons inside the nucleus
The size o	Electron s	Energy lev	Excited st	By selecting the probe using co			Excited state energy of the isotopic spin multiplet
The relati	Fg :Fe:Fn=	Fg :Fe:Fn=	Fg :Fe:Fn=	none of these			Fg :Fe:Fn=1:10^36:10^38
Which of	it is charg	it is spin d	it is veloci	it is independent of non –centra			it is independent of non –central component
Isotopic sp	1	0	½	-0.5			0
At the pea	Z is even l	Z is odd a	Both Z an	Both Z and N are even			Both Z and N are even
A deutero	96% time	96% time	92% time	92% time in S state and 8% tim			96% time in S state and 4% time in D state
The avera	Bonding e	Bonding	Bonding e	none of these			Bonding energy per nucleon
According	Positron	μ-meson	K-meson	π-meson			π-meson
A deutero	Cannot be	Can be dis	Can be dis	Can be disintegrated by photon			Can be disintegrated by photon of minimum energy 2.22MeV
Nuclei wit	Isotopes	isobars	isomers	isotones			Isotopes
Isotopes a	Neutron n	Proton nu	mass num	none of these			mass number
Nuclei, wi	isobars	isotones	isomers	Isotopes			isotones
The atoms	Isotopes	isotones	isomers	isobars			isomers
Nuclei, ha	Isobars	isotones	Mirror nu	isomers			Mirror nuclei
Dimensio	7*10^11 r	3*10^8 m	6*10^8 m	1.5*10^{8} m/s			7*10^11 m/s
The charg	(n-p)= (n-	(n-p) = (p-	(n-n) = (p-	(n-n) ≠ (p-p)			(n-n) = (p-p)
A tensor f	Quadrupo	Dipole mo	Octupole	Monopole			Quadrupole moment
Majorana	The excha	The excha	An exchar	None of the above			The exchange of the space coordinates
Heisenber	The excha	An exchar	The excha	None of the above			An exchange of both the position and the spin coordinates
Heisenber	Short rang	Charge in	Charge sy	Saturation of nuclear forces			Saturation of nuclear forces
The coulo	Z	2Z	Z(Z-1)	It is independent of Z			Z(Z-1)
In the nuc	Coulomb'	Nuclear fo	Atomic fo	Nucleons force			Nuclear force
Nuclear fo	Spin indep	Spin depe	Both (a) a	None of these			Spin dependent
Existence	Tensor for	Nuclear fo	Proton for	Deuteron forces			Tensor forces
Stability o	Mass defe	Binding en	Neutron-p	Ionisation potential			Ionisation potential
Proton has	1637 time	1737 time	1837 time	1937 times of an electron			1837 times of an electron
The nucle	Neutrons	Protons	neutrons a	electrons and neutrons			neutrons and protons
Nucleus is	positively	negatively	neutral	charge keeps on changing			positively charged
An unkno	Atomic m	Atomic nu	Principle	Orbital quantum number			Atomic number
An unkno	Atomic m	Atomic nu	Principle	Orbital quantum number			Atomic mass number
How many	12	6	18	3			6
How many	12	30	18	20			20
How many	12	11	18	24			12
How many	14	6	7	10			7
Low energ	l = 0	l = 1,2,3	l = 0,1,2,3	l = 1, S=1			l = 0
A nucleus	5.99fm,7.5	6.99fm, 8.	2.3fm,4.5	none of these			5.99fm,7.55fm
Rest mass	1.6725 ×1	1.6725 ×1	1.6725 ×1	None of these			1.6725 ×10-27kg
The size o	Electron s	Energy lev	Excited st	By selecting the probe using co			Excited state energy of the isotopic spin multiplet
The ratio c	2	4	8	16			2
Calculate	1.91392 A	0.19132A	0	-1.9132AMU			1.91392 AMU

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UNIT-II

SYLLABUS

Radioactivity: Alpha decay: Properties of α particles - Velocity and energy of α particles - Gamow's theory of α particles- Geiger - Nuttall law- α ray energies and fine structure of α rays - α disintegration energy-Low range α particles
Beta decay: Properties of β particles - General features of β ray spectrum – Pauli's hypothesis - Fermi's theory of β particles - Forms of interaction and selection rules - Fermi's and Gamow teller transition
Gamma decay: The absorption of γ rays by matter - Interaction of γ rays with matter - Measurement of γ ray energies - Dumont bent crystal spectrometer method-internal conversion – Applications

Properties of α particles:

1. Alpha, α – particle carries double the positive charge of proton, which is equal to the charge on the heliumnucleus.
2. Mass of an alpha, α – particle is roughly four times that of hydrogen atom i.e. it is equal to the mass of the heliumnucleus.

The above two properties establish that an alpha, α – particle is equivalent to helium nucleus (or a helium atom which has lost its two orbital electrons i.e. a doubly ionized heliumatom).

3. Alpha, α – particles are deflected by electric and magneticfields.
4. The velocity of alpha, α – particle ranges between 1.4 x 107 ms^{-1} to 2.1 x 107 ms^{-1}, depending upon the source emittingit.
5. Because of large mass, the penetrating power of α – particle is very small, it being 1/100 times that due to beta, β – rays and 1/10,000 times that due to γ – rays . α – particle can be easily stopped by an aluminium sheet, only 0.02 mmthick.
6. Because of large mass and large velocity, α – particle have large ionizing power. Each α – particle produces thousands of ions before beingabsorbed.

7. The range of alpha, α – particles in air (distance through which they can travel in air) depends upon the radioactive source producing it. At normal pressure in air, the range of α – particle varies from 3 to 8cm.

8. Alpha, α – particles produces fluorescence in certain substances, like barium – plantinocyanide andzinc-sulphide.

9. Alpha, α – particles affected photographic plateslightly.

10. Alpha, α – particles are scattered while passing through thin metal foils. Most of the α – particles are scattered at small angles, but a few of them are scattered at an angle more than 900 also.

Velocity and energy of alpha particles:

The measurement of velocity and energy of α particles are precisely done with the help of magnetic spectrograph, and outline of which is shown in the diagram. the α-particles emitted from a radioactive sources are collimated in a narrow beam by slit. A strong magnetic field of known strength, applied in a direction perpendicular to the particle beam, deflects the particles through 180°. The scattering of alpha particles from the walls, top and bottom of the chamber is avoided by using a number of slits. Particles having the same radius and are therefore focused on a photographic plate placed atP.

Let B_o= Strength of the magnetic field

ℓ = charge on the particle

M= mass of the particle

V = velocity of the particle

r = radius of the circular path described by the particle under magnetic field B_o.

$$B_o \ell v = Mv^2 / r$$

$$v = eB_o.r/M$$

since e/M for an alpha particle is known , the velocity is obtained from the above formula if B_o and r are measured .

The energy E is given by,

$$E = ½ Mv^2$$

using this relation , the calculated energy is $2.074 x 10^{-14} v^2$ Mev.

Gamow theory of alpha decay

As we have seen, the alpha separation energy is negative for heavy nuclei such as uranium, but these nuclei do not immediately decay. In fact, alpha decay mean lives vary from nanoseconds to gigayears. We have seen that the alpha particle can be regarded as trapped by a potential barrier. In order to escape into the environment, the alpha must tunnel through the barrier. This description of alpha decay, which also explains the wide range in lifetimes, was given by Gamow and was oe of the first successes of the new quantum theory (which introduced such counter-intuitive ideas astunnelling).

Suppose we have a wave packet representing an alpha particle with mass m_α and kinetic energy E impinging on a square potential barrier of height V;SPMgt;E and width Δr. Then the transmission coefficent T is obtained from 2nd year quantum mechanicsas

$$T \approx e^{-2\kappa\Delta r}$$

where $\kappa = \sqrt{2m_\alpha|V-E|}/\hbar$.

This can be extended to any barrier shape in the form of the WKB approximation:

$$T \approx \exp(-2\int_R^b \kappa(r)\,dr)$$

Here, R and b are the classical turning points of the motion inside and outside the barrier. We may take the barrier to be the sum of a square well nuclear potential of radius R, and a Coulomb potential arising from a charge within R,

$$V(r) = 0 \qquad \text{for } r < R$$
$$= \frac{1}{[4\pi\epsilon_0]}\frac{Z_\alpha Z_D e^2}{r} \qquad \text{for } r \geq R$$

We can equate (aproximately) the energy release Q in the alpha decay to the kinetic energy E of the alpha particle and to the potential at the outer classical turning point.

$$Q \approx E = \frac{Z_\alpha Z_D e^2}{[4\pi\epsilon_0]b}$$

and hence determine b:

$$b = \frac{Z_\alpha Z_D e^2}{[4\pi\epsilon_0]Q}$$

Hence theintegralover $\kappa(x)$ becomes

$$\begin{aligned} G &= \frac{2}{\hbar}\sqrt{2m_\alpha Q}\int_R^b \left[\frac{b}{r}-1\right]^{1/2} dr \\ &= \frac{2b}{\hbar}\sqrt{2m_\alpha Q}\left[\arccos\left(\frac{R}{b}\right)^{1/2} - \left(\frac{R}{b}\right)^{1/2}\left(1-\frac{R}{b}\right)^{1/2}\right] \\ &= \frac{4Z_\alpha Z_D e^2}{[4\pi\epsilon_0]\hbar v}\left[\arccos\left(\frac{R}{b}\right)^{1/2} - \left(\frac{R}{b}\right)^{1/2}\left(1-\frac{R}{b}\right)^{1/2}\right] \end{aligned}$$

where $Q = \frac{1}{2}m_\alpha v^2$ and the above expression for b has beenused.

For thickbarriers($R/b \ll 1$ or $V(R) \gg Q$) we can approximate $\arccos\sqrt{Rb} \approx \pi/2 - \sqrt{R/b}$, and hence

$$\begin{aligned} G &\approx \frac{4Z_\alpha Z_D e^2}{[4\pi\epsilon_0]\hbar v}\left(\frac{\pi}{2} - 2\sqrt{\frac{R}{b}}\right) \\ &= \frac{Z_\alpha Z_D e^2}{2\epsilon_0 \hbar v} - \frac{1}{\hbar}\left(\frac{8Z_\alpha Z_D e^2 m_\alpha R}{\pi\epsilon_0}\right)^{1/2} \end{aligned}$$

The decay constant for alpha decay is thus

$$\begin{aligned} \lambda &= \lambda_0 e^{-G} \\ &= \lambda_0 \exp\left[-2\pi\frac{Z_\alpha Z_D}{\hbar v}\frac{e^2}{[4\pi\epsilon_0]} + \frac{1}{\hbar}\left(32 Z_\alpha Z_D m_\alpha R\frac{e^2}{[4\pi\epsilon_0]}\right)^{1/2}\right] \end{aligned}$$

where

$$\lambda_0 = \frac{v}{2R} \approx \frac{c}{2R}\sqrt{(}\frac{2Q_\alpha}{m_\alpha c^2}$$

Thus

$$\ln\lambda = \ln\lambda_0 + \frac{1}{\hbar}\left(32Z_\alpha Z_D m_\alpha R\frac{e^2}{[4\pi\epsilon_0]}\right)^{1/2} - 2\pi\frac{Z_\alpha Z_D}{\hbar c}\frac{e^2}{[4\pi\epsilon_0]}\sqrt{\frac{m_\alpha c^2}{2Q_\alpha}}$$
$$= a' - \frac{b'}{\sqrt{Q_\alpha}}$$

The Geiger-Nutall equation is thus recovered. Note the extreme sensitivity of the decay constant on the energy in the above equation.

Alpha-Ray energies and fine structure of Alpha-Rays:

From the early measurements of energy and range of alpha particles, it was found that alpha particles emitted from a given nuclide have the same initial velocity and energy. But latter experiments showed that this is not the case. Rutherford, wood, Rosenblum etc. showed that the particles are emitted in groups of energies majority being emitted in one group and a smaller percentage in the long rage. For example ThC emits two groups of long range particles with energies 9.492Mev and 10.543 Mev as compared with energy of 8.780 Mev for the particles in the main group. The most recent magnetic spectrograph studies have shown the existence of 10.422 Mev group. For each million particles of the main group, there are about 40 particles in the 9.492 Mev group, 20 in the 10.422Mev group and 170 in the 10.543 Mev group. It was also shown by Roseblum that the normal alpha particles emitted by some nuclides fall into several closely spaced velocity groups through the difference is very small. This leads to the conclusion that alpha rays form a spectrum and have fine structure as well. The alpha particles spectra may be divided into three groups:

(a) spectra consisting of a single group orline

(b) spectra consisting of two or more discrete, closely spaced components with intensities of the same or of only slightly different order ofmagnitude.

(c) spectra consisting of a main group and groups of much higher energy particles, the latter containing, however, only a very small fraction of the number of particles in the main group.

Alpha disintegration energy:

We know that nucleons in nucleus are bound due to the presence of short-range nuclear force, also known as strong force which is attractive in nature. Nucleons mean number of protons and neutrons. But it's not meant that nucleus has only one force, there is also another kind of force which exists within the nucleus which is known as repulsive force. Its name comes from proton-proton repulsion. The range of the repulsive force is unlimited, where as the strong force has short range.

The nuclei which contain 210 numbers of nucleons or more are not stable in nature. The reason of it is that in such nuclei the strong force is hardly able to counterbalance the repulsive force because there exists large number of protons that have repulsive force between them and the range of repulsive force is unlimited. As a result Alpha decay occurs. In order to attain more stability such nuclei try to reduce theirsize.

But here is a question why Alpha decay occurs instead of individual protons or helium nuclei? The answer of it is that Alpha particles have high binding energy. In order to escape from nucleus, a particle must have kinetic energy, and only the mass of Alpha particle is sufficiently smaller than that of its constituent nucleons for such energy to be available.

By computing from the known masses of each particle and the parent and daughter nuclei, the energy is released known as disintegration energy, when various particles are emitted from large nuclei, and that energy is equal to the product of mass difference and square of speed of light. Here the mass difference means the difference in the masses of initial and final nuclei and the mass ofparticle.

When an Alpha particle emerges, the nucleus recoils with a small amount of kinetic energy, so we can say that the kinetic energy of emitted particle is not exactly equal to the disintegration energy. It can be shown from momentum and energy conservation that the kinetic energy of Alpha particle is related to disintegration energy and mass number, which is known as A, of originalnucleus.

There are some cases in which the emission of Alpha particle is energetically possible, but it is not true for all type of nuclei. If Alpha decay occurs in Uranium that has 232 mass number and 92 proton number, energy will be released. If we want to emit a proton or helium nucleus from such nucleus, we must provideenergy.

Long Range Alpha Particles:

The existence of long range alpha particles from some nuclei like RaC’ an ThC’ can be explained by assuming that the nuclide before emitting alpha particle exists in an excited state from some preceding disintegration (either by the emission of beta particle or gamma ray). Two possibilities occur in such case:

A gamma ray may first be emitted bringing the nucleus to its normal state then alpha disintegration takes place.

Or (2) the alpha particle may be emitted taking with it the excess energy of the excited nucleus.

The second process will naturally give the alpha particle energy much higher than the normal energy. The probability of the alpha particle following one of the above two processes is inversely proportional to the respective mean lives. But the mean life of an excited nucleus with gamma emission is very small- of the order of 10^{-12} secs, in comparison to the mean life of long range alpha particles. Thus the chances of the first phenomenon to take place are more in comparisonar to the other. But in certain cases like ThC′ and RaC′, the second process of alpha emission actually takes place which can be accounted for extremely short lives of the nuclei with respect to alpha particles of the order of 10^{-5} and 10^{-9} sec. these facts have been experimentally verified and found correct in case of ThC′. ThC′ is formed by beta integration of the ThC. This leaves the nuclide in an excited state giving rise to long range alpha particles and end product ThD.

Properties of beta particles:

A beta (β)- particle carries 1.6 x 10^{-19} C of negative charge, which is the charge on an electron.

The mass of β-particle is 9.1 x 10^{-31} kg, which is the same as that of electron.

The velocity of β-particles ranges from 33% to 99% of the velocity of light.

The β-particles ionize the gas through which they pass, but their ionizing power is only 1/100th that ofα-particles.

Because of small mass, the penetrating power of β-particles is very large.

The β-particles can also produce fluorescence in certain substance like barium-plantinocyanide and zinc sulphide.

They affect a photographic plate.

They are deflected by electric and magnetic fields, showing that they carry negative charge.

General features of beta ray spectrum:

These are energetic electrons, they are relatively light and carry a single negative charge. Their mass is equal to the mass of the orbital electrons with which they are interacting and unlike the alpha particle a much larger fraction of its kinetic energy can be lost in a single interaction.

Their path is not so straightforward. The beta particles follow a very zig-zag path through absorbing material. This resulting path of particle is longer than the linear penetration (range) into thematerial.

Since they have very low mass, beta particles reach mostly relativistic energies.

Beta particles also differ from other heavy charged particles in the fraction of energy lost by radiative process known as the bremsstrahlung. Therefore for high energy beta radiation shielding dense materials areinappropriate.

When the beta particle moves faster than the speed of light (phase velocity) in the material it generates a shock wave of electromagnetic radiation known as the Cherenkov radiation.

The beta emission has the continuous spectrum.

A 1 MeV beta particle can travel approximately 3.5 meters in air.

Due to the presence of the bremsstrahlung low atomic number (Z) materials are appropriate as beta particle shields.

Paulis Hypothesis of Beta Decay:

Pauli introduced concept of third particle, a neutral particle which gets emitted in β^-decay. This particle has the generic name of Neutrino. The total energy is shared by 3 particles

The recoil nucleus

The Electron

The Neutrino

Because of its comparatively great mass, the recoil energy of Nucleus is very small and nearly all Kinetic Energy is shared between the Beta particle and the Neutrino.

In addition to laws of conservation of charge and energy, we must also apply the laws of conservation Linear and angular momentum to every nuclear process. Taking our reference system as the parent nucleus at rest, the vector sum of Linear Momenta of the recoil nucleus, the beta particle and neutrino must bezero.

To conserve angular momentum in β^-decay, we note that parent and daughter nuclei are isobars; i.e. they have equal number of nucleons. Hence, the total change in nuclear angular momenta will be either zero or an integral multiple of$\hbar$.

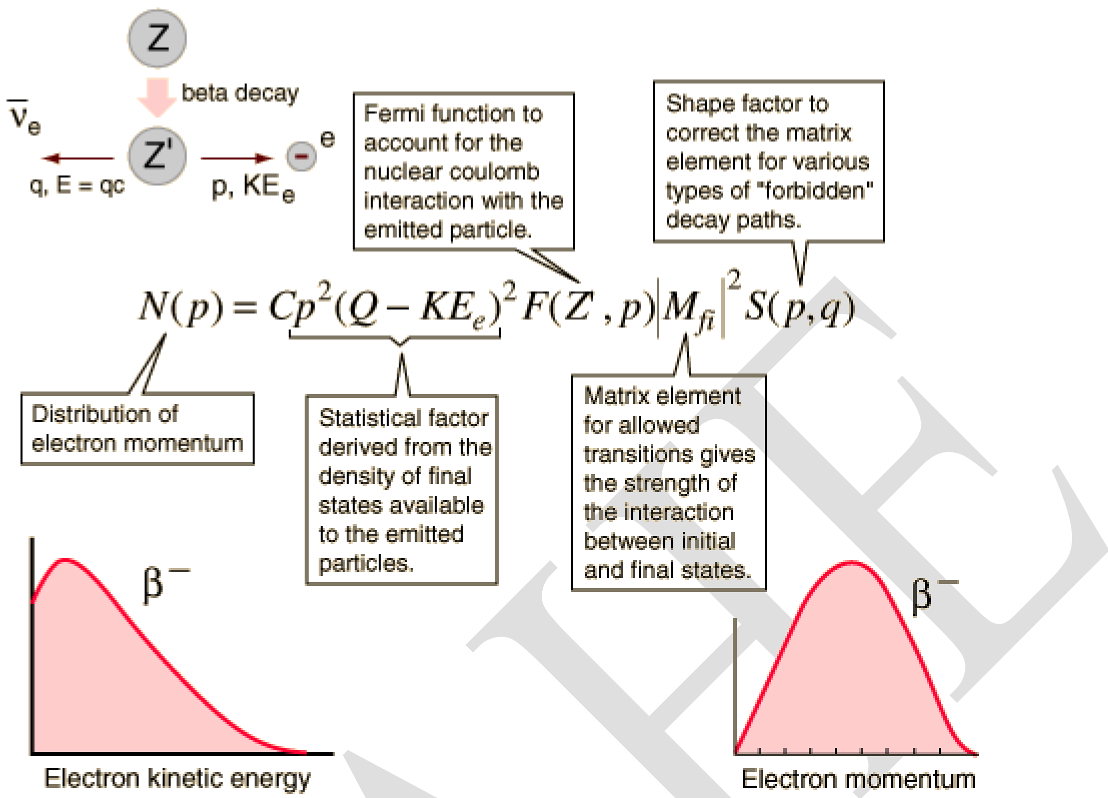
The beta particle has an intrinsic spin angular momenta of $1/2\hbar$.The vector sum of angular momenta of Neutrino and beta particle will be either zero or one in units of $\hbar$. The present accepted theory, which is supported by experimental evidence shows that there are two types of neutrino or two components of Neutrino. It has been found that the axis of spin of neutrino is parallel to its direction of motion; one type spins according to the left hand rule with respect to its direction of motion as its axis, the other component spins according to right hand rule. The first type is usually called neutrino represented by symbol ν, the second type is called antineutrino. The spin vector of neutrino points opposite to direction of its motion. The spin vector of anti neutrino points in the direction of its motion. Another way of saying this is that the helicity of neutrino is negative and that of anti neutrino is positive or one has right handed helicity and other has left handedhelicity.

Fermi Theory of Beta Decay

In 1930, Wolfgang Pauli postulated the existence of the neutrino to explain the continuous distribution of energy of the electrons emitted in beta decay. Only with the emission of a third particle could momentum and energy be conserved. By 1934, Enrico Fermi had developed a theory of beta decay to include the neutrino, presumed to be massless as well as chargeless.

Treating the beta decay as a transition that depended upon the strength of coupling between the initial and final states, Fermi developed a relationship which is now referred to as Fermi'sGoldenRule:

Straightforward in concept, Fermi's Golden Rule says that the transition rate is proportional to the strength of the coupling between the initial and final states factored by the density of final states available to the system. But the nature of the interaction which led to beta decay was unknown in Fermi's time (the weak interaction). It took some 20 years of work (Krane) to work out a detailed model which fit the observations. The nature of that model in terms of the distribution of electron momentum p is summarized in the relationshipbelow.



Forms of interaction:

Gravitation is by far the weakest of the four interactions at the atomic scale, where electromagnetic interactions dominate. But the idea that the weakness of gravity can easily be demonstrated by suspending a pin using a simple magnet (such as a refrigerator magnet) is fundamentally flawed. The only reason the magnet is able to hold the pin against the gravitational pull of the entire Earth is due to its relative proximity. There is clearly a short distance of separation between magnet and pin where a breaking point is reached, and due to the large mass of Earth this distance is disappointingly small.

Electromagnetism is the force that acts between electrically charged particles. This phenomenon includes the electrostatic force acting between charged particles at rest, and the combined effect of electric and magnetic forces acting between charged particles moving relative to each other. Electromagnetism is infinite-ranged like gravity, but vastly stronger, and therefore describes a number of macroscopic phenomena of everyday experience such as friction, rainbows, lightning, and all human-made devices using electric current, such as television, lasers, and computers.

Electromagnetism fundamentally determines all macroscopic, and many atomic levels, properties of the chemical elements, including all chemical bonding.

The strong interaction, or strong nuclear force, is the most complicated interaction, mainly because of the way it varies with distance. At distances greater than 10 femtometers, the strong force is practically unobservable. Moreover, it holds only inside the atomic nucleus.

After the nucleus was discovered in 1908, it was clear that a new force, today known as the nuclear force, was needed to overcome the electrostatic repulsion, a manifestation of electromagnetism, of the positively charged protons. Otherwise, the nucleus could not exist. Moreover, the force had to be strong enough to squeeze the protons into a volume that is about 10^{-15} m, much smaller than that of the entire atom. From the short range of this force, HidekiYukawa predicted that it was associated with a massive particle, whose mass is approximately 100 MeV.

The weak interaction or weak nuclear force is responsible for some nuclear phenomena such as beta decay. Electromagnetism and the weak force are now understood to be two aspects of a unifiedelectroweakinteraction—thisdiscoverywasthefirststeptowardtheunifiedtheory known as the Standard Model. In the theory of the electroweak interaction, the carriers of the weak force are the massive gauge bosons called the W and Z bosons. The weak interaction isthe only known interaction which does not conserve parity; it is left-right asymmetric. The weak interaction even violates CP symmetry but does conserve CPT.

Selection rules:

We have seen that beta decay results from an interaction of the nucleus with the beta neutrino field. The action of the nucleus on the field is to create the electron and neutron. The beta transitions takes place under certain quantum conditions. The quantum numbers which govern such transitions' are generally total angular momentum and parity. Spin for a nucleus is defined as I=Angular momentum.

Parity is defined as the property that the wave function changes sign or not when the space coordinates(x,y,z) are transformed by inversion. If the wave function changes sign, the parity is odd or negative and if not the parity is even or positive.

Fermi and Gamow-Teller Transition

The beta decay is caused by the weak interaction. The weak interaction is very short range, because the mediate particles, the $W^{\pm}$and Z^0bosons are 80 GeV and 91 GeV respectively. The effective range is like 10^{-3}fm. So, the interaction can assumed to be a delta function and only the coupling constant matter. The Fermi coupling constantis

$1.17 \times 10^{-11} (\hbar c)^2 \ \mathrm{MeV}^2$

The fundamental process of beta decay is the decay ofquark.

$u \xrightarrow{W^+} d + e^+ + \nu_e$

Since a pion is made from up and down quark, the decay of pion into position and electron neutrino is also due to weak interaction.

The Hamilton of the beta decay is

$H_w(\beta^{\pm}) = G_V \tau_{\mp} + G_A \sigma \tau_{\mp}$

where $G_V$is the vector coupling constant, the term is called Fermi transition. The is the$\tau_{\pm}$ isospin ladder operator. The beta+ decay changes the isospin from +1/2 (neutron) to -1/2 (proton). The $G_A$is the axial coupling constant, the term is called Gamow-Teller transition. is spin operatσor. Because of this operator, the Gamow-Teller transition did not preserveparity.

The $G_A$is different from G_V, which is caused by the effect of strong interaction. The Goldberger-Triemanrelation

$$g_A = \frac{G_A}{G_V} = \frac{f_\pi g_{\pi N}}{M_N c^2} = -1.3$$

where $f_\pi \sim 93 \ \mathrm{MeV}$is the pion decay constant. $g_{\pi N} \sim 14 \times 4\pi$is the coupling constant between pion and nucleon. This, we can see the effect of the strong interaction, in which pion is the meson for strong nuclearforce.

The transition probability can be estimated by Fermi-Golden rule

$$W(p_e) = \frac{2\pi}{\hbar} |\langle \psi_f | H | \psi_0 \rangle|^2 \rho(E_f)$$

the final state wavefunction

$$|\psi_f\rangle = \frac{1}{\sqrt{V}} e^{ik_e r} \frac{1}{\sqrt{V}} e^{ik_\nu r} |j_f m_f\rangle$$

$$e^{ikr} = \sum_L \sqrt{4\pi(2L+1)} i^L j_L(kr) Y_{L0}(\theta)$$

using long wavelength approximation, the spherical Bessel function can be approximated by the first term.

$$j_L(kr) \sim \frac{(kr)^L}{(2L+1)!!}$$

$$|\psi_f\rangle = \frac{1}{V}(1 + i\sqrt{\frac{4\pi}{3}} Y_{10} + \ldots)|j_f m_f\rangle$$

The first term 1, or L=0 is called allowed decay, so that the orbital angular momentum of the decayed nucleus unchanged. The higher order term, in which the weak interaction have longer range has very small probability and called L-th forbidden decay.

The density of state is

$$\rho(E_f) = \frac{V}{2\pi^2\hbar^7c^3} F(Z, E_e) p_e^2 (E_0 - E_e)((E_0 - E_e)^2 - (m_\nu c^2)^2)^2$$

where the $F(Z, E_e)$ is the Fermifunction.

The total transition probability is the integration with respect to the electron momentum.

$$W = \int W(p_e) dp_e = \frac{m_e^5 c^4}{2\pi^3\hbar^7} f(Z, E_0)|M|^2$$

where $f(Z, E_0)$ is the Fermi integral. Thehalf-life

$$T_{1/2} = \frac{\ln 2}{W}$$

To focus on the beta decay from the interference of the density of state, the ft-value is

$$ft = f(Z, E_0) T_{1/2} = \frac{2\pi^3\hbar^7}{m_e^5 c^4} \frac{\ln 2}{|M|^2}$$

The ft-value could be difference by several order.

There is a super-allowed decay from $0^+ \to 0^0$ with same isospin, which the GT does not involve. an exampleis

$$^{14}\mathrm{O} \to ^{14}\mathrm{N} + e^+ + \nu_e$$

The ft-value is 3037.7s, the smallest of known.

transition	L	$\log_{10} ft_{1/2}$	ΔJ		ΔT	$\Delta\pi$
			Fermi	GT		
Super allowed		3.1 ~ 3.6	$0^+ \to 0^+$	not exist	0	no
allowed	0	2.9 ~ 10	0	(0), 1	0, 1 ;$T_i = 0 \to T_f = 0$forbidden	no
1st forbidden	1	5 ~ 19	(0),1	0, 1, 2	0,1	yes
2nd forbidden	2	10 ~18	(1), 2	2, 3		no
3rd forbidden	3	17 ~ 22	(2), 3	3, 4		yes
4th forbidden	4	22 ~ 24	(3), 4	4, 5		no

The () means not possible if either initial or final state is zero. i.e $1^- \to 0^+$is not possible for 1st forbidde

KARPAGAM ACADEMY OF HIGHER EDUCATION,COIMBATORE-21
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CLASS:I MSC PHYSICS
NUCLEAR PHYSICS (19PHP203)
MULIPLE CHOICE QUESTIONS

Unit II

Questions	Option 1	Option 2	Option 3	Option 4	Answer
Which of t	α-rays	β-rays	γ-rays	x-rays	α-rays
The emiss	Shading o	Tunneling	Dischargi	None of these	Tunneling of the nucleus
Radioactiv	Irreversibl	Spontaneo	Self disint	All of the above	All of the above
Which of t	electron	$0n^1$	$1H^1$	$2He^4$	$2He^4$
Which of t	It carries a	It carries a	It can be c	It has zero rest mass and a neutr	It has zero rest mass and a neutral charge
The most	Atom emi	Nucleus e	Nucleus e	Nucleus emits a positron	Atom emits one or several X-rays
If the mas	Increase	Decrease	Remains t	None of these	Increase
Expected	E1	M4	E4	E3	E3
The minin	The neutro	The neutro	The positr	The neutron and positron are bo	The neutron and positron are both emitted with zero kinetic energy
A nucleus	Electron c	Internal co	Alpha dec	Beta decay	Internal conversion
To penetra	1GeV	100MeV	10MeV	1MeV	1MeV
A free neu	Neutrino	Gamma ra	Anti-neutr	Neutron	Anti-neutrino
In fermi’s	To find ou	To calcula	To find ou	None of these	To calculate the probability of β-transformation
β-particle	β-particle	β-particle	With β-pa	With β-particle a chargeless par	With β-particle a chargeless particle is also emitted so that the momentum and energy is distributed among these two particles and the recoiling nucleus
The total e	1.02MeV	0.511MeV	13.02MeV	40MeV	13.02MeV
A sensitiv	The angul	The electr	The neutri	None of these	The electron energy spectrum in beta decay
When a ne	Only an el	One electr	One electr	One electron and a proton are pr	One electron and an antineutrino are produced
The half-li	Temperatu	Pressure	Nature of	All of the above	Nature of the substance
Which of t	β-rays are	Γ-rays is h	A-particle	Protons and neutron have exactl	β-rays are the same as cathode rays
Why is β-	The bindin	Electrons	Alpha (α)	Positrons cannot exist in ordinar	Alpha (α) decay leaves nuclei neutron-rich
When an c	Hydrogen	A helium a	A helium i	β-particle	A helium ion
The penet	Minimum	10000 tim	1000 time	None of these	10000 times of α-rays and 100 times of β-rays
The pheno	Productio	Ejection o	ionisation	None of these	Production of an electron and a positron from γ-rays
Who deve	Rutherford	Fermi	Bohr	Goldstein	Fermi
A process	Compton e	Bragg’s la	Raman eff	None of these	Compton effect
Whenever	Pair annih	Pair produ	Meson pro	None of these	Pair annihilation
In the neu	oppositely	aligned to	aligned or	none of the above	oppositely directed
The long r	RaC’ and	RaA	RaF	Rn	RaC’ and ThC’
Which of t	RaA	RaF	Rn	All the above	All the above
Who poin	Gurney	Condon	Gamow	All of these	All of these
In the deca	Allowed b	Allowed b	Forbidden	Forbidden by F-selection rules a	Allowed by F-selection rules
A spin-1/2	1/2, 1, 3/2	0, 1	½ only	½, 3/2,5/2,7/2,…	½, 3/2,5/2,7/2,…
Rubidium	$38Kr^{87}$	$37Rb^{88}$	$38Sr^{87}$	$36Sr^{87}$	$38Sr^{87}$
Mean life	energy	frequency	wavelengt	none of the above	energy
Which of the followi		n_0^1	H	[He]_2^4	[He]
Which of the following is the β⁻ particle?				H_1	e_(-
Which of the following is the β+ particle?		n_0^		H_1^1	e_(+1)
What is the missing element from the following equation	(_86^220)Rn	_86^228)Rn	(_86^222)Rn	(_86^230)Rn	(_86^
What is th	$13N_7$	$12C_6$	$16O_8$	$14N_7$	$14N_7$
The nuclic	^{240}Np (Z=	240U (Z=	^{248}Cm (Z=	^{244}Am (Z=95)	240U (Z=92)
Expected	E1	M4	E4	E3	E3
The minin	1.8MeV	8MeV	40MeV	80keV	1.8MeV
The follov	Gamow T	Pauli spir	Fermi sele	Direc selection rule	Gamow Teller selection rule
The select	ΔJ=0 or Δ	$E_f=E_i=h\omega$	ΔS=0 to Δ	None of these	$E_f=E_i=h\omega$
By capturi	A neutrino	An antine	An α-parti	A positron	A neutrino
The Interr	N_e/N_γ	N_γ/N_e	N/N_e	sqrt(N/Ne)	N_e/N_γ
In the β-de	Energy dis	Angular d	Helicity di	Forward-backward asymmetry c	Forward-backward asymmetry of electrons
If R is the	Logλ=a+R	λ=a+logR	$\log\lambda=ae^R$	logλ=a+blogR	logλ=a+blogR
The equat	Meson pro	Pair produ	photon pro	None of these	Pair production
$1H_1+{}^0e_{-1}$	negatron e	positron e	orbital ele	all of the above	orbital electron capture
The long r	RaC’ and	RaA	RaF	Rn	RaC’ and ThC’
Almost all	α and elec	β and α	α, β and γ	None of the above	α, β and γ
nuclei like	short rang	long range	short or lo	none of the above	long range alpha particles
Spontaneo	potential e	kinetic ene	potential a	none of the above	kinetic energy

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RADIOACTIVITY

Objectives:

The main objective of this unit is to give the basic ideas about the phenomenon of radioactivity. After learning, one should be able to know about alpha, beta and gamma decays.

UNIT -III

Radioactivity: Alpha decay: Properties of particles - Velocity and energy of particles - Gamow's theory of particles- Geiger - Nuttall law- ray energies and fine structure of rays - disintegration energy-Low range particles

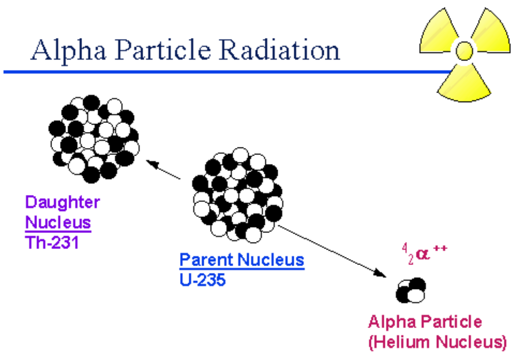
Beta decay: Properties of particles - General features of ray spectrum – Pauli's hypothesis - Fermi's theory of particles - Forms of interaction and selection rules - Fermi's and Gamow teller transition

Gamma decay: The absorption of rays by matter - Interaction of rays with matter - Measurement of ray energies - Dumont bent crystal spectrometer method-internal conversion –Applications.

RADIOACTIVITY:

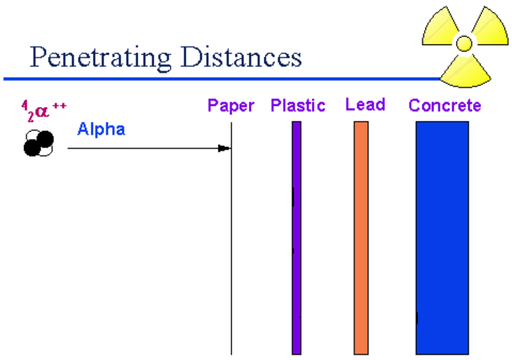
ALPHA DECAY

PROPERTIES OF PARTICLES



An alpha particle consists of two neutrons and two protons ejected from the nucleus of an atom. The alpha particle is identical to the nucleus of a helium atom. Examples of alpha emitters are radium, radon, thorium, and uranium.

Because alpha particles are charged and relatively heavy, they interact intensely with atoms in materials they encounter, giving up their energy over a very short range. In air, their travel distances are limited to no more than a few centimeters. As shown in the following illustration, alpha particles are easily shielded against and can be stopped by a single sheet of paper.



Since alpha particles cannot penetrate the dead layer of the skin, they do not present a hazard from exposure external to the body.

However, due to the very large number of ionizations they produce in a very short distance, alpha emitters can present a serious hazard when they are in close proximity to cells and tissues such as the lung. Special precautions are taken to ensure that alpha emitters are not inhaled, ingested or injected.

RANGE OF ALPHA PARTICLES

Composed of two protons and two neutrons, the alpha particle is a nucleus of the element helium. Because of its very large mass (more than 7000 times the mass of the beta particle) and its charge, it has a very short range. It is not suitable for radiation therapy since its range is less than a tenth of a millimeter inside the body. Its main radiation hazard comes when it is ingested into the body; it has great destructive power within its short range. In contact with fast-growing membranes and living cells, it is positioned for maximum damage.

Alpha particle emission is modeled as a barrier penetration process. The alpha particle is the nucleus of the helium atom and is the nucleus of highest stability.

VELOCITY AND ENERGY OF PARTICLES

An alpha particle emitted by a uranium nucleus has an initial speed of about 15 million meters/second (about 5% of the speed of light), which is fast but not as fast as a lighter beta particle. However, as a result of its high mass and relatively slow speed, combined with its positive charge, an alpha particle can easily remove electrons from – i.e. cause ionization of – the atoms in a substance, and its energy of motion is transferred to the medium. As it transfers energy it slows down. The rate of transfer depends on the medium. Alpha particles can penetrate up to 75 millimeters in air but much less in solid matter. They are said to have a high linear energy transfer (LET) and it is the rapid loss of energy in a small range which makes them such a radiation hazard if ingested.

Alpha particles have a typical kinetic energy of 5 MeV (that is, ≈ 0.13% of their total energy, i.e. 110 TJ/kg) and a speed of 15,000 km/s. This corresponds to a speed of around 0.05 c. There is surprisingly small variation around this energy, due to the heavy dependence of the half-life of this process on the energy produced (see equations in the Geiger–Nuttall law).

Because of their relatively large mass, +2 electric charges and relatively low velocity, alpha particles are very likely to interact with other atoms and lose their energy, so their forward motion is effectively stopped within a few centimeters of air.

Most of the helium produced on Earth (approximately 99% of it) is the result of the alpha decay of underground deposits of minerals containing uranium or thorium. The helium is brought to the surface as a byproduct of natural gas production.

RADIOACTIVITY

GAMOW'S THEORY OF PARTICLES

As we have seen, the alpha separation energy is negative for heavy nuclei such as uranium, but these nuclei do not immediately decay. In fact, alpha decay means lives vary from nanoseconds to giga years. We have seen that the alpha particle can be regarded as trapped by a potential barrier. In order to escape into the environment, the alpha must tunnel through the barrier. This description of alpha decay, which also explains the wide range in lifetimes, was given by Gamow and was one of the first successes of the new quantum theory (which introduced such counter-intuitive ideas as tunneling).

Suppose we have a wave packet representing an alpha particle with mass m_α and kinetic energy E impinging on a square potential barrier of height V;SPMgt;E and width Δr. Then the transmission coefficient T is obtained from 2nd year quantum mechanics as

$$T \approx e^{-2\kappa\Delta r}$$

where $\kappa = \sqrt{2m_\alpha|V-E|}/\hbar$.

This can be extended to any barrier shape in the form of the WKB approximation:

$$T \approx \exp(-2\int_R^b \kappa(r)\,dr)$$

Here, R and b are the classical turning points of the motion inside and outside the barrier. We may take the barrier to be the sum of a square well nuclear potential of radius R, and a Coulomb potential arising from a charge within R,

$$\begin{aligned} V(r) &= 0 \qquad \text{for } r < R \\ &= \frac{1}{[4\pi\epsilon_0]}\frac{Z_\alpha Z_D e^2}{r} \qquad \text{for } r \geq R \end{aligned}$$

We can equate (approximately) the energy release Q in the alpha decay to the kinetic energy E of the alpha particle and to the potential at the outer classical turning point.

$$Q \approx E = \frac{Z_\alpha Z_D e^2}{[4\pi\epsilon_0]b}$$

and hence determine b:

$$b = \frac{Z_\alpha Z_D e^2}{[4\pi\epsilon_0]Q}$$

Hence the integral over $\kappa(x)$ becomes

$$
\begin{aligned}
G &= \frac{2}{\hbar}\sqrt{2m_\alpha Q}\int_R^b \left[\frac{b}{r}-1\right]^{1/2} dr \\
&= \frac{2b}{\hbar}\sqrt{2m_\alpha Q}\left[\arccos\left(\frac{R}{b}\right)^{1/2} - \left(\frac{R}{b}\right)^{1/2}\left(1-\frac{R}{b}\right)^{1/2}\right] \\
&= \frac{4Z_\alpha Z_D e^2}{[4\pi\epsilon_0]\hbar v}\left[\arccos\left(\frac{R}{b}\right)^{1/2} - \left(\frac{R}{b}\right)^{1/2}\left(1-\frac{R}{b}\right)^{1/2}\right]
\end{aligned}
$$

where $Q = \frac{1}{2}m_\alpha v^2$ and the above expression for b has been used.

For thick barriers ($R/b \ll 1$ or $V(R) \gg Q$) we can approximate $\arccos\sqrt{Rb} \approx \pi/2 - \sqrt{R/b}$, and hence

$$
\begin{aligned}
G &\approx \frac{4Z_\alpha Z_D e^2}{[4\pi\epsilon_0]\hbar v}\left(\frac{\pi}{2} - 2\sqrt{\frac{R}{b}}\right) \\
&= \frac{Z_\alpha Z_D e^2}{2\epsilon_0 \hbar v} - \frac{1}{\hbar}\left(\frac{8Z_\alpha Z_D e^2 m_\alpha R}{\pi\epsilon_0}\right)^{1/2}
\end{aligned}
$$

The decay constant for alpha decay is thus

$$
\begin{aligned}
\lambda &= \lambda_0 e^{-G} \\
&= \lambda_0 \exp\left[-2\pi\frac{Z_\alpha Z_D}{\hbar v}\frac{e^2}{[4\pi\epsilon_0]} + \frac{1}{\hbar}\left(32 Z_\alpha Z_D m_\alpha R\frac{e^2}{[4\pi\epsilon_0]}\right)^{1/2}\right]
\end{aligned}
$$

where

$$
\lambda_0 = \frac{v}{2R} \approx \frac{c}{2R}\sqrt{(\frac{2Q_\alpha}{m_\alpha c^2}}
$$

Thus

$$
\begin{aligned}
\ln\lambda &= \ln\lambda_0 + \frac{1}{\hbar}\left(32 Z_\alpha Z_D m_\alpha R\frac{e^2}{[4\pi\epsilon_0]}\right)^{1/2} - 2\pi\frac{Z_\alpha Z_D}{\hbar c}\frac{e^2}{[4\pi\epsilon_0]}\sqrt{\frac{m_\alpha c^2}{2Q_\alpha}} \\
&= a' - \frac{b'}{\sqrt{Q_\alpha}}
\end{aligned}
$$

The Geiger-Nuttall equation is thus recovered. Note the extreme sensitivity of the decay constant on the energy in the above equation.

GEIGER - NUTTALL LAW

Geiger-Nuttall law or Geiger-Nuttall rule relates the decay constant of a radioactive isotope with the energy of the alpha particles emitted. Roughly speaking, it states that short-lived isotopes emit more energetic alpha particles than long-lived ones.

RADIOACTIVITY

The relationship also shows that half-lives are exponentially dependent on decay energy, so that very large changes in half-life make comparatively small differences in decay energy, and thus alpha particle energy. In practice, this means that alpha particles from all alpha-emitting isotopes across many orders of magnitude of difference in half-life, all nevertheless have about the same decay energy.

Formulated in 1911 by Hans Geiger and John Mitchell Nuttall, in its modern form the Geiger-Nuttall law is

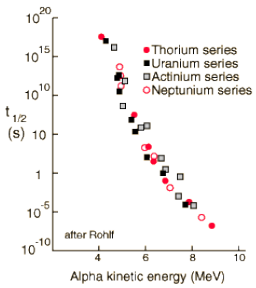
$$\ln \lambda = -a_1 \frac{Z}{\sqrt{E}} + a_2$$

where λ is the decay constant (λ = ln2/half-life), Z the atomic number, E the total kinetic energy (of the alpha particle and the daughter nucleus), and a1 and a2 are constants.

** RAY ENERGIES AND FINE STRUCTURE OF RAYS**

The energy of emitted alpha particles was a mystery to early investigators because it was evident that they did not have enough energy, according to classical physics, to escape the nucleus. Once an approximate size of the nucleus was obtained by Rutherford scattering, one could calculate the height of the Coulomb barrier at the radius of the nucleus. It was evident that this energy was several times higher than the observed alpha particle energies. There was also an incredible range of half lives for the alpha particle which could not be explained by anything in classical physics.

The resolution of this dilemma came with the realization that there was a finite probability that the alpha particle could penetrate the wall by quantum mechanical tunneling. Using tunneling, Gamow was able to calculate dependence for the half-life as a function of alpha particle energy which was in agreement with experimental observations.



Coulombic repulsion between the protons within a nucleus leads to increasingly larger ratios of neutron number N to proton number Z for stable nuclei, as the mass numbers increase. Neutron-deficient nuclei can improve their N/Z ratios by means of alpha decay. The decay occurs because the parent nucleus has a total mass greater than the sum of the masses of the daughter nucleus and the alpha particle. The energy converted from mass energy to kinetic energy, called the Q value, is shared between the daughter nucleus and the alpha particle in accordance with the conservation of momentum. Thus, each radioactive alpha-emitting nuclide emits the alpha with a characteristic kinetic energy, which is one fingerprint in identification of the emitter.

There are three major natural series, or chains, through which isotopes of heavy elements decay by successions of alpha decays. Within these series and with all reaction-produced alpha emitters as well, each isotope decays with a characteristic half-life and emits alpha particles of particular energies and intensities. The presence of these radioactive nuclides in nature depends upon either a continuous production mechanism, for example the interaction of cosmic rays with the atmosphere, or extremely long half-lives of heavy radioactive nuclides produced in past cataclysmic astrophysical events, which accounts for uranium and thorium ores in the Earth. The relative abundances of uranium-238, uranium-235, and their stable final decay products in ores of heavy elements can be used to calculate the age of the ore, and presumably the age of the Earth.

In addition to the study of alpha-particle emitters that appear in nature, alpha decay has provided a useful tool to study artificial nuclei, which do not exist in nature due to their short half-lives. Alpha decay is a very important decay mode for nuclei far from stability with a ratio of protons to neutrons that is too large to be stable, especially for nuclei with atomic mass greater than 150 u. Because of the ease of detecting and interpreting decay alpha particles, their observation has aided tremendously in studying these nuclei far from stability, extending the study of nuclei to the very edge of nuclear existence. Nuclear structure information for more than 400 nuclides has been obtained in this way. In addition, fine structure peaks appear in the alpha-particle spectra for many of these nuclides; each such fine structure peak gives similar information about an excited state in the daughter nucleus.

DISINTEGRATION ENERGY OF SPONTANEOUS ALPHA DECAY

Alpha decay occurs when the nucleus spontaneously ejects a α particle. A α particle is really 2 protons and 2 neutrons, or a He nucleus. So when an atom undergoes α decay, its atomic number decreases by 2 and its atomic mass decreases by 4. α particles do not penetrate much material, for they can be stopped by paper. An example of α decay is the following:

Pu239 $\rightarrow$ U235 + α particle (He-4 nucleus)

There is a difference in mass between the original nucleus and the sum of the mass of the α particle and resulting nucleus. This lost mass is converted into energy using the formula $E = mc^2$; the energy would equal the kinetic energy of the α particle and the recoil energy of the resulting nucleus.

α particles are usually mono-energetic, but they can have different energies, as in the case of 226 Ra. This isotope of radium has a small percentage of α particles that don't have their full energy; instead the nucleus is left excited and emits gamma rays. Some of these rays will transfer energy to an orbital electron in the process internal conversion.

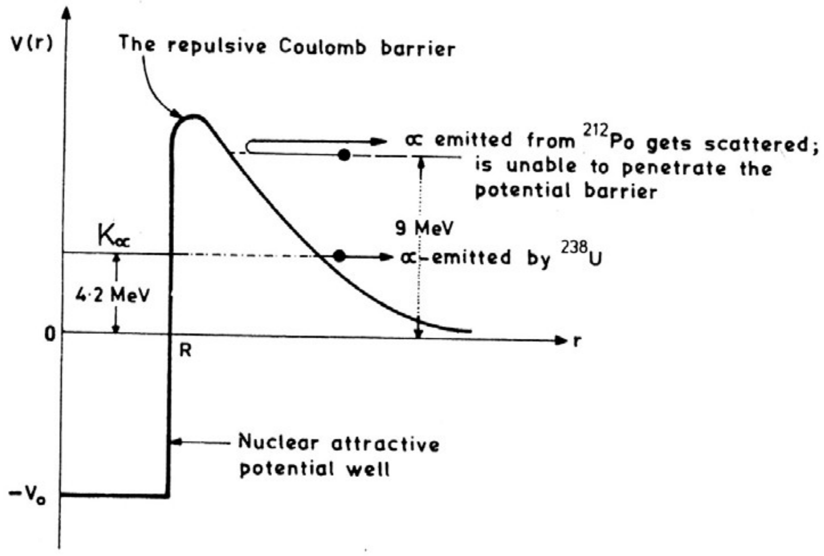
ALPHA DECAY PARADOX

Consider,

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + \alpha \quad KE(\alpha) = 4.275 \times \left(\frac{234}{238}\right) = 4.2\,MeV$$

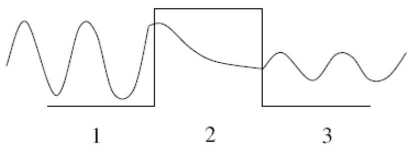
A 4.2 MeV α particle is able to come out of the Uranium nucleus.

However, α particle with KE (α) = 9 MeV (from ^{212}Po) is unable to penetrate $^{238}U_{92}$!



ALPHA DECAY PARADOX –BARRIER PENETRATION

Gamow, Gurney & Condon applied quantum mechanics of particle tunneling through the barrier to the problem of α decay.



$$\phi_1(x) = Ae^{ik_1x} + Be^{-ik_1x}$$

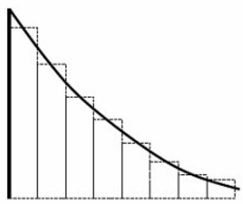
$$\hbar k_1 = \sqrt{2mE}$$

$$\phi_2(x) = Ce^{k_2x} + De^{-k_2x}$$

$$\hbar k_2 = \sqrt{2m(V_0 - E)}$$

$$\phi_3(x) = Fe^{ik_1x}$$

$$T = \frac{F^*F}{A^*A} = \left[1 + \frac{V_0^2}{4E(V_0 - E)}\sinh^2(k_2R)\right]^{-1}$$



$$T \sim \exp\left\{-a\frac{Z}{\sqrt{E}} + b\sqrt{ZR}\right\}$$

$$a = \frac{e^2\sqrt{2m}}{2\varepsilon_0\hbar} = 3.97\,(MeV)^{1/2}$$

$$b = \frac{8}{\hbar}\sqrt{\frac{me^2}{4\pi\varepsilon_0}} = 2.98\,(fm)^{-1/2}$$

E = α energy in MeV
R = radius of 'daughter' in fm
Z = atomic number of parent

BETA DECAY

PROPERTIES OF β PARTICLES

Beta minus particles (β^-) are electrons from the nucleus and are ejected by some radionuclides during a form of radioactive decay called beta-decay. The emission of the electron's antiparticle, the positron or beta plus particle (β^+), is also called beta decay. Beta-decay normally occurs in nuclei that have too many neutrons to achieve stability. It occurs commonly in the radioactive products of nuclear fission and occurs in natural radioactive decay chains following one or more alpha-decays

Beta particles have a mass which is half of one thousandth of the mass of a proton (Figure 1) and carry a single negative charge. Beta-particles are emitted with a continuous energy spectrum ranging from near zero energy up to a maximum energy specific to each radionuclide. (The actual radioactive decay process will always produce a certain fixed amount of energy but in beta-decay, the energy is split randomly between the beta particle and an almost undetectable, uncharged, particle called the neutrino). Beta particles are much less ionizing that alpha particles and generally do less damage for a given amount of energy deposition.

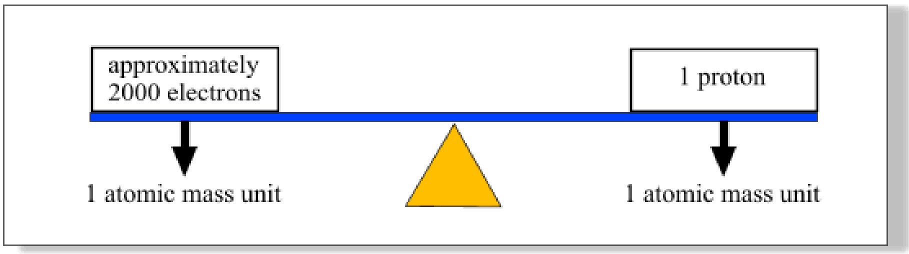


Figure 1

CONTINUOUS RAY SPECTRUM

With the beta decay the freely becoming Energy becomes on the emitted particles Electrons and Neutrino after a Wahrscheinlichkeitsgesetz (it means probability law) distributes, so that the beta-ray spectrum continuous spectrum is. It extends decreased by the energy zero up to the upper border, those by the transformation energy by those Recoil energy the daughter core is given.

Maximum beta energies:

Neutron 0,78 MeV (β-)
^{11}C 0.96 MeV (β+)
^{37}K 5.1 MeV (β+)
^{20}F 5.4 MeV (β-)

PAULI'S NEUTRINO HYPOTHESIS

The existence of neutrino was supposed in 1933 by the Austrian physicist Wolfgang Pauli (Nobel prize winner in 1945) to explain the variable kinetic energy of the electrons emitted by radioactive nuclei subjected to b decay.

Pauli postulated the existence of a neutral particle without mass, which is a particle suitable to explain the fact that the emitted electrons have a variable kinetic energy in the range between zero and a maximum value.

Admitting the existence of neutrino justifies for b decay the validity of the energy and linear momentum conservation principles.

In fact, if it is postulated the neutrinos are emitted with velocities opposite to the ones of electrons and with kinetic energies such that, if they are added to the ones of electrons, give a constant value, immediately are derived the characteristics observed experimentally for b decay.

Besides, because the mass of neutrino is considered nearly zero, the supposed particle must be considered to be moving with a velocity nearly equal to the one of light. Exist three types of neutrino with the respective antiparticles, associated respectively to electron, muon and t particle (lepton).

Neutrinos belong to the lepton family (electrons, positrons, muons, tauons and respective antiparticles) and are subjected only to weak interaction.

FERMI’S THEORY OF β DECAY

In 1930, Wolfgang Pauli postulated the existence of the neutrino to explain the continuous distribution of energy of the electrons emitted in beta decay. Only with the emission of a third particle could momentum and energy be conserved. By 1934, Enrico Fermi had developed a theory of beta decay to include the neutrino, presumed to be mass less as well as charge less.

Treating the beta decay as a transition that depended upon the strength of coupling between the initial and final states, Fermi developed a relationship which is now referred to as Fermi's Golden Rule:

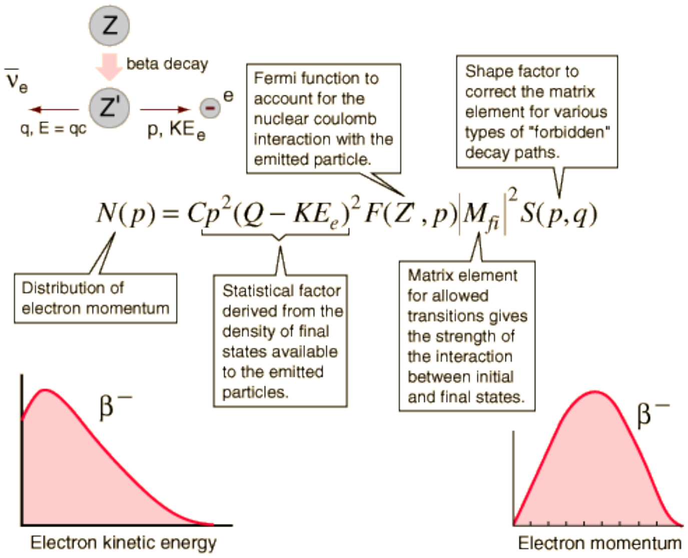
$$\lambda_{if} = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \rho_f \qquad \textit{Fermi's Golden Rule}$$

Transition probability

Matrix element for the interaction

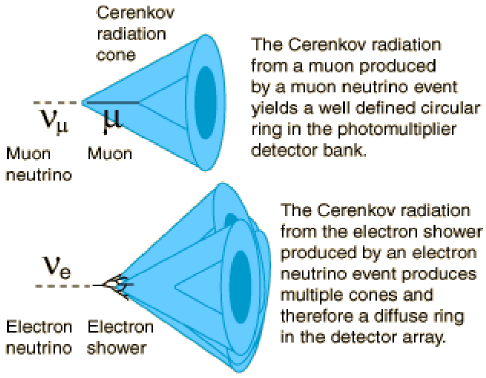
Density of final states

Straightforward in concept, Fermi's Golden Rule says that the transition rate is proportional to the strength of the coupling between the initial and final states factored by the density of final states available to the system. But the nature of the interaction which led to beta decay was unknown in Fermi's time (the weak interaction). It took some 20 years of work (Krane) to work out a detailed model which fit the observations. The nature of that model in terms of the distribution of electron momentum p is summarized in the relationship below.



THE DETECTION OF NEUTRINO

The first experimental observation of the neutrino interacting with matter was made by Frederick Reines, Clyde Cowan, Jr, and collaborators in 1956 at the Savannah River Plant in South Carolina. Their neutrino source was a nuclear reactor (it actually produced antineutrinos from beta decay).



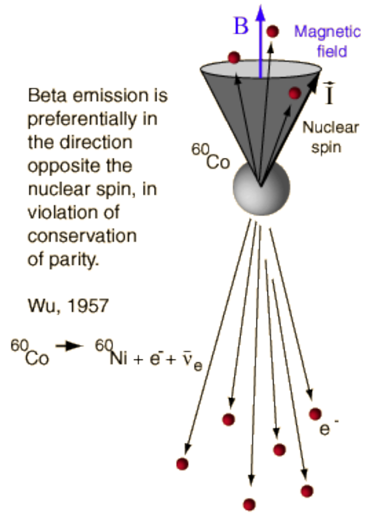
Modern neutrino detectors at IMB in Ohio and Kamiokande in Japan detected neutrinos from Supernova 1987A. A new neutrino detector at Sudbury, Ontario began collecting data in October of 1999. Another Japanese neutrino detector called Super Kamiokande became operational in April 1996.

An early set of experiments with a facility called the solar neutrino telescope, measured the rate of neutrino emission from the sun at only one third of the expected flux. Often referred to as the Solar Neutrino Problem, this deficiency of neutrinos has been difficult to explain. Recent results from the Sudbury Neutrino Observatory suggest that a fraction of the electron neutrinos produced by the sun are transformed into muon neutrinos on the way to the earth. The observations at Sudbury are consistent with the solar models of neutrino flux assuming that this "neutrino oscillation" is responsible for observation of neutrinos other than electron neutrinos.

PARITY NON-CONSERVATION IN BETA DECAY

The electromagnetic and strong interactions are invariant under the parity transformation. It was a reasonable assumption that this was just the way nature behaved, oblivious to whether the coordinate system was right-handed or left-handed. But for several years physicists had puzzled over the decay of the neutral kaons, which had equal mass but decayed to products of opposite parity. In 1956, T. D. Lee and C. N. Yang predicted the nonconservation of parity in the weak interaction. Their prediction was quickly tested when C. S. Wu and collaborators studied the beta decay of Cobalt-60 in 1957.

By lowering the temperature of cobalt atoms to about 0.01K, Wu was able to "polarize" the nuclear spins along the direction of an applied magnetic field. The directions of the emitted electrons were then measured. Equal numbers of electrons should be emitted parallel and antiparallel to the magnetic field if parity is conserved, but they found that more electrons were emitted in the direction opposite to the magnetic field and therefore opposite to the nuclear spin.



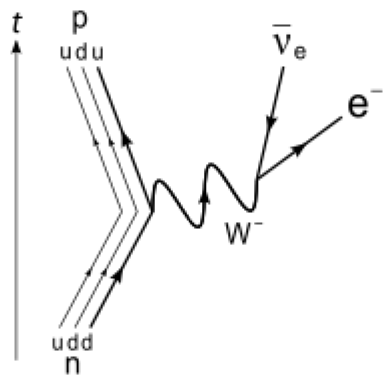
This and subsequent experiments have consistently shown that a neutrino always has its intrinsic angular momentum (spin) pointed in the direction opposite its velocity. It is called a left-handed particle as a result. Anti-neutrinos have their spins parallel to their velocity and are therefore right-handed particles. Therefore we say that the neutrino has an intrinsic parity.

The idea that nature at a very fundamental level can tell the difference between "left-handed" and "right-handed" systems is a radical one. It was thought for a time that the combination of the parity operation (=P) and "charge conjugation" (changing each particle into its antiparticle = C) was an inviolate conservation law (CP invariance). But the study of the Kaon decay in 1964 showed a violation of CP. If you add time reversal (=T) to the picture, then it appears that the combination of all three leaves the system indistinguishable from the original (CPT invariance).

FORMS OF INTERACTION AND SELECTION RULES

There are two types of weak interaction (called vertices). The first type is called the "charged current interaction" because it is mediated by particles that carry an electric charge (the $W+$ or $W-$
bosons), and is responsible for the beta decay phenomenon. The second type is called the "neutral current interaction" because it is mediated by a neutral particle, the Z boson.

Charged current interaction



The Feynman diagram for beta-minus decay of a neutron into a proton, electron and electron anti-neutrino, via an intermediate heavy $W-$ boson

In one type of charged current interaction, a charged lepton (such as an electron or a muon, having a charge of −1) can absorb a W+ boson (a particle with a charge of +1) and be thereby converted into a corresponding neutrino (with a charge of 0), where the type ("family") of neutrino (electron, muon or tau) is the same as the type of lepton in the interaction, for example:

$$\mu^- + W^+ \to \nu_\mu$$

Similarly, a down-type quark (d with a charge of $-\frac{1}{3}$) can be converted into an up-type quark (u, with a charge of $+\frac{2}{3}$), by emitting a W^-boson or by absorbing a W^+boson. More precisely, the down-type quark becomes a quantum superposition of up-type quarks: that is to say, it has a possibility of becoming any one of the three up-type quarks, with the probabilities given in the CKM matrix tables. Conversely, an up-type quark can emit a W^+ boson – or absorb a W^- boson – and thereby be converted into a down-type quark, for example:

$$d \to u + W^-$$

$$d + W^+ \to u$$

$$c \to s + W^+$$

$$c + W^- \to s$$

The W boson is unstable so will rapidly decay, with a very short lifetime. For example:

$$W^- \to e^- + \bar{\nu}_e$$

$$W^+ \to e^+ + \nu_e$$

Decay of the W boson to other products can happen, with varying probabilities.

In the so-called beta decay of a neutron (see picture, above), a down quark within the neutron emits a virtual W^- boson and is thereby converted into an up quark, converting the neutron into a proton. Because of the energy involved in the process (i.e., the mass difference between the down quark and the up quark), the W^- boson can only be converted into an electron and an electron-antineutrino. At the quark level, the process can be represented as:

$$d \to u + e^- + \bar{\nu}_e$$

Neutral current interaction

In neutral current interactions, a quark or a lepton (e.g., an electron or a muon) emits or absorbs a neutral Z boson. For example:

$$e^- \to e^- + Z^0$$

Like the W boson, the Z boson also decays rapidly, for example:

$$Z^0 \rightarrow b + \bar{b}$$

In beta transition following selection rules has been classified as :

1. Fermi selection rule include those transitions in which neither the angular momentum nor the parity undergoes a change, andHere I is written for angular momentum and P is for parity.
2. Gamow Teller selection rules include those transition in which there is no change in parity of the nucleus, but angular momentum is changed, or ±1(0-), not allowed) and or we can say, that I=0 to I'=0 transition is not allowed because the spin momentum must be carried away.

Now it is recalled that when electron and neutrino are emitted with zero orbital angular momentum they have large transition probabilities, forand are large at the nucleus, for s orbits. Thus , l=0 favors allowed transitions while l 0 favours forbidden transitions. The two possibilities of allowed transitions are mentioned as :

(1) Beta particle and neutrino are emitted with opposite spins, therefore the total momentum carried off by the two particles is

+

i.e., there is no change in the spin direction of the nucleon. Thus the angular momentum of the nucleus remains unchanged. This corresponds to Fermi transition.

(2) It the two particles are emitted with parallel spins the total angular momentum carried away by the two particles is

+

i.e., nucleon spin is reversed. The possible changes in the angular momentum of the nucleus are , ±1 (with the exception of 0 – 0 transition).

Fermi transition	parity change
Gamow Teller transition	Parity change

FERMI'S AND GAMOW TELLER TRANSITION

When one wants to consider a particular nucleus as a neutrino detector, one needs to know the Gamow-Teller strengths for the nuclear transitions that can be induced by neutrino capture. The (p,n) reaction can be used to measure these strengths. The ideas behind measuring GT strengths with the (p,n) reaction are discussed in references.

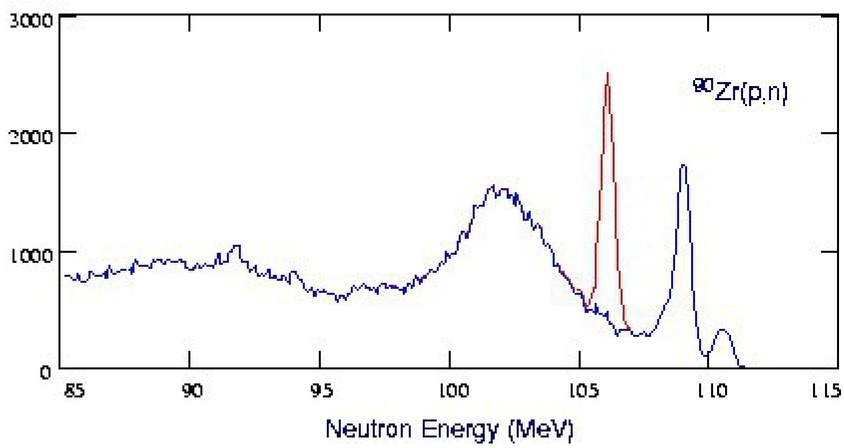
It is easy to understand qualitatively how a (p,n) reaction induces a Fermi or Gamow-Teller transition. Imagine that a high-speed proton traverses a nucleus, exchanges its charge with a bound neutron, and continues nearly undeflected on its path as a neutron. Since the neutron emerges with nearly the momentum that the proton had, there must have been rather little disruption of the nucleus. This happens when the bound neutron becomes a bound proton without changing its spatial wave function. This is a Fermi transition if there is no spin exchange or a Gamow-Teller transition if there is spin exchange. More formally we can describe the transitions as the result of the transition operator t (F), or s t(GT) summed over nucleons. At small momentum transfer these are the dominant operators in both (p,n) and allowed b-decay. Thus, F and GT transitions dominate the 0-deg (p,n) spectrum.

It is seen in reference that the specific Fermi and Gamow-Teller cross sections vary quite a bit from nucleus to nucleus in a way that is not reproduced by reaction theory calculations. We can, however, bypass that problem by normalizing each (p,n) spectrum to the IAS (Fermi) transition, which appears in every (p,n) spectrum from a nucleus with more neutrons than protons. That, however, is not as simple as it sounds, because the IAS transition does not appear as an isolated peak in most spectra of interest. Rather, it appears as a peak riding on top of a complex structure due to GT transitions.

At IUCF we have developed two procedures for isolating the IAS peak from the GT background under it. One procedure uses polarized protons and measurement of the spin direction of the observed neutrons. For the Fermi component the spin direction of the neutron must be the same as that of the proton, because the Fermi operator does not contain a spin operator. On the other hand the GT operator flips the spin with a 2/3 probability. Another procedure that does not require polarization measurements is to use the energy dependence of the ratio of the GT to F specific cross sections. For this method two spectra measured with different proton energies are compared.

Figure 1 shows the result of determining the Fermi component in a ^{90}Zr (p, n) ^{90}Nb spectrum.

Fermi peak in red. Remaining spectrum after subtraction in blue.



The technique of using the (p, n) reaction to determine GT strengths is now being applied to two nuclei, ^{160}Gd and ^{176}Yb, which have been proposed as neutrino detectors. The proposed scheme is a real-time, flavor-specific detector that is sensitive to the neutrinos from all the branches of the solar cycle.

GAMMA DECAY

Introduction

Gamma radiation, also known as gamma rays or hyphenated as gamma-rays and denoted as γ, is electromagnetic radiation of high frequency and therefore energy. Gamma rays are ionizing radiation and are thus biologically hazardous. Gamma rays are classically produced by the decay from high energy states of atomic nuclei (gamma decay), but also in many other ways. Natural sources of gamma rays on Earth include gamma decay from naturally-occurring radioisotopes such as potassium-40, and also as a secondary radiation from various atmospheric interactions with cosmic ray particles. Some rare terrestrial natural sources that produce gamma rays that are not of a nuclear origin, are lightning strikes and terrestrial gamma-ray flashes, which produce high energy emissions from natural high-energy voltages. Gamma rays are produced by a number of astronomical processes in which very high-energy electrons are produced. Such electrons produce secondary gamma rays by the mechanisms of bremsstrahlung, inverse Compton scattering and synchrotron radiation. A large fraction of such astronomical gamma rays are screened by Earth's atmosphere and must be detected by spacecraft. Notable artificial sources of gamma rays include fission such as occurs in nuclear reactors, and high energy physics experiments, such as neutral pion decay and nuclear fusion.

The first gamma ray source to be discovered historically was the radioactive decay process called gamma decay. In this type of decay, an excited nucleus emits a gamma ray almost immediately upon formation. Isomeric transition, however, can produce inhibited gamma decay with a measurable and much longer half-life. Paul Villard, a French chemist and physicist, discovered gamma radiation in 1900, while studying radiation emitted from radium. Villard's radiation was named "gamma rays" by Ernest Rutherford in 1903. Gamma rays were named in order of their penetrating power: alpha rays least, followed by beta rays, followed by gamma rays as the most penetrating.

Gamma rays typically have frequencies above 10 exahertz (or $>10^{19}$ Hz), and therefore have energies above 100 keV and wavelengths less than 10 picometers (less than the diameter of an atom). However, this is not a hard and fast definition but rather only a rule-of-thumb description for natural processes. Gamma rays from radioactive decay commonly have energies of a few hundred keV, and almost always less than 10 MeV. On the other side of the decay energy range, there is effectively no lower limit to gamma energy derived from radioactive decay. By contrast, the energies of gamma rays from astronomical sources can be much higher, ranging over 10 TeV, at a level far too large to result from radioactive decay.

The distinction between X-rays and gamma rays has changed in recent decades. Originally, the electromagnetic radiation emitted by X-ray tubes almost invariably had a longer wavelength than the radiation (gamma rays) emitted by radioactive nuclei. Older literature distinguished between X- and gamma radiation on the basis of wavelength, with radiation shorter than some arbitrary wavelength, such as 10^{-11} m, defined as gamma rays. However, with artificial sources now able to duplicate any electromagnetic radiation that originates in the nucleus, as well as far higher energies, the wavelengths characteristic of radioactive gamma ray sources vs. other types, now completely overlaps. Thus, gamma rays are now usually distinguished by their origin: X-rays are emitted by definition by electrons outside the nucleus, while gamma rays are emitted by the nucleus. Exceptions to this convention occur in astronomy, where gamma decay is seen in the afterglow of certain supernovas, but other high energy processes known to involve other than radioactive decay are still classed as sources of gamma radiation. A notable example is extremely powerful bursts of high-energy radiation normally referred to as long duration gamma-ray bursts, which produce gamma rays by a mechanism not compatible with radioactive decay. These bursts of gamma rays, thought to be due to the collapse of stars called hypernovas, are the most powerful events so far discovered in the cosmos.

GAMMA RAY EMISSION

Gamma radiation is one of the three types of natural radioactivity. Gamma rays are electromagnetic radiation, like X-rays. The other two types of natural radioactivity are alpha and beta radiation, which are in the form of particles. Gamma rays are the most energetic form of electromagnetic radiation, with a very short wavelength of less than one-tenth of a nanometer.

Gamma radiation is the product of radioactive atoms. Depending upon the ratio of neutrons to protons within its nucleus, an isotope of a particular element may be stable or unstable. When the binding energy is not strong enough to hold the nucleus of an atom together, the atom is said to be unstable. Atoms with unstable nuclei are constantly changing as a result of the imbalance of energy within the nucleus. Over time, the nuclei of unstable isotopes spontaneously disintegrate, or transform, in a process known as radioactive decay. Various types of penetrating radiation may be emitted from the nucleus and/or its surrounding electrons. Nuclides which undergo radioactive decay are called radionuclides. Any material which contains measurable amounts of one or more radionuclides is a radioactive material.

SELECTION RULES

Consider a beta transition between two nuclear states of well defined angular momentum with the emission of, say, an electron and an antineutrino. In this transition, the total angular momentum and the parity of the angular momentum states must be conserved. The total angular momentum is the sum of orbital and intrinsic contributions. Thus the change in angular momentum between initial and final states is $\mathbf{J}_{if} = \mathbf{L} + \mathbf{S}$ where $\mathbf{L}$ and $\mathbf{S}$ are the orbital angular momentum and spin carried off by the outgoing leptons.

Transitions with $\mathbf{L} = 0$ are known as allowed transitions; the parity change is $(-1)^L$ and so allowed transitions must have the same parity in initial and final states. Transitions with $\mathbf{L} \neq 0$ are known as forbidden (although they can occur, as we shall see, via higher order terms in the matrix element).

Thus, for allowed transitions, $\mathbf{J}_{if} = mathbfS = \mathbf{s}_e + \mathbf{s}_\nu$. Since the leptons have spin half, there are two cases to consider, S=0 or S=1. The S=0 transitions are known as Fermi transitions; the electron and antineutrino have ``antiparallel'' spins and $J_{ij} = 0$. The S=1 transitions are known as Gamow-Teller transitions; the electron and antineutrino have ``parallel'' spins and $J_{ij} = 0$ or 1. (However, since there must be a change of one unit in angular momentum, $J_{if} = 0$ requires a change of `magnetic' substate, $\Delta M = 1$. Thus the spin is reoriented; because of this $J_i = 0$ to $J_f = 0$ GT transitions are forbidden -- there is only an M=0 substate. This spin substate transition can be viewed as a ``spin-flip''. Thus GT transitions are referred to as ``spin-flip transitions''.)

THE ABSORPTION OF RAYS BY MATTER

When a gamma ray passes through matter, the probability for absorption is proportional to the thickness of the layer, the density of the material, and the absorption cross section of the material. The total absorption shows an exponential decrease of intensity with distance from the incident surface:

$$I(x) = I_0 \cdot e^{-\mu x}$$

where x is the distance from the incident surface, μ = nσ is the absorption coefficient, measured in cm^{-1}, n the number of atoms per cm^3 of the material (atomic density), σ the absorption cross section in cm^2 and x the distance from the incident surface of the gamma rays in cm.

As it passes through matter, gamma radiation ionizes via three processes: the photoelectric effect, Compton scattering, and pair production.

Photoelectric effect: This describes the case in which a gamma photon interacts with and transfers its energy to an atomic electron, causing the ejection of that electron from the atom. The kinetic energy of the resulting photoelectron is equal to the energy of the incident gamma photon minus the energy that originally bound the electron to the atom (binding energy). The photoelectric effect is the dominant energy transfer mechanism for X-ray and gamma ray photons with energies below 50 keV (thousand electron volts), but it is much less important at higher energies.
Compton scattering: This is an interaction in which an incident gamma photon loses enough energy to an atomic electron to cause its ejection, with the remainder of the original photon's energy emitted as a new, lower energy gamma photon whose emission direction is different from that of the incident gamma photon, hence the term "scattering". The probability of Compton scattering decreases with increasing photon energy. Compton scattering is thought to be the principal absorption mechanism for gamma rays in the intermediate energy range 100 keV to 10 MeV. Compton scattering is relatively independent of the atomic number of the absorbing material, which is why very dense materials like lead are only modestly better shields, on a per weight basis, than are less dense materials.
Pair production: This becomes possible with gamma energies exceeding 1.02 MeV, and becomes important as an absorption mechanism at energies over 5 MeV (see illustration at right, for lead). By interaction with the electric field of a nucleus, the energy of the incident photon is converted into the mass of an electron-positron pair. Any gamma energy in excess of the equivalent rest mass of the two particles (totaling at least 1.02 MeV) appears as the kinetic energy of the pair and in the recoil of the emitting nucleus. At the end of the positron's range, it combines with a free electron, and the two annihilate, and the entire mass of these two is then converted into two gamma photons of at least 0.51 MeV energy each (or higher according to the kinetic energy of the annihilated particles).

The secondary electrons (and/or positrons) produced in any of these three processes frequently have enough energy to produce much ionization themselves.

INTERACTION OF RAYS WITH MATTER

Gamma rays are photons (quanta of light) and have no electric charge and no rest mass. Therefore, the interaction of gamma rays with matter is weak. There are 3 mechanisms that are important from the point of view of radiation protection.

Photoelectric Effect

An electron is emitted from an atom (ionization process) with energy equal to the energy of the gamma ray. The electron then moves through matter and loses its energy as described for beta interactions. This is the predominant effect at low gamma energies.

Compton Scattering

The gamma ray interacts with an electron, causing an increase in the electron's energy. A new gamma ray with a smaller energy is then emitted. The electron interacts as explained earlier. The new gamma ray can escape from the matter or can be absorbed through the photoelectric effect. The Compton effect is the predominant effect at intermediate gamma energies.

Pair Production

High-energy gamma rays are absorbed and two particles are created (an electron and a positron) and share the energy of the gamma ray. The electron interacts with matter, as explained above for beta interaction. The positron loses its energy through ionization or excitation. If it is stationary, the positron interacts with an electron creating two gamma rays with energies of 511 keV each (annihilation radiation). These two gamma rays can escape or interact with matter through the Compton scattering or Photoelectric effect.

The absorption of gamma rays obeys an exponential law. There is no definite range of absorption for gamma rays in matter. Protection against gamma rays (as well as against X-rays) is best obtained with heavy materials (lead or other metals), as well as with large quantities of concrete or other materials. For example, the earth's atmosphere protects us against high-energy gamma rays and other high-energy radiation coming from outer space.

MEASUREMENT OF γ RAY ENERGIES

The measure of gamma rays' ionizing ability is called the exposure:

The coulomb per kilogram (C/kg) is the SI unit of ionizing radiation exposure, and is the amount of radiation required to create 1 coulomb of charge of each polarity in 1 kilogram of matter.
The röntgen (R) is an obsolete traditional unit of exposure, which represented the amount of radiation required to create 1 esu of charge of each polarity in 1 cubic centimeter of dry air. 1 röntgen = 2.58×10^{-4} C/kg

However, the effect of gamma and other ionizing radiation on living tissue is more closely related to the amount of energy deposited rather than the charge. This is called the absorbed dose:

The gray (Gy), which has units of (J/kg), is the SI unit of absorbed dose, and is the amount of radiation required to deposit 1 joule of energy in 1 kilogram of any kind of matter.
The rad is the (obsolete) corresponding traditional unit, equal to 0.01 J deposited per kg. 100 rad = 1 Gy.

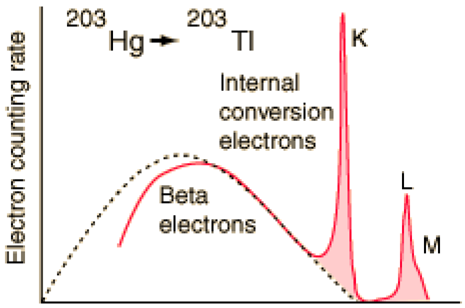
The equivalent dose is the measure of the biological effect of radiation on human tissue. For gamma rays it is equal to the absorbed dose.

The sievert (Sv) is the SI unit of equivalent dose, which for gamma rays is numerically equal to the gray (Gy).
The rem is the traditional unit of equivalent dose. For gamma rays it is equal to the rad or 0.01 J of energy deposited per kg. 1 Sv = 100 rem.

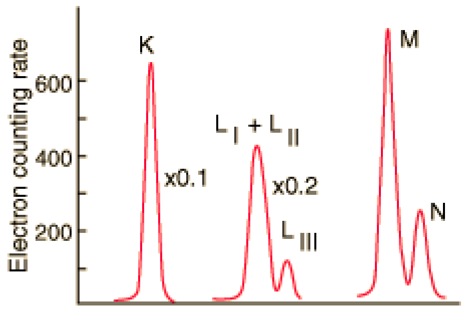
INTERNAL CONVERSION

Internal conversion is another electromagnetic process which can occur in the nucleus and which competes with gamma emission. Sometimes the multipole electric fields of the nucleus interact with orbital electrons with enough energy to eject them from the atom. This process is not the same as emitting a gamma ray which knocks an electron out of the atom. It is also not the same as beta decay, since the emitted electron was previously one of the orbital electrons, whereas the electron in beta decay is produced by the decay of a neutron.

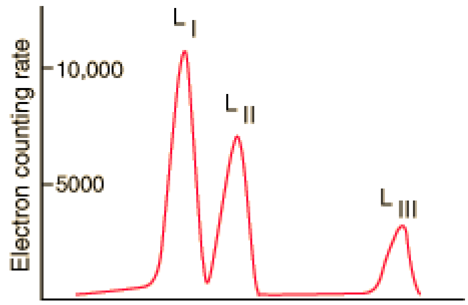
An example used by Krane is that of ^{203}Hg, which decays to ^{203}Tl by beta emission, leaving the ^{203}Tl in an electromagnetically excited state. It can proceed to the ground state by emitting a 279.190 keV gamma ray, or by internal conversion. In this case the internal conversion is more probable. Since the internal conversion process can interact with any of the orbital electrons, the result is a spectrum of internal conversion electrons which will be seen as superimposed upon the electron energy spectrum of the beta emission. The energy yield of this electromagnetic transition can be taken as 279.190 keV, so the ejected electrons will have that energy minus their binding energy in the ^{203}Tl daughter atom.



Electron emissions from the Hg-203 to Tl-203 decay, measured by A. H. Wapstra, et al., Physica 20, 169 (1954).



At higher resolution, the internal conversion electrons from the L, M and N shells can be resolved. Z. Sujkowski, Ark. Fys. 20, 243 (1961).

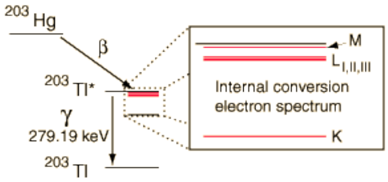


At even higher resolution, the three L shells can be resolved. From C. J. Herrlander and R. L. Graham, Nucl. Phys. 58, 544 (1964).

The resolution of the electron detection is good enough that such internal conversion electron spectra can be used to study the binding energies of the electrons in heavy atoms. In this case, the measured electron energies can be subtracted from the transition energy as indicated by the gamma emission, 279.190 keV.

Binding energies for ^{203}Tl	
K	85.529 keV
L_I	15.347 keV
L_{II}	14.698 keV

L_{III}	12.657 keV
M	3.704 keV



In addition to information from the internal conversion electrons about the binding energies of the electrons in the daughter atom, the relative intensities of these internal conversion electron peaks can give information about the electric multipole character of the nucleus.

NUCLEAR ISOMERISM

Isomers decay to lower energy states of the nuclide through two isomeric transitions:

γ (gamma) emission (emission of a high-energy photon)
internal conversion (the energy is used to ionize the atom)

Isomers may also decay into other elements, though the rate of decay may differ between isomers. For example, ^{177m}Lu beta decays to ^{177}Hf with half-life 160.4 d, or can undergo internal transition to ^{177}Lu with half-life 160.4 d, then beta decays to ^{177}Hf with half-life 6.68 d.

An isomeric transition is a radioactive decay process that involves emission of a gamma ray from an atom where the nucleus is in an excited metastable state, referred to in its excited state, as **a** nuclear isomer**.**

The emission of a gamma ray from an excited nuclear state allows the nucleus to lose energy and reach a lower energy state, sometimes its ground state. In certain cases, the excited nuclear state following a nuclear reaction or other type of radioactive decay, has a half live that is more than 100 to 1000 times longer than the average 10^{-12} seconds, and this excited state is referred to as a metastable nuclear excited state. Some nuclei are able to stay in this metastable excited state for minutes, hours, days, or occasionally far longer, before undergoing gamma decay, in which they emit a gamma ray.

The process of isomeric transition (that is, the gamma decay of nuclear isomers), is therefore similar to any gamma emission from any excited nuclear state, but differs in that it involves excited metastable states of nuclei with longer half lives. These states are created, as in all nuclei that undergo gamma radioactive decay, following the emission of an alpha, beta particle, or occasionally other types of particles that leave the nucleus in an excited state.

The gamma ray may transfer its energy directly to one of the most tightly bound electrons causing that electron to be ejected from the atom, a process termed the photoelectric effect. This should not be confused with the internal conversion process, in which no gamma ray photon is produced as an intermediate particle.

APPLICATIONS

Gamma rays travel to Earth across vast distances of the universe, only to be absorbed by Earth's atmosphere. Different wavelengths of light penetrate Earth's atmosphere to different depths. Instruments aboard high-altitude balloons and such satellites as the Compton Observatory provide our only view of the gamma spectrum sky.

Gamma-induced molecular changes can also be used to alter the properties of semi-precious stones, and is often used to change white topaz into blue topaz.

Non-contact industrial sensors used in the Refining, Mining, Chemical, Food, Soaps and Detergents, and Pulp and Paper industries, in applications measuring levels, density, and thicknesses commonly use sources of gamma. Typically these use Co-60 or Cs-137 isotopes as the radiation source.

In the US, gamma ray detectors are beginning to be used as part of the Container Security Initiative (CSI). These US$5 million machines are advertised to scan 30 containers per hour. The objective of this technique is to screen merchant ship containers before they enter US ports.

Gamma radiation is often used to kill living organisms, in a process called irradiation. Applications of this include sterilizing medical equipment (as an alternative to autoclaves or chemical means), removing decay-causing bacteria from many foods or preventing fruit and vegetables from sprouting to maintain freshness and flavor.

Despite their cancer-causing properties, gamma rays are also used to treat some types of cancer, since the rays kill cancer cells also. In the procedure called gamma-knife surgery, multiple concentrated beams of gamma rays are directed on the growth in order to kill the cancerous cells. The beams are aimed from different angles to concentrate the radiation on the growth while minimizing damage to surrounding tissues.

Gamma rays are also used for diagnostic purposes in nuclear medicine in imaging techniques. A number of different gamma-emitting radioisotopes are used. For example, in a PET scan a radiolabled sugar called flude oxyglucose emits positrons that are converted to pairs of gamma rays that localize cancer (which often takes up more sugar than other surrounding tissues). The most common gamma emitter used in medical applications is the nuclear isomer technetium-99m which emits gamma rays in the same energy range as diagnostic X-rays. When this radionuclide tracer is administered to a patient, a gamma camera can be used to form an image of the radioisotope's distribution by detecting the gamma radiation emitted (see also SPECT). Depending on what molecule has been labeled with the tracer, such techniques can be employed to diagnose a wide range of conditions (for example, the spread of cancer to the bones in a bone scan).

Body response

When gamma radiation breaks DNA molecules, a cell may be able to repair the damaged genetic material, within limits. However, a study of Rothkamm and Lobrich has shown that this repair process works well after high-dose exposure but is much slower in the case of a low-dose exposure.

Risk assessment

The natural outdoor exposure in Great Britain ranges from 2 to 4 nSv/h (nanosieverts per hour). Natural exposure to gamma rays is about 1 to 2 mSv per year, and the average total amount of radiation received in one year per inhabitant in the USA is 3.6 mSv. There is a small increase in the dose, due to naturally occurring gamma radiation, around small particles of high atomic number materials in the human body caused by the photoelectric effect.

By comparison, the radiation dose from chest radiography (about 0.06 mSv) is a fraction of the annual naturally occurring background radiation dose, A chest CT delivers 5 to 8 mSv. A whole-body PET/CT scan can deliver 14 to 32 mSv depending on the protocol. The dose from fluoroscopy of the stomach is much higher, approximately 50 mSv (14 times the annual yearly background).

An acute full-body equivalent single exposure dose of 1 Sv (1000 mSv) causes slight blood changes, but 2.0–3.5 Sv (2.0–3.5 Gy) causes very severe syndrome of nausea, hair loss, and hemorrhaging, and will cause death in a sizable number of cases—-about 10% to 35% without medical treatment. A dose of 5 Sv (5 Gy) is considered approximately the LD_{50} (lethal dose for 50% of exposed population) for an acute exposure to radiation even with standard medical treatment. A dose higher than 5 Sv (5 Gy) brings an increasing chance of death above 50%. Above 7.5–10 Sv (7.5–10 Gy) to the entire body, even extraordinary treatment, such as bone-marrow transplants, will not prevent the death of the individual exposed. (Doses much larger than this may, however, are delivered to selected parts of the body in the course of radiation therapy.)

For low dose exposure, for example among nuclear workers, who receive an average yearly radiation dose of 19 mSv, the risk of dying from cancer (excluding leukemia) increases by 2 percent. For a dose of 100 mSv, that risk increase is at 10 percent. By comparison, risk of dying from cancer was increased by 32 percent for the survivors of the atomic bombing of Hiroshima and Nagasaki.

Questions:

1. Explain the properties of alpha particles.
2. Explain the range of alpha particles.
3. Discuss the Gamow's theory of alpha particles.
4. Explain Geiger-Nuttall law.
5. Explain the properties of beta particles.
6. Explain Pauli's neutrino hypothesis.
7. Discuss Fermi's theory of beta decay.
8. Explain the interaction of gamma rays with matter.
9. Explain the measurement of gamma ray energies.
10. Explain the term nuclear isomerism.

KARPAGAM ACADEMY OF HIGHER EDUCATION,COIMBATORE-21

DEPARTMENT OF PHYSICS

CLASS:I MSC PHYSICS

NUCLEAR PHYSICS (18PHP203)

MULIPLE CHOICE QUESTIONS

UNIT - III

QUESTIONS	opt1	opt2	opt3	opt4	opt5	opt6	answer
Which model has been very successful in explaining a number of nuclear properties	Shell mo	Liquid dr	Bohr mod	Collective model			Shell model
Shell model fails to explain	The large	The grour	The excit	All the above			All the above
Possible reason for the discrepancy in shell model is	magnetic	nuclei is c	nucleus is	1 & 2			1 & 2
The deformation of the nucleus is attributed to the……………………of one or more loosely nucleons on the remaining nucleus	Magnetizi	polarizing	electrolyz	none of the above			polarizing action
Standing waves will occur whenever the radius of the body is an odd multiple of the wavelength divided by	4	3	2	1			4
The nucleons move in a potential which is not spherically symmetrical have…………….types of motions	Four	one	two	three			two
Which model is the combination of liquid drop and shell model	Collectiv	Unified m	optical mo	Super-conductivity model			Collective model
The unified model was developed by	Bohr	Mottelson	Bohr and	Rainwater			Bohr and Mottelson
Which is the hybrid of liquid drop model and distorted shell model	Collective	optical mo	Unified m	none of the above			Unified model
In which model the shell model potential is assumed non-spherical and the nucleons move independently	Collective	Liquid dr	Optical m	unified model			unified model
The mathematical theory of unified model was developed by	Nilsson	Rainwater	Davydov	Bohr and Kalcker			Nilsson
Nilsson model has been successful in describing the properties of	Heavier d	odd nucle	both a & b	even nuclei			both a & b
The optical model of the nucleus is developed from an analogy of nuclear scattering with that of-	Scattering	Reflection	Diffractio	None of the above			Scattering of light
The collective motion of the nucleons in a deformed nucleus may be ……………………..in character	rotational	vibrationa	rotational	electronic			rotational or vibrational
Which nucleon needs large energy for excitation	Paired nu	unpaired r	odd neutr	odd proton			Paired nucleon
Odd nuclei consists of one or two	unpaired r	paired nu	unpaired r	All of the above			unpaired nucleons
The series of rotational levels, beginning with the ground state of an even-even nucleus has	J=2,4,6	J=1,2,3	J=1,3,5	J=0,1,2,3,4			J=2,4,6
Negative parity have only ………………….of angular momentum	even valu	odd value	even or oc	zero			odd values
The study of nuclear shell model introduces many new ideas familiar in	molecular	quantum p	Atomic ph	Thermal physics			Atomic physics
Which model introduces many new ideas familiar in molecular physics, into nuclear physics	Unified m	Liquid dr	Collective	Nilsson model			Collective model
The deviations of ……………………… From the Schmidt curve make shell model less acceptable	dipole mo	magnetic	orbital mo	spin moment			magnetic moment
Who suggested in odd A nuclei by considering the polarization of the even-even core by the motion of the odd nucleon	Bohr and	J. Rainwa	Bohr	Nilsson			J. Rainwater
The λ=2 quadrupole surface vibrational state is generally known as a	one phonc	two phonc	four phon	six phonon state			one phonon state
The Nilsson model has been successful in describing the	Properties	Properties	Properties	a & b			a & b
The amount of dimming the intensity can be calculated by knowing the	refractive	Absorptio	refractive	Extinction coefficient			refractive index and Absorption coefficient
The λ=1 motion implies …………………… motion of the whole system	rotational	vibrationa	translatior	translational			translational
Magic numbers are	2,8,20,28	2,8,20,28	2,8,20,40	20,40,50,82,126			2,8,20,28,50,82,126
In which model, it is assumed that the nucleons in the nucleus move independently in a common potential	Extreme s	Collective	unified mo	Nilsson model			Extreme single particle model
The closure of a shell for the harmonic oscillator potential occurs corresponding to neutron or proton numbers	8,18,20,3	2,8,20,40	18,30,50,	2,8,20,28,50,82,126			2,8,20,40,70,112 and 168
The shell closes at particle numbers 2,8,18,20,34,40,58… for	Square-we	harmonic	spin-orbit	finite square-well			Square-well of infinite depth
Tin has ……………	Ten stable	six stable	unstable is	none of the above			Ten stable isotopes
Which model is the forerunner of the collective model of nuclear structure?	Shell mod	Liquid dr	Fermi gas	unified model			Liquid drop model
Which of the following property of the liquid drop is not similar to nucleus	surface te	molecules	latent hea	Molecules attract one another a			Molecules attract one another at distances larger than the dimensions of the electron shells
The motion of the molecules in the liquid and motion of the nucleons in the nuclei is of ………………. and ……….. Character, respectively	Classical	Quantum	molecular	molecular and Quantum			Classical and Quantum
If the forces between the external nucleons and the core are repulsive, the ………………….. is formed	oblate sph	prolate sp	spherical	octupole			prolate spheroid
If the forces between the external nucleons and the core are attractive,……………………….. is formed	oblate sph	prolate sp	spherical	octupole			oblate spheroid
Prof. Rainwater, Prof. A.Bohr and Prof. Mottelson shared the nobel prize in physics for their work on……………………….. of nuclei	Nilsson m	Collective	Optical m	Liquid drop model			Collective model
Nilsson found that, upon deformation of the nuclear surface, each level splits into	2(2j+1)	(2j+1)/2	j+1	2j+1			(2j+1)/2
The nuclear isomerism has been successfully explained by	Liquid dr	unified m	single par	Fermi gas model			single particle model
Nuclei with N or Z near the end of a shell are found in …………. Distinct groups, known as islands of isomerism	three	two	seven	four			four
The curves of magnetic moment are known as	spectral li	Schmidt l	Balmer lii	None of the above			Schmidt lines
The mechanism of nuclear fission was first explained by Bohr and Wheeler on the basis of	liquid dro	Shell mod	Optical m	Unified model			liquid drop model of the nucleus
Angular momenta and parity for N^{16} is	$½^-$	$5/2^+$	2^-	3^-			2^-
The expected shell model spin and parity assignment for the ground state of ^{11}B is	$3/2^+$	$3/2^-$	$5/2^+$	$½^-$			$3/2^-$
Parity corresponding to	electron is	electron is	electron a	electron and proton is even			electron and proton is even
Which of the following is not correct for shell model	Spin-orbit	Each nucl	Pauli excl	As a spherical nucleus is a centr			As a spherical nucleus is a central field, existence of average field is not necessary
In the nuclear shell model, the spin of the ground state of an odd A nucleus	is decided	is always	is always	is decided by the core			is decided by the last unpaired nucleus
A condition for nuclear isomerism	The prese	The prese	The prese	The existence of mirror nuclei			The presence of an energy level near the ground state differing strongly in angular momentum
In nuclear shell model, orbitals are filled in order $1s_{1/2}$, $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$ etc. What is responsible for splitting between the $p_{3/2}$ and $p_{1/2}$ orbitals?	Binding e	Emission	Mirror nu	Spin-orbit coupling of nucleons			Spin-orbit coupling of nucleons
The expected shell model spin and parity assignment for the ground state of ^{15}C is	$5/2^+$	$1/2^+$	$3/2^-$	$½^-$			$5/2^+$
The expected shell model spin and parity assignment for the ground state of ^{7}Li is	$3/2^-$	$3/2^+$	$5/2^+$	$5/2^-$			$3/2^-$
The expected shell model spin and parity assignment for the ground state of ^{31}P is	$1/2^+$	$5/2^-$	$3/2^+$	$3/2^-$			$1/2^+$
The expected shell model spin and parity assignment for the ground state of ^{141}Pr is	$3/2^+$	$5/2^+$	$1/2^+$	$½^-$			$5/2^+$
Nuclear shell model is proposed by	Faraday	Bohr	M.G.May	None of these			M.G.Mayer
Nuclear shell model is based on the realization that there are specific number of protons (Z) and neutrons(N) generally referred to as	quantum	magic nur	bonding e	critical number			Magic number
There is a critical energy called …………which must be reached for complete separation	Activatio	Thermal e	Nuclear e	none of these			Activation energy
Seaborg’s expression is given by	E_f =19.0-(	E_f =19.0-(	E_f =19.0-(	None of these			$E_f = 19.0-0.36Z^2/A$
The first theoretical treatment of the fission event based on the liquid drop model of the nucleus was given by	Yukawa	Bohr	Bohr and	None of these			Bohr and Wheeler
Property associated with the shape and is a measure of deviation of nucleus spherical shape is called	Magnetic	Electric q	Angular n	None of these			Electric quadrupole moment
The nucleus may have quadrupole moment only if its angular momentum	≥2	≥1	≤1	Zero			≥2
Which of the following reactions involves no change in target nucleus	disintegra	radiative	direct rea	elastic scattering			elastic scattering
For any spherical symmetric distribution of positive charge in the nucleus, the net quadrupole moment is	1	>1	<1	Zero			zero
In spallation reactions, heavy nuclei splits in	two nucle	one nucle	no change	more than four nuclei			two nuclei
Direct reactions include	pickup rea	stripping r	1 & 2	spontaneous decay			1 & 2
Bohr and Wheeler theory is explained based on	Shell mod	Unified m	nilsson mo	Liquid drop model			Liquid drop model

NUCLEAR REACTION

Objectives:

The main objective of this unit is to give more ideas about the different processes involved in a nuclear reaction. Also gives some elementary information about the stages of nuclear reaction and the types of nuclear reactions.

Nuclear reactions: Nuclear fission and fusion - Kinds of reaction and conservation laws - energetics of nuclear reaction – Applications of Nuclear Energy – Nuclear Reactors - Isospin - Reaction cross section-Continuum theory of nuclear reaction - Resonance - Briet Wigner Dispersion formula - Stages of nuclear reaction - Statistical theory of nuclear reaction - Evaporation probability and cross section – Kinematics of stopping and pickup reaction - Surface reaction

NUCLEAR REACTIONS

NUCLEAR FISSION AND FUSION

Nuclear fusion and **nuclear fission** are two different types of energy-releasing reactions in which energy is released from high-powered atomic bonds between the particles within the nucleus. The main difference between these two processes is that fission is the splitting of an atom into two or more smaller ones while fusion is the fusing of two or more smaller atoms into a larger one.

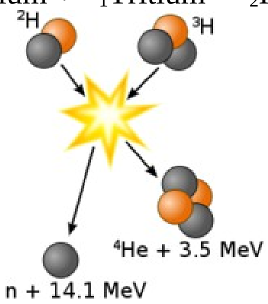
Comparison chart

	Nuclear Fission	**Nuclear Fusion**
Definition:	Fission is the splitting of a large atom into two or more smaller ones.	Fusion is the fusing of two or more lighter atoms into a larger one.
Conditions:	Critical mass of the substance and high-speed neutrons are required.	High density, high temperature environment is required.
Energy requirement:	Takes little energy to split two atoms in a fission reaction.	Extremely high energy is required to bring two or more protons close enough that nuclear forces overcome their electrostatic repulsion.
Natural occurrence of the process:	Fission reaction does not normally occur in nature.	Fusion occurs in stars, such as the sun.
Byproducts of the reaction:	Fission produces many highly radioactive particles.	Few radioactive particles are produced by fusion reaction, but if a fission "trigger" is used, radioactive particles will result from that.
Energy Ratios:	The energy released by fission is a million times	The energy released by fusion is three to four times

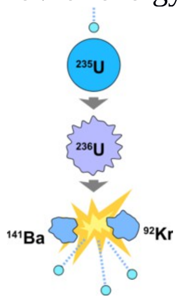
	Nuclear Fission	Nuclear Fusion
	greater than that released in chemical reactions; but lower than the energy released by nuclear fusion.	greater than the energy released by fission.
Nuclear weapon:	One class of nuclear weapon is a fission bomb, also known as an atomic bomb or atom bomb.	One class of nuclear weapon is the hydrogen bomb, which uses a fission reaction to "trigger" a fusion reaction.

Definitions

Nuclear fusion is the reaction in which two or more nuclei combine together to form a new element with higher atomic number (more protons in the nucleus). The energy released in fusion is related to E = mc ^{2} (Einstein's famous energy-mass equation). On earth, the most likely fusion reaction is Deuterium–Tritium reaction. Deuterium and Tritium are both isotopes of hydrogen. $^2{}_1$Deuterium + $^3{}_1$Tritium = $^4{}_2$He + $^1{}_0$n + 17.6 MeV



Fusion of deuterium with tritium creating helium-4, freeing a neutron, and releasing 17.59 MeV of energy.



Fission Reaction

Nuclear fission is the splitting of a massive nucleus into photons in the form of gamma rays, free neutrons, and other subatomic particles. In a typical nuclear reaction involving ^{235}U and a neutron:

$^{235}{}_{92}$U + n = $^{236}{}_{92}$U

followed by

$^{236}{}_{92}$U = $^{144}{}_{56}$Ba + $^{89}{}_{36}$Kr + 3n + 177 MeV

Physics behind both fission and fusion processes

The more the binding energy held within the bonds of an atom, more stable is an atom. Binding energy is the amount of energy held within the bonds of the atoms. The most stable is the nucleon of iron atom, which neither fuses nor splits. That's why iron is at the top of the binding energy curve. Each atom tries to become more stable by increasing its binding energy. For atomic nuclei lighter than iron and nickel, energy can be extracted by combining these nuclei together through nuclear fusion. In contrast, for atomic nuclei heavier than iron or nickel, energy can be released by splitting the heavy nuclei through nuclear fission.

Conditions for fission and fusion

For a fission reaction, two conditions need to be satisfied:

- Critical mass of the substance (the minimum amount of mass is required for fission to be self-sustaining).
- A relatively slow neutron is required to initiate the process.

For a nuclear fusion reaction to occur it is necessary to bring two nuclei so close that nuclear forces become active and glue the nuclei together. Nuclear forces are small-distance forces and have to act against the electrostatic forces were positively charged nuclei repel each other. This is the reason why nuclear fusion reactions occur mostly in high density, high temperature environment.

Chain Reaction

Both fission and fusion nuclear reactions are chain reactions. A nuclear chain reaction occurs when one nuclear reaction causes an average of one or more nuclear reactions, thus leading to a self-propagating number of these reactions. The specific nuclear reaction may be the fission of heavy isotopes (e.g. ^{235} U) or the fusion of light isotopes (e.g. ^{2}H and ^{3}H).

Fission chain reactions occur because of interactions between neutrons and fissile isotopes and a fusion chain reaction occurs under extreme pressure and temperature conditions, which are maintained by the energy released in the fusion process.

Energy ratios

The energy released by fusion is three to four times greater than the energy released by fission. This is because the amount of mass transformed into energy is that much greater in a fusion reaction than in a fission reaction.

Natural occurrence

In nature, fusion occurs in stars. On Earth, nuclear fusion was first achieved in the explosion of the Hydrogen bomb. In a non-destructive manner, fusion has also been reached in different experimental devices aimed at studying the possibility of producing energy in a controlled fashion.

On the other hand, fission is a nuclear process which does not normally occur in nature. The reason for this is that it requires a large mass and an incident neutron to initiate the process. But there have been examples where nuclear fission has occurred in natural reactors. This was discovered in 1972 wherein uranium deposits were found at one location which could self sustain a natural chain reaction. 16 deposits have been discovered of these deposits at this lone site.

Effects

If accidentally, a fission reaction goes out of control as a result of not controlling the emission of neutrons, a nuclear meltdown can happen which can then release highly radioactive particles in the atmosphere. In contrast, in case of nuclear fusion if the reaction goes out of control, the reaction would stop automatically as it it'll cool down. In addition, in case of nuclear fusion reaction, the amount of radioactive materials produced as waste is very small and the maximum damage which could happen is the vaporization of anything in the immediate vicinity of the reaction.

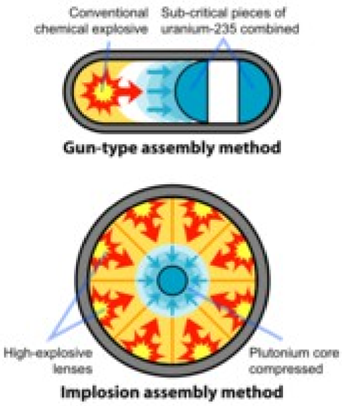
With regards to these factors it can be said that a fusion reaction is a more environmentally friendly method of producing nuclear power. Energy requirement: It takes less energy to split two atoms with fission than it does to fuse two atoms, which is why fission reactors were developed first, and why fusion reactors have not been developed yet.

History of human-engineered nuclear reactions

While an atom bomb is an example of nuclear fission, a hydrogen bomb is an example of nuclear fusion. The testing of a hydrogen bomb arising out of fusion was first conducted in 1951 though the idea of such nuclear fusion had been proposed as early as 1941. This bomb was tested at full scale in 1952.

Atom Bombs based on nuclear fission were tested first in World War II. The first atomic bomb used as a weapon was detonated by the United States in 1945 on the Japanese city of Hiroshima. The first test detonation of an atomic bomb was conducted in New Mexico State in 1945.

Nuclear weapons



Two methods of assembling fission bombs

One class of nuclear weapons, a fission bomb, otherwise known as an atomic bomb or atom bomb, is a fission reactor designed to liberate as much energy as possible and as rapidly as possible, before the released energy causes the reactor to explode (and the chain reaction to stop).

Another class is the hydrogen bomb, which functions by fusion of lighter nuclei into the heavier one. Hydrogen bomb or H-bomb is a weapon deriving its energy from the nuclear fusion of hydrogen isotopes, though in most applications the bulk of its destructive energy comes from uranium fission, not hydrogen fusion. Extremely high temperatures are required in order to initiate a fusion reaction which also gives the hydrogen bomb the name of a thermonuclear bomb.

Cost

Nuclear fission: The inefficiency of cost comes into play when it is considered that nuclear fuel creates heat and this heat is used to boil the water and the steam produced is used to turn turbine to generate electricity. This transformation from heat energy to electrical energy is cumbersome and expensive. A second source of inefficiency is that clean-up and storage of

nuclear waste is very expensive because the waste is radioactive and finally security issues add to the cost of nuclear energy.
Nuclear fusion: For fusion to occur the atoms must be confined in the magnetic field and raised to a temperature of 100 million Kelvin or more. This takes lot of electricity and hence cost inefficiency comes in the picture. Hence both are cost inefficient logically for productive and non destructive purpose.

Advantages of fusion over fission
In case of fusion reactions, fusion reactors cannot sustain a chain reaction so they can never melt down like fission reactors. Fusion reaction produces very less or, if the right atoms are chosen, no radioactive waste. In case of nuclear fission large radioactive waste is produced and disposal of radioactive waste is a complicated problem. For nuclear power, fusion is the better choice.

KINDS OF REACTION AND CONSERVATION LAWS

While the number of possible nuclear reactions is immense, there are several types which are more common, or otherwise notable. Some examples include:

- Fusion reactions — two light nuclei join to form a heavier one, with additional particles (usually protons or neutrons) thrown off to conserve momentum.
- Spallation — a nucleus is hit by a particle with sufficient energy and momentum to knock out several small fragments or, smash it into many fragments.
- Induced gamma emission belongs to a class in which only photons were involved in creating and destroying states of nuclear excitation.
- Alpha decay - Though driven by the same underlying forces as spontaneous fission, α decay is usually considered to be separate from the latter. The often-quoted idea that "nuclear reactions" are confined to induced processes is incorrect. "Radioactive decays" are a subgroup of "nuclear reactions" that are spontaneous rather than induced. For example, so-called "hot alpha particles" with unusually high energies may actually be produced in induced ternary fission, which is an induced nuclear reaction (contrasting with spontaneous fission). Such alphas occur from spontaneous ternary fission as well.
- Neutron-induced nuclear fission reactions – a very heavy nucleus, spontaneously or after absorbing additional light particles (usually neutrons), splits into two or sometimes three pieces. This is an induced nuclear reaction. Spontaneous fission, which occurs without assistance of the neutron, is usually not considered a nuclear reaction. At most, it is not an induced nuclear reaction.

Direct reactions

An intermediate energy projectile transfers energy or picks up or loses nucleons to the nucleus in a single quick (10^{-21} second) event. Energy and momentum transfer are relatively small. These are particularly useful in experimental nuclear physics, because the reaction mechanisms are often simple enough to calculate with sufficient accuracy to probe the structure of the target nucleus.

Inelastic scattering

Only energy and momentum are transferred.

- (p,p') tests differences between nuclear states
- (α, α') measures nuclear surface shapes and sizes. Since α particles that hit the nucleus react more violently, elastic and shallow inelastic α scattering are sensitive to the shapes and sizes of the targets, like light scattered from a small black object.
- (e, e') is useful for probing the interior structure. Since electrons interact less strongly than do protons and neutrons, they reach to the centers of the targets and their wave functions are less distorted by passing through the nucleus.

Transfer reactions

Usually at moderately low energy, one or more nucleons are transferred between the projectile and target. These are useful in studying outer shell structure of nuclei.

- (α, n) and (α, p) reactions. Some of the earliest nuclear reactions studied involved an alpha particle produced by alpha decay, knocking a nucleon from a target nucleus.
- (d, n) and (d, p) reactions. A deuteron beam impinges on a target; the target nuclei absorb either the neutron or proton from the deuteron. The deuteron is so loosely bound that this is almost the same as proton or neutron capture. A compound nucleus may be formed, leading to additional neutrons being emitted more slowly. (d, n) reactions are used to generate energetic neutrons.
- The strangeness exchange reaction (K, π) has been used to study hyper nuclei.
- The reaction $^{14}N(\alpha, p)^{17}O$ performed by Rutherford in 1917 (reported 1919), is generally regarded as the first nuclear transmutation experiment.

Reactions with neutrons

Reactions with neutrons are important in nuclear reactors and nuclear weapons. While the best known neutron reactions are neutron scattering, neutron capture, and nuclear fission, for some light nuclei (especially odd-odd nuclei) the most probable reaction with a thermal neutron is a transfer reaction:

Some reactions are only possible with fast neutrons:

- (n,2n) reactions produce small amounts of protactinium-231 and uranium-232 in the thorium cycle which is otherwise relatively free of highly radioactive actinide products.
- $^{9}Be + n \rightarrow 2\alpha + 2n$ can contribute some additional neutrons in the beryllium neutron reflector of a nuclear weapon.
- $^{7}Li + n \rightarrow T + \alpha + n$ unexpectedly contributed additional yield in Castle Bravo, Castle Romeo, and Castle Yankee, the three highest-yield nuclear tests conducted by the U.S.

Compound nuclear reactions

Either a low energy projectile is absorbed or a higher energy particle transfers energy to the nucleus, leaving it with too much energy to be fully bound together. On a time scale of about 10^{-19}seconds, particles, usually neutrons are "boiled" off. That is, it remains together until enough energy happens to be concentrated in one neutron to escape the mutual attraction. Charged particles rarely boil off because of the coulomb barrier. The excited quasi-bound nucleus is called a compound nucleus.

- Low energy (e, e' xn), (γ, xn) (the xn indicating one or more neutrons), where the gamma or virtual gamma energy is near the giant dipole resonance. These increase the need for radiation shielding around electron accelerators

Conservation law, also called law of conservation, in physics, several principles that state that certain physical properties (i.e., measurable quantities) do not change in the course of time within an isolated physical system. In classical physics, laws of this type govern energy, momentum, angular momentum, mass, and electric charge. In particle physics, other conservation laws apply to properties of subatomic particles that are invariant during interactions. An important function of conservation laws is that they make it possible to predict the macroscopic behaviour of a system without having to consider the microscopic details of the course of a physical process or chemical reaction.

Conservation of energy implies that energy can be neither created nor destroyed, although it can be changed from one form (mechanical, kinetic, chemical, etc.) into another. In an isolated system the sum of all forms of energy therefore remains constant. For example, a falling body has a constant amount of energy, but the form of the energy changes from potential to kinetic. According to the theory of relativity, energy and mass are equivalent. Thus, the rest mass of a body may be considered a form of potential energy, part of which can be converted into other forms of energy.

Conservation of linear momentum expresses the fact that a body or system of bodies in motion retains its total momentum, the product of mass and vector velocity, unless an external force is applied to it. In an isolated system (such as the universe), there are no external forces, so momentum is always conserved. Because momentum is conserved, its components in any direction will also be conserved. Application of the law of conservation of momentum is important in the solution of collision problems. The operation of rockets exemplifies the conservation of momentum: the increased forward momentum of the rocket is equal but opposite in sign to the momentum of the ejected exhaust gases.

Conservation of angular momentum of rotating bodies is analogous to the conservation of linear momentum. Angular momentum is a vector quantity whose conservation expresses the law that a body or system that is rotating continues to rotate at the same rate unless a twisting force, called a torque, is applied to it. The angular momentum of each bit of matter consists of the product of its mass, its distance from the axis of rotation, and the component of its velocity perpendicular to the line from the axis.

Conservation of mass implies that matter can be neither created nor destroyed—i.e., processes that change the physical or chemical properties of substances within an isolated system (such as conversion of a liquid to a gas) leave the total mass unchanged. Strictly speaking, mass is not a conserved quantity. However, except in nuclear reactions, the conversion of rest mass into other forms of mass-energy is so small that, to a high degree of precision, rest mass may be thought of as conserved.

Conservation of charge states that the total amount of electric charge in a system does not change with time. At a subatomic level, charged particles can be created, but always in pairs with equal positive and negative charge so that the total amount of charge always remains constant.

In particle physics, other conservation laws apply to certain properties of nuclear particles, such as baryon number, lepton number, and strangeness. Such laws apply in addition to those of mass, energy, and momentum encountered in everyday life and may be thought of as analogous to the conservation of electric charge.

The laws of conservation of energy, momentum, and angular momentum are all derived from classical mechanics. Nevertheless, all remain true in quantum mechanics and relativistic mechanics, which have replaced classical mechanics as the most fundamental of all laws. In the deepest sense, the three conservation laws express the facts, respectively, that physics does not change with passing time, with displacement in space, or with rotation in space.

ENERGETICS OF NUCLEAR REACTION

Albert Einstein's mass-energy equivalence relates energy and mass in nuclear reactions:

$$E=mc^2$$

Each time an energy change happens, there is also a mass change that is related by the constant c^2 or (the speed of light squared). Energy changes in chemical reactions are small, making the mass change insignificant. However, on a nuclear level, there is a significant amount of energy change in comparison and therefore a discernible mass change. In Albert Einstein's mass-energy equivalence, "m" is the net change in mass in kilograms and "c" is a constant in meters per second. Two units to express nuclear energy are joules (J) and mega electron volts (MeV).

$$1.6022 \times 10^{-13} \text{ J} = 1 \text{ MeV}$$

The energy of 1 atomic mass unit is:

1 atomic mass unit (u) = 1.4924×10^{-10} J = 931.5 MeV

By knowing the mass change in amu, the energy released can be directly calculated using these conversion factors, which have already taken into account mass conversions and the value of c^2. Also, the mass-energy sums of a nuclear reaction must equal each other. The sum of the mass and energy of the reactants are equivalent to the sum of the mass and energy of the products.

NUCLEAR REACTION

Defintions

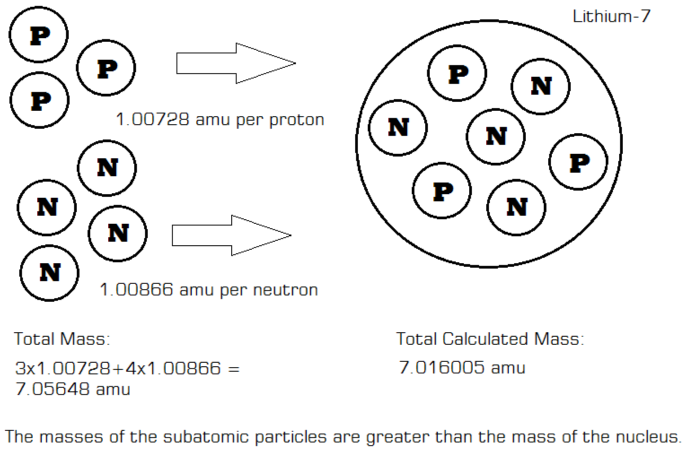


Figure 1

The nucleus weighs less than the masses of the individual subatomic particles. Where does this mass go when a nucleus is formed? Recall Einstein's mass-energy equivalence and how matter and energy are essentially different configurations of the same thing. Mass is lost, and energy is released as the nucleons come together to form the nucleus. This energy is known as the nuclear binding energy. Einstein's mass-energy equivalence can be rewritten in the following terms:

$$\text{nuclear binding energy} = \text{mass defect} \times c^2$$

Nuclear binding energy is also the defined as the energy required to break apart a nucleus.

Binding Energy and Nuclei Size

The mass number 60 is the maximum binding energy for each nucleon. This means that the binding energy increases when small nuclei join together to form larger nuclei in a process known as nuclear fusion. For nuclei with mass numbers greater than 60, the heavier nuclei will break down into smaller nuclei in a process known as nuclear fission.

For fusion processes, the binding energy per nucleon will increase and some of the mass will be converted and released as energy (recall Figure 1). Fission processes also release energy when heavy nuclei decompose into lighter nuclei. The driving force behind fission and fusion is for an atomic nuclei to become more stable. So nuclei with a mass number of approximately 60 will be the most stable, which explains why iron is the most stable element in the universe. Elements with mass numbers around 60 will also be stable elements, while elements with extremely large atomic masses will be unstable.

ISOSPIN

Isospin is a term introduced to describe groups of particles which have nearly the same mass, such as the proton and neutron. This doublet of particles is said to have isospin 1/2, with projection +1/2 for the proton and -1/2 for the neutron. The three pions compose a triplet, suggesting isospin 1. The projections are +1 for the positive, 0 and -1 for the neutral and negative pions. Isospin is used as an axis in particle diagrams, with strangeness being the other axis. Isospin is not really spin, and doesn't have the units of angular momentum - the spin term is tacked on because the addition of the isospins follows the same rules as spin.

Isospin is a dimensionless quantity associated with the fact that the strong interaction is independent of electric charge. Any two members of the proton-neutron isospin doublet experience the same strong interaction: proton-proton, proton-neutron, neutron-neutron have the same strong force attraction.

At the quark level, the up and down quarks form an isospin doublet (I=1/2) and the projection I_3 = +1/2 is assigned to the up quark and I_3 =-1/2 to the down. (The subscript 3 is used here for the third component rather than the z used withspin and orbital angular momentum because most of the literature does so.) The other quarks are assigned isospin I=0. Isospin is related to other quantum numbers for the particles by

$$\frac{q}{e} = I_3 + \frac{S+B}{2}$$

I_3 = projection of isotopic spin
S = strangeness
B = baryon number
q = charge (q/e used to make it dimensionless)

This relationship is called the Gell Mann-Nishijima formula. Some references use T for isospin, but it appears that most use I for isospin and T for weak isospin.

Isospin is associated with a conservation law which requires strong interaction decays to conserve isospin, as illustrated by the process

$$\overset{uds}{\Sigma^0} \rightarrow \overset{uds}{\Lambda^0} + \gamma$$

$$I=1 \neq I=0$$

which does not involve any transmutation of quarks, so would be expected to decay by strong interaction. However, it does not conserve isospin, and is observed to decay by the electromagnetic interaction, but not by the strong interaction. The experimental discrimination is made by the observation of its decay lifetime, presuming by the totalitarian principle that if it could decay by the strong interaction, it would.

REACTION CROSS SECTION

In nuclear physics, it is convenient to express the probability of a particular event by a cross section. Statistically, the centers of the atoms in a thin foil can be considered as points evenly distributed over a plane. The center of an atomic projectile striking this plane has geometrically a definite probability of passing within a certain distance r of one of these points. In fact, if there are n atomic centers in an area A of the plane, this probability is $(n\pi r^2)/A$, which is simply the ratio of the aggregate area of circles of radius r drawn around the points to the whole area. If we think of the atoms as impenetrable steel discs and the impinging particle as a bullet of negligible diameter, this ratio is the probability that the bullet will strike a steel disc, i.e., that the atomic projectile will be stopped by the foil. If it is the fraction of impinging atoms getting through the foil which is measured, the result can still be expressed in terms of the equivalent stopping cross section of the atoms. This notion can be extended to any interaction between the impinging particle and the atoms in the target. For example, the probability that an alpha particle striking a beryllium target will produce a neutron can be expressed as the equivalent cross section of beryllium for this type of reaction.

RESONANCE

Nuclear reaction analysis (NRA) is a nuclear method in materials science to obtain concentration vs. depth distributions for certain target chemical elements in a solid thin film.

If irradiated with select projectile nuclei at kinetic energies E_{kin} these target elements can undergo a nuclear reaction under resonance conditions for a sharply defined resonance energy. The reaction product is usually a nucleus in an excited state which immediately decays, emitting ionizing radiation.

To obtain depth information the initial kinetic energy of the projectile nucleus (which has to exceed the resonance energy) and its stopping power (energy loss per distance traveled) in the sample has to be known. To contribute to the nuclear reaction the projectile nuclei have to slow down in the sample to reach the resonance energy. Thus each initial kinetic energy corresponds to a depth in the sample where the reaction occurs (the higher the energy, the deeper the reaction).

For example, a commonly used reaction to profile hydrogen is

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + \alpha + \gamma \text{ (4.965MeV)}$$

with a resonance at 6.385 MeV. The energetic emitted γ ray is characteristic of the reaction and the number that is detected at any incident energy is proportional to the concentration at the respective depth of hydrogen in the sample. The H concentration profile is then obtained by scanning the ^{15}N incident beam energy. Hydrogen is an element inaccessible to RBS due to its low mass, although it is often analyzed by elastic recoil detection.

NRA can also be used non-resonantly. For example, deuterium can easily be profiled with a ^{3}He beam without changing the incident energy by using the

$$^{3}He + D = \alpha + p + 18.353 \text{ MeV}$$

reaction. The energy of the fast proton detected depends on the depth of the deuterium atom in the sample.

BRIET WIGNER DISPERSION FORMULA

The Breit-Wigner formula says that the cross section for a resonance is proportional to

1/ (2Sa+1) (2Sb+1),

where Sa and Sb are the spins of the incident particles.

SURFACE REACTION

By reactions on surfaces it is understood reactions in which at least one of the steps of the reaction mechanism is the adsorption of one or more reactants. The mechanisms for these reactions, and the rate equations are of extreme importance for heterogeneous catalysis.

Simple decomposition

If a reaction occurs through these steps:

A + S AS → Products

Where A is the reactant and S is an adsorption site on the surface. If the rate constants for the adsorption, desorption and reaction are k_1, k_{-1} and k_2, then the global reaction rate is:

$$r = -\frac{dC_A}{dt} = k_2 C_{AS} = k_2 \theta C_S$$

where C_{AS} is the concentration of occupied sites, θ is the surface coverage and C_S is the total number of sites (occupied or not).

C_S is highly related to the total surface area of the adsorbent: the greater the surface area, the more sites and the faster the reaction. This is the reason why heterogeneous catalysts are usually chosen to have great surface areas (in the order of a hundred m^2/gram)

If we apply the steady state approximation to AS, then:

$$\frac{dC_{AS}}{dt} = 0 = k_1 C_A C_S (1-\theta) - k_2 \theta C_S - k_{-1} \theta C_S$$

so

$$\theta = \frac{k_1 C_A}{k_1 C_A + k_{-1} + k_2}$$

and

$$r = -\frac{dC_A}{dt} = \frac{k_1 k_2 C_A C_S}{k_1 C_A + k_{-1} + k_2}.$$

Note that, with $K_1 = \frac{k_1}{k_{-1}}$, the formula was divided by k_{-1}.

The result is completely equivalent to the Michaelis-Menten kinetics. The rate equation is complex, and the reaction order is not clear. In experimental work, usually two extreme cases are looked for in order to prove the mechanism. In them, the rate-determining step can be:

- **Limiting step: Adsorption/Desorption**

$k_2 >> \ k_1 C_A, k_{-1}$, so $r \approx k_1 C_A C_S$.

The order respect to A is 1. Examples of this mechanism are N_2O on gold and HI on platinum

- **Limiting Step: Reaction**

$k_2 << \ k_1 C_A, k_{-1}$ so $\theta = \frac{k_1 C_A}{k_1 C_A + k_{-1}}$

which is just Langmuir isotherm and $r = \frac{K_1 k_2 C_A C_S}{K_1 C_A + 1}$.

Depending on the concentration of the reactant the rate changes:

- Low concentrations, then $r = K_1 k_2 C_A C_S$, that is to say a first order reaction in component A.
- High concentration, then $r = k_2 C_S$. It is a zeroth order reaction in component A.

Bimolecular reaction

Langmuir-Hinshelwood mechanism

This mechanism proposes that both molecules adsorb and the adsorbed molecules undergo a bimolecular reaction:

A + S AS

B + S BS

AS + BS → Products

The rate constants are now k_1, k_{-1}, k_2, k_{-2} and k for adsorption/desorption of A, adsorption/desorption of B, and reaction. The rate law is: $r = k\theta_A \theta_B C_S^2$

Proceeding as before we get $\theta_A = \frac{k_1 C_A \theta_E}{k_{-1} + k C_S \theta_B}$, where θ_E is the fraction of empty sites, so $\theta_A + \theta_B + \theta_E = 1$. Let us assume now that the rate limiting step is the reaction of the adsorbed molecules, which is easily understood: the probability of two adsorbed molecules colliding is low. Then $\theta_A = K_1 C_A \theta_E$, with $K_i = k_i / k_{-i}$, which is nothing but Langmuir isotherm for two adsorbed gases, with adsorption constants K_1 and K_2. Calculating θ_E from θ_A and θ_B we finally get

$$r = kC_S^2 \frac{K_1 K_2 C_A C_B}{(1 + K_1 C_A + K_2 C_B)^2}.$$

The rate law is complex and there is no clear order respect to any of the reactants but we can consider different values of the constants, for which it is easy to measure integer orders:

- **Both molecules have low adsorption**

That means that $1 >> K_1 C_A, K_2 C_B$, so $r = C_S^2 K_1 K_2 C_A C_B$. The order is one respect to both the reactants

- **One molecule has very low adsorption**

In this case $K_1 C_A, 1 >> K_2 C_B$, so $r = C_S^2 \frac{K_1 K_2 C_A C_B}{(1 + K_1 C_A)^2}$. The reaction order is 1 respect to B. There are two extreme possibilities now:

1. At low concentrations of A, $r = C_S^2 K_1 K_2 C_A C_B$, and the order is one respect to A.
2. At high concentrations, $r = C_S^2 \frac{K_2 C_B}{K_1 C_A}$. The order is minus one respect to A. The higher the concentration of A, the slower the reaction goes, in this case we say that A inhibits the reaction.

- **One molecule has very high adsorption**

One of the reactants has very high adsorption and the other one doesn't adsorb strongly.

$K_1 C_A >> 1, K_2 C_B$, so $r = C_S^2 \frac{K_2 C_B}{K_1 C_A}$. The reaction order is 1 respect to B and -1 respect to A. Reactant A inhibits the reaction at all concentrations.

The following reactions follow a Langmuir-Hinshelwood mechanism:

- $2\ CO + O_2 \rightarrow 2\ CO_2$ on a platinum catalyst.
- $CO + 2H_2 \rightarrow CH_3OH$ on a ZnO catalyst.

- $C_2H_4 + H_2 \rightarrow C_2H_6$ on a copper catalyst.
- $N_2O + H_2 \rightarrow N_2 + H_2O$ on a platinum catalyst.
- $C_2H_4 + ½ O_2 \rightarrow CH_3CHO$ on a palladium catalyst.
- $CO + OH \rightarrow CO_2 + H^+ + e^-$ on a platinum catalyst.

Eley-Rideal mechanism

In this mechanism, proposed in 1938 by D. D. Eley and E. K. Rideal, only one of the molecules adsorbs and the other one reacts with it directly from the gas phase, without adsorbing:

$$A(g) + S(s) \rightleftharpoons AS(s)$$

$$AS(s) + B(g) \rightarrow \text{Products}$$

Constants are k_1, k_{-1} and k and rate equation is $r = kC_S\theta_A C_A C_B$. Applying steady state approximation to AS and proceeding as before (considering the reaction the limiting step once more) we get $r = C_S C_B \frac{K_1 C_A}{K_1 C_A + 1}$. The order is one respect to B. There are two possibilities, depending on the concentration of reactant A:

- At low concentrations of A, $r = C_S K_1 K_2 C_A C_B$, and the order is one with respect to A.

- At high concentrations of A, $r = C_S K_2 C_B$, and the order is zero with respect to A.

The following reactions follow a Eley-Rideal mechanism:

- $C_2H_4 + ½ O_2$ (adsorbed) $\rightarrow H_2COCH_2$ The dissociative adsorption of oxygen is also possible, which leads to secondary products carbon dioxide and water.
- $CO_2 + H_2$(ads.) $\rightarrow H_2O + CO$
- $2NH_3 + 1½ O_2$ (ads.) $\rightarrow N_2 + 3H_2O$ on a platinum catalyst
- $C_2H_2 + H_2$ (ads.) $\rightarrow C_2H_4$ on nickel or iron catalysts

THE Q- EQUATION
Introduction

In writing down the reaction equation, in a way analogous to a chemical equation, one may in addition give the reaction energy on the right side:

Target nucleus + projectile → Final nucleus + ejectile + Q.

For the particular case discussed above, the reaction energy has already been calculated as Q = 22.4 MeV. Hence:

$$ {}^{6}_{3}\mathrm{Li} + {}^{2}_{1}\mathrm{H} \rightarrow 2\,{}^{4}_{2}\mathrm{He} + 22.4\ \mathrm{MeV} $$

The reaction energy (the "Q-value") is positive for exothermal reactions and negative for endothermal reactions. On the one hand, it is the difference between the sums of kinetic energies on the final side and on the initial side. But on the other hand, it is also the difference between the nuclear rest masses on the initial side and on the final side (in this way, we have calculated the Q-value above).

Questions:

1. Distinguish between nuclear fission and fusion.
2. Explain the energetics of nuclear reaction.
3. Write a note on reaction cross section.
4. Discuss the continuum theory of nuclear reaction.
5. Explain Briet Wigner Dispersion formula.
6. Write down the stages of nuclear reaction.
7. Explain the statistical theory of nuclear reaction.
8. Discuss surface reaction.
9. Explain the types of nuclear reactions.
10. Write down the Q equation.

KARPAGAM ACADEMY OF HIGHER EDUCATION,COIMBATORE-21

DEPARTMENT OF PHYSICS

CLASS:I MSC PHYSICS

NUCLEAR PHYSICS (18PHP203)

MULIPLE CHOICE QUESTIONS

UNIT - IV

QUESTIONS	opt1	opt2	opt3	opt4	opt5	opt6	answer
A proton cannot decay into a neutron and a neutrino as the conservation law violated will be	Energy (a:	Angular n	Charge	All the above			All the above
The following reaction: ${}^{1}n_{0}+{}^{235}U_{92}\rightarrow{}^{141}Ba_{56}+{}^{92}Kr_{36}+3{}^{1}n_{0}$ is called	Fusion	Fission	Alpha dec	Beta decay			Fission
Four factor formula is given by	ηεpf	ηαpf	σΩpf	σΩpa			ηεpf
The effective area possessed by a nucleus for removing the incident particles from a collimated beam by all possible process is called	Total nucl	Total nuc	Scatterin	None of these			Total nuclear cross-section
A device in which nuclear fission can be carried out through a sustained and a controlled chain reaction is called	Nuclear p	Nuclear re	Nuclear tr	None of these			Nuclear reactor
Nuclear fuel, moderator control rods, coolant and protective shield are the parts of	Nuclear re	Nuclear p	Nuclear e	None of these			Nuclear reactor
The ratio of the number of fission produced by a given generation of neutrons to the number of fissions of the preceding generation of neutrons is called	K-factor c	Gain factc	Power fac	None of these			K-factor or reproduction factor
The following reaction: ${}^{2}H_{1}+{}^{3}H_{1}\rightarrow{}^{4}He_{2}+{}^{1}n_{0}$ is called	Fusion	Fission	Alpha dec	Beta decay			Fusion
What is fission?	The joinir	The proce	The splitti	The scientific creation of bubbl			The splitting of atoms into smaller pieces.
Conservation laws that describe events involving the elementary particles include the conservation of	energy	linear and	electric ch	All of these are correct			All of these are correct
The initial fragments formed by fission have	More prot	More neu	About the	Number of proton and neutron (			More neutrons than protons
Which of the potential fusion reaction will not result in the net release of energy	${}^{6}Li+{}^{6}Li$	${}^{4}He+{}^{4}He$	${}^{20}Ne+{}^{20}N$	${}^{35}Cl+{}^{35}Cl$			${}^{35}Cl+{}^{35}Cl$
A generic fission event is ${}^{235}U+n\rightarrow X+Y+2n$. Which of the following pairs cannot represent X and Y?	${}^{141}Xe+{}^{93,}$	${}^{139}Cs+{}^{95}$	${}^{156}Nd+{}^{79}$	None of these			${}^{156}Nd+{}^{79}Ge$
The following reaction: He_2^4+O_8^16→H_1^1+F_9^18 is called	An elastic	An inelast	A pick up	A stripping reaction			A stripping reaction
Typical energy released in a nuclear fission and a nuclear fusion reaction are respectively	50MeV ar	200MeV	1000MeV	200MeV and 10MeV			200MeV and 10MeV
The decay of $n=p+e^{-1}$	Cannot cc	Can conse	Data in su	None of these			Cannot conserve angular momentum
Which of the following argument is not concerned with the statement " electrons do not exist in the nucleus"?	Statistics	Binding e	Electron r	β-decay			Electron magnetic moment
A thermal neutron having speed v impinges on a ${}^{235}U$ nucleus. The reaction cross-section is proportional to	v^{-1}	v	$v^{1/2}$	v-${}^{1/2}$			v^{-1}
The disintegration series of the heavy elements will give ${}^{209}Bi$ as a stable nucleus	Actinium	Neptuniu	Thorium s	Uranium series			Neptunium series
Suppose that a neutron at rest in free space decays into a proton and an electron. This process would violates	conservati	conservati	conservati	conservation of angular moment			conservation of linear momentum
The width of a nuclear excited state	inversely	inversely	Directly p	Independent of half-life			inversely proportional to its mass
In a nuclear reaction, the mass of the reaction products is	Always ec	Always le	Always gr	different from the sum of collid			Always less than the sum of the masses of the colliding nuclei
Which among the following is true about neutrinos and antineutrinos?	All neutri	All neutri	There are	No handedness is associated wi			All neutrinos are left handed and all antineutrinos are right handed
Find the incorrect statement	The nucle	The bounc	The energ	A system of two neutrons which			The energy levels of triplet state is higher than singlet state
For controlled thermonuclear fusion, which has largest cross section	$D+D\rightarrow{}^{3}H$	D+D→T+	$D+T\rightarrow{}^{4}H$	None of these			$D+T\rightarrow{}^{4}He+n+17.6MeV$
Assume the neutrino mass is exactly zero, then	The neutri	The neutri	The antine	The antineutrino spin point dire			The antineutrino spin does the reverse of neutrino
An electron and a proton enter a magnetic field with equal velocities. Which will experience more force?	electron	Proton	Both expe	Neither of them experience any			Both experience same force
On the basis of Q values, determine if the ${}^{98}Tc$ nucleus can decay by β^- decay	1.796MeV	0.662MeV	1.684MeV	None of these			1.796MeV
On the basis of Q values, determine if the ${}^{98}Tc$ nucleus can decay by β^+ decay	1.796MeV	0.662MeV	1.684MeV	None of these			0.662MeV
On the basis of Q values, determine if the ${}^{98}Tc$ nucleus can decay by electron capture	1.796MeV	0.662MeV	1.684MeV	None of these			1.684MeV
A 2MeV neutron is emitted in a fission reactor. If it loses half of its kinetic energy in each collision with a moderator atom, how many collisions must it undergo to achieve thermal energy (0.039eV)	23	24	25	26			26
Which of the following probe can produce complication?	Electrons	Proton	Neutrons	Photons			Photons
Which of the following is true for β-decay of the neutron? The process	Violates b	Violates	Conserves	Conserves both parity and charg			Violates both parity and charge conjugation symmetry
To penetrate the coulomb barrier of a light nucleus, a proton must have a minimum energy of the order of?	1GeV	100MeV	10MeV	1MeV			1MeV
Identify the process which takes place when the mass of the parent atom is greater than the mass of the daughter atom	Electron c	Positron e	Electron e	γ-emission			Electron capture
In the classification of neutrons based on energy, the neutrons in the energy range of 1eV to 100eV are known as	Cold neut	Epitherma	Resonanc	Thermal neutron			Resonance neutron
The kinetic energy of the α-particle (Kα) in an alpha decay in terms of the Q-value reaction is given by	(A-4/A)Q	(4Q/A)	(AQ/4)	(Q/4A)			(A-4/A)Q
Masses of two isobars ${}_{29}Cu^{64}$ and ${}_{30}Zn^{64}$ are 63.9298. It can be concluded from these data that	Both the i	Zn^{64} is rac	Cu^{64} is ra	Cu^{64} is radioactive decaying to			Cu^{64} is radioactive decaying to Zn^{64} through β-decay
The reaction ${}^{12}C_{6}+{}^{1}H_{1}\rightarrow{}^{13}N_{6}+\gamma$ is called	Capture re	Particle-p	Fission re	Fusion reaction			Capture reaction
If Q is –ve, reaction involved is	Endo-ergi	Exoergic	neutral	None of these			Endo-ergic
The theory of low energy deuteron stripping was first put forth by	Thomson	Oppenhei	Seaborg	Yukawa			Oppenheimer and Phillips
The inverse of the stripping reaction is called a	Pick-up re	Nuclear re	Endotherr	Exoergic reaction			Pick-up reaction
The energy dependence the cross section of a reaction between two particles, close to resonance energy E_0 is described by	Bethe-Blc	Breit-Wig	Gamous-T	Bethe-Weizacker formula			Breit-Wigner formula
The antiparticle of an electron is the positron which was discovered by	Anderson	Yukawa	J.J.Thoms	Einstein			Anderson
When the projectile gains nucleons from the target, the nuclear reaction is referred to as	Stripping	Pickup rea	Exoergic	None of these			Pickup reaction
When the projectile loses nucleons to the target, the nuclear reaction is referred to as	Stripping	Pickup rea	Exoergic	None of these			Stripping reaction
The analytic relationship between the kinetic energy of the projectile and the outgoing particle and the nuclear disintegration energy is called as the	Q equatio	scattering	reaction c	none of these			Q equation
The scattering of alpha particles in gold is a good example of	inelastic s	disintegra	radiative c	elastic scattering			elastic scattering
If the sum of the masses of incident particle and target nucleus is greater than that of masses of the product nuclei. The reaction is said to be	exoergic	endoergic	exoergic c	none of these			exoergic
Breit-Wigner formula leads to the conclusion that at low neutron energies the cross-section should be inversely proportional to the	target ene	neutron sp	neutron er	neutron angular momentum			neutron energy
The cross section which defines a distribution of emitted particles with respect to the solid angle is called	partial crc	differentia	Total cros	all the above			differential cross section
when a nucleus is excited, excited energy is considered as increase in temperature and this known as	Nuclear te	excitation	temperatu	none of these			Nuclear temperature

ELEMENTARY PARTICLES

Objectives:
The main objective of this unit is to give an elementary idea about the different elementary particles available in nature. Also it gives some information about the Quark model and SU3 symmetry.

Elementary Particles : Types of interaction in nature-typical strengths and time-scales, conservation laws, charge-conjugation, Parity and Time reversal, CPT theorem, GellMann-Nishijima formula, intrinsic parity of pions, resonances, symmetry classification of elementary particles, quark hypothesis, charm, beauty and truth, gluons, quark confinement, asymptotic freedom.

TYPES OF INTERACTION PARTICLE PHYSICS
BUILDING BLOCKS OF NUCLEUS
Neutron, a particle in the atomic nucleus which has no electric charge. the neutron has a mass very nearly equal to that of a proton, the nucleus of the hydrogen atom. The neutron and the proton are believed to be the fundamental building stones of which all atomic nuclei are composed.
According to present theory, any nucleus is composed of neutrons and protons. This theory has replaced the older one, held until 1932, that protons and electrons were the building stones of the nucleus. This older theory had encountered grave difficulties. The most striking, perhaps, was that electrons never come out of atomic nuclei in collisions. Moreover, according to quantum mechanics, electrons cannot be compressed into such a small space as the inside of a nucleus. Additional arguments were the spin and the statistics of atomic nuclei, and the peculiar phenomena connected with beta radioactivity. The electron-proton hypothesis has been completely discarded.

The proton-neutron hypothesis had by 1947 met with considerable success and had been used to explain a number of fundamental properties of atomic nuclei. It is fairly well established that protons and neutrons can be treated inside the nucleus by the ordinary laws of quantum mechanics.

According to the proton-neutron hypothesis the atomic number Z (charge) of a nucleus is equal to the number of protons contained in it. The mass number *A*, *i.e.*, the integer nearest to the atomic weight, is the sum of the numbers of protons and neutrons since each of these particles contributes about one unit of atomic weight. The isotopes of a given element, therefore, all contain the same number of protons but varying numbers of neutrons; for instance, any isotope of the element carbon contains 6 protons, the most abundant isotope C^{12}contains in addition 6 neutrons, whereas the less abundant stable isotope C^{13} contains 7 neutrons.

Perhaps the most important information about a nucleus is provided by its exact weight. From it the binding energy of the nucleus can be deduced, with the help of Einstein's relation, $E = mc^2$. For instance, the helium nucleus has a mass of 4.00390. Since its atomic number is 2 and its mass number 4, it contains 2 neutrons and 2 protons; the combined weight of these 4 particles is 4.03410. The difference between this and the weight of the helium nucleus represents the force (more precisely, the energy) with which the 4 particles are held together in the nucleus. Because of the large value of the velocity of light, *c*, the energy represented by this mass difference is tremendous. The formation of 4 gr. of helium from 2 gr. of hydrogen and 2 gr. of neutrons releases as much energy as the burning of about 100 tons of coal.

A binding of this tremendous strength cannot be because of electric forces; moreover, no such forces could act on neutrons anyway, because of the absence of electric charge. Gravitational forces are even more inadequate to account for the tight binding. A new force must therefore be assumed which is known as nuclear force. The exact character of nuclear forces is not known; but it is known that they act only over very short distances, having a range of about 3×10^{-13} cm. and being negligible outside this range. The exploration of nuclear forces is the prime objective of nuclear physics, and neutrons have proved to be most valuable tools in this research. The scattering of neutrons of various velocities by protons has given the most fundamental information about nuclear forces.

NUCLEONS

In chemistry and physics, a **nucleon** is one of the particles that makes up the atomic nucleus. Each atomic nucleus consists of one or more nucleons, and each atom in turn consists of a cluster of nucleons surrounded by one or more electrons. There are two kinds of nucleon: the neutron and the proton. The mass number of a given atomic isotope is identical to its number of nucleons. Thus the term nucleon number may be used in place of the more common terms mass number or atomic mass number.

Until the 1960s, nucleons were thought to be elementary particles, each of which would not then have been made up of smaller parts. Now they are known to be composite particles, made of three quarks bound together by the so-called strong interaction. The interaction between two or more nucleons is called internucleon interactions or nuclear force, which is also ultimately caused by the strong interaction. (Before the discovery of quarks, the term "strong interaction" referred to just internucleon interactions.)

Nucleons sit at the boundary where particle physics and nuclear physics overlap. Particle physics, particularly quantum chromo dynamics, provides the fundamental equations that explain the properties of quarks and of the strong interaction. These equations explain quantitatively how quarks can bind together into protons and neutrons (and all the other hadrons). However, when multiple nucleons are assembled into an atomic nucleus (nuclide), these fundamental equations become too difficult to solve directly (see lattice QCD). Instead, nuclides are studied within nuclear physics, which studies nucleons and their interactions by approximations and models, such as the nuclear shell model. These models can successfully explain nuclide properties, for example, whether or not a certain nuclide undergoes radioactive decay.

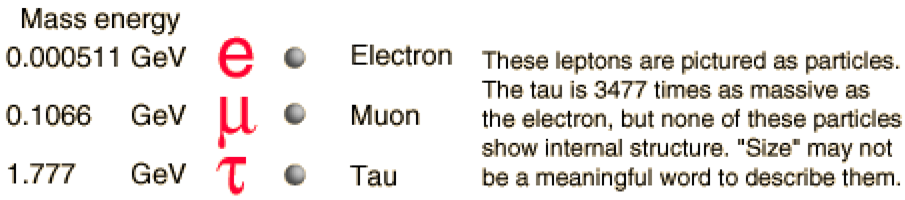
The proton and neutron are both baryons and both fermions. In the terminology of particle physics, these two particles make up an isospin doublet ($\mathbf{I} = \frac{1}{2}$). This explains why their masses are so similar, with the neutron just 0.1% heavier than the proton.

LEPTONS

Leptons and quarks are the basic building blocks of matter, i.e., they are seen as the "elementary particles". There are six leptons in the present structure, the electron, muon, and tau particles and their associated neutrinos. The different varieties of the elementary

ELEMENTARY PARTICLES

particles are commonly called "flavors", and the neutrinos here are considered to have distinctly different flavor.



Important principles for all particle interactions are the conservation of lepton number and the conservation of baryon number.

Now that we have experimental evidence for six leptons, a relevant question is "Are there more?" The present standard model assumes that there are no more than three generations. One of the pieces of experimental evidence for that is the measured hydrogen/helium abundance ratio in the universe. When the process of nucleosynthesis from the big bang is modeled, the number of types of neutrinos affects the abundance of helium. The observed abundance agrees with three types of neutrinos.

MESONS

Mesons are intermediate mass particles which are made up of a quark-antiquark pair. Three quark combinations are called baryons. Mesons are bosons, while the baryons are fermions. Recent experimental evidence shows the existence of five-quark combinations which are being called pentaquarks.

BARYONS

Baryons are massive particles which are made up of three quarks in the standard model. This class of particles includes the proton and neutron. Other baryons are the lambda, sigma, xi, and omega particles. Baryons are distinct from mesons in that mesons are composed of only two quarks. Baryons and mesons are included in the overall class known as hadrons, the particles which interact by the strong force. Baryons are fermions, while the mesons are bosons. Besides charge and spin (1/2 for the baryons), two other quantum numbers are assigned to these particles: baryon number (B=1) and strangeness (S), which in the chart can be seen to be equal to -1 times the number of strange quarks included.

The conservation of baryon number is an important rule for interactions and decays of baryons. No known interactions violate conservation of baryon number.

Recent experimental evidence shows the existence of five-quark combinations which are being called pentaquarks. The pentaquark would be included in the classification of baryons, albeit an "exotic" one. The pentaquark is composed of four quarks and an antiquark, like a combination of an ordinary baryon plus a meson.

HYPERONS

Hyperon, quasi-stable member of a class of subatomic particles known as baryons that are composed of three quarks. More massive than their more-familiar baryon cousins, the nucleons (protons and neutrons), hyperons are distinct from them in that they contain one or more strange quarks. Hyperons, in order of increasing mass, include the lambda-zero (Λ^0) particles, a triplet of sigma (Σ) particles, a doublet of xi (Ξ) particles, and the omega-minus (Ω^-) particle. Each of the seven particles, detected during the period 1947–64, also has a corresponding antiparticle. The discovery of the omega-minus hyperon was suggested by the Eightfold Way of classifying hadrons, the more-general group of subatomic particles to which hyperons are assigned. Hadrons are composed of quarks and interact with one another via the strong force.

Hyperons are produced by the strong force in the time it takes for a particle traveling at nearly the speed of light to cross the diameter of a subatomic particle, but their decay by the weak force (which is involved in radioactive decay) takes millions of millions of times longer. Because of this behaviour, hyperons—along with K-mesons, with which they are often produced—were named strange particles. This behaviour has since been ascribed to the weak decays of the specific quarks—also called strange—that they contain.

HADRONS

Particles that interact by the strong interaction are called hadrons. This general classification includes mesons and baryons but specifically excludes leptons, which do not interact by the strong force. The weak interaction acts on both hadrons and leptons.

Hadrons are viewed as being composed of quarks, either as quark-antiquark pairs (mesons) or as three quarks (baryons). There is much more to the picture than this, however, because the constituent quarks are surrounded by a cloud of gluons, the exchange particles for the color force.

Recent experimental evidence shows the existence of five-quark combinations which are being called pentaquarks.

STRANGE PARTICLES

The strange quark (and antiquark) is unstable and decays into an up quark, an electron and an electron antineutrino.

In 1947 the British physicists Rochester and Butler observed new particles (see article).These particles came in two forms: a neutral one that decayed into the pions p+ and p- , and a positively charge one that decayed into a muon m+ (heavy anti-electron) and a photon. Later a negative one was observed.

Many similar particles have since been found, both of 'mesonic' (quark and anti-quark) and baryonic (triple quark) types. They are collectively known as strange particles.

The surprising thing about these particles was that their life time was so long. Typically the decay times due to strong interactions are very fast, of the order of a femto second (10^{-15} s). The decay time of the K mesons was about 10^{-10} s, much more typical of a weak decay. It was discovered that in weak interactions strangeness (strangely!) was not conserved! Kaons decay by many mechanisms (that you do NOT have to recall - but should not be surprised to see quoted in examinations questions. For example when a K+, the lightest particle to contain a strange quark, decays to a p+, which is comprised of ordinary quarks only, the strange quark is converted into a “down” quark. This is forbidden in any direct process by the Standard Model. So it is no wonder they are called strange!

Using accelerators it was found that strange particles are typically formed in pairs. This mechanism was called 'associated production', and is highly suggestive of an additive conserved quantity, such as charge, which was called strangeness and allocated a quantum number.

Strange particles:

- contain an 's' quark or antiquark
- have surprisingly long lives (100,000 times longer than expected!)
- are produced in pairs which suggest that they have an additive conserved quality.

CLASSIFICATION OF FUNDAMENTAL FORCES AND ELEMENTARY PARTICLES

A quark is any of a group of subatomic particles believed to be among the fundamental constituents of matter. In much the same way that protons and neutrons make up atomic nuclei, these particles themselves are thought to consist of quarks. Quarks constitute all hadrons (baryons and mesons)--i.e., all particles that interact by means of the strong force, the force that binds the components of the nucleus.

According to prevailing theory, quarks have mass and exhibit a spin (i.e., type of intrinsic angular momentum corresponding to a rotation around an axis through the particle). Quarks appear to be truly fundamental. They have no apparent structure; that is, they cannot be resolved into something smaller. Quarks always seem to occur in combination with other quarks or antiquarks, never alone. For years physicists have attempted to knock a quark out of a baryon in experiments with particle accelerators to observe it in a free state but have not yet succeeded in doing so.

Throughout the 1960s theoretical physicists, trying to account for the ever-growing number of subatomic particles observed in experiments, considered the possibility that protons and neutrons were composed of smaller units of matter. In 1961 two physicists, Murray Gell-Mann of the United States and Yuval Ne`eman of Israel, proposed a particle classification scheme called the Eightfold Way, based on the mathematical symmetry group SU(3), that described strongly interacting particles in terms of building blocks. In 1964 Gell-Mann introduced the concept of quarks as a physical basis for the scheme, adopting the fanciful term from a passage in James Joyce's novel Finnegans Wake. (The American physicist George Zweig developed a similar theory independently that same year and called his fundamental particles "aces.") Gell-Mann's model provided a simple picture in which all mesons are shown as consisting of a quark and an antiquark and all baryons as composed of three quarks. It postulated the existence of three types of quarks, distinguished by distinctive "flavours." These three quark types are now commonly designated as "up" (u), "down" (d), and "strange" (s). Each carries a fractional electric charge (i.e., a charge less than that of the electron). The up and down quarks are thought to make up protons and neutrons and are thus the ones observed in ordinary matter. Strange quarks occur as components of K mesons and various other extremely short-lived subatomic particles that were first observed in cosmic rays but that play no part in ordinary matter.

Most problems with quarks were resolved by the introduction of the concept of color, as formulated in quantum chromodynamics (QCD). In this theory of strong interactions, developed in 1977, the term color has nothing to do with the colors of the everyday world but rather represents a special quantum property of quarks. The colors red, green, and blue are ascribed to quarks, and their opposites, minus-red, minus-green, and minus-blue, to antiquarks. According to QCD, all combinations of quarks must contain equal mixtures of these imaginary colors so that they will cancel out one another, with the resulting particle having no net color. A baryon, for example, always consists of a combination of one red, one green, and one blue quark. The property of color in strong interactions plays a role analogous to an electric charge in electromagnetic interactions. Charge implies the exchange of photons between charged particles. Similarly, color involves the exchange of massless particles called gluons among quarks. Just as photons carry electromagnetic force, gluons transmit the forces that bind quarks together. Quarks change their colour as they emit and absorb gluons, and the exchange of gluons maintains proper quark color distribution.

The first two you are familiar with, gravity is the attractive force between all matter, electromagnetic force describes the interaction of charged particles and magnetics. Light (photons) is explained by the interaction of electric and magnetic fields.

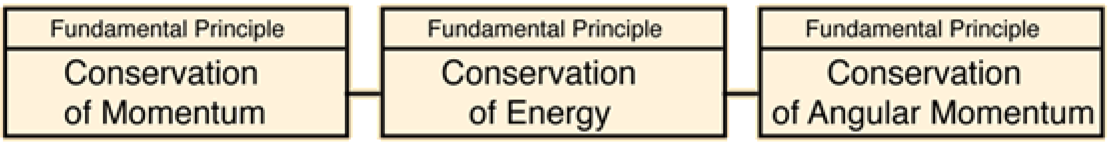
The strong force binds quarks into protons, neutrons and mesons, and holds the nucleus of the atom together despite the repulsive electromagnetic force between protons. The weak force controls the radioactive decay of atomic nuclei and the reactions between leptons (electrons and neutrinos).

Current physics (called quantum field theory) explains the exchange of energy in interactions by the use of force carriers, called bosons. The long range forces have zero mass force carriers, the graviton and the photon. These operate on scales larger than the solar system. Short range forces have very massive force carriers, the W+, W- and Z for the weak force, the gluon for the strong force. These operate on scales the size of atomic nuclei.

So, although the strong force has the greatest strength, it also has the shortest range.

BASIC CONSERVATION LAWS

If a system does not interact with its environment in any way, then certain mechanical properties of the system cannot change. They are sometimes called "constants of the motion". These quantities are said to be "conserved" and the conservation laws which result can be considered to be the most fundamental principles of mechanics. In mechanics, examples of conserved quantities are energy, momentum, and angular momentum. The conservation laws are exact for an isolated system.

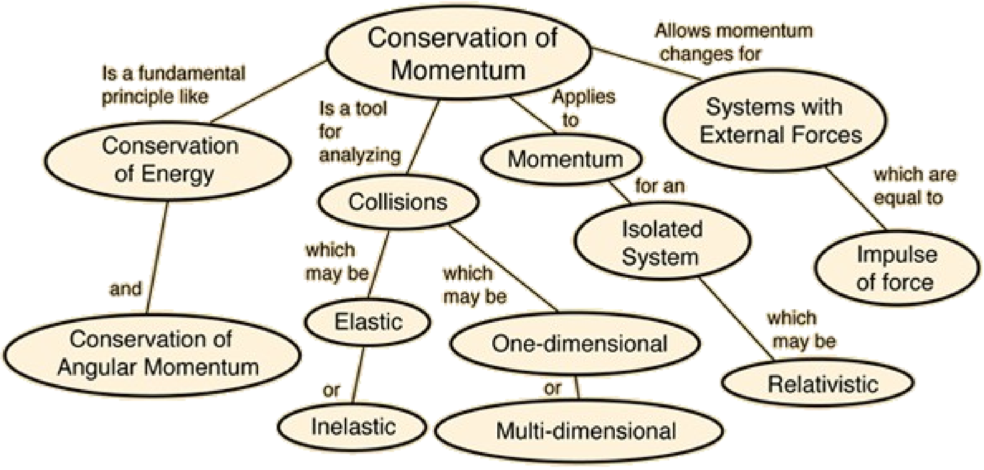


Stated here as principles of mechanics, these conservation laws have far-reaching implications as symmetries of nature which we do not see violated. They serve as a strong constraint on any theory in any branch of science.

Conservation of Momentum

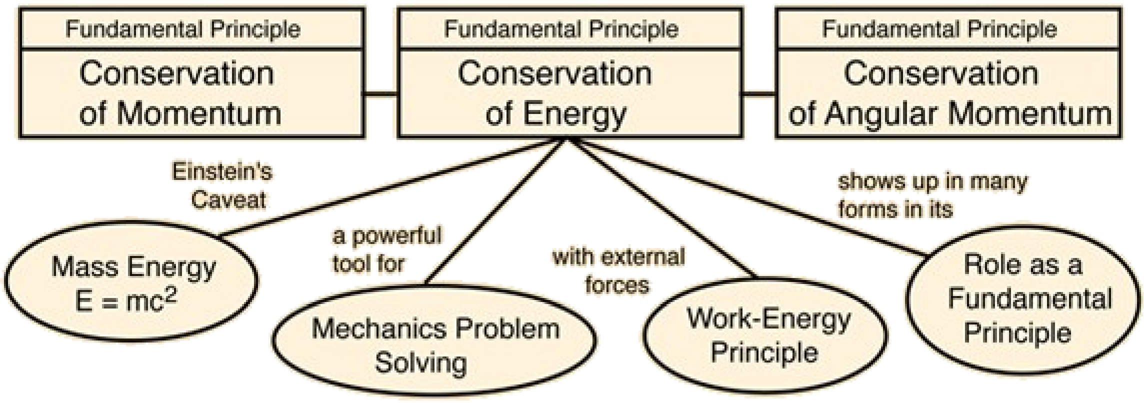
The momentum of an isolated system is a constant. The vector sum of the momenta mv of all the objects of a system cannot be changed by interactions within the system. This puts a strong constraint on the types of motions which can occur in an isolated system. If one part of the system is given a momentum in a given direction, then some other part or parts of the system must simultaneously be given exactly the same momentum in the opposite direction. As far as we can tell, conservation of momentum is an absolute symmetry of nature. That is, we do not know of anything in nature that violates it.

ELEMENTARY PARTICLES



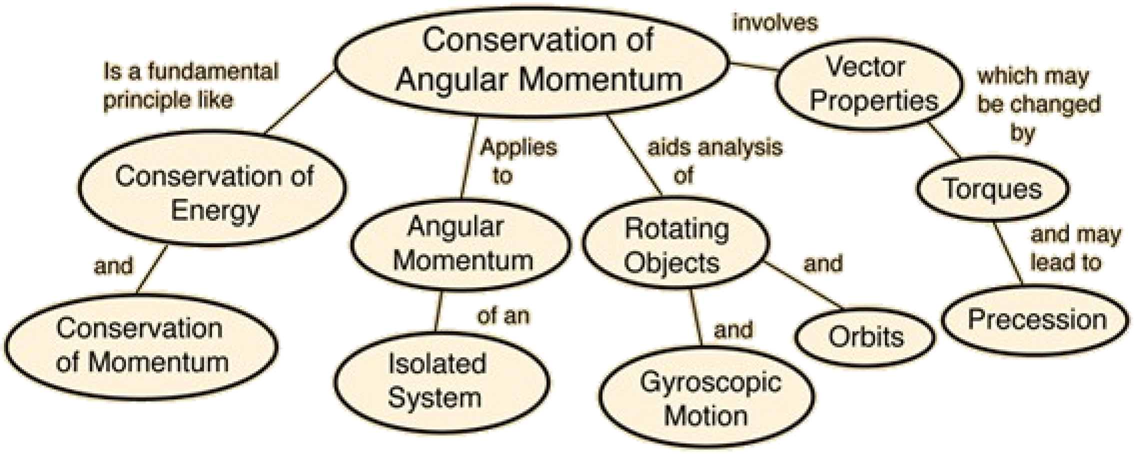
Conservation of Energy

Energy can be defined as the capacity for doing work. It may exist in a variety of forms and may be transformed from one type of energy to another. However, these energy transformations are constrained by a fundamental principle, the Conservation of Energy principle. One way to state this principle is "Energy can neither be created nor destroyed". Another approach is to say that the total energy of an isolated system remains constant.



Conservation of Angular Momentum

The angular momentum of an isolated system remains constant in both magnitude and direction. The angular momentum is defined as the product of the moment of inertia I and the angular velocity. The angular momentum is a vector quantity and the vector sum of the angular momenta of the parts of an isolated system is constant. This puts a strong constraint on the types of rotational motions which can occur in an isolated system. If one part of the system is given an angular momentum in a given direction, then some other part or parts of the system must simultaneously be given exactly the same angular momentum in the opposite direction. As far as we can tell, conservation of angular momentum is an absolute symmetry of nature. That is, we do not know of anything in nature that violates it.



ADDITION OF CONSERVATION LAWS
BARYONIC, LEPTONIC STRANGENESS AND ISOSPIN CHARGES/QUANTUM NUMBERS, GELLMANN NISHIJIMA FORMULA

In developing the standard model for particles, certain types of interactions and decays are observed to be common and others seem to be forbidden. The study of interactions has led to a number of conservation laws which govern them. These conservation laws are in addition to the classical conservation laws such as conservation of energy, charge, etc., which still apply in the realm of particle interactions. Strong overall conservation laws are the conservation of baryon number and the conservation of lepton number. Specific quantum numbers have been assigned to the different fundamental particles, and other conservation laws are associated with those quantum numbers.

From another point of view, it would seem that any localized particle of finite mass should be unstable, since the decay into several smaller particles provides many more ways to distribute the energy, and thus would have higher entropy. This idea is even stated as a principle called the "totalitarian principle" which might be stated as "every process that is not forbidden must occur". From this point of view, any decay process which is expected but not observed must be prevented from occurring by some conservation law. This approach has been fruitful in helping to determine the rules for particle decay.

Conservation laws for parity, isospin, and strangeness have been developed by detailed observation of particle interactions. The combination of charge conjugation (C), parity (P) and time reversal (T) is considered to be a fundamental symmetry operation - all physical particles and interactions appear to be invariant under this combination. Called CPT invariance, this symmetry plumbs the depths of our understanding of nature.

Another part of the high energy physicist's toolkit in anticipating what interactions can be expected is "crossing symmetry". Any interaction which is observed can be used to predict other related interactions by "crossing" any particle across the reaction symbol and turning it into it's antiparticle.

Conservation of Baryon Number

Nature has specific rules for particle interactions and decays, and these rules have been summarized in terms of conservation laws. One of the most important of these is the conservation of baryon number. Each of the baryons is assigned a baryon number B=1. This can be considered to be equivalent to assigning eachquark a baryon number of 1/3. This implies that the mesons, with one quark and one antiquark, have a baryon number B=0. No known decay process or interaction in nature changes the net baryon number.

The neutron and all heavier baryons decay directly to protons or eventually form protons, the proton being the least massive baryon. This implies that the proton has nowhere to go without violating the conservation of baryon number, so if the conservation of baryon number holds exactly, the proton is completely stable against decay. One prediction of grand unification of forces is that the proton would have the possibility of decay, so that possibility is being investigated experimentally.

Conservation of baryon number prohibits a decay of the type

$$p + n \rightarrow p + \mu^{+} + \mu^{-}$$
$$B = 1 + 1 \neq 1 + 0 + 0$$

but with sufficient energy permits pair production in the reaction

$$p + n \rightarrow p + n + p + \bar{p}$$
$$B = 1 + 1 = 1 + 1 + 1 - 1$$

The fact that the decay

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$

is observed implied that there is no corresponding principle of conservation of meson number. The pion is a meson composed of a quark and an antiquark, and on the right side of the equation there are only leptons. (Equivalently, you could assign a baryon number of 0 to the meson.)

Conservation of Lepton Number

Nature has specific rules for particle interactions and decays, and these rules have been summarized in terms of conservation laws. One of the most important of these is the conservation of lepton number. This rule is a little more complicated than the conservation of baryon number because there is a separate requirement for each of the three sets of leptons, the electron, muon and tau and their associated neutrinos.

The first significant example was found in the decay of the neutron. When the decay of the neutron into a proton and an electron was observed, it did not fit the pattern of two-particle decay. That is, the electron emitted does not have a definite energy as is required by conservation of energy and momentum for a two-body decay. This implied the emission of a third particle, which we now identify as the electron antineutrino.

$$n \not\rightarrow p^+ + e^-$$
$$n \rightarrow p^+ + e^- + \bar{\nu}_e$$

The assignment of a lepton number of 1 to the electron and -1 to the electron antineutrino keeps the lepton number equal to zero on both sides of the second react on above, while the first reaction does not conserve lepton number.

The observation of the following two decay processes leads to the conclusion that there is a separate lepton number for muons which must also be conserved.

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

The first reaction above (decay of the pion) is known to be a two-body decay by the fact that a well-defined muon energy is observed from the decay. However, the decay of the muon into an electron produces a distribution of electron energies, showing that it is at least a three-body decay. In order for both electron lepton number and muon lepton number to be conserved, then the other particles must be an electron anti-neutrino and a muon neutrino.

Isospin

Isospin is a term introduced to describe groups of particles which have nearly the same mass, such as the proton and neutron. This doublet of particles is said to have isospin 1/2, with projection +1/2 for the proton and -1/2 for the neutron. The three pions compose a triplet, suggesting isospin 1. The projections are +1 for the positive, 0 and -1 for the neutral and negative pions. Isospin is used as an axis in particle diagrams, with strangeness being the other axis. Isospin is not really spin, and doesn't have the units of angular momentum - the spin term is tacked on because the addition of the isospins follows the same rules as spin.

Isospin is a dimensionless quantity associated with the fact that the strong interaction is independent of electric charge. Any two members of the proton-neutron isospin doublet experience the same strong interaction: proton-proton, proton-neutron, neutron-neutron have the same strong force attraction.

At the quark level, the up and down quarks form an isospin doublet (I=1/2) and the projection I_3 = +1/2 is assigned to the up quark and I_3 =-1/2 to the down. (The subscript 3 is used here for the third component rather than the z used with spin and orbital angular momentum because most of the literature does so.) The other quarks are assigned isospin I=0. Isospin is related to other quantum numbers for the particles by

$$\frac{q}{e} = I_3 + \frac{S+B}{2}$$

I_3 = projection of isotopic spin

S = strangeness

B = baryon number

q = charge (q/e used to make it dimensionless)

This relationship is called the Gell Mann-Nishijima formula. Some references use T for isospin, but it appears that most use I for isospin and T for weak isospin.

Isospin is associated with a conservation law which requires strong interaction decays to conserve isospin, as illustrated by the process

$$\underset{I=1}{\overset{uds}{\Sigma^0}} \rightarrow \underset{I=0}{\overset{uds}{\Lambda^0}} + \gamma \qquad I=1 \neq I=0$$

which does not involve any transmutation of quarks, so would be expected to decay by strong interaction. However, it does not conserve isospin, and is observed to decay by the electromagnetic interaction, but not by the strong interaction. The experimental discrimination is made by the observation of its decay lifetime, presuming by the totalitarian principle that if it could decay by the strong interaction, it would.

INVARIANCE UNDER TIME REVERSAL (T) CHARGE CONJUGATION (C) AND PARITY

Many of the profound ideas in nature manifest themselves as symmetries. A symmetry in a physical experiment suggests that something is conserved, or remains constant, during the experiment. So conservation laws and symmetries are strongly linked.

Three of the symmetries which usually, but not always, hold are those of charge conjugation (C), parity (P), and time reversal (T):

- Charge conjugation(C): reversing the electric charge and all the internal quantum numbers.
- Parity (P): space inversion; reversal of the space coordinates, but not the time.

- Time reversal (T): replacing t by -t. This reverses time derivatives like momentum and angular momentum.

Examples in nature can be cited for the violation of each of these symmetries individually. It was thought for a time that CP (parity transformation plus charge conjugation) would always leave a system invariant, but the notable example of the neutral kaons has shown a slight violation of CP symmetry.

We are left with the combination of all three, CPT, a profound symmetry consistent with all known experimental observations.

On the theoretical side, CPT invariance has received a great deal of attention. Georg Ludens, Wolfgang Pauli and Julian Schwinger independently showed that invariance under Lorentz transformations implies CPT invariance. CPT invariance itself has implications which are at the heart of our understanding of nature and which do not easily arise from other types of considerations.

- Integer spin particles obey Bose-Einstein statistics and half-integer spin particles obey Fermi-Dirac statistics. Operators with integer spins must be quantized using commutation relations, while anticommutation relations must be used for operators with half integer spin.
- Particles and antiparticles have identical masses and lifetimes. This arises from CPT invariance of physical theories.
- All the internal quantum numbers of antiparticles are opposite to those of the particles.

P VIOLATION, C VIOLATION AND CP CONSERVATION

Although parity is conserved in electromagnetism, strong interactions and gravity, it turns out to be violated in weak interactions. The Standard Model incorporates parity violation by expressing the weak interaction as a chiral gauge interaction. Only the left-handed components of particles and right-handed components of antiparticles participate in weak interactions in the Standard Model. This implies that parity is not symmetry of our universe, unless a hidden mirror sector exists in which parity is violated in the opposite way.

It was suggested several times and in different contexts that parity might not be conserved, but in the absence of compelling evidence these suggestions were not taken seriously. A careful review by theoretical physicists Tsung Dao Lee and Chen Ning Yang went further, showing that while parity conservation had been verified in decays by the strong or electromagnetic interactions, it was untested in the weak interaction. They proposed several possible direct experimental tests. They were almost ignored, but Lee was able to convince his Columbia colleague Chien-Shiung Wuto try it. She needed special cryogenic facilities and expertise, so the experiment was done at the National Bureau of Standards.

In 1957 C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson found a clear violation of parity conservation in the beta decay of cobalt-60. As the experiment was winding down, with double-checking in progress, Wu informed Lee and Yang of their positive results, and saying the results need further examination, she asked them not to publicize the results first. However, Lee revealed the results to his Columbia colleagues on 4th January 1957 at a "Friday Lunch" gathering of the Physics Department of Columbia. Three of them, R. L. Garwin, Leon Lederman, and R. Weinrich modified an existing cyclotron experiment, and they immediately verified the parity violation. They delayed publication of their results until after Wu's group was ready, and the two papers appeared back to back in the same physics journal.

After the fact, it was noted that an obscure 1928 experiment had in effect reported parity violation in weak decays, but since the appropriate concepts had not yet been developed, those results had no impact. The discovery of parity violation immediately explained the outstanding τ–θ puzzle in the physics of kaons.

In 2010, it was reported that physicists working with the Relativistic Heavy Ion Collider (RHIC) had created a short-lived parity symmetry-breaking bubble in quark-gluon plasmas. An experiment conducted by several physicists including Yale's Jack Sandweiss as part of the STAR collaboration, showed a variation in the law of parity itself.

CP VIOLATION, CP violation in the standard model

In particle physics, CP violation is a violation of the postulated CP-symmetry: the combination of C-symmetry (charge conjugation symmetry) and P-symmetry (parity symmetry). CP-symmetry states that the laws of physics should be the same if a particle were interchanged with its antiparticle (C symmetry), and left and right were swapped (P symmetry). The discovery of CP violation in 1964 in the decays of neutral kaons resulted in the Nobel Prize in Physics in 1980 for its discoverers James Cronin and Val Fitch.

It plays an important role both in the attempts of cosmology to explain the dominance of matter over antimatter in the present Universe, and in the study of weak interactions in particle physics.

CP is the product of two symmetries: C for charge conjugation, which transforms a particle into its antiparticle, and P for parity, which creates the mirror image of a physical system. The strong interaction and electromagnetic interaction seem to be invariant under the combined CP transformation operation, but this symmetry is slightly violated during certain types of weak decay. Historically, CP-symmetry was proposed to restore order after the discovery of parity violation in the 1950s.

The idea behind parity symmetry is that the equations of particle physics are invariant under mirror inversion. This leads to the prediction that the mirror image of a reaction (such as a chemical reaction or radioactive decay) occurs at the same rate as the original reaction. Parity symmetry appears to be valid for all reactions involving electromagnetism and strong interactions. Until 1956, parity conservation was believed to be one of the fundamental geometric conservation laws (along with conservation of energy and conservation of momentum). However, in 1956 a careful critical review of the existing experimental data by theoretical physicists Tsung-Dao Lee and Chen Ning Yang revealed that while parity conservation had been verified in decays by the strong or electromagnetic interactions, it was untested in the weak interaction. They proposed several possible direct experimental tests. The first test based on beta decay of Cobalt-60 nuclei was carried out in 1956 by a group led by Chien-Shiung Wu, and demonstrated conclusively that weak interactions violate the P symmetry or, as the analogy goes, some reactions did not occur as often as their mirror image.

Overall, the symmetry of a quantum mechanical system can be restored if another symmetry *S* can be found such that the combined symmetry *PS* remains unbroken. This rather subtle point about the structure of Hilbert space was realized shortly after the discovery of *P* violation, and it was proposed that charge conjugation was the desired symmetry to restore order.

Simply speaking, charge conjugation is a simple symmetry between particles and antiparticles, and so CP-symmetry was proposed in 1957 by Lev Landau as the true symmetry between matter and antimatter. In other words a process in which all particles are exchanged with their antiparticles was assumed to be equivalent to the mirror image of the original process.

Indirect CP violation

In 1964, James Cronin, Val Fitch with coworkers provided clear evidence (which was first announced at the 12th ICHEP conference in Dubna) that CP-symmetry could be broken. This work won them the 1980 Nobel Prize. This discovery showed that weak interactions violate not only the charge-conjugation symmetry C between particles and antiparticles and the P or parity, but also their combination. The discovery shocked particle physics and opened the door to questions still at the core of particle physics and of cosmology today. The lack of an exact CP-symmetry, but also the fact that it is so nearly a symmetry, created a great puzzle.

Only a weaker version of the symmetry could be preserved by physical phenomena, which was CPT symmetry. Besides C and P, there is a third operation, time reversal (T), which corresponds to reversal of motion. Invariance under time reversal implies that whenever a motion is allowed by the laws of physics, the reversed motion is also an allowed one. The combination of CPT is thought to constitute an exact symmetry of all types of fundamental interactions. Because of the CPT symmetry, a violation of the CP-symmetry is equivalent to a violation of the T symmetry. CP violation implied nonconservation of T, provided that the long-held CPT theorem was valid. In this theorem, regarded as one of the basic principles of quantum field theory, charge conjugation, parity, and time reversal are applied together.

Direct CP violation

The kind of CP violation discovered in 1964 was linked to the fact that neutral kaons can transform into their antiparticles (in which each quark is replaced with the other's antiquark) and vice versa, but such transformation does not occur with exactly the same probability in both directions; this is called *indirect* CP violation. Despite many searches, no other manifestation of CP violation was discovered until the 1990s, when the NA31 experiment at CERN suggested evidence for CP violation in the decay process of the very same neutral kaons (*direct* CP violation). The observation was somewhat controversial, and final proof for it came in 1999 from the KTeV experiment at Fermilab and the NA48 experiment at CERN.

In 2001, a new generation of experiments, including the BaBar Experiment at the Stanford Linear Accelerator Center (SLAC) and the Belle Experiment at the High Energy Accelerator Research Organization (KEK) in Japan, observed direct CP violation in a different system, namely in decays of the B mesons. By now a large number of CP violation processes in B meson decays have been discovered. Before these "B-factory" experiments, there was a logical possibility that all CP violation was confined to kaon physics. However, this raised the question of why it's *not* extended to the strong force, and furthermore, why this is not predicted in the unextended Standard Model, despite the model being undeniably accurate with "normal" phenomena.

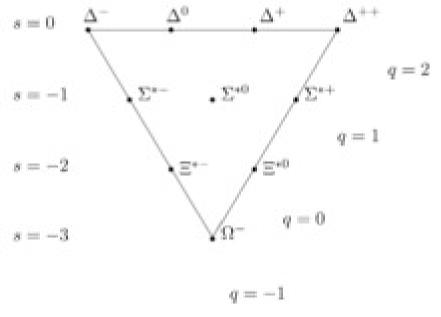
In 2011, a first indication of CP violation in decays of neutral D mesons was reported by the LHCb experiment at CERN.

The CP violation is incorporated in the Standard Model by including a complex phase in the CKM matrix describing quark mixing. In such scheme a necessary condition for the appearance of the complex phase, and thus for CP violation, is the presence of at least three generations of quarks.

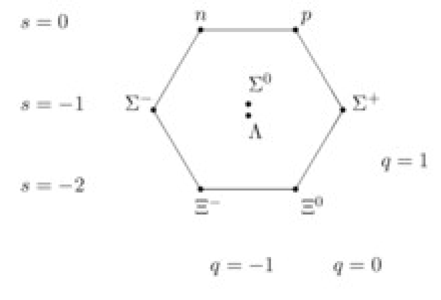
EIGHT FOLD WAY AND SUPER MULTIPLES

In physics, the Eightfold Way is a term coined by American physicist Murray Gell-Mann for a theory organizing subatomic baryons and mesons into octets (alluding to the Noble Eightfold Path of Buddhism). The theory was independently proposed by Israeli physicist Yuval Ne'eman and led to the subsequent development of the quark model.

In addition to organizing the mesons and spin-1/2 baryons into an octet, the principles of the Eightfold Way also applied to the spin-3/2 baryons, forming a decuplet. However, one of the particles of this decuplet had never been previously observed. Gell-Mann called this particle the Ω−
and predicted in 1962 that it would have a strangeness −3, electric charge −1 and a mass near 1,680 MeV/c^2. In 1964, a particle closely matching these predictions was discovered by a particle accelerator group at Brookhaven. Gell-Mann received the 1969 Nobel Prize in Physics for his work on the theory of elementary particles.



The baryon decuplet



The baryon octet

The Eightfold Way may be understood in modern terms as a consequence of flavor symmetries between various kinds of quarks. Since the strong nuclear force affects quarks the same way regardless of their flavor, replacing one flavor of quark with another in a hadron should not alter its mass very much. Mathematically, this replacement may be described by elements of the SU(3) group. The octets and other arrangements are representations of this group.

SU3 SYMMETRY AND QUARK MODEL

The special unitary group of degree *n*, denoted SU(*n*), is the group of $n \times n$ unitary matrices with determinant 1. The group operation is that of matrix multiplication. The special unitary group is a subgroup of the unitary group U(*n*), consisting of all $n \times n$ unitary matrices, which is itself a subgroup of the general linear group GL(*n*, **C**).

The SU(n) groups find wide application in the Standard Model of particle physics, especially SU(2) in the electroweak interaction and SU(3) in QCD.

The simplest case, SU(1), is the trivial group, having only a single element. The group SU(2) is isomorphic to the group of quaternions of norm 1, and is thus diffeomorphic to the 3-sphere. Since unit quaternions can be used to represent rotations in 3-dimensional space (up to sign), we have a surjective homomorphism from SU(2) to the rotation group SO(3) whose kernel is $\{+I, -I\}$.

Properties

The special unitary group SU(*n*) is a real matrix Lie group of dimension $n^2 - 1$. Topologically, it is compact and simply connected. Algebraically, it is a simple Lie group (meaning its Lie algebra is simple; see below). The center of SU(*n*) is isomorphic to the cyclic group $\mathbf{Z}_n$. Its outer automorphism group, for $n \geq 3$, is $\mathbf{Z}_2$, while the outer automorphism group of SU(2) is the trivial group.

The Lie algebra of SU(n), denoted by $\mathfrak{su}(n)$ is generated by n^2 operators, which satisfy the commutator relationship (for $i,j,k,l = 1, 2, ..., n$)

$$\left[\hat{O}_{ij}, \hat{O}_{kl}\right] = \delta_{jk}\hat{O}_{il} - \delta_{il}\hat{O}_{kj}.$$

Additionally, the operator

$$\hat{N} = \sum_{i=1}^{n} \hat{O}_{ii}$$

satisfies

$$\left[\hat{N}, \hat{O}_{ij}\right] = 0$$

which implies that the number of independent generators is n^2-1.

In physics, the quark model is a classification scheme for hadrons in terms of their valence quarks—the quarks and antiquarks which give rise to the quantum numbers of the hadrons.

The quark model was originally just a very good classification scheme to organize the depressingly large number of hadrons that were being discovered starting in the 1950s and continuing through the 1960s but it received experimental verification beginning in the late 1960s and continuing to the present. Hadrons are not "fundamental", but their "valence quarks" are thought to be, the quarks and antiquarks which give rise to the quantum numbers of the hadrons.

These quantum numbers are labels identifying the hadrons, and are of two kinds. One set comes from the Poincaré symmetry—J^{PC}, where J, P and C stand for the total angular momentum, P-symmetry, and C-symmetry respectively. The remainders are flavour quantum numbers such as the isospin, strangeness, charm, and so on. The quark model is the follow-up to the Eightfold Way classification scheme.

All quarks are assigned a baryon number of ⅓. Up, charm and top quarks have an electric charge of +⅔, while the down, strange, and bottom quarks have an electric charge of −⅓. Antiquarks have the opposite quantum numbers. Quarks are also spin-½ particles, meaning they are fermions.

Mesons are made of a valence quark−antiquark pair (thus have a baryon number of 0), while baryons are made of three quarks (thus have a baryon number of 1). This article discusses the quark model for the up, down, and strange flavours of quark (which form an approximate SU(3) symmetry). There are generalizations to larger number of flavours.

Isospin symmetry

In quantum mechanics, when a Hamiltonian has a symmetry, that symmetry manifests itself through a set of states that have the same energy; that is, the states are degenerate. In particle physics, the near mass-degeneracy of the neutron and proton points to an approximate symmetry of the Hamiltonian describing the strong interactions. The neutron does have a slightly higher mass due to isospin breaking; this is due to the difference in the masses of the up and down quarks and the effects of the electromagnetic interaction. However, the appearance of an approximate symmetry is still useful, since the small breakings can be described by a perturbation theory, which gives rise to slight differences between the near-degenerate states.

SU(2)

Heisenberg's contribution was to note that the mathematical formulation of this symmetry was in certain respects similar to the mathematical formulation of spin, whence the name "isospin" derives. To be precise, the isospin symmetry is given by the invariance of the Hamiltonian of the strong interactions under the action of the Lie group SU(2). The neutron and the proton are assigned to the doublet (the spin-½, **2**, or fundamental representation) of SU(2). The pions are assigned to the triplet (the spin-1, **3**, or adjoint representation) of SU(2).

Just as is the case for regular spin, isospin is described by two quantum numbers, I, the total isospin, and I_3, the component of the spin vector in some direction.

CHARMONIUM AND BOTTOMIUM

In particle physics, quarkonium (pl. quarkonia) designates a flavorless meson whose constituents are a quark and its own antiquark. Examples of quarkonia are the J/ψ meson (an example of charmonium, cc) and the ϒ meson (bottomonium, bb). Because of the high mass of the top quark, toponium does not exist, since the top quark decays through the electroweak interaction before a bound state can form. Usually quarkonium refers only to charmonium and bottomonium, and not to any of the lighter quark–antiquark states. This usage is because the lighter quarks (up,down, and strange) are much less massive than the heavier quarks, and so the physical states actually seen in experiments are quantum mechanical mixtures of the light quark states. The much larger mass differences between the charm and bottom quarks and the lighter quarks results in states that are well defined in terms of a quark–antiquark pair of a given flavour.

Charmonium states

In the following table, the same particle can be named with the spectroscopic notation or with its mass. In some cases excitation series are used: Ψ' is the first excitation of Ψ (for historical reasons, this one is called *J/ψ* particle); Ψ'' is a second excitation, and so on. That is, names in the same cell are synonymous.

Some of the states are predicted, but have not been identified; others are unconfirmed. The quantum numbers of the X(3872) particle are unknown; its identity is debated. It may be:

- a candidate for the 1^1D_2 state;
- a charmonium hybrid state;
- a $D^0\bar{D}^{*0}$ molecule.

In 2005, the BaBar experiment announced the discovery of a new state: Y(4260). CLEO and Belle have since corroborated these observations. At first, Y(4260) was thought to be a charmonium state, but the evidence suggests more exotic explanations, such as a D "molecule", a 4-quark construct, or a hybrid meson.

Term symbol $n^{2S+1}L_J$	**$I^G(J^{PC})$**	**Particle**	**mass (MeV/c^2)**
1^1S_0	$0^+(0^{-+})$	$\eta_c(1S)$	2,980.3±1.2
1^3S_1	$0^-(1^{--})$	$J/\psi(1S)$	3,096.916±0.011
1^1P_1	$0^-(1^{+-})$	$h_c(1P)$	3,525.93±0.27
1^3P_0	$0^+(0^{++})$	$\chi_{c0}(1P)$	3,414.75±0.31
1^3P_1	$0^+(1^{++})$	$\chi_{c1}(1P)$	3,510.66±0.07
1^3P_2	$0^+(2^{++})$	$\chi_{c2}(1P)$	3,556.20±0.09
2^1S_0	$0^+(0^{-+})$	$\eta_c(2S)$, or η'_c	3,637±4
2^3S_1	$0^-(1^{--})$	$\psi(3686)$	3,686.09±0.04
1^1D_2	$0^+(2^{-+})$	$\eta_{c2}(1D)^\dagger$	
1^3D_1	$0^-(1^{--})$	$\psi(3770)$	3,772.92±0.35
1^3D_2	$0^-(2^{--})$	$\psi_2(1D)$	
1^3D_3	$0^-(3^{--})$	$\psi_3(1D)^\dagger$	
2^1P_1	$0^-(1^{+-})$	$h_c(2P)^\dagger$	
2^3P_0	$0^+(0^{++})$	$\chi_{c0}(2P)^\dagger$	
2^3P_1	$0^+(1^{++})$	$\chi_{c1}(2P)^\dagger$	
2^3P_2	$0^+(2^{++})$	$\chi_{c2}(2P)^\dagger$	

???	$0^?(?^?)$†	$X(3872)$	3,872.2±0.8
???	$?^?(1^{--})$	$Y(4260)$	4,263+8 −9

Notes:

* Needs confirmation.

† Predicted, but not yet identified.

† Interpretation as a 1^{--} charmonium state not favored.

Bottomonium states

In the following table, the same particle can be named with the spectroscopic notation or with its mass.

Some of the states are predicted, but have not been identified; others are unconfirmed.

Term symbol $n^{2S+1}L_J$	$I^G(J^{PC})$	**Particle**	**mass (MeV/c²)**
1^1S_0	$0^+(0^{-+})$	$\eta_b(1S)$	9,390.9±2.8
1^3S_1	$0^-(1^{--})$	$\Upsilon(1S)$	9,460.30±0.26
1^1P_1	$0^-(1^{+-})$	$h_b(1P)$	
1^3P_0	$0^+(0^{++})$	$\chi_{b0}(1P)$	9,859.44±0.52
1^3P_1	$0^+(1^{++})$	$\chi_{b1}(1P)$	9,892.76±0.40
1^3P_2	$0^+(2^{++})$	$\chi_{b2}(1P)$	9,912.21±0.40
2^1S_0	$0^+(0^{-+})$	$\eta_b(2S)$	
2^3S_1	$0^-(1^{--})$	$\Upsilon(2S)$	10,023.26±0.31
1^1D_2	$0^+(2^{-+})$	$\eta_{b2}(1D)$	
1^3D_1	$0^-(1^{--})$	$\Upsilon(1D)$	
1^3D_2	$0^-(2^{--})$	$\Upsilon_2(1D)$	10,161.1±1.7
1^3D_3	$0^-(3^{--})$	$\Upsilon_3(1D)$	
2^1P_1	$0^-(1^{+-})$	$h_b(2P)$	
2^3P_0	$0^+(0^{++})$	$\chi_{b0}(2P)$	10,232.5±0.6
2^3P_1	$0^+(1^{++})$	$\chi_{b1}(2P)$	10,255.46±0.55
2^3P_2	$0^+(2^{++})$	$\chi_{b2}(2P)$	10,268.65±0.55
3^3S_1	$0^-(1^{--})$	$\Upsilon(3S)$	10,355.2±0.5
3^3P_J	$0^+(J^{++})$	$\chi_b(3P)$	10,530±5 (stat.) ± 9 (syst.)
4^3S_1	$0^-(1^{--})$	$\Upsilon(4S)$ or $\Upsilon(10580)$	10,579.4±1.2
5^3S_1	$0^-(1^{--})$	$\Upsilon(10860)$	10,865±8
6^3S_1	$0^-(1^{--})$	$\Upsilon(11020)$	11,019±8

Notes:

[*] Preliminary results. Confirmation needed.

The χ_b (3P) state was the first particle discovered in the Large Hadron Collider.

Questions:

1. Write a note on the building blocks of a nucleus.
2. Write a short note on leptons.
3. Explain mesons.
4. Write a note on baryons.
5. What are hyperons?
6. Write a detailed note on hadrons.
7. Explain Gellmann Nishijima formula.
8. Discuss TCP theorem.
9. Give an introduction to Quark model.

KARPAGAM ACADEMY OF HIGHER EDUCATION,COIMBATORE-21
DEPARTMENT OF PHYSICS

CLASS:I MSC PHYSICS

NUCLEAR PHYSICS (18PHP203)
MULIPLE CHOICE QUESTIONS
UNIT - V

QUESTIONS	opt1	opt2	opt3	opt4	opt5	opt6	answer
Which operator is connected with spatial inversion	Parity	Charge co	Time Rev	All the above			Parity
The concept of a particle-antiparticle pair was originally developed by	Planck's	Einstein	J.J.Thoms	P.A.M.Dirac			P.A.M.Dirac
A symmetry scheme known as the ………………in which all the known particles and resonances are grouped together to form families	Eight fold	Five fold	Six fold w	None of these			Eight fold way
In SU(3), SU stands for	Single uni	Special ur	Special ur	None of these			Special unitary
Isospin conservation law is obeyed by	All the fou	The EM,w	Weak and	Strong interaction only			Strong interaction only
Strangeness conservation law holds good in	Strong and	All the fou	Weak and	Weak only			Strong and electromagnetic interactions
Which conservation laws hold good in Strong and electromagnetic interactions	Strangene	Parity	(a) & (b)	isospin			(a) & (b)
The process of changing every particle into its anti-particle is known as	Charge co	Time reve	Parity	All the above			Charge conjugation
Mesons have zero intrinsic spin but Baryons have	Half integ	Full integ	No any in	None of these			Half integral intrinsic spin
The particles of masses between π-meson mass and proton mass were called	Heavy me	Hyperons	Leptons	None of these			Heavy mesons (k-meson)
The particles of masses between proton and deuterium mass were called	k-meson	Hyperons	Leptons	None of these			Hyperons
Nucleons (protons and neutrons), Lamda particle(λ^0), sigma particle (∑), cascade particle (≡) and omega particles are called	Hyperons	Leptons	Baryons	None of these			Baryons
Baryons heavier than nucleons are called	Hyperons	Leptons	Lamda pa	None of these			Hyperons
A combination of a down quark (d) and an anti up quark u¯ called a	π^0 meson	A proton	π^- meson	Neutron			π^- meson
If π- was formed by a d quark and u quark the conservation law violated	Angular m	Charge an	Linear mo	Charge and Lepton number			Charge and baryon number
An experiment is performed to search for evidence of the reaction pp→HK+K+. How many quarks must H contain?	Two	Three	Four	Six			Six
A neutral elementary particle whose isotopic spin projection is J_Z=+1/2 and Baryon charge B=+1. The particle is	$\wedge^0$	Ξ^0	$\sum^0$	n			Ξ^0
∑^-→∧^0+π^- is forbidden by	Conservat	Conservat	Conservat	Conservation of energy			Conservation of energy
The mode of decay for a neutron is observed n→p+e^- because the conservation laws does this process violates	Energy an	Energy an	angular m	Charge and baryon number			angular momentum and lepton number
The iso spin and the strangeness of Ω^- baryon are	1,-3	0,-3	1,3	0,3			0,-3
∧^0→p+k^- is forbidden as it violates	Charge co	Conservat	Conservat	Conservation of Le and Lμ			Conservation of β-violation
The quarks particle (u,d,s) possess fractional electric charges according to	2/3 e,-1/3	-2/3 e,1/3	-1/3 e,2/3	1/3 e,2/3 e,-2/3 e			2/3 e,-1/3 e,-1/3 e
The baryon number of proton, the lepton number of proton, the baryon number of electron and the lepton number of electron are respectively	Zero,zero,	one,one,ze	one,zero,z	Zero,one,one and zero			one,zero,zero and one
Except for mass, the properties of the muon most closely resemble the properties of the	Electron	Photon	Pions	Protons			Electron
If π^- was formed by a d quark and a u quark, the conservation law violated	Angular m	Charge an	Linear mo	Charge and lepton number			Charge and baryon number
The reaction proceed by strong interaction π^-+p→Ξ^-+K^0+X, identify X	π^+	K^0	p	γ			K^0
Quarks are elementary particles, first proposed by Gellmann to explain the discrepencies in	Structure	Eight fold	Structure	Baryon structure			Structure of resonance particles discovered earlier
A conservation law that is not universal but applies only to certain kinds of interactions is conservation of	lepton nur	baryon nu	spin	strangeness			strangeness
The particle decay ∧→p+π^- must be a weak interaction because	The π^- is a	The ∧ has	It does no	No neutrino is produced in the d			It does not conserve strangeness
The interaction that describes the forces among nucleons that hold nuclei together is	the strong	the electro	the weak	the gravitational interaction			the strong nuclear (hadronic) interaction
Current thought is that all matter is composed of is	six quarks	four quark	six leptons	six quarks and six leptons			six quarks and six leptons
Particles that participate in the strong nuclear interaction are called	neutrinos	hadrons	leptons	electrons			hadrons
Which of the following choices lists the four known types of forces in nature in order of decreasing strength?	strong nuc	electroma	strong nuc	strong nuclear, weak nuclear, ele			strong nuclear, electromagnetic, weak nuclear, gravitational
The conservation law violated by the reaction p → π^0 + e^+ is the conservation of	charge	energy	linear mor	lepton number and baryon numb			lepton number and baryon number
The concept of strangeness was introduced by	GellMann	Mayer	Bohr	None of these			GellMann and Nishijima
Meson production predominates at bombarding energy of	10MeV	few hundr	Several hu	1MeV			Several hundred MeV
Which neutral unstable particle was named as lambda	Leptons	mesons	hyperons	hadrons			hyperons
The first hyperon was found in cosmic rays in 1947 by	Rochester	Gellmann	Mayer	J.J.Thomson			
The time reversal process is the creation of an electron-positron pair by the collision of	one photo	particles	waves	two photons			two photons
Isospin numbers are associated with hadrons but not with	leptons	mesons	hyperons	all of above			leptons
In a weak interaction involving change in strangeness of baryons or mesons, the change in strangeness must be equal to the change in	parity	charge	time	all the above			charge
Bosons are particles with intrinsic angular momentum equal to an	integral m	Half integ	No any mu	None of these			integral multiple of h
Fermions are all those particles in which the spin is	Full integr	No any sp	Half integ	None of these			Half integral
Strong interactions between elementary particles are responsible for the	decay of p	total cross	fission	all the above			total cross section as a function of energy
The process of mutual annihilation of particles and anti-particles is an example of	nuclear in	coulomb r	electroma	all the above			electromagnetic interaction
$\wedge^0$+p=$\sum^+$+n proceeds via	Strong int	Em intera	Weak inte	Cannot be predicted			Strong interaction
Which one of the following nuclear processes is forbidden?	ν¯+p→n+e	π^-→e^-+ν_e+	π^-+p→n+	μ^-→e^-+$(\nu_e)^-$+ν_μ			π^-→e^-+ν_e+π^0
d+d=α+π^0 is forbidden due to violating the conservation of	Strangene	Iso spin	Baryon nu	Energy			Iso spin
π^-+n=k^++$\wedge^0$ is forbidden by violating	Conservat	Conservat	Conservat	Conservation of charge and third			Conservation of charge and third component of iso spin
k^++n=$\sum^+$+π^0 proceeds via	Strong int	Em intera	Weak inte	Cannot be predicted			Strong interaction
Consider the reactions ∑^+=n+e^++ν_e k^+=π^++e^++e^-	Both of th	Both of th	Both of th	Both of them are forbidden due			Both of them proceed via the weak interaction
By considering the quark makeup of the various particles, deduce the identity of the unknown particles in the reaction ∑^0+p=∑^++γ+? (∑0 =uds,p=uud, ∑+=uus)	proton	neutron	pions	omega			neutron
which of the following is allowed reaction	μ^+→e^+	π^+→μ^+	p+p→p+∑	p→e^++νe			π^+→μ^++ν_μ
Which of the following is forbidden	π^-+p→∑	π^-+p→k	π^-+n→Ξ	k^-+p→Ω^-+k^++k^0			π^-+n→Ξ^-+k^++k^-
K-mesons and η-mesons are allotted	Negative	Positive p	Both type	No parity			Negative parity
Which of the following reactions violates lepton number conservation?	e^++e^-—	e^-+p→ν	e^++n→p	μ^-→e^-+ν+ν¯			e^++n→p+ν
Which one of the following nuclear processes is forbidden?	ν¯+p→n+e	π^-→e^-+	π^-+p→n	μ^-→e^-+(ν_e)¯+ν_μ			π^-→e^-+ν_e+π^0
Proton and neutron form an	isospin do	doublet	isospin	triplet			isospin doublet
A zero spin particle can exist in	two state	zero state	three state	All the above			two state
A spin particle can exist in	two state	zero state	three state	All the above			three state
The proton and neutron mass in terms of energy is about	0.5MeV	1BeV	several M	few MeV			1BeV
Massles Bosons are subject to	strong, we	Weak inte	Strong int	electromagnetic interaction only			electromagnetic interaction only
Pion was found to exist in	positive cl	negative c	zero charg	all three charged states			all three charged states
Mass of pion was estimated to be	$270m_e$	$270m_n$	0	1			$270m_e$
muon particle was found to have a life time of	10^{-6} sec	10^{-8} sec	10^{6} sec	50s			10^{-6} sec