KARPAGAM ACADEMY OF HIGHER EDUCATION

(Deemed to be University)
(Established Under Section 3 of UGC Act 1956)
Coimbatore - 641021.
(For the candidates admitted from 2018 onwards)

DEPARTMENT OF PHYSICS

SUBJECT: NUCLEAR PHYSICS
SEMESTER : II
SUBJECT CODE: 18PHP203
CLASS : I M.Sc

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

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 -III

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 - 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

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.

TEXT BOOKS:

1. Pandya. M.L. and R. P. S. Yadav, 2004, Elements of Nuclear Physics, 1st edition Kedar Nath Ram Nath, Meerut.
2. D.C Tayal , 4th edition 2011, Nuclear Physics, Himalaya Publishing House, New Delhi.
3. Introduction to Nuclear Physics- Harald, Enge, The Perseus Books Group.
4. Nuclear Physics: Theory and Experiment- R. R. Roy, B.P. Nigam, New Age International Pvt Ltd.

REFERENCES:

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

NUCLEAR MASS AND CHARGE

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NUCLEAR MASS AND CHARGE

MASSES OF NUCLEI

Apparently, an individual nucleus cannot be put on a scale to measure its mass. Then how can nuclear masses are measured? This is done with the help of the devices called mass spectrometers. In them, a flux of identical nuclei, accelerated to certain energy, is directed to a screen where it makes a visible mark. Before striking the screen, this flux passes through magnetic field, which is perpendicular to velocity of the nuclei. As a result, the flux is deflected to certain angle. The greater the mass, the smaller is the angle (because of inertia). Thus, measuring the displacement of the mark from the center of the screen, we can find the deflection angle and then calculate the mass. Since mass and energy are equivalent, in nuclear physics it is customary to measure masses of all particles in the units of energy, namely, in MeV. Examples of masses of subatomic particles are given in Table 1

Table: 1 Masses of electron, nucleons, and some nuclei.

particle	number of protons	number of neutrons	mass (MeV)
e	0	0	0.511
p	1	0	938.272
n	0	1	939.566
${}^{2}_{1}H$	1	1	1875.613
${}^{3}_{1}H$	1	2	2808.920
${}^{3}_{2}He$	2	1	2808.391

$^{4}_{2}$He	2	2	3727.378
$^{7}_{3}$Li	3	4	6533.832
$^{9}_{4}$Be	4	5	8392.748
$^{12}_{6}$C	6	6	11174.860
$^{16}_{8}$O	8	6	14895.077
$^{238}_{92}$U	92	146	221695.831

The values given in this table, are the energies to which the nuclear masses are equivalent.
There are several advantages of using the units of MeV to measure particle masses. First of all, like with nuclear energies, we avoid handling very small numbers that involve ten to the power of something. For example, if we were measuring masses in kg, the electron mass would be $m_e = 9.1093897 \times 10^{-31}$ kg. When masses are given in the equivalent energy units, it is very easy to calculate the mass defect. Indeed, adding the masses of proton and neutron, given in the second and third rows of Table 1, and subtracting the mass of $^{2}_{1}$H, we obtain the binding energy 2.225MeV of the deuteron without further ado. One more advantage comes from particle physics. In collisions of very fast moving particles new particles (like electrons) can be created from vacuum, i.e. kinetic energy is directly transformed into mass. If the mass is expressed in the energy units, we know how much energy is needed to create this or that particle, without calculations.

SIZES OF NUCLEI

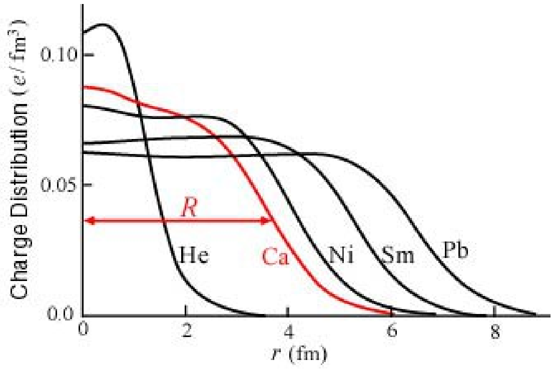
It had already been known from the analyses with the Rutherford atomic model that the nuclear size is smaller than 2×10^{-14}m roughly speaking. How can we more precisely measure the size of individual nucleus?

When we intend to measure the size of an object, we irradiate light on the object and observe the reflected light. The reflection occurs because of the interaction between the light and object.

Similarly, in order to measure the nuclear radius, it appears convenient to bombard some kinds of particles to the nucleus and observe their reaction. For this purpose, alpha particles, nucleons, electrons, photons etc. could be candidates as projectiles. Among them, electrons must be the most convenient. Electrons can interact with protons because they are both electrically charged. But electrons do not so strongly interact with neutron, so that the reflection of electrons, i.e. electron scattering, can be used only for the measurement of the charge distribution (or the proton distribution) in a nucleus.

NUCLEAR MASS AND CHARGE

The proton distribution in a nucleus may not always be equal to the mass distribution including both of protons and neutrons. However it would be possible to get a rough estimation of the nuclear mass distribution and the nuclear radius.



This type of precise measurements have been carried out and a lot of detailed data of the nuclear charge distribution for various nuclei have been obtained. A part is shown in the following figure.

[Experimental Data of Nuclear Charge Distributions]

The data obtained by the electron scattering. As an example, the red curve shows the proton distribution in Ca whose radius is shown by *R*.

NUCLEAR SPINS AND DIPOLE MOMENTS

It is common practice to represent the total angular momentum of a nucleus by the symbol I and to call it "nuclear spin". For electrons in atoms we make a clear distinction between electron spin and electron orbital angular momentum, and then combine them to give the total angular momentum. But nuclei often act as if they are a single entity with intrinsic angular momentum I. Associated with each nuclear spin is a nuclear magnetic moment which produces magnetic interactions with its environment.

The nuclear spins for individual protons and neutrons parallels the treatment of electron spin, with spin 1/2 and an associated magnetic moment. The magnetic moment is much smaller than that of the electron. For the combination neutrons and protons into nuclei, the situation is more complicated.

A characteristic of the collection of protons and neutrons (which are fermions) is that a nucleus of odd mass number A will have a half-integer spin and a nucleus of even A will have integer spin. The suggestion that the angular momenta of nucleons tend to form pairs is supported by the fact that all nuclei with even Z and even N have nuclear spin I=0. For example, in the nuclear data table for iron below, all the even A nuclides have spin I=0 since there are even numbers of both neutrons and protons. The half-integer spins of the odd-A nuclides suggests that this is the nuclear spin contributed by the odd neutron.

Isotopes of Iron

Z	A	Atomic Mass (u)	Nuclear Mass(GeV/c2	Binding Energy(MeV)	Spin	Natural Abund.	Half-life	Decay	Q MeV

26	54	53.939613	50.2315	471.77	0	0.059	stable	...	...
26	55	54.938296	51.1618	481.07	3/2	...	2.7y	EC	0.23
26	56	55.934939	52.0902	492.26	0	0.9172	stable	...	...
26	57	56.935396	53.0221	499.91	1/2	0.021	stable	...	...
26	58	57.933277	53.9517	509.96	0	0.0028	stable	...	...
26	60	59.934077	55.8154	525.35	0	...	1.5My	b-	0.24

The nuclear data of cobalt, just above iron in the periodic table, shows dramatically different nuclear spins I. The nuclides with even neutron number show half-integer spins associated with the odd proton, while those with odd neutron number show large integer spins associated with the two nucleons which are unpaired.

Isotopes of Cobalt

Z	A	Atomic Mass (u)	Nuclear Mass(GeV/c2	Binding Energy(MeV)	Spin	Natural Abund.	Half-life	Decay	Q MeV
27	56	55.939841	52.0943	486.92	4	...	77.7d	b+	4.57
27	57	56.936294	53.0225	498.29	7/2	...	271d	EC	0.84
27	59	58.933198	54.8826	517.32	7/2	1.00	stable	...	...
27	60	59.933820	55.8147	524.81	5	...	5.272y	b-	2.82

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 angular momentum.

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

$$\mu_B = \frac{e\hbar}{2m_e} = 9.2740154x10^{-24} J/T = 5.7883826x10^{-5} eV/T \quad \text{Bohr magneton}$$

$$\text{Orbital} \qquad \mu_L = -g_L \frac{e}{2m_e} L \qquad \mu_{Lz} = -g_L \frac{e\hbar}{2m_e} m_\ell = -m_\ell \mu_B$$

$$\text{since} \quad g_L = 1$$

$$\text{Spin} \qquad \mu_S = -g_S \frac{e}{2m_e} S \qquad \mu_{Sz} = -g_S \frac{e\hbar}{2m_e} m_s = -2m_s \mu_B = \pm \mu_B$$

$$g_S = 2.0023 \approx 2$$

Generally, the measured quantity is proportional to the z-component of the magnetic moment (the component along the experimentally determined direction such as the direction of an applied magnetic field, etc.). In this treatment, the use of a "gyro magnetic ratio" or "g-factor" is introduced. The g-factor for orbital is just $g_L = 1$, but the electron spin g-factor is approximately $g_S = 2$.

For the nuclear case we proceed in a parallel manner. The nuclear magnetic moment is expressed in terms of the nuclear spin in the form

Nuclear magnetic moment $\mu = g\frac{e}{2m_p}I$ $\mu_z = g\frac{e\hbar}{2m_p}m_I = g\mu_N m_I$

where we have now introduced a new unit called a nuclear magnetron.

Nuclear magneton $\mu_N = 5.05084x10^{-27} J/T = 3.15245x10^{-8}\ eV/T$

For free protons and neutrons with spin I =1/2, the magnetic moments are of the form

$$\mu_z = \frac{1}{2}g\mu_N$$

Where
Proton: g = 5.5856912 +/- 0.0000022
Neutron: g = -3.8260837 +/- 0.0000018
The proton g-factor is far from the $g_S = 2$ for the electron and even the uncharged neutron have a sizable magnetic moment! For the neutron, this suggests that there is internal structure involving the movement of charged particles, even though the net charge of the neutron is zero. If g=2 were an expected value for the proton and g=0 were expected for the neutron, then it was noted by early researchers that the proton g-factor is 3.6 units above its expected value and the neutron value is 3.8 units below its expected value. This approximate symmetry was used in trial models of the magnetic moment, and in retrospect is taken as an indication of the internal structure of quarks in the standard model of the proton and neutron.
Note that the maximum effective magnetic moment of a nucleus in nuclear magnetrons will be the g-factor multiplied by the nuclear spin. For a proton with g = 5.5857 the quoted magnetic moment is m = 2.7928 nuclear magnetrons.

Nuclide	Nuclear spin I	Magnetic moment m in m_N
n	1/2	-1.9130418
p	1/2	+2.7928456
^{2}H(D)	1	+0.8574376
^{17}O	5/2	-1.89279
^{57}Fe	1/2	+0.09062293
^{57}Co	7/2	+4.733
^{93}Nb	9/2	+6.1705

STABILITY OF NUCLEI

Why is it that certain combinations of nucleons are stable in a nucleus while others are not? A complete answer to this question cannot yet be given, largely because the exact nature of the forces holding the nucleons together is still only partially understood. We can, however, point to several factors which affect nuclear stability. The most obvious is the neutron/ proton ratio. As we discuss in "Further Modes of Decay", if this is too high or too low, it makes for an unstable nucleus.

If we plot the number of neutrons against the number of protons for all known stable (i.e., nonradioactive) nuclei, we obtain the result shown in Fig. 1. All the stable nuclei lie within a definite area called the zone of stability. For low atomic numbers most stable nuclei have a neutron/proton ratio which is very close to 1. As the atomic number increases, the zone of stability corresponds to a gradually increasing neutron/proton ratio. In the case of the heaviest stable isotope, 20983Bi for instance, the neutron/proton ratio is 1.518. If an unstable isotope lies to the left of the zone of stability in Fig. 1, it is neutron rich and decays by β emission. If it lies to the right of the zone, it is proton rich and decays by positron emission or electron capture.

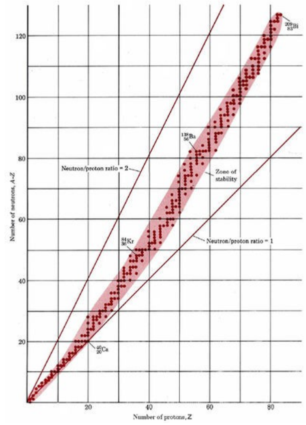


Figure 1 The number of neutrons plotted against the number of protons for all the stable nuclei. Note how the neutron/proton ratio increases for the heavier elements.

Another factor affecting the stability of a nucleus is whether the number of protons and neutrons is even or odd. Among the 354 known stable isotopes, 157 (almost half) have an even number of protons and an even number of neutrons. Only five have an odd number of both kinds of nucleons. In the universe as a whole (with the exception of hydrogen) we find that the even-numbered elements are almost always much more abundant than the odd-numbered elements close to them in the periodic table.

Finally there is a particular stability associated with nuclei in which either the number of protons or the number of neutrons is equal to one of the so-called "magic" numbers 2, 8, 20, 28, 50, 82, and 126. These numbers correspond to the filling of shells in the structure of the nucleus. These shells are similar in principle but different in detail to those found in electronic structure. Of particular stability, and also of high abundance in the universe, are nuclei in which both the-number of protons and the number of neutrons correspond to magic numbers. Examples are He, O, Ca, and Pb.

INSTABILITY OF NUCLEI AND BINDING ENERGY OF A NUCLEUS

A phenomenon concluded from empirical evidence. A model to explain this is based on the idea of nuclear shells. The number of protons and neutron in the nucleus. The nucleons fill up inside the nucleus in shells; each shell has a specific allotment of nucleons. Incomplete shell gives rise to instability.

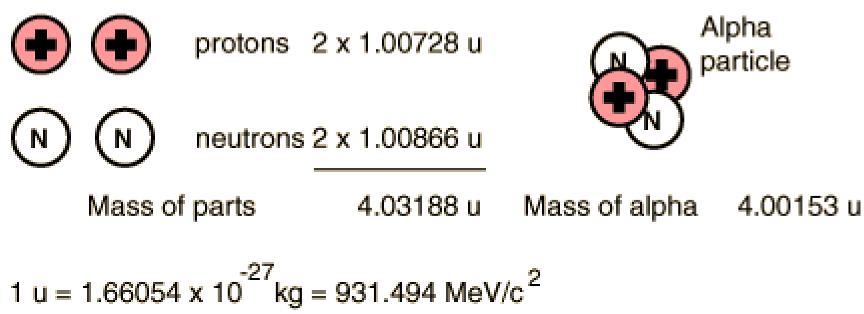
The number of nucleons also affects the stability and such numbers are called 'magic numbers', 2, 8, 20, 28, 50, 82, 126. There are nuclides which have doubled the magic number, called

'double magic'. Magic and Double Magic numbers are characterized by higher binding energies per nucleon for nuclides.
The mechanism of stability may be calculated by using Schrödinger's equation if the nuclear potential is known.

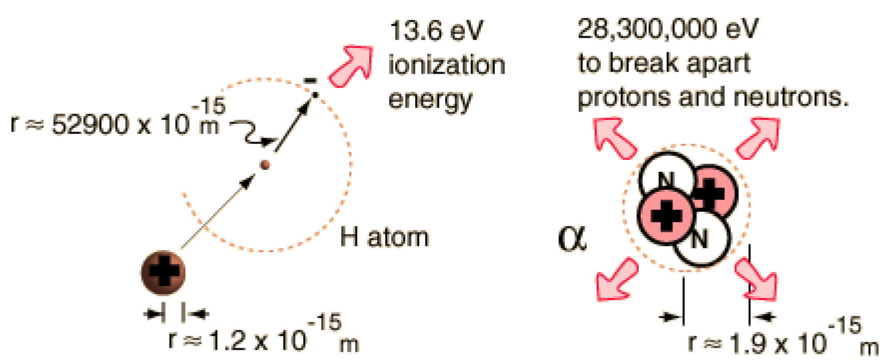
Nuclei are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it. The difference is a measure of the nuclear binding energy which holds the nucleus together. This binding energy can be calculated from the Einstein relationship:

Nuclear binding energy = Δmc^2

For the alpha particle Δm= 0.0304 u which gives a binding energy of 28.3 MeV.



The enormity of the nuclear binding energy can perhaps be better appreciated by comparing it to the binding energy of an electron in an atom. The comparison of the alpha particle binding energy with the binding energy of the electron in a hydrogen atom is shown below. The nuclear binding energies are on the order of a million times greater than the electron binding energies of atoms.



Comparison of atomic and nuclear scales and binding energy

SEMI-EMPIRICAL MASS FORMULA
The mass of a nucleus defined by *A* and *Z* is given by

$$M(A,Z) = Zm_H + (A-Z)m_n - B(A,Z)/c^2$$

The semi-empirical mass formula, based on the liquid drop model, considers five contributions to the binding energy:

The volume term $a_V A$. Since the nuclear force is saturated, each nucleon contributes about 16MeV to the binding of the nucleus.

The surface term, which gives the reduction in binding resulting from the reduced binding at the nuclear surface, $-a_S A^{2/3}$

The Coulomb term, which represents the Coulomb repulsion of the $Z(Z-1)/2$ pairs of protons in the nucleus. For a spherical nucleus of radius $R = r_0 A^{1/3}$ with the charge spread evenly throughout the sphere the Coulomb energy is

$$-\frac{3}{5}\frac{1}{[4\pi\epsilon_0]}\frac{Z(Z-1)e^2}{r_0 A^{1/3}}$$

For a general charge distribution not too different from the above, this can be parameterized as

$$-a_C\frac{Z^2}{A^{1/3}}$$

The asymmetry term, this accounts for the difference between proton and neutron number. If there were no Coulomb interaction between protons, we would expect, from symmetry arguments applied to a Fermi gas, to find equal numbers of protons and neutrons. In order to generate the observed neutron excess (in most nuclei) we need to shift nucleons from the `proton side' to the `neutron side' of these two Fermi gases. These neutrons can only be added above the Fermi level, so energy must be put into the system. This is the asymmetry energy which reduces the nuclear binding. Note that the system is symmetrical about $N=Z$; the same energy would be required to shift nucleons the other way if we require a proton excess. Thus to lowest order, we can expect the energy to vary as $(N-Z)^2$; in addition, the Fermi gas energy level spacing varies as $1/A$ so that the asymmetry term is

$$-a_A\frac{(N-Z)^2}{A} = -a_A\frac{(A-2Z)^2}{A}$$

An empirical term to take into account the observed pairing of nuclei:

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N \text{even} (A \text{even}) \\ 0 & A \text{odd} \\ -\delta_0 & Z, N \text{odd} (A \text{even}) \end{cases}$$

We note that of 342 (beta-) stable nuclei in the 1993 mass compilation, there are are 209 with even A, even Z; 70 with odd A, even Z; 59 with even A, odd Z and only 4 with odd A and Z (^{2}H, ^{6}Li, ^{10}B, ^{14}N. Clearly pairing enhances stability (or binding energy). This can also be seen, for instance, in the neutron separation energies of neighbouring isotopes, etc.

The binding energy is thus

NUCLEAR MASS AND CHARGE

$$B(A,Z) = a_V A - a_S A^{2/3} - a_A \frac{(A-2Z)^2}{A} - a_C \frac{Z^2}{A^{1/3}} + \delta(A,Z)$$

The coefficients are determined by fitting to a suitably large data set of masses (hence semi-empirical). A typical set is (all values in MeV):

$$a_V = 15.8 \quad a_S = 18.3$$
$$a_C = 0.714 \quad a_A = 23.2$$
$$\delta_0 = \frac{12}{A^{1/2}}$$

NATURE OF NUCLEAR FORCE

The nuclear force

The force that controls the motions of the atomic electrons is the electromagnetic force. To bind the nucleus together, however, there must be a strong attractive nuclear force of a totally different kind, strong enough to overcome the repulsive force of the positively charged nuclear protons and to bind both protons and neutrons into the tiny nuclear volume. The nuclear force must also be of short range because its influence does not extend very far beyond the nuclear "surface." The nuclear force is due to a strong force that binds quarks together to form neutrons and protons.

The Forces of Nature

Gravitational Force

The attractive force that binds the progressively growing galaxy together is the gravitational force. It's the force that not only holds you to the Earth but also reaches out across the vastness of intergalactic space. Although no two particles are every truly isolated, the following equation expresses the gravitational force between two objects of mass m_1 and m_2:

$$F = G\frac{m_1 m_2}{r^2}$$

(Newton's law of gravitation)

where G (the gravitational constant) = 6.67 X 10^{-11} Nm^2/kg^2 and r is the distance between the two objects.

Electromagnetic Force

Two electrons exert repellent electromagnetic forces on each other. At a deeper level, this interaction is described by a highly successful theory called quantum electrodynamics. From this point of view we say that each electron detects the presence of the other by exchanging virtual photons with it, the photon being the quantum of the electromagnetic field.

Weak Force

The weak force is a short-range force which is responsible for accounting for beta decay within the nucleus. The role of the weak interaction seems to be confined to causing beta decays in nuclei whose neutron/proton ratios are not appropriate for stability.

Strong Force

The theory of the strong force, that is, the force that acts between quarks, has also been developed. They are nuclear forces which are repulsive at very short range as well as being attractive at greater nucleon-nucleon distances. This keeps the nucleons in the nucleus packed together but not meshed together. There's no easy way to describe the theory behind this theory also known as the Meson theory of nuclear forces.

FORM OF NUCLEON-NUCLEON POTENTIAL

Two-nucleon systems such as the deuteron, the nucleus of a deuterium atom, as well as proton-proton or neutron-proton scattering are ideal for studying the *NN* force. Such systems can be described by attributing a potential (such as the Yukawa potential) to the nucleons and using the potentials in a Schrödinger equation. The form of the potential is derived phenomenologically, although for the long-range interaction, meson-exchange theories help to construct the potential. The parameters of the potential are determined by fitting to experimental data such as the deuteron binding energy or *NN* elastic scattering cross sections (or, equivalently in this context, so-called *NN* phase shifts).

The most widely used *NN* potentials are the Paris potential, the Argonne AV18 potential, the CD-Bonn potential and the Nijmegen potentials.

A more recent approach is to develop effective field theories for a consistent description of nucleon-nucleon and three-nucleon forces. In particular, chiral symmetry breaking can be analyzed in terms of an effective field theory (called chiral perturbation theory) which allows perturbative calculations of the interactions between nucleons with pions as exchange particles.

From nucleons to nuclei

The ultimate goal of nuclear physics would be to describe all nuclear interactions from the basic interactions between nucleons. This is called the microscopic or ab initio approaches of nuclear physics. There are two major obstacles to overcome before this dream can become reality:

Calculations in many-body systems are difficult and require advanced computation techniques.
There is evidence that three-nucleon forces (and possibly higher multi-particle interactions) play a significant role. This means that three-nucleon potentials must be included into the model.

This is an active area of research with ongoing advances in computational techniques leading to better first-principles calculations of the nuclear shell structure. Two- and three-nucleon potentials have been implemented for nuclear masses up to A=12.

Nuclear potentials

A successful way of describing nuclear interactions is to construct one potential for the whole nucleus instead of considering all its nucleon components. This is called the macroscopic approach. For example, scattering of neutrons from nuclei can be described by considering a plane wave in the potential of the nucleus, which comprises a real part and an imaginary part. This model is often called the optical model since it resembles the case of light scattered by an opaque glass sphere.

Nuclear potentials can be local or global: local potentials are limited to a narrow energy range and/or a narrow nuclear mass range, while global potentials, which have more parameters and are usually less accurate, are functions of the energy and the nuclear mass and can therefore, be used in a wider range of applications.

CHARGE INDEPENDENCE AND CHARGE SYMMETRY OF NUCLEAR FORCES

The nuclear force is only felt among hadrons. At small separations between nucleons (less than ~ 0.7 femtometer (fm) between their centers, depending upon spin alignment) the force becomes repulsive, which keeps the nucleons at a certain average separation, even if they are of different types. This repulsion is to be understood in terms of the Pauli exclusion force for identical nucleons (such as two neutrons or two protons), and also a Pauli exclusion between quarks of the same type within nucleons, when the nucleons are different (a proton and a neutron, for example). As will be discussed, the nuclear force also has a "tensor" component which depends on whether or not the spins of the nucleons are aligned or anti-aligned. A graph of internuclear forces and potentials is presented in the reference:

At distances larger than 0.7 fm the force becomes attractive between spin-aligned nucleons, becoming maximal at a center-center distance of about 0.9 fm. Beyond this distance the force drops essentially exponentially, until beyond about 2.0 fm separation, the force drops to negligibly small values.

At short distances (less than 1.7 fm or so), the nuclear force is stronger than the Coulomb force between protons; it thus overcomes the repulsion of protons inside the nucleus. However, the Coulomb force between protons has a much larger range due to its decay as the inverse square of charge separation, and Coulomb repulsion thus becomes the only significant force between protons when their separation exceeds about 2 to 2.5 fm.

To disassemble a nucleus into unbound protons and neutrons would require doing work against the nuclear force. Conversely, energy is released when a nucleus is created from other nucleons or nuclei: the nuclear binding energy. Because of mass–energy equivalence (i.e. Einstein's famous formula $E = mc^2$), releasing this energy causes the mass of the nucleus to be lower than the total mass of the individual nucleons, leading to the so-called "mass deficit".

The nuclear force is nearly independent of whether the nucleons are neutrons or protons. This property is called charge independence. It depends on whether the spins of the nucleons are parallel or antiparallel, and has a noncentral or tensor component. This part of the force does not conserve orbital angular momentum, which is a constant of motion under central forces.

Since nucleons have no color charge, the nuclear force does not directly involve the force carriers of quantum chromo dynamics, the gluons. However, just as electrically neutral atoms (each composed of cancelling charges) attract each other via the second-order effects of electrical polarization, via the van der Waals forces (London forces), so by analogy, "color-neutral" nucleons may attract each other by a type of polarization which allows some basically gluon-mediated effects to be carried from one color-neutral nucleon to another, via the virtual mesons which transmit the forces, and which themselves are held together by virtual gluons. It is this van der Waals-like nature which is responsible for the term "residual" in the term "residual strong force." The basic idea is that while the nucleons are "color-neutral," just as atoms are "charge-neutral," in both cases, polarization effects acting between near-by neutral particles allow a "residual" charge effect to cause net charge-mediated attraction between uncharged species, although it is necessarily of a much weaker and less direct nature than the basic forces which act internally within the particles.

GROUND STATE OF DEUTERIUM

Deuterium, also called heavy hydrogen, is one of two stable isotopes of hydrogen. It has a natural abundance in Earth's oceans of about one atom in 6,420 of hydrogen (~156.25 ppm on an atom basis). Deuterium accounts for approximately 0.0156% (or on a mass basis: 0.0312%) of all naturally occurring hydrogen in Earth's oceans, while the most common isotope (hydrogen-1 or protium) accounts for more than 99.98%. The abundance of deuterium changes slightly from one kind of natural water to another.

The nucleus of deuterium, called a deuteron, contains one proton and one neutron, whereas the far more common hydrogen isotope, protium, has no neutron in the nucleus. The deuterium isotope's name is formed from the Greek deuteros meaning "second", to denote the two particles composing the nucleus. Deuterium was discovered and named in 1931 by Harold Urey, earning him a Nobel Prize in 1934 after the discovery of the neutron in 1932 made the structure of deuterium obvious. Soon after deuterium's discovery, Urey and others produced samples of water in which deuterium has been highly concentrated with respect to protium, a substance popularly known as heavy water.

Because deuterium is destroyed in the interiors of stars faster than it is produced, and because other natural processes are thought to produce only an insignificant amount of deuterium, it is presently thought that nearly all deuterium found in nature was produced in the Big Bang 13.7 billion years ago, and that the basic or primordial ratio of hydrogen-1 (protium) to deuterium (about 26 atoms of deuterium per million hydrogen) has its origin from that time. This is the ratio found in the gas giant planets, such as Jupiter. However, different astronomical bodies are found to have different ratios of deuterium to hydrogen-1, and this is thought to be as a result of natural isotope separation processes that occur from solar heating of ices in comets. Like the water-cycle in Earth's weather, such heating processes may enrich deuterium with respect to protium. In fact, the discovery of deuterium/protium ratios in a number of comets very similar to the mean ratio in Earth's oceans has led to theories that much of Earth's ocean water has a cometary origin.

The deuteron wave function must be antisymmetric if the isospin representation is used (since a proton and a neutron are not identical particles, the wave function need not be antisymmetric in general). Apart from their isospin, the two nucleons also have spin and spatial distributions of their wave function. The latter is symmetric if the deuteron is symmetric under parity (i.e. have an "even" or "positive" parity), and antisymmetric if the deuteron is antisymmetric under parity (i.e. have an "odd" or "negative" parity). The parity is fully determined by the total orbital angular momentum of the two nucleons: if it is even then the parity is even (positive), and if it is odd then the parity is odd (negative).

The deuteron, being an isospin singlet, is antisymmetric under nucleons exchange due to isospin, and therefore must be symmetric under the double exchange of their spin and location. Therefore it can be in either of the following two different states:

Symmetric spin and symmetric under parity. In this case, the exchange of the two nucleons will multiply the deuterium wave function by (−1) from isospin exchange, (+1) from spin exchange and (+1) from parity (location exchange), for a total of (−1) as needed for antisymmetry.

Antisymmetric spin and antisymmetric under parity. In this case, the exchange of the two nucleons will multiply the deuterium wave function by (−1) from isospin exchange, (−1) from spin exchange and (−1) from parity (location exchange), again for a total of (−1) as needed for antisymmetry.

In the first case the deuteron is a spin triplet, so that its total spin s is 1. It also has an even parity and therefore even orbital angular momentum l ; The lower its orbital angular momentum, the lower its energy. Therefore the lowest possible energy state has $s = 1$, $l = 0$.

In the second case the deuteron is a spin singlet, so that its total spin s is 0. It also has an odd parity and therefore odd orbital angular momentum l. Therefore the lowest possible energy state has $s = 0$, $l = 1$.

Since $s = 1$ gives a stronger nuclear attraction, the deuterium ground state is in the $s = 1$, $l = 0$ state.

The same considerations lead to the possible states of an isospin triplet having $s = 0$, $l =$ even or $s = 1$, $l =$ odd. Thus the state of lowest energy has $s = 1$, $l = 1$, higher than that of the isospin singlet.

The analysis just given is in fact only approximate, both because isospin is not an exact symmetry, and more importantly because the strong nuclear interaction between the two nucleons is related to angular momentum in spin-orbit interaction that mixes different s and l states. That is, s and l are not constant in time (they do not commute with the Hamiltonian), and over time a state such as $s = 1$, $l = 0$ may become a state of $s = 1$, $l = 2$. Parity is still constant in time so these do not mix with odd l states (such as $s = 0$, $l = 1$). Therefore the quantum state of the deuterium is a superposition (a linear combination) of the $s = 1$, $l = 0$ state and the $s = 1$, $l = 2$ state, even though the first component is much bigger. Since the total angular momentum j is also a good quantum number (it is a constant in time), both components must have the same j, and therefore $j = 1$. This is the total spin of the deuterium nucleus.

To summarize, the deuterium nucleus is antisymmetric in terms of isospin, and has spin 1 and even (+1) parity. The relative angular momentum of its nucleons l is not well defined, and the deuteron is a superposition of mostly $l = 0$ with some $l = 2$.

SPIN STATES

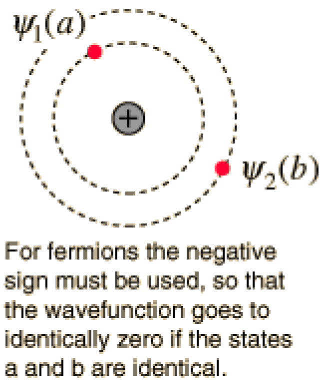
Deuterium is one of only four stable nuclides with an odd number of protons and odd number of neutrons. (2H, 6Li, 10B, 14N; also, the long-lived radioactive nuclides 40K, 50V, 138La, 180mTa occur naturally.) Most odd-odd nuclei are unstable with respect to beta decay, because the decay products are even-even, and are therefore more strongly bound, due to nuclear pairing effects. Deuterium, however, benefits from having its proton and neutron coupled to a spin-1 state, which gives a stronger nuclear attraction; the corresponding spin-1 state does not exist in the two-neutron or two-proton system, due to the Pauli exclusion principle which would require one or the other identical particle with the same spin to have some other different quantum number, such as orbital angular momentum. But orbital angular momentum of either particle gives a lower binding energy for the system, primarily due to increasing distance of the particles in the steep gradient of the nuclear force. In both cases, this causes the diproton and dineutron nucleus to be unstable.

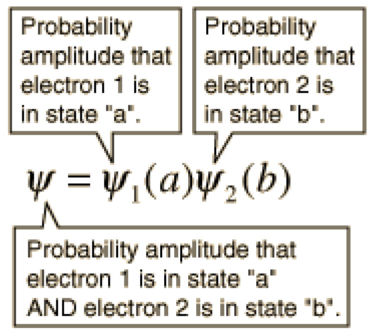
The proton and neutron making up deuterium can be dissociated through neutral current interactions with neutrinos. The cross section for this interaction is comparatively large, and deuterium was successfully used as a neutrino target in the Sudbury Neutrino Observatory experiment.

PAULI'S EXCLUSION PRINCIPLE

No two electrons in an atom can have identical quantum numbers. This is an example of a general principle which applies not only to electrons but also to other particles of half-integer spin (fermions). It does not apply to particles of integer spin (bosons).

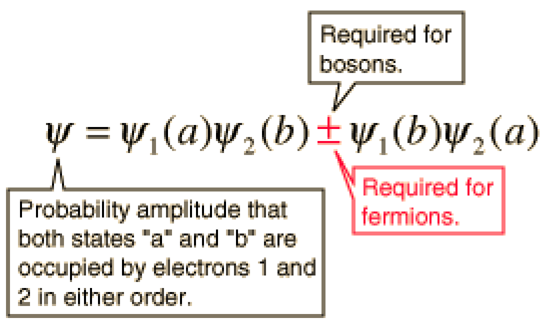
The nature of the Pauli exclusion principle can be illustrated by supposing that electrons 1 and 2 are in states a and b respectively. The wave function for the two electron system would be





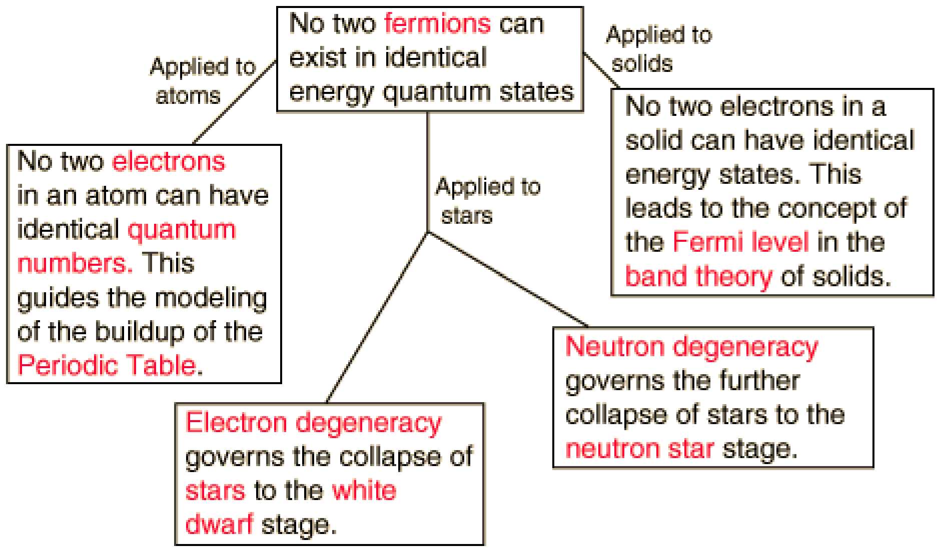
but this wave function is unacceptable because the electrons are identical and indistinguishable. To account for this we must use a linear combination of the two possibilities since the determination of which electron is in which state is not possible to determine.

The wave function for the state in which both states "a" and "b" are occupied by the electrons can be written



The Pauli exclusion principle is part of one of our most basic observations of nature: particles of half-integer spin must have antisymmetric wave functions, and particles of integer spin must have symmetric wave functions. The minus sign in the above relationship forces the wave function to vanish identically if both states are "a" or "b", implying that it is impossible for both electrons to occupy the same state.

APPLICATIONS



TENSOR FORCE

A spin-dependent force between nucleons, having the same form as the interaction between magnetic dipoles; it is introduced to account for the observed values of the magnetic dipole moment and electric quadrupole moment of the deuteron.

EXCHANGE FORCE

All four of the fundamental forces involve the exchange of one or more particles. Even the underlying colour force which is presumed to hold the quarks together to make up the range of observed particles involves an exchange of particles labeled gluons.

Such exchange forces may be either attractive or repulsive, but are limited in range by the nature of the exchange force. The maximum range of an exchange force is dictated by the uncertainty principle since the particles involved are created and exist only in the exchange process - they are called "virtual" particles. Such exchange forces are often pictured with Feynman diagrams.

Questions:

1. Write a note on masses of nuclei.
2. Explain the sizes of nuclei.
3. Write a note on nuclear spins of nuclei.
4. Explain binding energy of a nucleus.
5. Discuss semi-empirical mass formula.
6. Explain the nature of nuclear force.
7. Write a note on charge independence and charge symmetry of nuclear forces.
8. Explain the wave mechanics of ground state of deuterium.
9. Explain Pauli's exclusion principle.

10. Write a short note on (i) Tensor force and (ii) Exchange force.

KARPAGAM ACADEMY OF HIGHER EI
DEPARTMENT OF I
CLASS:I MSC PHYSICS
NUCLEAR PHYSICS (
MULIPLE CHOICE Q
UNIT -I

QUESTIONS

The atomic number is equivalent to which of the following?
The atomic mass number is equivalent to which of the following?
Which of the following particles has the smallest mass?
Which of the following statements about the mass of an atom is true?
Neutrons has the charge
Which of the following is correct for the number of neutrons in the nucleus?
What law did Ernest Rutherford use to estimate the size of the nucleus?
Why are nuclear energy levels more complex than electron energy levels?
Which of the following about the nuclear force is true?
Isotopes of an element:
Binding energy is:
When nucleons form a stable nucleus, binding energy is:
An isotope with a high Binding Energy per nucleon:
Why do heavier nuclei have a greater ratio of neutrons to protons than lighter nuclei?
The fact that the binding energy per nucleon is roughly a constant over most of the range of stable nuclei is a
Nucleus "a" contains 5 protons and 5 neutrons and has radius R. The radius of nucleus "b", which contains 3
The particles which can be added to the nucleus of an atom without changing its chemical properties are call
The mass number of a nucleus is
Barlett forces is
Forces involved in proton-proton scattering is
Which one of the following hypothesis supports the charge independence of nuclear forces?
Which of the following is in the increasing order for the stability of nucleus
The energy equivalent of 1 a.m.u. is
Nucleus contains protons and neutrons. The electrons revolve around the nucleus. For atoms of small mass, t
Stability of atomic nucleus is not influence by
In stable nuclides up to Z=20, the n/p ratio=
The asymmetry terms in the Weizsacker semi-empirical formula is because of
The size of the nucleus cannot be determined by
The relative strength of the gravitational coulomb’s and nuclear forces are
Which of the following statements is in correct for the nuclear force between two nucleon
Isotopic spin of the nuclear ground state for deuteron
At the peaks of the nuclear binding energy curve
A deuteron spends
The average energy required to extract one nucleon from the nucleus is called
According to Yukawa theory, the nuclear forces between the nucleons act through the existence of
A deuteron
Nuclei with the same mass number A, but different atomic number Z, are called
Isotopes are nuclei with the same atomic number Z but different
Nuclei, with an equal number of neutrons are called
The atoms, which have the same Z and same A but are distinguished by their different life times are called

Nuclei, having the same mass number A, but with the proton and neutron number interchanged are called
Dimension of nucleus is of the order of 1 Fermi. With what velocity should electrons move so that it is found
The charge symmetry of the nuclear force is given by
A tensor force is capable of explaining the deuteron
Majorana force is
Heisenberg force is
Heisenberg's idea of exchange forces are useful in explaining the
The coulomb repulsion term which contributes to the binding energy of a nucleus AXZ is proportional to
In the nucleus the forces exist between nucleons, called
Nuclear forces are non-central forces and are
Existence of an electric quadrupole moment in deuteron indicates that non-central type of forces are called
Stability of atomic nucleus is not influence by
Proton has the charge
The nucleus consists of
Nucleus is
An unknown chemical element is presented by the following formula: $_{Z}X^{A}$. What is the name of index Z?
An unknown chemical element is presented by the following formula: $_{Z}X^{A}$. What is the name of index A?
How many electrons are in the $_{6}C^{12}$ atom?
How many nucleons are in the $_{10}Ne^{20}$ atom?
How many neutrons are in the $_{11}Na^{23}$ atom?
How many protons are in the $_{7}N^{14}$ atom?
Low energy nucleon-nucleon scattering involves only
A nucleus with A=235 splits into two new nuclei whose mass numbers are in the ratio 2:1. Then the radii of ı
Rest mass of proton is
The size of the nucleus cannot be determined by
The ratio of the sizes of $_{82}Pb^{209}$ and $_{12}Mg^{26}$ nuclei is approx.
Calculate the mass defect of 235U. The mass of U-235 is 235.0439 AMU.

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PHYSICS

(18PHP203)
UESTIONS

opt1	opt2	opt3	opt4	opt5	opt6	answer
The numb	The numb	The numb	The number of α–particles in th			The number of protons in the at
The numb	The numb	The numb	The number of α–particles in th			The number of nucleons in the a
Proton	Electron	Neutron	Nucleus			Electron
It is evenl	It is evenl	It is conce	It is concentrated in the nucleus			It is concentrated in the nucleus
1639 time	1739 time	1839 time	1939 times of an electron			1839 times of an electron
N = A –Z	N = Z – A	N=Z +A	N = Z			N = A –Z
Conservat	Conservat	Conservat	Conservation of energy			Conservation of energy
Nuclear en	Nuclear en	Nuclear en	Electron energy levels depend o			Nuclear energy levels depend on
It is an att	It is an att	It is much	It is a strong, short-range, attrac			It is a strong, short-range, attrac
have the s	have the s	have diffe	have different number of electro			have the same number of proton
the amoun	the amoun	the amoun	the amount of energy released w			the amount of energy required to
created fro	destroyed	transform	released as high energy photons			released as high energy photons
will decay	is very un	is very sta	has very few electrons			is very stable
to add mo	to provide	to provide	to provide more attractive strong			to provide more attractive strong
short rang	long range	weak	strong			short range
8R	R	2R	1.4R			2R
Electrons	Neutrons	Protons	None of the above			Neutrons
Always le	Always eq	Always m	Sometimes more than & someti			Sometimes more than & someti
The excha	The excha	An exchan	None of the above			The exchange of the spin coordi
Nuclear fo	Coulomb r	Nuclear as	Electromagnetic forces			Nuclear as well as coulomb repu
The nucle	The nucle	The nucle	None of the above			The nuclear forces between n-p,
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
933.17Me	93.3 MeV	9331MeV	None of these			933.17MeV
p=n=e	p=e=n	p=e=n	n=p-1=e			p=e=n
Mass defe	Binding en	Neutron-p	Ionisation potential			Ionisation potential
1	>1	<1	None of these			1
Non-spher	Non-zero	Unequal n	Odd number of protons inside th			Unequal number of protons and
Electron s	Energy lev	Excited st	By selecting the probe using co			Excited state energy of the isoto
Fg :Fe:Fn=	Fg :Fe:Fn=	Fg :Fe:Fn=	none of these			Fg :Fe:Fn=1:10^36:10^38
it is charge	it is spin d	it is veloci	it is independent of non –centra			it is independent of non –central
1	0	½	-0.5			0
Z is even l	Z is odd a	Both Z an	Both Z and N are even			Both Z and N are even
96% time	96% time	92% time	92% time in S state and 8% tim			96% time in S state and 4% tim
Bonding e	Bonding e	Bonding e	none of these			Bonding energy per nucleon
Positron	µ-meson	K-meson	π-meson			π-meson
Cannot be	Can be dis	Can be dis	Can be disintegrated by photon			Can be disintegrated by photon
Isotopes	isobars	isomers	isotones			Isotopes
Neutron n	Proton nu	mass numb	none of these			mass number
isobars	isotones	isomers	Isotopes			isotones
Isotopes	isotones	isomers	isobars			isomers

Isobars	isotones	Mirror nu	isomers	Mirror nuclei
7*10^11 n	3*10^8 m/	6*10^8 m/	$1.5*10^8$ m/s	7*10^11 m/s
(n-p)= (n-1	(n-p) = (p-	(n-n) = (p-	(n-n) ≠ (p-p)	(n-n) = (p-p)
Quadrupo	Dipole mc	Octupole 1	Monopole	Quadrupole moment
The excha	The excha	An exchar	None of the above	The exchange of the space coor
The excha	An exchar	The excha	None of the above	An exchange of both the positio
Short rang	Charge in	Charge sy	Saturation of nuclear forces	Saturation of nuclear forces
Z	2Z	Z(Z-1)	It is independent of Z	Z(Z-1)
Coulomb'	Nuclear fc	Atomic fo	Nucleons force	Nuclear force
Spin indep	Spin deper	Both (a) a	None of these	Spin dependent
Tensor fo	Nuclear fc	Proton for	Deuteron forces	Tensor forces
Mass defe	Binding er	Neutron-p	Ionisation potential	Ionisation potential
1637 time	1737 time	1837 time	1937 times of an electron	1837 times of an electron
Neutrons	Protons	neutrons a	electrons and neutrons	neutrons and protons
positively	negatively	neutral	charge keeps on changing	positively charged
Atomic ma	Atomic nu	Principle	Orbital quantum number	Atomic number
Atomic ma	Atomic nu	Principle	Orbital quantum number	Atomic mass number
12	6	18	3	6
12	30	18	20	20
12	11	18	24	12
14	6	7	10	7
l = 0	l = 1,2,3	l = 0,1,2,3	l = 1, S=1	l = 0
5.99fm,7.5	6.99fm, 8.	2.3fm,4.5	none of these	5.99fm,7.55fm
1.6725 ×1	1.6725 ×1	1.6725 ×1	None of these	1.6725 ×10-27kg
Electron s	Energy lev	Excited st	By selecting the probe using co	Excited state energy of the isoto
2	4	8	16	2
1.91392 A	0.19132A	0	-1.9132AMU	1.91392 AMU

om
ıtom

ı attractive and repulsive forces
tive force between the nucleons
ıs and electrons, but a different number of neutrons
ɔ break a nucleus apart into protons and neutrons
or particles

g nuclear force to balance the repulsive electromagnetic force

nes equal to its atomic number
nates
ılsive forces
, n-n and p-p are equal

neutrons inside the nucleus
ɔpic spin multiplet

l component

e in D state

of minimum energy 2.22MeV

dinates
n and the spin coordinates

pic spin multiplet

NUCLEAR MODEL

Objectives:
The main objective of this unit is to give attention to different nuclear models viz. liquid drop model, shell model, collective model and optical model.

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

NUCLEAR MODELS
LIQUID DROP MODEL
Introduction

Scattering experiments suggest that nuclei have approximately constant density, so that the nuclear radius can be calculated by using that density as if the nucleus were a drop of a uniform liquid. A liquid drop model of the nucleus would take into account the fact that the forces on the nucleons on the surface is different from those on nucleons on the interior where they are completely surrounded by other attracting nucleons. This is something similar to taking account of surface tension as a contributor to the energy of a tiny liquid drop. The volume of the liquid drop is proportional to the mass number A, and the surface would then be proportional to the two-thirds power of A.

The first step toward a liquid drop model of the nucleus would then be to postulate a volume term and a surface term in the form:

$$E_b \approx \underbrace{C_1 A}_{\text{Volume term}} \underbrace{- C_2 A^{2/3}}_{\text{Surface term}}$$

This simple model in fact gives a reasonable approximation of the variation of nuclear binding energy with mass number when the constants have the values

$$C_1 = 15.75 MeV, \quad C_2 = 17.8 MeV$$

Another contribution to the binding energy would be the coulomb repulsion of the protons, so there should be a negative term proportional to the square of the atomic number Z :

$$\Delta E_b^{Coulomb} \approx \frac{-(0.711 MeV)Z^2}{A^{1/3}}$$

The Pauli principle favors nuclei in which A=2Z, so the empirical model of binding energy contains a term of the form

$$\Delta E_b^{Pauli} \approx \frac{-(23.7MeV)(A-2Z)^2}{A}$$

The Pauli principle also favours nuclear configurations with even numbers of neutrons and protons. In the liquid drop model, this is included by using the even-odd nucleus as a reference and adding a correction term which is positive for even-even nuclei and negative for odd-odd nuclei. This strategy for modeling the nuclear binding energy is attributed to Weizsacker and called the Weizsacker formula.

WEIZSACKER'S SEMI-EMPIRICAL MASS FORMULA

The Weizsaecker formula is an empirically refined form of the liquid drop model for the binding energy of nuclei. It is also referred to as the "semi-empirical mass formula" and the "Bethe-Weizaecker formula". Expressed in terms of the mass number A and the atomic number Z for an even-odd nucleus, the Weizsaecker formula is

$$E_b^{even-odd} \approx \underbrace{(15.75MeV)A}_{Volume\ term} - \underbrace{(17.8MeV)A^{2/3}}_{Surface\ term} - \underbrace{\frac{(0.711MeV)Z^2}{A^{1/3}}}_{Coulomb\ term} - \underbrace{\frac{(23.7MeV)(A-2Z)^2}{A}}_{Pauli\ term}$$

Using the even-odd as a reference, there are then correction terms for even-even and odd-odd nuclei, the even-even groupings of protons and neutrons being favored in stability.

$$E_b^{even-even} \approx E_b^{even-odd} + \frac{11.18MeV}{\sqrt{A}}$$

$$E_b^{odd-odd} \approx E_b^{even-odd} - \frac{11.18MeV}{\sqrt{A}}$$

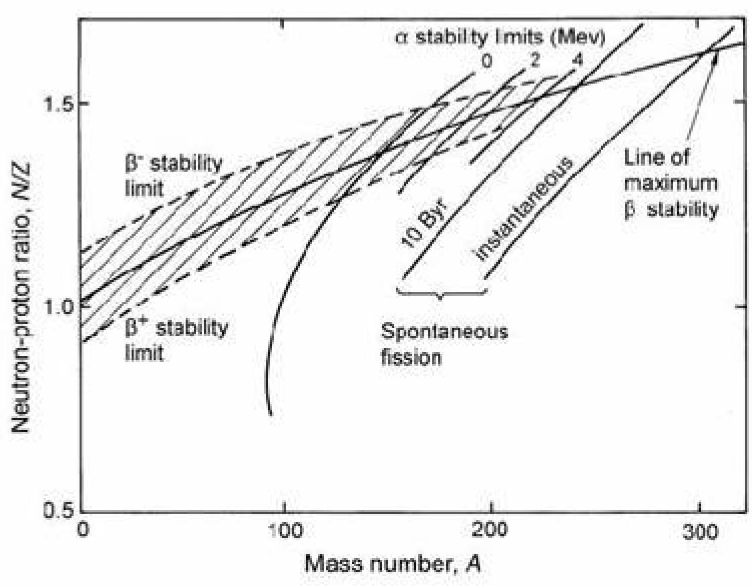
Top of Form

An estimate of nuclear binding energy can then be obtained by first applying the even-odd formula.

STABILITY LIMITS AGAINST SPONTANEOUS FISSION

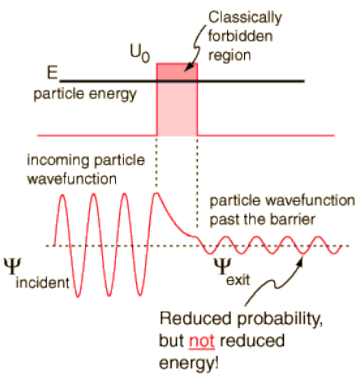
Nuclear stability and decay are best understood in the context of the chart of nuclides. It has already been noted that naturally occurring nuclides define a path in the chart of the nuclides, corresponding to the greatest stability of proton/neutron ratio. For nuclides of low atomic mass, the greatest stability is achieved when the number of neutrons and protons are approximately equal ($N = Z$) but as atomic mass increases, the stable neutron/proton ratio increases until $N/Z = 1.5$. Theoretical stability limits are illustrated on a plot of N/Z against mass number (A) in Fig. below.

The path of stability is in fact an energy 'valley' into which the surrounding unstable nuclides tend to fall, emitting particles and energy. This constitutes the process of radioactive decay. The nature of particles emitted depends on the location of the unstable nuclide relative to the energy valley. Unstable nuclides on either side of the valley usually decay by 'isobaric' processes. That is, a nuclear proton is converted to a neutron, or vice-versa, but the mass of the nuclide does not change significantly (except for the 'mass defect' consumed as nuclear binding energy). In contrast, unstable nuclides at the high end of the energy valley often decay by emission of a heavy particle (e.g. a " particle), thus reducing the overall mass of the nuclide.



Theoretical stability limits of nuclides illustrated on a plot of *N*/*Z* against mass number (*A*). Lower limits for "emission are shown for" energies of 0, 2 and 4 MeV. Stability limits against spontaneous fission are shown for half-lives of 10^{10} yr and zero (instantaneous fission).

BARRIER PENETRATION



According to classical physics, a particle of energy E less than the height U_0 of a barrier could not penetrate - the region inside the barrier is classically forbidden. But the wave function associated with a free particle must be continuous at the barrier and will show an exponential decay inside the barrier. The wave function must also be continuous on the far side of the barrier, so there is a finite probability that the particle will tunnel through the barrier.

As a particle approaches the barrier, it is described by a free particle wave function. When it reaches the barrier, it must satisfy the Schrodinger equation in the form

$$\frac{-\hbar^2}{2m}\frac{\partial^2\Psi(x)}{\partial x^2} = (E-U_0)\Psi(x)$$

Which has the solution

$$\Psi = Ae^{-\alpha x} \text{ where } \alpha = \sqrt{\frac{2m(U_0-E)}{\hbar^2}}$$

Note that in addition to the mass and energy of the particle, there is a dependence on the fundamental physical constant Planck's constant h. Planck's constant appears in the Planck hypothesis where it scales the quantum energy of photons, and it appears in atomic energy levels which are calculated using the Schrodinger equation.

DECAY PROBABILITIES FOR SPONTANEOUS FISSION

Spontaneous fission (SF) is a form of radioactive decay that is found only in very heavy chemical elements. Because the nuclear binding energy of the elements reaches its maximum at anatomic mass number greater than about 58 atomic mass units (u), spontaneous breakdown into smaller nuclei and a few isolated nuclear particles becomes possible at heavier masses.

Because of the constraints in forming the daughter fission-product nuclei, spontaneous fission into known nuclides becomes theoretically possible (that is, energetically possible) for some atomic nuclei with atomic masses greater than 92 atomic mass units (a.m.u.), with the probability of spontaneous fission increasing as the atomic mass number increases above this value.

The lightest natural nuclides that are hypothetically subject to spontaneous fission are niobium-93 and molybdenum-94 (elements #41 and #42, respectively). Spontaneous fission has never been observed in the naturally-occurring isotopes of these elements, however. In practice, these are stable isotopes.

Spontaneous fission is feasible over practical observation times only for atomic masses of 232 a.m.u. or more. These are elements at least as heavy as thorium-232 – which has a half-life somewhat longer than the age of the Universe. Thorium-232 is the lightest primordial nuclide that has left evidence of undergoing spontaneous fission in its minerals.

The known elements most susceptible to spontaneous fission are the synthetic high-atomic-number actinide elements with odd atomic numbers: mendelevium and lawrencium, and also some of the the transactinide very-heavy elements, such as rutherfordium.

For naturally occurring thorium, uranium-235, and uranium-238, spontaneous fission does occur rarely, but in the vast majority of the radioactive decay of these atoms, alpha decay or beta decayoccurs instead. Hence, the spontaneous fission of these isotopes is usually negligible, except in using the exact branching ratios when finding the radioactivity of a sample of these elements.

Mathematically, the criterion for whether spontaneous fission can occur in a time short enough to be observed by present methods is approximately:

$$Z^2/A \geq 47.$$

where Z is the atomic number and A is the mass number (e.g., 235 for U-235).

As the name suggests, spontaneous fission gives much the same result as induced nuclear fission. However, like other forms of radioactive decay, it occurs due to quantum tunneling, without the atom having been struck by a neutron or other particle as in induced nuclear fission. Spontaneous fissions release neutrons as all fissions do, so if a critical mass is present, a spontaneous fission can initiate a self-sustaining chain reaction. Also, radioisotopes for which spontaneous fission is not negligible can be used as neutron sources. For example, californium-252 (half-life 2.645 years, SF branch ratio about 3.1 percent) can be used for this purpose. The neutrons released can be used to inspect airline luggage for hidden explosives; to gauge the moisture content of soil in highway and building and construction; or to measure the moisture of materials stored in silos, for example.

As long as the spontaneous fission gives a negligible reduction of the number of nuclei that can undergo such fission, this process can be approximated closely as a Poisson process. In this situation, for short time intervals the probability of a spontaneous fission is directly proportional to the length of time.

The spontaneous fission of uranium-238 and uranium-235 does leave trails of damage in the crystal structure of uranium-containing minerals when the fission fragments recoil through them. These trails, or fission tracks, are the foundation of the radiometric dating method called fission track dating.

Spontaneous fission rates

Nuclide	Half-life	Fission prob. per decay	Neutrons per fission	Neutrons per (g.s)
^{235}U	7.04×10^{8} years	7.0×10^{-11}	1.86	1.0×10^{-5}
^{238}U	4.47×10^{9} years	5.4×10^{-7}	2.07	0.0136
^{239}Pu	2.41×10^{4} years	4.4×10^{-12}	2.16	2.2×10^{-2}
^{240}Pu	6569 years	5.0×10^{-8}	2.21	920
^{250}Cm	8300 years	0.80	?	?
^{252}Cf	2.638 years	3.09×10^{-2}	3.73	2.3×10^{12}

In practice ^{239}Pu will invariably contain a certain amount of ^{240}Pu due to the tendency of ^{239}Pu to absorb an additional neutron during production. ^{240}Pu's high rate of spontaneous fission events makes it an undesirable contaminant. Weapons-grade plutonium contains no more than 7.0% ^{240}Pu.

The rarely-used gun-type atomic bomb has a critical insertion time of about one millisecond, and the probability of fission during this time interval should be small. Therefore only ^{235}U is suitable. Almost all nuclear bombs use some kind of implosion method.

Spontaneous fission can occur much more rapidly when the nucleus of an atom undergoes super deformation.

NUCLEON EMISSION

A decay mechanism in which a particularly unstable nuclide regains some stability by the emission of a nucleon (i.e. a proton or neutron). Proton emitters have fewer neutrons than their stable isotopes. Proton emitters are therefore found below the Segrè plot stability line. For example, ^{17}Ne (neon–17) has three fewer neutrons than its most abundant stable isotope ^{20}Ne (neon–20). There are no naturally occurring proton emitters. Neutron emitters have many more neutrons than their stable isotopes. For this reason, emitters may be found above the stability line on the Segrè plot and in most cases can also decay by negative beta decay. There are no naturally occurring neutron emitters. They are usually produced in nuclear reactors by the negative beta decay of fission products. An example of a neutron emitter is ^{99}Y (yttrium–99), which has 10 more neutrons than the stable isotope ^{89}Y (yttrium–89).

SHELL MODEL

Introduction

In nuclear physics and nuclear chemistry, the nuclear shell model is a model of the atomic nucleus which uses the Pauli exclusion principle to describe the structure of the nucleus in terms of energy levels. The first shell model was proposed by Dmitry Ivanenko (together with E. Gapon) in 1932. The model was developed in 1949 following independent work by several physicists, most notably Eugene Paul Wigner, Maria Goeppert-Mayer and J. Hans D. Jensen, who shared the 1963 Nobel Prize in Physics for their contributions.

The shell model is partly analogous to the atomic shell model which describes the arrangement of electrons in an atom, in that a filled shell results in greater stability. When adding nucleons (protons or neutrons) to a nucleus, there are certain points where the binding energy of the next nucleon is significantly less than the last one. This observation, that there are certain magic numbers of nucleons: 2, 8, 20, 28, 50, 82, 126 which are more tightly bound than the next higher number, is the origin of the shell model.

Note that the shells exist for both protons and neutrons individually, so that we can speak of "magic nuclei" where one nucleon type is at a magic number, and "doubly magic nuclei", where both are. Due to some variations in orbital filling, the upper magic numbers are 126 and, speculatively, 184 for neutrons but only 114 for protons, playing a role in the search of the so-called island of stability. There have been found some semi magic numbers, notably Z=40. 16 may also be a magic number.

In order to get these numbers, the nuclear shell model starts from an average potential with a shape something between the square well and the harmonic oscillator. To this potential a spin orbit term is added. Even so, the total perturbation does not coincide with experiment and an empirical spin orbit coupling, named the Nilsson Term, and must be added with at least two or three different values of its coupling constant, depending on the nuclei being studied.

Nevertheless, the magic numbers of nucleons, as well as other properties, can be arrived at by approximating the model with a three-dimensional harmonic oscillator plus a spin-orbit interaction. A more realistic but also complicated potential is known as Woods Saxon potential.

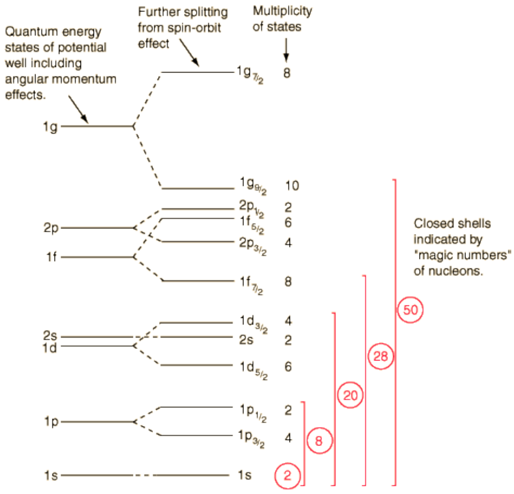
Igal Talmi developed a method to obtain the information from experimental data and use it to calculate and predict energies which have not been measured. This method has been successfully used by many nuclear physicists and has led to deeper understanding of nuclear structure. The theory which gives a good description of these properties was developed. This description turned out to furnish the shell model basis of the elegant and successful Interacting boson model.

THE EVIDENCE THAT LED TO THE SHELL MODEL

Visualizing the densely packed nucleus in terms of orbits and shells seems much less plausible than the corresponding shell model for atomic electrons. You can easily believe that an atomic electron can complete many orbits without running into anything, but you expect protons and neutrons in a nucleus to be in a continuous process of collision with each other. But dense-gas type models of nuclei with multiple collisions between particles didn't fit the data and remarkable patterns like the "magic numbers" in the stability of nuclei suggested the seemingly improbable shell structure.

With the enormous strong force acting between them and with so many nucleons to collide with, how can nucleons possibly complete whole orbits without interacting? This has the marks of a Pauli Exclusion Principle process, where two fermions cannot occupy the same quantum state. If there are no nearby, unfilled quantum states that are in reach of the available energy for an interaction, then the interaction will not occur. This is a essentially quantum idea - if there is not an available "hole" for a collision to knock a nucleon into, then the collision will not occur. There is no classical analog to this situation.

The evidence for a kind of shell structure and a limited number of allowed energy states suggests that a nucleon moves in some kind of effective potential well created by the forces of all the other nucleons. This leads to energy quantization in a manner similar to the square well and harmonic oscillator potentials. Since the details of the well determine the energies, much effort has gone into construction of potential wells for the modeling of the observed nuclear energy levels. Solving for the energies from such potentials gives a series of energy levels like that at left below. The labels on the levels are somewhat different from the corresponding symbols for atomic energy levels. The energy levels increase with orbital angular momentum quantum number l, and the s, p, d, f... symbols are used for l=0,1,2,3... just like the atomic case. But there is really no physical analog to the principal quantum number n, so the numbers associated with the level just start at n=1 for the lowest level associated with a given orbital quantum number, giving such symbols as 1g which could not occur in the atomic labeling scheme. The quantum number for orbital angular momentum is not limited to n as in the atomic case.



In addition to the dependence on the details of the potential well and the orbital quantum number, there is a sizable spin-orbit interaction which splits the levels by an amount which increases with orbital quantum number. This leads to the overlapping levels as shown in the illustration. The subscript indicates the value of the total angular momentum j, and the multiplicity of the state is 2j + 1. The contribution of a proton to the energy is somewhat different from that of a neutron because of the coulomb repulsion, but it makes little difference in the appearance of the set of energy levels.

With this set of identified nuclear states and the magic numbers, we can predict the net nuclear spin of a nucleus and represent its nuclear state by based on the identification of the level of the odd nucleon in the order of states shown above. The parity of the state can also be predicted, so the single particle shell model has shown itself to be of significant benefit in characterizing nuclei.

MAIN ASSUMPTIONS OF THE SINGLE-PARTICLE SHELL MODEL

In the extreme single particle model, one assumes that the ground state of an odd-A nucleus is determined by the quantum numbers of the odd nucleon after the A-1 other nucleons have coupled to spin 0. Thus, ^{40}Ca with 20 protons and 20 neutrons would have all its nucleons paired and the I^p should be 0^+. Indeed, the table in the back of Krane reports the experimental I^p is 0^+. By looking at the level predictions one would expect the next neutron to go into the $f_{7/2}$ level and hence, she would expect the I^p of ^{41}Ca to be $7/2^-$. Likewise, since the last level filling before N = 20 was the $d_{3/2}$ level, we would expect the ground state of ^{39}Ca to have an of $3/2^+$. A glimpse in the appendix shows that these expectations are satisfied by experimental values. Another point of interest is the presence of two excited states in ^{41}Ca at an energy of about 2 MeV which have $I^p$of $3/2^+$ and $3/2^-$. These first of these states is produced by raising one neutron from the $d_{3/2}$ state to form a pair in the $f_{7/2}$ level but leaving an unpaired neutron in the $d_{3/2}$ state. The second is produced by raising the odd neutron from the $f_{7/2}$ level to the $p_{3/2}$ level. These data indicate that the energy gap between the $d_{3/2}$ state and the $f_{7/2}$ level is about 2 MeV, and the gap between the $f_{7/2}$ and $p_{3/2}$ level is similar.(To be precise we would need to consider the difference in the pairing energy for two neutrons in the f and d states.) Such observations seem to justify the shell model approach for nuclei near the closed shells.

The magnetic moment of a nucleon in an orbit has orbital and intrinsic parts. The total moment is predicted to be different for $j = l + 1/2$ and $j = l - 1/2$ levels because of the difference in coupling of the orbital and spin parts. The single-particle predictions are shown as solid lines in Fig. 5.9, page 127 and are called Schmidt limits. It is noted that most of the measured magnetic moments are smaller than the Schmidt limits. Recalling that the intrinsic

component of the magnetic moment depends on the charge and current distributions within the nucleon. We conclude that when other nucleons are present, the charge distribution of the interacting nucleons is affected, thus changing the intrinsic moment when the nucleon is bound to other nucleons to form a nucleus. If one reduces the g_s for bound nucleons to be 0.6 of the g_s for free nucleons, then the Schmidt predictions are the dashed lines, which do indeed kind of trace the experimental data. This result suggests that the polarizing effects is such as to make g_s(bound) = 0.6 g_s(free).
Electric Quadrupole Moments are not predicted very well by the spherical shell model. For nuclei near closed shells, the calculations tend to give the correct sign, but the magnitude is usually missed by factors of about 2 or 3. Away from closed shells where several valence nucleons may occupy a particular orbital, the quadrupole moments become very large demonstrating large collective effects in nuclear motion.

SPIN ORBIT COUPLING OF AN ELECTRON BOUND IN AN ATOM

Using some semi classical electrodynamics and non-relativistic quantum mechanics, in this section we present a relatively simple and quantitative description of the spin-orbit interaction for an electron bound to an atom, up to first order in perturbation theory. This gives results that agree reasonably well with observations. A more rigorous derivation of the same result would start with the Dirac equation, and achieving a more precise result would involve calculating small corrections from quantum electrodynamics.

Energy of a magnetic moment

The energy of a magnetic moment in a magnetic field is given by:

$$\Delta H = -\boldsymbol{\mu} \cdot \boldsymbol{B},$$

where **μ** is the magnetic moment of the particle and **B** is the magnetic field it experiences.

Magnetic field

We shall deal with the magnetic field first. Although in the rest frame of the nucleus, there is no magnetic field, there *is* one in the rest frame of the electron. Ignoring for now that this frame is not inertial, in SI units we end up with the equation

$$\boldsymbol{B} = -\frac{\boldsymbol{v} \times \boldsymbol{E}}{c^2},$$

where **v** is the velocity of the electron and **E** the electric field it travels through. Now we know that E is radial so we can rewrite $\boldsymbol{E} = \left|\frac{E}{r}\right| \boldsymbol{r}$. Also we know that the momentum of the electron $\boldsymbol{p} = m_e \boldsymbol{v}$. Substituting this in and changing the order of the cross product gives:

$$\boldsymbol{B} = \frac{\boldsymbol{r} \times \boldsymbol{p}}{m_e c^2} \left| \frac{E}{r} \right|.$$

Next, we express the electric field as the gradient of the electric potential $\boldsymbol{E} = -\boldsymbol{\nabla} V$. Here we make the central field approximation, that is, that the electrostatic potential is spherically symmetric, and so is only a function of radius. This approximation is exact for hydrogen, and indeed hydrogen-like systems. Now we can say

$$|E| = \frac{\partial V}{\partial r} = \frac{1}{e} \frac{\partial U(r)}{\partial r},$$

where $U = Ve$ is the potential energy of the electron in the central field, and *e* is the elementary charge. Now we remember from classical mechanics that the angular momentum of a particle $\boldsymbol{L} = \boldsymbol{r} \times \boldsymbol{p}$. Putting it all together we get

$$\boldsymbol{B} = \frac{1}{m_e e c^2} \frac{1}{r} \frac{\partial U(r)}{\partial r} \boldsymbol{L}.$$

It is important to note at this point that *B* is a positive number multiplied by *L*, meaning that the magnetic field is parallel to the orbital angular momentum of the particle.

Magnetic Moment of the Electron

The magnetic moment of the electron is

$$\boldsymbol{\mu} = -g_s \mu_B \boldsymbol{S}/\hbar,$$

where $\boldsymbol{S}$ is the spin angular momentum vector, μ_B is the Bohr magneton and $g_s \approx 2$ is the electron spin g-factor. Here, $\boldsymbol{\mu}$ is a negative constant multiplied by the spin, so the magnetic moment is antiparallel to the spin angular momentum.

The spin-orbit potential consists of two parts. The Larmor part is connected to interaction of the magnetic moment of electron with magnetic field of nucleus in the co-moving frame of electron. The second contribution is related to Thomas precession.

Larmor interaction energy

The Larmor interaction energy is

$$\Delta H_L = -\boldsymbol{\mu} \cdot \boldsymbol{B}.$$

Substituting in this equation expressions for the magnetic moment and the magnetic field, one gets

$$\Delta H_L = \frac{2\mu_B}{\hbar m_e e c^2} \frac{1}{r} \frac{\partial U(r)}{\partial r} \boldsymbol{L} \cdot \boldsymbol{S}.$$

Now, we have to take into account Thomas precession correction for the electron's curved trajectory.

Thomas interaction energy

In 1926 Llewellyn Thomas relativistically recomputed the doublet separation in the fine structure of the atom. Thomas precession rate, $\boldsymbol{\Omega}_T$, is related to the angular frequency of the orbital motion, $\boldsymbol{\omega}$, of a spinning particle as follows

$$\boldsymbol{\Omega}_T = \boldsymbol{\omega}(1-\gamma),$$

where γ is the Lorentz factor of moving particle. The Hamiltonian producing the spin precession $\boldsymbol{\Omega}_T$ is given by

$$\Delta H_T = \boldsymbol{\Omega}_T \cdot \boldsymbol{S}.$$

To the first order in $(v/c)^2$, we obtain

$$\Delta H_T = -\frac{\mu_B}{\hbar m_e e c^2}\frac{1}{r}\frac{\partial U(r)}{\partial r}\boldsymbol{L}\cdot\boldsymbol{S}.$$

Total interaction energy

The total spin-orbit potential in an external electrostatic potential takes the form

$$\Delta H \equiv \Delta H_L + \Delta H_T = \frac{\mu_B}{\hbar m_e e c^2}\frac{1}{r}\frac{\partial U(r)}{\partial r}(\boldsymbol{L}\cdot\boldsymbol{S}).$$

The net effect of Thomas precession is the reduction of the Larmor interaction energy by factor 1/2 which came to be known as the Thomas half.

Evaluating the energy shift

Thanks to all the above approximations, we can now evaluate the detailed energy shift in this model. In particular, we wish to find a basis that diagonalizes both H_0 (the non-perturbed Hamiltonian) and ΔH. To find out what basis this is, we first define the total angular momentum operator

$$\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}.$$

Taking the dot product of this with itself, we get

$$J^2 = L^2 + S^2 + 2\boldsymbol{L}\cdot\boldsymbol{S}$$

(since **L** and **S** commute), and therefore

$$\boldsymbol{L}\cdot\boldsymbol{S}=\frac{1}{2}(\boldsymbol{J}^2-\boldsymbol{L}^2-\boldsymbol{S}^2)$$

It can be shown that the five operators H_0, J^2, L^2, S^2, and J_z all commute with each other and with ΔH. Therefore, the basis we were looking for is the simultaneous Eigen basis of these five operators (i.e., the basis where all five are diagonal). Elements of this basis have the five quantum numbers: n (the "principal quantum number") j (the "total angular momentum quantum number"), l (the "orbital angular momentum quantum number"), s (the "spin quantum number"), and j_z (the "z-component of total angular momentum").

To evaluate the energies, we note that

$$\left\langle\frac{1}{r^3}\right\rangle=\frac{2}{a^3n^3l(l+1)(2l+1)}$$

for hydrogenic wavefunctions (here $a=\hbar/Z\alpha m_e c$ is the Bohr radius divided by the nuclear charge Z); and

$$\langle\boldsymbol{L}\cdot\boldsymbol{S}\rangle=\frac{1}{2}(\langle\boldsymbol{J}^2\rangle-\langle\boldsymbol{L}^2\rangle-\langle\boldsymbol{S}^2\rangle)$$

$$=\frac{\hbar^2}{2}(j(j+1)-l(l+1)-s(s+1))$$

Final Energy Shift

We can now say

$$\Delta E=\frac{\beta}{2}(j(j+1)-l(l+1)-s(s+1))$$

where

$$\beta=\frac{-\mu_B}{m_e ec^2}\left\langle\frac{1}{r}\frac{\partial U(r)}{\partial r}\right\rangle$$

For hydrogen, we can write the explicit result

$$\beta(n,l)=\frac{\mu_0}{4\pi}g_s\mu_B^2\frac{1}{n^3a_0^3l(l+1/2)(l+1)}$$

For any hydrogen-like atom with Z protons

$$\beta(n,l)=Z^4\frac{\mu_0}{4\pi}g_s\mu_B^2\frac{1}{n^3a_0^3l(l+1/2)(l+1)}$$

THE COLLECTIVE MODEL OF THE NUCLEUS

NUCLEAR MODEL

Collective model, also called unified model, description of atomic nuclei that incorporates aspects of both the shell nuclear model and the liquid-drop model to explain certain magnetic and electric properties that neither of the two separately can explain.

In the shell model, nuclear energy levels are calculated on the basis of a single nucleon (proton or neutron) moving in a potential field produced by all the other nucleons. Nuclear structure and behaviour are then explained by considering single nucleons beyond a passive nuclear core composed of paired protons and paired neutrons that fill groups of energy levels, or shells. In the liquid-drop model, nuclear structure and behaviour are explained on the basis of statistical contributions of all the nucleons (much as the molecules of a spherical drop of water contribute to the overall energy and surface tension). In the collective model, high-energy states of the nucleus and certain magnetic and electric properties are explained by the motion of the nucleons outside the closed shells (full energy levels) combined with the motion of the paired nucleons in the core. Roughly speaking, the nuclear core may be thought of as a liquid drop on whose surface circulates a stable tidal bulge directed toward the rotating unpaired nucleons outside the bulge. The tide of positively charged protons constitutes a current that in turn contributes to the magnetic properties of the nucleus. The increase in nuclear deformation that occurs with the increase in the number of unpaired nucleons accounts for the measured electric quadrupole moment, which may be considered a measure of how much the distribution of electric charge in the nucleus departs from spherical symmetry.

COLLECTIVE MODEL

EXPLANATION OF QUADRUPOLE MOMENTS

To explain the large quadrupole moments we return to the picture of the nucleus as a collective body. The basic idea of this Model is that interactions between the outer nucleons and the closed shell core lead to permanent deformation. This is expected to be a particularly strong effect midway between shell closures. In the case of a permanent deformation the single particle states have to be calculated in a non-spherical potential. The spacing of the energy levels then depends upon the magnitude of the distortion. This marriage of the single particle and the corporate models presents very difficult theoretical problems so we will just concentrate on the qualitative features.

As noted above doubly closed shell nuclei are very stable with a first excited state well removed from the ground state. One nucleon more or one less than this very stable configuration will exhibit single particle states. Nuclei further away from the closed shells should be easily deformed leading to excited states due to the vibrational motion of the core. In the region of half filled shells the nuclei are permanently deformed and consequently have large quadrupole moments and also rotational energy levels.

These points are illustrated in the table below which lists the type of energy levels observed for a wide range of even-even nuclei. The examples given cover those nuclei in the region just below ^{208}Pb (Z = 82, N = 126). As additional evidence the approximate sizes of the quadrupole moments of the odd A nuclei in this same region are also listed (in fm^2).

Nuclides	^{150}Sm...^{152}Gd	^{152}Sm...^{190}Os	^{200}Pt...^{200}Hg	^{206}Pb	^{207}Pb	^{208}Pb
Spectra	vibrational	rotational	vibrational	two particle	one particle	"magic"
Q(odd A)	50	200-700-200	50	-	-	-

PREDICTION OF SIGN OF ELECTRIC QUADRUPOLE MOMENTS

Consider a nuclear charge distribution with charge density ρ_c placed in an external electrical potential, or "voltage" φ. The potential energy due to the external field is

$$V = \int \varphi \rho_c \, \mathrm{d}^3\vec{r}$$

It may be noted that since nuclear energies are of the order of MeV, an external field is not going to change the nuclear charge distribution ρ. It would need to have a million volt drop over a couple of femtometers to make a dent in it. Unless you shoot very high energy charged particles at the nucleus, that is not going to happen. Also, the current discussion assumes that the external field is steady or at least quasi-steady. That should be reasonable in many cases, as nuclear internal time scales are very fast.

Since nuclei are so small compared to normal external fields, the electric potential φ can be well represented by a Taylor series. That gives the potential energy as

$$V = \varphi_0 \int \rho_c \, \mathrm{d}^3\vec{r} + \sum_{i=1}^{3} \left(\frac{\partial \varphi}{\partial r_i}\right)_0 \int r_i \rho \, \mathrm{d}^3\vec{r} + \sum_{i=1}^{3}\sum_{j=1}^{3} \frac{1}{2} \left(\frac{\partial^2 \varphi}{\partial r_i \partial r_j}\right)_0 \int r_i r_j \rho \, \mathrm{d}^3\vec{r}$$

where $(r_1, r_2, r_3) = (x, y, z)$ are the three components of position and 0 indicates that the derivative is evaluated at the origin, the center of the nucleus.

The first integral in the expression above is just the net nuclear charge q. This makes the first term exactly the same as the potential energy of a point charge. The second integral defines the "electric dipole moment" in the i-direction. It is nonzero if on average the charge is shifted somewhat towards one side of the nucleus. But nuclei do not have nonzero electric dipole moments. The reason is that nuclei have definite parity; the wave function is either the same or the same save for a minus sign when you look at the opposite side of the nucleus. Since the probability of a proton to be found at a given position is proportional to the square magnitude of the wave function, it is just as likely to be found at one side as the other one. (That should really be put more precisely for the picky. The dipole contribution of any set of positions of the protons is cancelled by an opposite contribution from the set of opposite nucleon positions.)

The last integral in the expression for the potential energy defines the quadrupole matrix or tensor. You may note a mathematical similarity with the moment of inertia matrix of a solid body in classical mechanics. Just like there, the quadrupole matrix can be simplified by rotating the coordinate system to principal axes. That rotation gets rid of the integrals $\int r_i r_j \rho \mathrm{d}^3\vec{r}$ for $i \neq j$, so what is left is

$$V = V_{\rm pc} + \frac{1}{2}\left(\frac{\partial^2\varphi}{\partial x^2}\right)_0 \int x^2\rho\,\mathrm{d}^3\vec{r} + \frac{1}{2}\left(\frac{\partial^2\varphi}{\partial y^2}\right)_0 \int y^2\rho\,\mathrm{d}^3\vec{r} + \frac{1}{2}\left(\frac{\partial^2\varphi}{\partial z^2}\right)_0 \int z^2\rho\,\mathrm{d}^3\vec{r}$$

where the first term is the potential of the point charge.

Note that the average of x^2, y^2, and z^2 is $\frac{1}{3}r^2$. It is convenient to subtract that average in each integral. The subtraction does not change the value of the potential energy. The reason is that the sum of the three second order derivatives of the external field φ is zero due to Maxwell's first equation. All that then leads to a definition of an electric quadrupole moment for a single axis, taken to be the z-axis, as

$$Q \equiv \frac{1}{e}\int (3z^2 - r^2)\rho\,\mathrm{d}^3\vec{r}$$

For simplicity, the nasty fractions have been excluded from the definition of Q. Also, it has been scaled with the charge e of a single proton.

That gives Q units of square length, which is easy to put in context. Recall that nuclear sizes are of the order of a few femtometer. So the SI unit square femtometer, fm^2 or 10^{-30} m^2, works quite nicely for the quadrupole moment Q as defined. It is therefore needless to say that most sources do not use it. They use the "barn," a non-SI unit equal to 10^{-28} m^2. The reason is historical; during the Second World War some physicists figured that the word "barn" would hide the fact that work was being done on nuclear bombs from the Germans. Of course, that did not work since so few memos and reports are one-word ones. However, physicists discovered that it did help confusing students, so the term has become very widely used in the half century since then. Also, unlike a square femtometer, the barn is much too large compared to a typical nuclear cross section, producing all these sophisticated looking tiny decimal fractions.

To better understand the likely values of the quadrupole moment, consider the effect of the charge distribution of a single proton. If the charge distribution is spherically symmetric, the averages of x^2, y^2 and z^2 are equal, making Q zero. However, consider the possibility that the charge distribution is not spherical, but an ellipsoid of revolution, a "spheroid.". If the axis of symmetry is the z-axis, and the charge distribution hugs closely to that axis, the spheroid will look like a cigar or zeppelin. Such a spheroid is called "prolate." The value of Q is then about $\frac{2}{5}$ of the square nuclear radius R. If the charge distribution stays close to the xy-plane, the spheroid will look like a flattened sphere. Such a spheroid is called "oblate." In that case the value of Q is about $-\frac{2}{5}$ of the square nuclear radius. Either way, the values of Q is noticeably less than the square nuclear radius.

It may be noted that the quadrupole integrals also pop up in the description of the electric field of the nucleus itself. Far from the nucleus, the deviations in its electric field from that of a point charge are proportional to the same integrals.

OPTICAL MODEL

NILSSON MODEL

ELEMENTARY IDEAS

The purpose of the Nilsson model is to produce a basic single-particle model applicable to nearly all deformed nuclei. It accounts for most of the observed features of single-particle levels in hundreds of deformed nuclei. The single-particle Hamiltonian used originally by Nilsson, for a nucleus with symmetry axis z, is:

$$H = \frac{\mathbf{p}^2}{2m} + \frac{m[\omega_x^2(\mathbf{x}^2+\mathbf{y}^2)+\omega_z^2\mathbf{z}^2]}{2} + C\mathbf{l}\bullet\mathbf{s} + D\mathbf{l}^2 \tag{1}$$

where the first term of the potential is the kinetic energy of the single-particle, the second term is the anisotropic harmonic oscillator which is used as an average field, with ω_x^2 = $\omega_0^2(1+\frac{2}{3}\epsilon_2)$ = ω_y^2 and ω_z^2 = $\omega_0^2(1-\frac{4}{3}\epsilon_2$) for the case of symmetry axis z. ϵ_2 is the parameter of deformation introduced by Nilsson and is related to β_2, to first order, by $\beta_2 \simeq$ 1.05 ϵ_2. The third term is the spin-orbit interaction which has to be added to reproduce the correct magic numbers, with C=-2 $\hbar\omega_0\kappa$ giving the strength of the spin orbit force. The fourth term, with D=- $\hbar\omega_0\kappa\mu$, accounts for the fact that, at large distances from the centre of the nucleus, the nucleons experience a deeper potential in the realistic case as compared to the harmonic oscillator, thus shifting the levels with higher l-values to lower energy. Different values of κ and μ are used for different shells by fitting the experimental data. Positive parity orbits are indicated by solid lines, negative parity by dashed lines. These diagrams show the single-particle energy levels for neutrons between the closed shells at 50 and 82 as a function of ϵ_2 deformation. The difference in energy between both proton and neutron single-particle levels is due to the Coulomb repulsion of the protons which is considered with an appropriate choice of the constants κ and μ . A typical Nilsson orbit is labeled as follows:

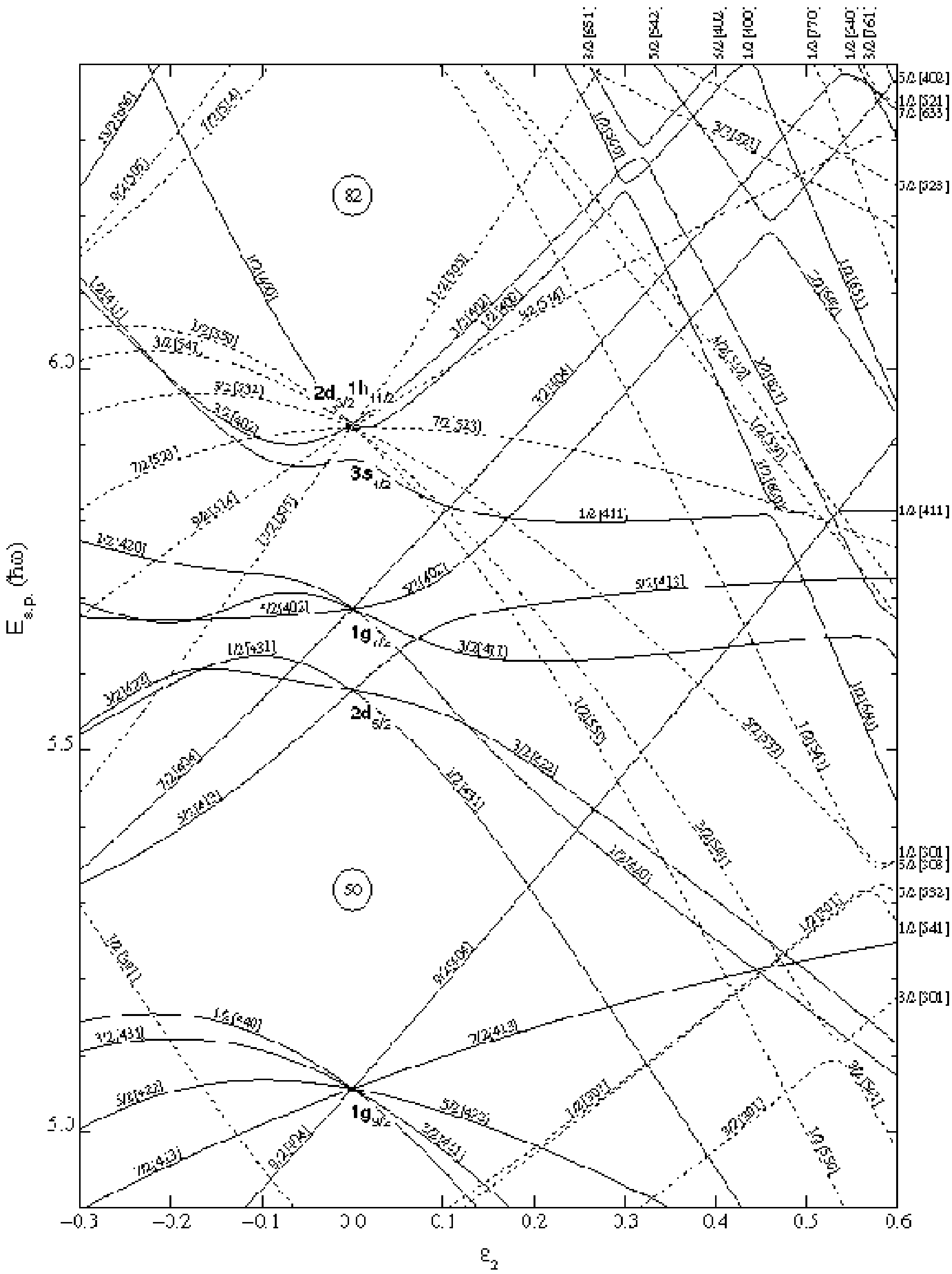


Figure: The Nilsson diagram of single particle levels for neutrons (50 $\leq$ N $\leq$ 82) as a function of deformation ϵ_2.

NUCLEAR MODEL

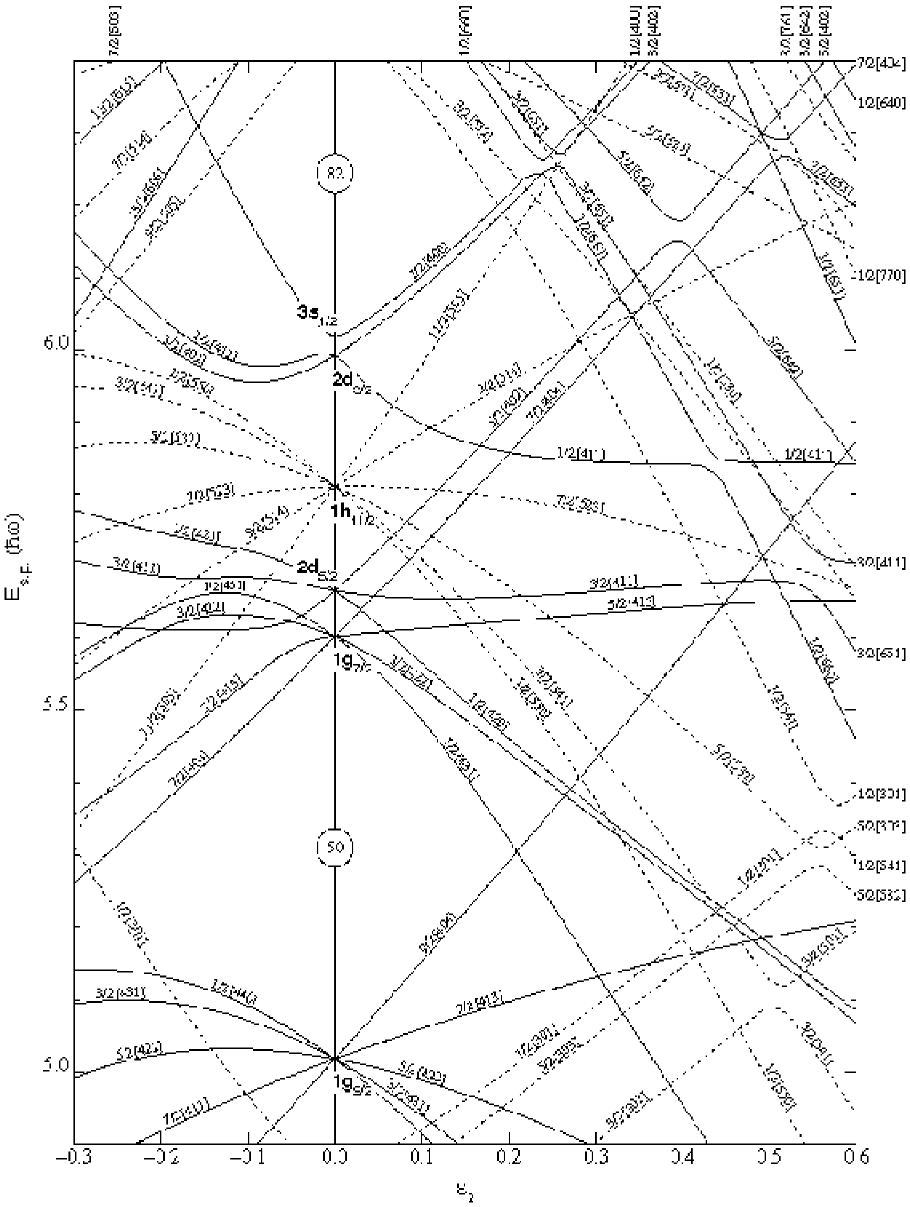


Figure: The Nilsson diagram of single particle levels for protons (50 ≤ N ≤ 82) as a function of deformation ϵ_2.

$$\Omega^{\pi}[N n_z \Lambda] \qquad (2)$$

where the first quantum number, Ω, gives the projection of the single-particle angular momentum, j, onto the symmetry axis and π is its parity. Inside the brackets the three quantum numbers are N, the principal quantum number of the major shell (or the number of oscillator quanta (1 $\hbar\omega$, 2 $\hbar\omega$,...)); n_z, the number of nodes in the wave function along the z axis; and Λ the projection of the orbital angular momentum l_i on the symmetry axis, l_{iz}. The reflection symmetry in nuclei means that the components +Ω and -Ω will have the same energy, giving the levels a degeneracy of two, as compared as (2j+1) for single particle states in spherical nuclei. Ω is the only good quantum number (apart from the parity) and the others (N,n_z and Λ) are not good quantum numbers for low deformations. These three quantum numbers become good quantum numbers at large deformations and therefore are called asymptotic quantum numbers.

Questions:

1. Give an introduction to liquid drop model.
2. Write down the Weizsacker semi-empirical mass formula.
3. Write a note on barrier penetration.
4. Explain nucleon emission.
5. Give an introduction to shell model.
6. Write down the main assumptions of the single-particle shell model.
7. Write down the predictions of the shell model.
8. Explain the collective model of the nucleus.
9. Explain the prediction of sign of electric quadrupole moments.
10. Write down the elementary ideas of Nilsson model.

KARPAGAM ACADEMY OF HIGHER E

DEPARTMENT OF

CLASS:I MSC PHYSICS

NUCLEAR PHYSICS

MULIPLE CHOICE (

UNIT - II

QUESTIONS

Which of the following have the highest ionisation power?
The emission of α-particles in terms of the penetration of nuclear potential barrier is called
Radioactivity is
Which of the following is the alpha particle?
Which of the following about the gamma ray is true?
The most probable process after an Internal conversion electron is ejected from an atom with a high atomi
If the mass of a radioactive sample is doubled, the activity of the sample will
Expected types of gamma ray transition between states of odd A nuclei g9/2→ g1/2
The minimum energy of an antineutrino to produce the reaction will be, when
A nucleus is in excited state. If it is not able to de-excite itself by gamma emission, it can de-excite throug
To penetrate the coulomb barrier of a light nucleus, a proton must have a minimum energy of the order of?
A free neutron decays into a proton with the emission of an electron and a third particle to conserve the an
In fermi's theory of β-decay the important thing is
β-particle spectrum is found to be continuous upto a certain maximum because
The total energy of the γ-ray when an electron and a positron of energy 6MeV get annihilated is
A sensitive way to measure the mass of the electron neutrino is to measure
When a neutron is converted into a proton
The half-life period of a radioactive sample depends upon
Which of the following is correct statement?
Why is β- decay more common than β+ decay among naturally occurring radioactive elements?
When an α-particle captures an electron, it becomes
The penetrating powers of γ-rays are
The phenomenon of pair production is
Who developed theory to explain continuous β-ray neutrino theory
A process of interaction of an electron with a x-ray photon in which the incident photon gives a part of its
Whenever an electron and positron come very close to each other and γ photons are produced. This pheno
In the neutrino the spin and angular momentum vector are
The long range alpha particles exist in nuclei like
Which of the following alpha particle spectra consist of a single group
Who pointed out that a particle inside the nucleus may escape with energy much less than its potential ene
In the decay $O^{14} \rightarrow N^{14*} + e^{+} + \nu\ (0^{+} \rightarrow 0^{+})$
A spin-1/2 particle A undergoes the decay A→B+C+D Where it is known that B & C are also spin-1/2 pa
Rubidium $_{37}Rb^{87}$ is a naturally occurring nuclide that undergoes beta-minus decay. The nuclide, which is t
Mean life of a radioactive atom between two successive disintegrations is inversely proportional to
Which of the following is the alpha particle?
Which of the following is the β^{-} particle?

Which of the following is the β+ particle?

What is the missing element from the following equation

What is the missing element from the following equation ${}^{14}C_6 \rightarrow ? + {}^{0}e_{-1}$

The nuclide ${}^{244}Pu$ (Z=94) is an alpha emitter. It will decay into

Expected types of gamma ray transition between states of odd A nuclei $g_{9/2} \rightarrow g_{1/2}$

The minimum energy of antineutrino of 1.80MeV to produce inverse beta decay reaction is [Mn=939.57M

The following equation is an example of $He^4 \rightarrow Li^6$ and $\beta^- + \nu^-$

The selection rule for γ-rays photon is

By capturing an electron, ${}^{55}Mn_{25}$ transforms into ${}^{54}Cr_{24}$ releasing

The Internal conversion coefficient is defined as

In the β-decay of neutron ,n→p+e^-+(ν_e)¯the anti-neutrino ν¯, escapes detection. Its existence is inferred

If R is the range of α-particles and λ is decay constant, then Geiger Nuttal Law is

The equation $h\nu = {}_1\beta^0 + {}_1\beta^0$ represents

$1H_1 + {}^{0}e_{-1} \rightarrow {}^{1}n_0$ is an example of

The long range alpha particles exist in nuclei like

Almost all the substances undergoing natural radioactivity are found to emit either

nuclei like RaC' and ThC' exists as

Spontaneous alpha disintegration energy is obtained by multiplying………………of alpha particle by the

:DUCATION,COIMBATORE-21
' PHYSICS

; (18PHP203)
QUESTIONS

opt1	opt2	opt3	opt4	opt5	opt6	answer
α-rays	β-rays	γ-rays	x-rays			α-rays
Shading o	Tunneling	Dischargi	None of these			Tunneling of the nucleus
Irreversibl	Spontaneo	Self disint	All of the above			All of the above
electron	$0n^{1}$	$1H^{1}$	$2He^{4}$			$2He^{4}$
It carries a	It carries a	It can be d	It has zero rest mass and a neutr			It has zero rest mass and a neutr
Atom emi	Nucleus e	Nucleus e	Nucleus emits a positron			Atom emits one or several X-ra
Increase	Decrease	Remains t	None of these			Increase
E1	M4	E4	E3			E3
The neutr	The neutr	The positr	The neutron and positron are bo			The neutron and positron are bo
Electron c	Internal cc	Alpha dec	Beta decay			Internal conversion
1GeV	100MeV	10MeV	1MeV			1MeV
Neutrino	Gamma ra	Anti-neutr	Neutron			Anti-neutrino
To find ou	To calcula	To find ou	None of these			To calculate the probability of β
β-particle	β-particle	With β-pa	With β-particle a chargeless par			With β-particle a chargeless par
1.02MeV	0.511MeV	13.02MeV	40MeV			13.02MeV
The angul	The electr	The neutri	None of these			The electron energy spectrum in
Only an el	One electr	One electr	One electron and a proton are p			One electron and an antineutrin
Temperat	Pressure	Nature of	All of the above			Nature of the substance
β-rays are	Γ-rays is h	A-particle	Protons and neutron have exactl			β-rays are the same as cathode r
The bindi	Electrons	Alpha (α)	Positrons cannot exist in ordina			Alpha (α) decay leaves nuclei n
Hydrogen	A helium	A helium	β-particle			A helium ion
Minimum	10000 tim	1000 time	None of these			10000 times of α-rays and 100 t
Productio	Ejection o	ionisation	None of these			Production of an electron and a
Rutherfor	Fermi	Bohr	Goldstein			Fermi
Compton	Bragg's la	Raman eff	None of these			Compton effect
Pair annih	Pair produ	Meson prc	None of these			Pair annihilation
oppositely	aligned to	aligned or	none of the above			oppositely directed
RaC' and	RaA	RaF	Rn			RaC' and ThC'
RaA	RaF	Rn	All the above			All the above
Gurney	Condon	Gamow	All of these			All of these
Allowed b	Allowed b	Forbidden	Forbidden by F-selection rules a			Allowed by F-selection rules
1/2, 1, 3/2	0, 1	½ only	½, 3/2,5/2,7/2,…			½, 3/2,5/2,7/2,…
$38Kr^{87}$	$37Rb^{88}$	$38Sr^{87}$	$36Sr^{87}$			$38Sr^{87}$
energy	frequency	wavelengt	none of the above			energy
𝑒_(−1	𝑛_0^1	𝐻_1	〖He〗_2^4			〖He〗
𝑒_(+1)	𝑒_(−1)	𝑛_0^	H_1			e_(-

e_(	e_(−1	n_0^	H_1^1	e_(+1)
(_86^220)Rn	(_86^228)Rn	(_86^222)Rn	(_86^230)Rn	(_86^
$13N_7$	$12C_6$	$16O_8$	$14N_7$	$14N_7$
^{240}Np (Z=!	240U (Z=!	^{248}Cm (Z=	^{244}Am (Z=95)	240U (Z=92)
E1	M4	E4	E3	E3
1.8MeV	8MeV	40MeV	80keV	1.8MeV
Gamow T	Pauli spin	Fermi sele	Direc selection rule	Gamow Teller selection rule
ΔJ=0 or Δ	$E_f=E_i=h\omega$	ΔS=0 to Δ	None of these	$E_f=E_i=h\omega$
A neutrino	An antinei	An α-parti	A positron	A neutrino
N_e/N_γ	N_γ/N_e	N/N_e	sqrt(N/Ne)	N_e/N_γ
Energy dis	Angular d	Helicity di	Forward-backward asymmetry c	Forward-backward asymmetry c
Logλ=a+R	λ=a+logR	$\log\lambda=ae^R$	logλ=a+blogR	logλ=a+blogR
Meson pro	Pair produ	photon pro	None of these	Pair production
negatron e	positron e	orbital ele	all of the above	orbital electron capture
RaC’ and	RaA	RaF	Rn	RaC’ and ThC’
α and elec	β and α	α, β and γ	None of the above	α, β and γ
short rang	long range	short or lo	none of the above	long range alpha particles
potential e	kinetic ene	potential a	none of the above	kinetic energy

al charge
ys

th emitted with zero kinetic energy

-transformation
ticle is also emitted so that the momentum and energy is distributed among these two particles an

beta decay
are produced

ays
eutron-rich

imes of β-rays
positron from γ-rays

›f electrons

d the recoiling nucleus

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

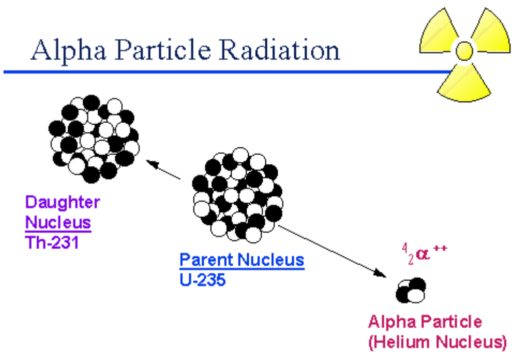
Beta decay: Properties of particles - General features of ray spectrum – Pauli's hypothesis - Fermi's theory of particles - Forms of interaction and selection rules - Fermi's and Gamow teller transition

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:

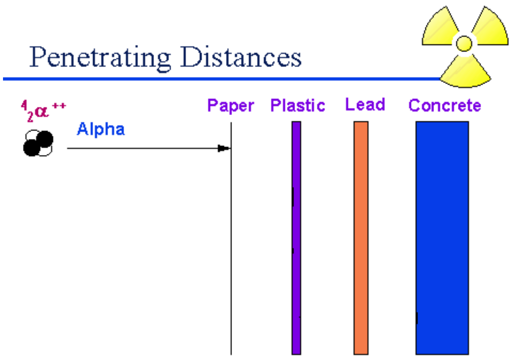
ALPHA DECAY

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,

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

We can equate (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.

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

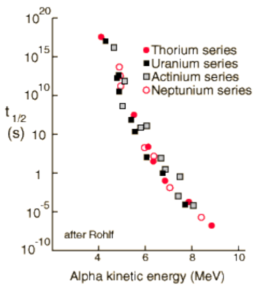
$$\ln \lambda = -a_1 \frac{Z}{\sqrt{E}} + a_2$$

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.

α RAY ENERGIES AND FINE STRUCTURE OF α 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:

$$\text{Pu239} \rightarrow \text{U235} + \alpha \text{ particle (He-4 nucleus)}$$

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.

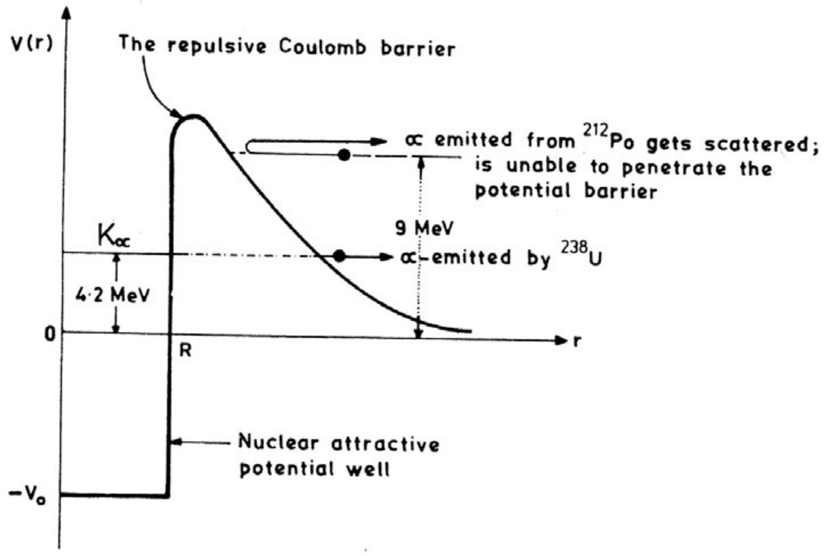
ALPHA DECAY PARADOX

Consider,

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

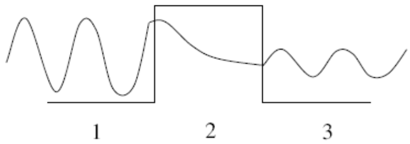
A 4.2 MeV α particle is able to come out of the Uranium nucleus.

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.



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

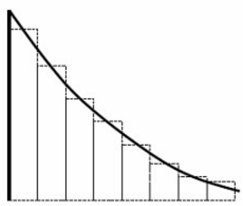
$$\hbar k_1 = \sqrt{2mE}$$

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

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

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

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



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

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

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

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.

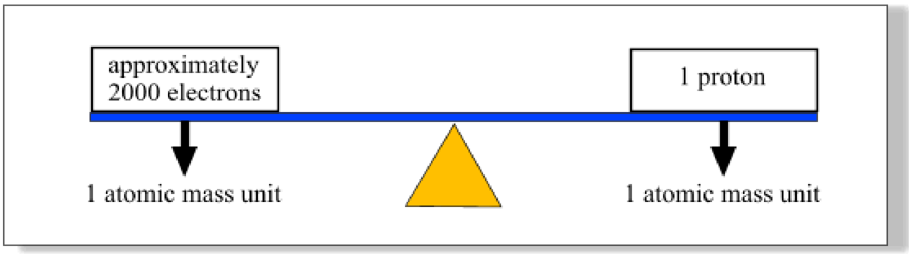


Figure 1

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

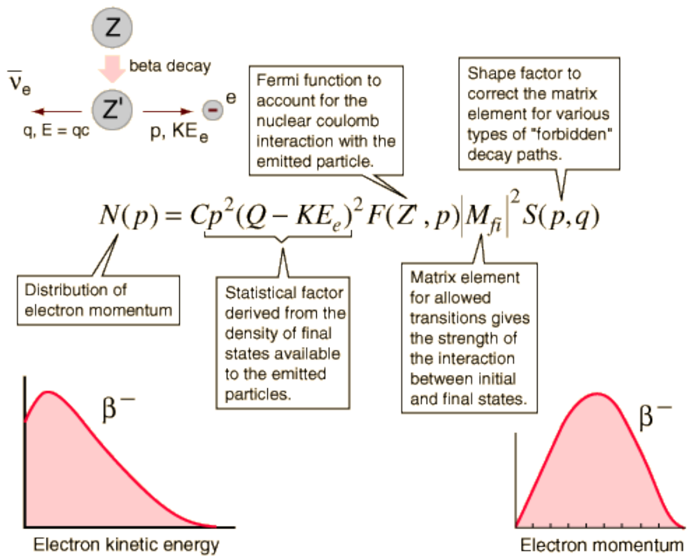
In 1930, Wolfgang Pauli postulated the existence of the neutrino to explain the continuous distribution of energy of the electrons emitted in beta decay. Only with the emission of a third particle could momentum and energy be conserved. By 1934, Enrico Fermi had developed a theory of beta decay to include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

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

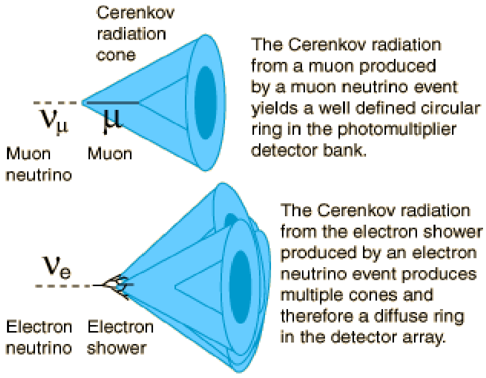
Transition probability — *Matrix element for the interaction* — *Density of final states*

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).



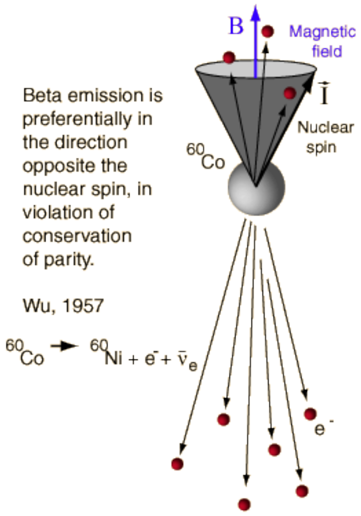
Modern neutrino detectors at IMB in Ohio and Kamiokande in Japan detected neutrinos from Supernova 1987A. A new neutrino detector at Sudbury, Ontario began collecting data in October of 1999. Another Japanese neutrino detector called Super Kamiokande became operational in April 1996.

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.



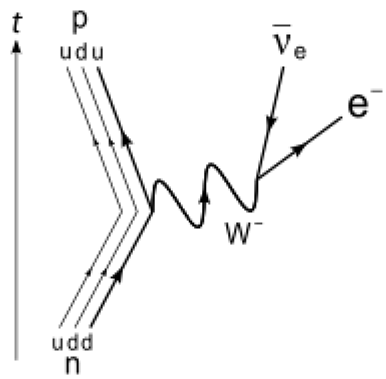
This and subsequent experiments have consistently shown that a neutrino always has its intrinsic angular momentum (spin) pointed in the direction opposite its velocity. It is called a left-handed particle as a result. Anti-neutrinos have their spins parallel to their velocity and are therefore right-handed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

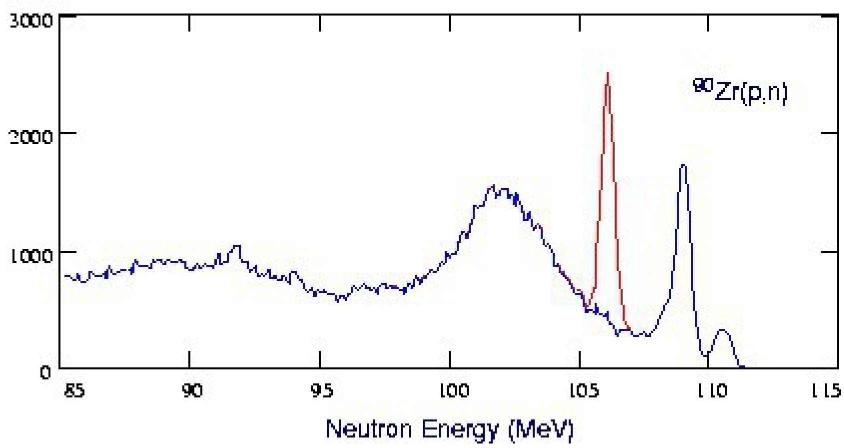
It is easy to understand qualitatively how a (p,n) reaction induces a Fermi or Gamow-Teller transition. Imagine that a high-speed proton traverses a nucleus, exchanges its charge with a bound neutron, and continues nearly undeflected on its path as a neutron. Since the neutron emerges with nearly the 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, $\mathbf{J}_{if} = mathbbfS = \mathbf{s}_e + \mathbf{s}_\nu$. 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 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.

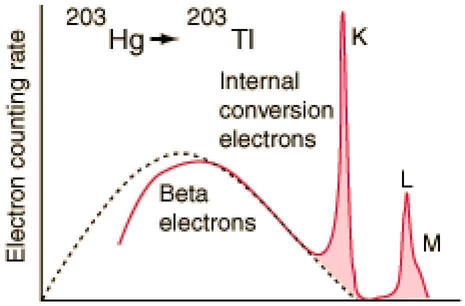
The equivalent dose is the measure of the biological effect of radiation on human tissue. For gamma rays it is equal to the absorbed dose.

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.

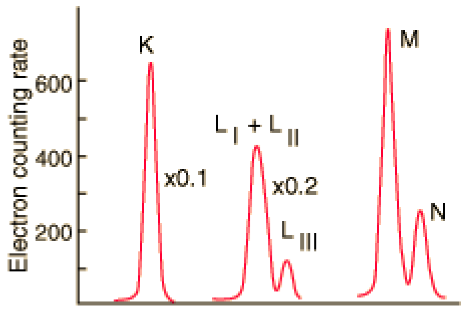
INTERNAL CONVERSION

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.

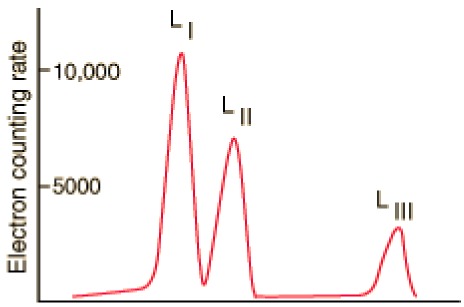
An example used by Krane is that of ^{203}Hg, which decays to ^{203}Tl by beta emission, leaving the ^{203}Tl in an electromagnetically excited state. It can proceed to the ground state by emitting a 279.190 keV gamma ray, or by internal conversion. In this case the internal conversion is more probable. 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).

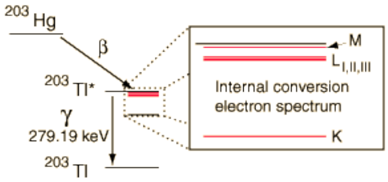


At even higher resolution, the three L shells can be resolved. From C. J. Herrlander and R. L. Graham, Nucl. Phys. 58, 544 (1964).

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.

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NUCLEAR PHYSICS
MULIPLE CHOICE (
UNIT - II

QUESTIONS

Which model has been very successful in explaining a number of nuclear properties
Shell model fails to explain
Possible reason for the discrepancy in shell model is
The deformation of the nucleus is attributed to the……………………of one or more loosely nucleons on t
Standing waves will occur whenever the radius of the body is an odd multiple of the wavelength divided b
The nucleons move in a potential which is not spherically symmetrical have…………….types of motions
Which model is the combination of liquid drop and shell model
The unified model was developed by
Which is the hybrid of liquid drop model and distorted shell model
In which model the shell model potential is assumed non-spherical and the nucleons move independently
The mathematical theory of unified model was developed by
Nilsson model has been successful in describing the properties of
The optical model of the nucleus is developed from an analogy of nuclear scattering with that of-
The collective motion of the nucleons in a deformed nucleus may be ……………………..in character
Which nucleon needs large energy for excitation
Odd nuclei consists of one or two
The series of rotational levels, beginning with the ground state of an even-even nucleus has
Negative parity have only ………………….of angular momentum
The study of nuclear shell model introduces many new ideas familiar in
Which model introduces many new ideas familiar in molecular physics, into nuclear physics
The deviations of ………………………. From the Schmidt curve make shell model less acceptable
Who suggested in odd A nuclei by considering the polarization of the even-even core by the motion of the
The λ=2 quadrupole surface vibrational state is generally known as a
The Nilsson model has been successful in describing the
The amount of dimming the intensity can be calculated by knowing the
The λ=1 motion implies …………………… motion of the whole system
Magic numbers are
In which model, it is assumed that the nucleons in the nucleus move independently in a common potential
The closure of a shell for the harmonic oscillator potential occurs corresponding to neutron or proton numl
The shell closes at particle numbers 2,8,18,20,34,40,58… for
Tin has ……………
Which model is the forerunner of the collective model of nuclear structure?
Which of the following property of the liquid drop is not similar to nucleus
The motion of the molecules in the liquid and motion of the nucleons in the nuclei is of ………………. an
If the forces between the external nucleons and the core are repulsive, the ………………….. is formed
If the forces between the external nucleons and the core are attractive,……………………….. is formed
Prof. Rainwater, Prof. A.Bohr and Prof. Mottelson shared the nobel prize in physics for their work on……

Nilsson found that, upon deformation of the nuclear surface, each level splits into
The nuclear isomerism has been successfully explained by
Nuclei with N or Z near the end of a shell are found in ………… Distinct groups, known as islands of iso
The curves of magnetic moment are known as
The mechanism of nuclear fission was first explained by Bohr and Wheeler on the basis of
Angular momenta and parity for N^{16} is
The expected shell model spin and parity assignment for the ground state of ^{11}B is
Parity corresponding to
Which of the following is not correct for shell model
In the nuclear shell model, the spin of the ground state of an odd A nucleus
A condition for nuclear isomerism
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 responsib
The expected shell model spin and parity assignment for the ground state of ^{15}C is
The expected shell model spin and parity assignment for the ground state of ^{7}Li is
The expected shell model spin and parity assignment for the ground state of ^{31}P is
The expected shell model spin and parity assignment for the ground state of ^{141}Pr is
Nuclear shell model is proposed by
Nuclear shell model is based on the realization that there are specific number of protons (Z) and neutrons(
There is a critical energy called …………which must be reached for complete separation
Seaborg's expression is given by
The first theoretical treatment of the fission event based on the liquid drop model of the nucleus was given
Property associated with the shape and is a measure of deviation of nucleus spherical shape is called
The nucleus may have quadrupole moment only if its angular momentum
Which of the following reactions involves no change in target nucleus
For any spherical symmetric distribution of positive charge in the nucleus, the net quadrupole moment is
In spallation reactions, heavy nuclei splits in
Direct reactions include
Bohr and Wheeler theory is explained based on

:DUCATION,COIMBATORE-21
' PHYSICS

; (18PHP203)
QUESTIONS
I

opt1	opt2	opt3	opt4	opt5	opt6	answer
Shell moc	Liquid drc	Bohr mod	Collective model			Shell model
The large	The groun	The excite	All the above			All the above
magnetic	nuclei is c	nucleus is	1 & 2			1 & 2
Magnetizi	polarizing	electrolyzi	none of the above			polarizing action
4	3	2	1			4
Four	one	two	three			two
Collective	Unified m	optical mc	Super-conductivity model			Collective model
Bohr	Mottelson	Bohr and l	Rainwater			Bohr and Mottelson
Collective	optical mc	Unified m	none of the above			Unified model
Collective	Liquid drc	Optical mo	unified model			unified model
Nilsson	Rainwater	Davydov a	Bohr and Kalcker			Nilsson
Heavier de	odd nuclei	both a & b	even nuclei			both a & b
Scattering	Reflection	Diffractio	None of the above			Scattering of light
rotational	vibrationa	rotational	electronic			rotational or vibrational
Paired nuc	unpaired n	odd neutrc	odd proton			Paired nucleon
unpaired n	paired nuc	unpaired n	All of the above			unpaired nucleons
J=2,4,6	J=1,2,3	J=1,3,5	J=0,1,2,3,4			J=2,4,6
even value	odd values	even or od	zero			odd values
molecular	quantum p	Atomic ph	Thermal physics			Atomic physics
Unified m	Liquid drc	Collective	Nilsson model			Collective model
dipole mo	magnetic i	orbital mo	spin moment			magnetic moment
Bohr and l	J. Rainwat	Bohr	Nilsson			J. Rainwater
one phono	two phonc	four phono	six phonon state			one phonon state
Properties	Properties	Properties	a & b			a & b
refractive	Absorptio	refractive	Extinction coefficient			refractive index and Absorption
rotational	vibrationa	translation	translational			translational
2,8,20,28,	2,8,20,28,	2,8,20,40,	20,40,50,82,126			2,8,20,28,50,82,126
Extreme s	Collective	unified mc	Nilsson model			Extreme single particle model
8,18,20,34	2,8,20,40,	18,30,50,	2,8,20,28,50,82,126			2,8,20,40,70,112 and 168
Square-we	harmonic	spin-orbit	finite square-well			Square-well of infinite depth
Ten stable	six stable	unstable is	none of the above			Ten stable isotopes
Shell mod	Liquid drc	Fermi gas	unified model			Liquid drop model
surface ter	molecules	latent heat	Molecules attract one another at			Molecules attract one another at
Classical a	Quantum a	molecular	molecular and Quantum			Classical and Quantum
oblate sph	prolate spl	spherical	octupole			prolate spheroid
oblate sph	prolate spl	spherical	octupole			oblate spheroid
Nilsson m	Collective	Optical mo	Liquid drop model			Collective model

2(2j+1)	(2j+1)/2	j+1	2j+1	(2j+1)/2
Liquid drc	unified mc	single part	Fermi gas model	single particle model
three	two	seven	four	four
spectral lii	Schmidt li	Balmer lin	None of the above	Schmidt lines
liquid droj	Shell mod	Optical mc	Unified model	liquid drop model of the nucleus
$½^-$	$5/2^+$	2^-	3^-	2^-
$3/2^+$	$3/2^-$	$5/2^+$	$½^-$	$3/2^-$
electron is	electron is	electron ai	electron and proton is even	electron and proton is even
Spin-orbit	Each nucle	Pauli excl	As a spherical nucleus is a centr	As a spherical nucleus is a centr
is decided	is always z	is always i	is decided by the core	is decided by the last unpaired n
The preser	The preser	The preser	The existence of mirror nuclei	The presence of an energy level
Binding ei	Emission (	Mirror nuc	Spin-orbit coupling of nucleons	Spin-orbit coupling of nucleons
$5/2^+$	$1/2^+$	$3/2^-$	$½^-$	$5/2^+$
$3/2^-$	$3/2^+$	$5/2^+$	$5/2^-$	$3/2^-$
$1/2^+$	$5/2^-$	$3/2^+$	$3/2^-$	$1/2^+$
$3/2^+$	$5/2^+$	$1/2^+$	$½^-$	$5/2^+$
Faraday	Bohr	M.G.Maye	None of these	M.G.Mayer
quantum i	magic nun	bonding ei	critical number	Magic number
Activation	Thermal e	Nuclear ei	none of these	Activation energy
E_f =19.0-0	E_f =19.0-0	E_f =19.0-0	None of these	E_f =19.0-0.36Z^2/A
Yukawa	Bohr	Bohr and '	None of these	Bohr and Wheeler
Magnetic (	Electric qu	Angular m	None of these	Electric quadrupole moment
≥2	≥1	≤1	Zero	≥2
disintegrat	radiative c	direct reac	elastic scattering	elastic scattering
1	>1	<1	Zero	zero
two nuclei	one nuclei	no change	more than four nuclei	two nuclei
pickup rea	stripping r	1 & 2	spontaneous decay	1 & 2
Shell mod	Unified m	nilsson mc	Liquid drop model	Liquid drop model

coefficient

distances larger than the dimensions of the electron shells s

al field, existence of average field is not necessary
ucleus
near the ground state differing strongly in angular momentum

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.

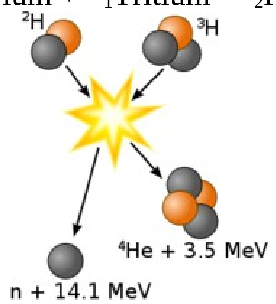
Comparison chart

	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

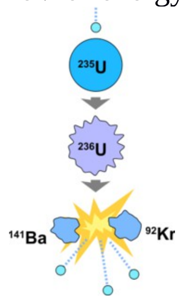
	Nuclear Fission	Nuclear Fusion
	greater than that released in chemical reactions; but lower than the energy released by nuclear fusion.	greater than the energy released by fission.
Nuclear weapon:	One class of nuclear weapon is a fission bomb, also known as an atomic bomb or atom bomb.	One class of nuclear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

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

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.

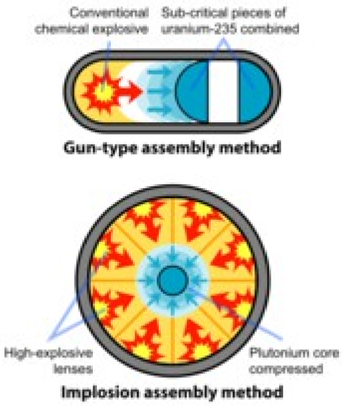
With regards to these factors it can be said that a fusion reaction is a more environmentally friendly method of producing nuclear power. Energy requirement: It takes less energy to split two atoms with fission than it does to fuse two atoms, which is why fission reactors were developed first, and why 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.

NUCLEAR REACTION

- 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

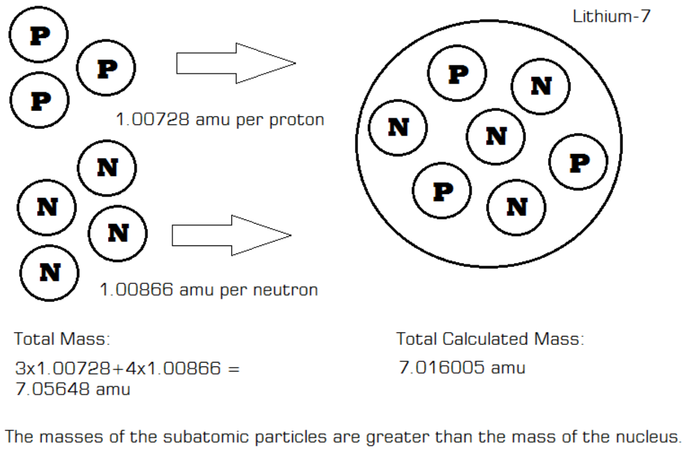


Figure 1

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

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

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

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

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:

$$A + S \rightleftharpoons AS \rightarrow \text{Products}$$

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

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

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:

$$A + S \rightleftharpoons AS$$

$$B + S \rightleftharpoons BS$$

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 $\theta_A = \dfrac{k_1 C_A \theta_E}{k_{-1} + k C_S \theta_B}$, 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

$$r = kC_S^2 \frac{K_1K_2C_AC_B}{(1 + K_1C_A + K_2C_B)^2}.$$

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 $1 >> K_1C_A, K_2C_B$, so $r = C_S^2K_1K_2C_AC_B$. The order is one respect to both the reactants

- **One molecule has very low adsorption**

In this case $K_1C_A, 1 >> K_2C_B$, so $r = C_S^2 \frac{K_1K_2C_AC_B}{(1 + K_1C_A)^2}$. The reaction order is 1 respect to B. There are two extreme possibilities now:

1. At low concentrations of A, $r = C_S^2K_1K_2C_AC_B$, and the order is one respect to A.
2. At high concentrations, $r = C_S^2 \frac{K_2C_B}{K_1C_A}$. 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.

$K_1C_A >> 1, K_2C_B$, so $r = C_S^2 \frac{K_2C_B}{K_1C_A}$. 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:

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

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,C
DEPARTMENT OF PHYSICS

CLASS:I MSC PHYSICS

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

QUESTIONS

A proton cannot decay into a neutron and a neutrino as the conservation law violated will be
The following reaction: $^{1}n_{0}+ {}^{235}U_{92} \rightarrow {}^{141}Ba_{56} + {}^{92}Kr_{36} + 3\,{}^{1}n_{0}$ is called
Four factor formula is given by
The effective area possessed by a nucleus for removing the incident particles from a collimated beam by al
A device in which nuclear fission can be carried out through a sustained and a controlled chain reaction is
Nuclear fuel, moderator control rods, coolant and protective shield are the parts of
The ratio of the number of fission produced by a given generation of neutrons to the number of fissions of
The following reaction: $^{2}H_{1}+{}^{3}H_{1} \rightarrow {}^{4}He_{2}+{}^{1}n_{0}$ is called
What is fission?
Conservation laws that describe events involving the elementary particles include the conservation of
The initial fragments formed by fission have
Which of the potential fusion reaction will not result in the net release of energy
A generic fission event is $^{235}U + n \rightarrow X+Y+2n$. Which of the following pairs cannot represent X and Y?
The following reaction: He_2^4+O_8^16→H_1^1+F_9^18 is called
Typical energy released in a nuclear fission and a nuclear fusion reaction are respectively
The decay of $n=p+e^{-1}$
Which of the following argument is not concerned with the statement " electrons do not exist in the nucleu
A thermal neutron having speed ν impinges on a ^{235}U nucleus. The reaction cross-section is proportional to
The disintegration series of the heavy elements will give ^{209}Bi as a stable nucleus
Suppose that a neutron at rest in free space decays into a proton and an electron. This process would violat
The width of a nuclear excited state
In a nuclear reaction, the mass of the reaction products is
Which among the following is true about neutrinos and antineutrinos?
Find the incorrect statement
For controlled thermonuclear fusion, which has largest cross section
Assume the neutrino mass is exactly zero, then
An electron and a proton enter a magnetic field with equal velocities. Which will experience more force?
On the basis of Q values, determine if the ^{98}Tc nucleus can decay by β^{-} decay
On the basis of Q values, determine if the ^{98}Tc nucleus can decay by β^{+} decay
On the basis of Q values, determine if the ^{98}Tc nucleus can decay by electron capture
A 2MeV neutron is emitted in a fission reactor. If it loses half of its kinetic energy in each collision with a
Which of the following probe can produce complication?
Which of the following is true for β-decay of the neutron? The process
To penetrate the coulomb barrier of a light nucleus, a proton must have a minimum energy of the order of?
Identify the process which takes place when the mass of the parent atom is greater than the mass of the dau

In the classification of neutrons based on energy, the neutrons in the energy range of 1eV to 100eV are knc
The kinetic energy of the α-particle (Kα) in an alpha decay in terms of the Q-value reaction is given by
Masses of two isobars $_{29}Cu^{64}$ and $_{30}Zn^{64}$ are 63.9298. It can be concluded from these data that
The reaction $^{12}C_6 + {}^1H_1 \rightarrow {}^{13}N_6 + \gamma$ is called
If Q is –ve, reaction involved is
The theory of low energy deuteron stripping was first put forth by
The inverse of the stripping reaction is called a
The energy dependence the cross section of a reaction between two particles, close to resonance energy E_0
The antiparticle of an electron is the positron which was discovered by
When the projectile gains nucleons from the target, the nuclear reaction is referred to as
When the projectile loses nucleons to the target, the nuclear reaction is referred to as
The analytic relationship between the kinetic energy of the projectile and the outgoing particle and the nuc
The scattering of alpha particles in gold is a good example of
If the sum of the masses of incident particle and target nucleus is greater than that of masses of the product
Breit-Wigner formula leads to the conclusion that at low neutron energies the cross-section should be inve
The cross section which defines a distribution of emitted particles with respect to the solid angle is called
when a nucleus is excited, excited energy is considered as increase in temperature and this known as

OIMBATORE-21

opt1	opt2	opt3	opt4	opt5	opt6	answer
Energy (as	Angular m	Charge	All the above			All the above
Fusion	Fission	Alpha dec	Beta decay			Fission
ηεpf	ηαpf	σΩpf	σΩpa			ηεpf
Total nucl	Total nuc	Scattering	None of these			Total nuclear cross-section
Nuclear po	Nuclear re	Nuclear tra	None of these			Nuclear reactor
Nuclear re	Nuclear po	Nuclear en	None of these			Nuclear reactor
K-factor o	Gain facto	Power fac	None of these			K-factor or reproduction factor
Fusion	Fission	Alpha dec	Beta decay			Fusion
The joinin	The proces	The splitti	The scientific creation of bubble			The splitting of atoms into smal
energy	linear and	electric ch	All of these are correct			All of these are correct
More proto	More neut	About the	Number of proton and neutron c			More neutrons than protons
^{6}Li + ^{6}Li	^{4}He + ^{4}He	^{20}Ne + ^{20}N	^{35}Cl + ^{35}Cl			^{35}Cl + ^{35}Cl
^{141}Xe + ^{93}S	^{139}Cs + ^{95}F	^{156}Nd + ^{79}(	None of these			^{156}Nd + ^{79}Ge
An elastic	An inelast	A pick up	A stripping reaction			A stripping reaction
50MeV ar	200MeV a	1000MeV	200MeV and 10MeV			200MeV and 10MeV
Cannot co	Can conse	Data in su	None of these			Cannot conserve angular momen
Statistics	Binding en	Electron m	β-decay			Electron magnetic moment
ν^{-1}	ν	$\nu^{1/2}$	ν-$^{1/2}$			ν^{-1}
Actinium	Neptunium	Thorium s	Uranium series			Neptunium series
conservati	conservati	conservati	conservation of angular momen			conservation of linear momentu
inversely p	inversely p	Directly p	Independent of half-life			inversely proportional to its mas
Always eq	Always les	Always gr	different from the sum of collid			Always less than the sum of the
All neutrin	All neutrin	There are	No handedness is associated wi			All neutrinos are left handed anc
The nucle	The bound	The energ	A system of two neutrons which			The energy levels of triplet state
D+D→^{3}H	D+D→T+	D+T→^{4}He	None of these			D+T→^{4}He+n+17.6MeV
The neutri	The neutri	The antine	The antineutrino spin point dire			The antineutrino spin does the re
electron	Proton	Both expe	Neither of them experience any			Both experience same force
1.796MeV	0.662MeV	1.684MeV	None of these			1.796MeV
1.796MeV	0.662MeV	1.684MeV	None of these			0.662MeV
1.796MeV	0.662MeV	1.684MeV	None of these			1.684MeV
23	24	25	26			26
Electrons	Proton	Neutrons	Photons			Photons
Violates b	Violates p	Conserves	Conserves both parity and charg			Violates both parity and charge
1GeV	100MeV	10MeV	1MeV			1MeV
Electron c	Positron e	Electron e	γ-emission			Electron capture

Cold neutı	Epitherma	Resonance	Thermal neutron	Resonance neutron
(A-4/A)Q	(4Q/A)	(AQ/4)	(Q/4A)	(A-4/A)Q
Both the is	Zn^{64} is rad	Cu^{64} is rac	Cu^{64} is radioactive decaying to	Cu^{64} is radioactive decaying to
Capture re	Particle-pa	Fission rea	Fusion reaction	Capture reaction
Endo-ergi	Exoergic	neutral	None of these	Endo-ergic
Thomson	Oppenheir	Seaborg	Yukawa	Oppenheimer and Phillips
Pick-up re	Nuclear re	Endotherm	Exoergic reaction	Pick-up reaction
Bethe-Blo	Breit-Wig	Gamous-T	Bethe-Weizacker formula	Breit-Wigner formula
Anderson	Yukawa	J.J.Thoms	Einstein	Anderson
Stripping	Pickup rea	Exoergic r	None of these	Pickup reaction
Stripping	Pickup rea	Exoergic r	None of these	Stripping reaction
Q equatioı	scattering	reaction cı	none of these	Q equation
inelastic s	disintegrat	radiative c	elastic scattering	elastic scattering
exoergic	endoergic	exoergic o	none of these	exoergic
target enei	neutron sp	neutron er	neutron angular momentum	neutron energy
partial cro	differentia	Total cros	all the above	differential cross section
Nuclear te	excitation	temperatu	none of these	Nuclear temperature

ler pieces.

ntum

m
ss
masses of the colliding nuclei
d all antineutrinos are right handed
is higher than singlet state

everse of neutrino

conjugation symmetry

Zn^{64} through β-decay

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.

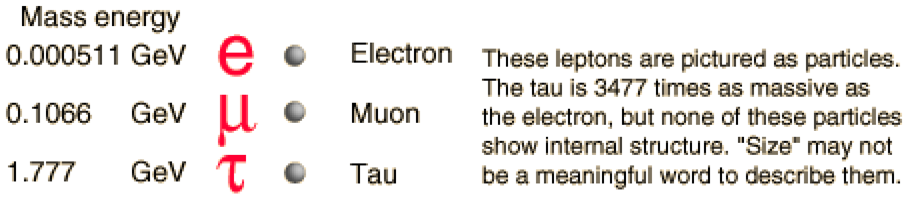
Until the 1960s, nucleons were thought to be elementary particles, each of which would not then have been made up of smaller parts. Now they are known to be composite particles, made of three quarks bound together by the so-called strong interaction. The interaction between two or more nucleons is called 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 (**I** = ½). 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 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.

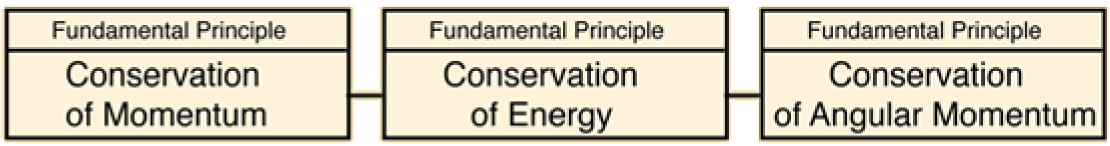
The strong force binds quarks into protons, neutrons and mesons, and holds the nucleus of the atom together despite the repulsive electromagnetic force between protons. The weak force controls the radioactive decay of atomic nuclei and the reactions between leptons (electrons and neutrinos).

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.

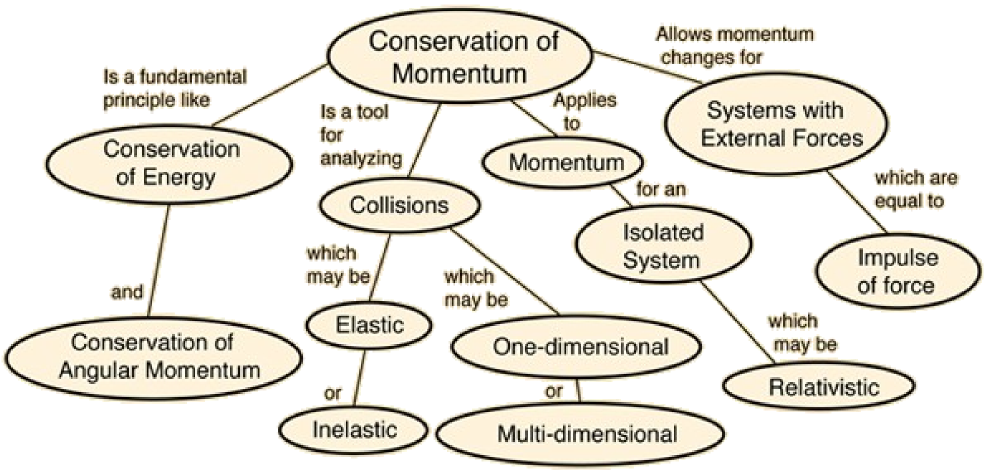


Stated here as principles of mechanics, these conservation laws have far-reaching implications as symmetries of nature which we do not see violated. They serve as a strong constraint on any theory in any branch of science.

Conservation of Momentum

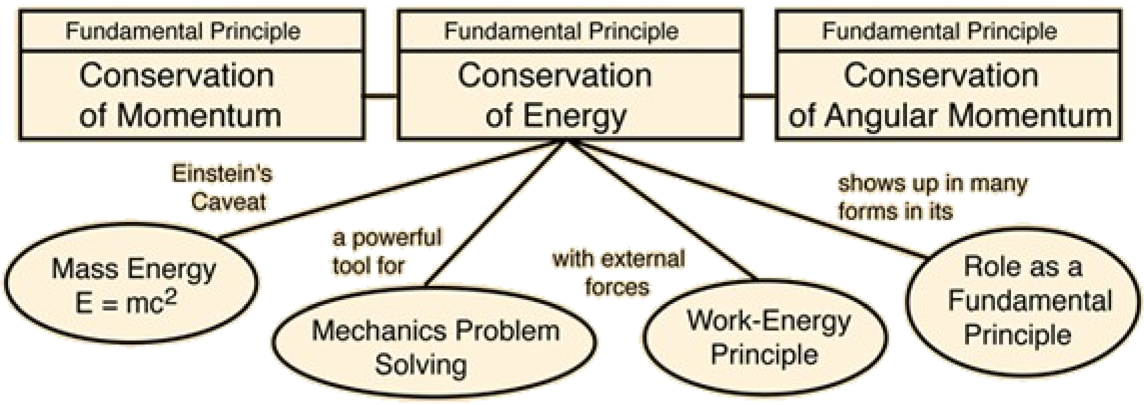
The momentum of an isolated system is a constant. The vector sum of the momenta mv of all the objects of a system cannot be changed by interactions within the system. This puts a strong constraint on the types of motions which can occur in an isolated system. If one part of the system is given a momentum 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



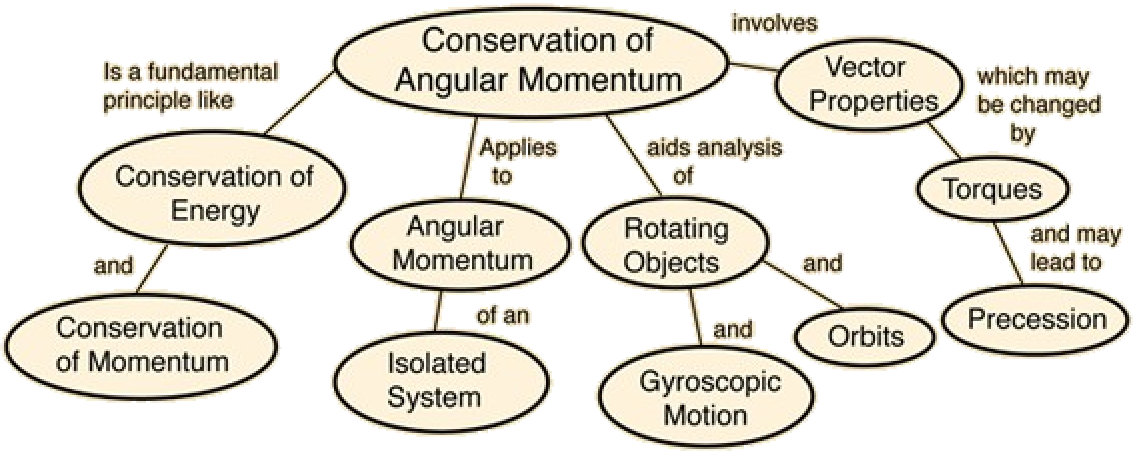
Conservation of Energy

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 each quark 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

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

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.

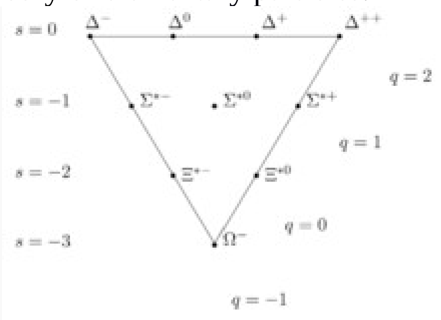
In 2011, a first indication of CP violation in decays of neutral D mesons was reported by the LHCb experiment at CERN.

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.

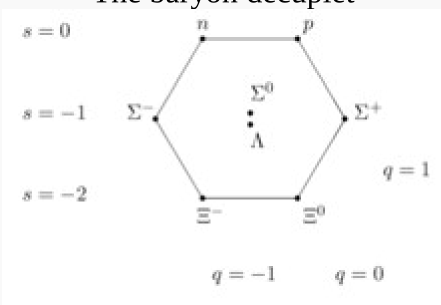
EIGHT FOLD WAY AND SUPER MULTIPLES

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 $+\frac{2}{3}$, while the down, strange, and bottom quarks have an electric charge of $-\frac{1}{3}$. 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/c²)**
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/c^2)
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.

QUESTIONS

Which operator is connected with spatial inversion
The concept of a particle-antiparticle pair was originally developed by
A symmetry scheme known as the ………………in which all the known particles and resonances are grou
In SU(3), SU stands for
Isospin conservation law is obeyed by
Strangeness conservation law holds good in
Which conservation laws hold good in Strong and electromagnetic interactions
The process of changing every particle into its anti-particle is known as
Mesons have zero intrinsic spin but Baryons have
The particles of masses between π-meson mass and proton mass were called
The particles of masses between proton and deuterium mass were called
Nucleons (protons and neutrons), Lamda particle(λ^0), sigma particle (∑), cascade particle (≡) and omega p
Baryons heavier than nucleons are called
A combination of a down quark (d) and an anti up quark u^{-} called a
If π- was formed by a d quark and u quark the conservation law violated
An experiment is performed to search for evidence of the reaction pp→HK+K+. How many quarks must H
A neutral elementary particle whose isotopic spin projection is J_Z=+1/2 and Baryon charge B=+1. The part
∑^-→ʌ^0+π^- is forbidden by
The mode of decay for a neutron is observed n→p+e^- because the conservation laws does this process viol
The iso spin and the strangeness of Ω^- baryon are
ʌ^0→p+k^- is forbidden as it violates
The quarks particle (u,d,s) possess fractional electric charges according to
The baryon number of proton, the lepton number of proton, the baryon number of electron and the lepton r
Except for mass, the properties of the muon most closely resemble the properties of the
If π^- was formed by a d quark and a u quark, the conservation law violated
The reaction proceed by strong interaction $\pi^-+p\rightarrow\Xi^-+K^0+X$, identify X
Quarks are elementary particles, first proposed by Gellmann to explain the discrepencies in
A conservation law that is not universal but applies only to certain kinds of interactions is conservation of
The particle decay $\Lambda\rightarrow p+\pi^-$ must be a weak interaction because
The interaction that describes the forces among nucleons that hold nuclei together is
Current thought is that all matter is composed of is
Particles that participate in the strong nuclear interaction are called
Which of the following choices lists the four known types of forces in nature in order of decreasing strengt
The conservation law violated by the reaction $p \rightarrow \pi^0 + e^+$ is the conservation of
The concept of strangeness was introduced by
Meson production predominates at bombarding energy of

Which neutral unstable particle was named as lambda
The first hyperon was found in cosmic rays in 1947 by
The time reversal process is the creation of an electron-positron pair by the collision of
Isospin numbers are associated with hadrons but not with
In a weak interaction involving change in strangeness of baryons or mesons, the change in strangeness mu
Bosons are particles with intrinsic angular momentum equal to an
Fermions are all those particles in which the spin is
Strong interactions between elementary particles are responsible for the
The process of mutual annihilation of particles and anti-particles is an example of
$\wedge^0+p=\sum^++n$ proceeds via
Which one of the following nuclear processes is forbidden?
$d+d=\alpha+\pi^0$ is forbidden due to violating the conservation of
$\pi^-+n=k^++\wedge^0$ is forbidden by violating
$k^++n=\sum^++\pi^0$ proceeds via
Consider the reactions ∑^+=n+e^++ν_e k^+=π^++e^++e^-
By considering the quark makeup of the various particles, deduce the identity of the unknown particles in t
which of the following is allowed reaction
Which of the following is forbidden
K-mesons and η-mesons are allotted
Which of the following reactions violates lepton number conservation?
Which one of the following nuclear processes is forbidden?
Proton and neutron form an
A zero spin particle can exist in
A spin particle can exist in
The proton and neutron mass in terms of energy is about
Massles Bosons are subject to
Pion was found to exist in
Mass of pion was estimated to be
muon particle was found to have a life time of

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opt1	opt2	opt3	opt4	opt5	opt6	answer
Parity	Charge co	Time Reve	All the above			Parity
Planck's	Einstein	J.J.Thoms	P.A.M.Dirac			P.A.M.Dirac
Eight fold	Five fold v	Six fold w	None of these			Eight fold way
Single uni	Special un	Special un	None of these			Special unitary
All the fou	The EM,w	Weak and	Strong interaction only			Strong interaction only
Strong and	All the fou	Weak and	Weak only			Strong and electromagnetic inte
Strangene	Parity	(a) & (b)	isospin			(a) & (b)
Charge co	Time reve	Parity	All the above			Charge conjugation
Half integ	Full integr	No any int	None of these			Half integral intrinsic spin
Heavy me	Hyperons	Leptons	None of these			Heavy mesons (k-meson)
k-meson	Hyperons	Leptons	None of these			Hyperons
Hyperons	Leptons	Baryons	None of these			Baryons
Hyperons	Leptons	Lamda pai	None of these			Hyperons
π^0 meson	A proton	π^- meson	Neutron			π^- meson
Angular m	Charge an	Linear mo	Charge and Lepton number			Charge and baryon number
Two	Three	Four	Six			Six
$\wedge^0$	Ξ^0	$\sum^0$	n			Ξ^0
Conservat	Conservat	Conservat	Conservation of energy			Conservation of energy
Energy an	Energy an	angular m	Charge and baryon number			angular momentum and lepton r
1,-3	0,-3	1,3	0,3			0,-3
Charge co	Conservat	Conservat	Conservation of Le and Lμ			Conservation of β-violation
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
Zero,zero,	one,one,ze	one,zero,z	Zero,one,one and zero			one,zero,zero and one
Electron	Photon	Pions	Protons			Electron
Angular m	Charge an	Linear mo	Charge and lepton number			Charge and baryon number
π^+	K^0	p	γ			K^0
Structure c	Eight fold	Structure c	Baryon structure			Structure of resonance particles
lepton nur	baryon nu	spin	strangeness			strangeness
The π^- is a	The ∧ has	It does not	No neutrino is produced in the c			It does not conserve strangeness
the strong	the electro	the weak r	the gravitational interaction			the strong nuclear (hadronic) int
six quarks	four quark	six leptons	six quarks and six leptons			six quarks and six leptons
neutrinos	hadrons	leptons	electrons			hadrons
strong nuc	electromag	strong nuc	strong nuclear, weak nuclear, el			strong nuclear, electromagnetic,
charge	energy	linear mon	lepton number and baryon numl			lepton number and baryon numb
GellMann	Mayer	Bohr	None of these			GellMann and Nishijima
10MeV	few hundr	Several hu	1MeV			Several hundred MeV

Leptons	mesons	hyperons	hadrons	hyperons
Rochester	Gellmann	Mayer	J.J.Thomson	
one photo	particles	waves	two photons	two photons
leptons	mesons	hyperons	all of above	leptons
parity	charge	time	all the above	charge
integral m	Half integ	No any mu	None of these	integral multiple of h
Full integ	No any sp	Half integ	None of these	Half integral
decay of p	total cross	fission	all the above	total cross section as a function
nuclear in	coulomb r	electroma	all the above	electromagnetic interaction
Strong int	Em intera	Weak inte	Cannot be predicted	Strong interaction
$\bar{\nu}$+p→n+e	$\pi^-\to e^-+\nu_e+$	π^-+p→n+k	$\mu^-\to e^-+\overline{(\nu_e)}+\nu_\mu$	$\pi^-\to e^-+\nu_e+\pi^0$
Strangene	Iso spin	Baryon nu	Energy	Iso spin
Conservat	Conservat	Conservat	Conservation of charge and thir	Conservation of charge and thir
Strong int	Em intera	Weak inte	Cannot be predicted	Strong interaction
Both of th	Both of th	Both of th	Both of them are forbidden due	Both of them proceed via the we
proton	neutron	pions	omega	neutron
μ^+→e^+	π^+→μ^+	p+p→p+∑	p→e^++νe	π^+→μ^++ν_μ
π^-+p→∑	π^-+p→k^	π^-+n→Ξ^	k^-+p→Ω^-+k^++k^0	π^-+n→Ξ^-+k^++k^-
Negative p	Positive pa	Both type	No parity	Negative parity
e^++e^-→	e^-+p→ν+	e^++n→p	μ^-→e^-+ν+$\bar{\nu}$	e^++n→p+ν
$\bar{\nu}$+p→n+e	π^-→e^-+	π^-+p→n-	μ^-→e^-+$\overline{(\text{ν\_e})}$+ν_μ	π^-→e^-+ν_e+π^0
isospin do	doublet	isospin	triplet	isospin doublet
two state	zero state	three state	All the above	two state
two state	zero state	three state	All the above	three state
0.5MeV	1BeV	several Me	few MeV	1BeV
strong, we	Weak inte	Strong int	electromagnetic interaction only	electromagnetic interaction only
positive ch	negative c	zero charg	all three charged states	all three charged states
$270m_e$	$270m_n$	0	1	$270m_e$
10^{-6} sec	10^{-8} sec	10^{6} sec	50s	10^{-6} sec

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weak nuclear, gravitational

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KARPAGAM ACADEMY OF HIGHER EDUCATION,
COIMBATORE – 641 021
DEPARTMENT OF PHYSICS
I M. Sc. PHYSICS
I-Internal Examination (February 2019)
NUCLEAR PHYSICS

Date:05.02.2019 FN **Marks: 50**

Duration: 2 Hrs.

PART – A (20 × 1 = 20 Marks)

Objective Type Questions:

1) The nucleon density at the centre of any nucleus is
a) proportional to A b) proportional A^2
c) proportional Z d) almost the same

2) The non-central part of the nuclear force is called
a) Electromagnetic force b) Tensor force
c) Magnetic force d) Static force

3) Majorana force is due to
a) exchange of space b) exchange of spin
c) exchange of space and spin d) exchange of moments

4) Wigner force is such a force which
a) depends on S and L b) depends on S only
c) depends on L only d) independent of S and L

5) The mass of pi meson is
a) 270 times that of electron b) 270 times that of proton
c) 140 times that of electron d) 140 times that of proton

6) The difference between the total mass of the individual nucleons and the mass of the nucleus is known as
a) mass defect b) binding energy
c) packing fraction d) mass excess

7) The energy equivalent of mass defect is
a) packing energy b) binding energy
c) mass excess d) packing fraction

8) The mass of the neutron is
a) equal to that of proton b) equal to that of electron
c) half of that of proton d) 1836 times that of proton

9) According to proton-neutron theory
a) electron pre-exists in the nucleus which is emitted as beta particle
b) electron is created at the time of beta emission
c) neutron gets converted into a proton, electron and a neutrino
d) electron is emitted from the outer shell

10) Which of the following statements if not true?
a) There are discrete energy levels in the nucleus
b) The energy of the nucleus has a continuous range
c) There are discrete but varying energies for the nucleus
d) All the above statements are correct

11) Natural radioactivity is exhibited by
a) nucleons b) heavier nuclides c) lighter nuclides d) electrons

12) Fundamental law of radioactive decay was given by _______
a) Marie curie b) piere curie c) Rutherford and Soddy d) Henry Becquerel

13) Quantum mechnical explanations for alpha particle was given by
a) condon b) Gamow c) Gurney d) all the three

14) Mean life of a radioactive atom between successive disintegration is _________- to energy
a) inversely proportional b) directly proportional c) equal d) not equal

15) When alpha particles are emitted, it leaves daughter nuclei in __________
a) ground state b) excited state c) may be ground or in excited state d) near to ground state

16) Fermi Theory of beta decay equation is good with ________
a) Rutherford curve b) Pauli curve c) Sergent curve d) Fermi

17) The nuclear wave functions and particle motions support
a) Fermi gas model b) unified model
c) collective model d) liquid drop model

18) The depth of the potential well for proton gas in a Fermi model is
a) equal to the depth of potential well of neutron gas
b) less than the depth of the potential well of the neutron gas
c) more than the depth of the potential well of the neutron gas
d) can be less or more than that of neutron gas

19) The average kinetic energy of nucleons inside nucleus is of the order of
a) 1 MeV b) 10 MeV c) 100 MeV d) 0.1 MeV

20) The average energy of majority of the alpha particles is
a) 7 Mev b) 8 Mev c) 16 Mev d) 17 MeV

PART – B (3 × 2 = 6 Marks)

Short Answer Type Questions:

21. Write down about Ground state of Deuterium.
22. What is Pauli's exclusion principle.
23. What are the Properties of α particles.

PART – C (3 × 8 = 24 Marks)

Answer ALL questions:

24. a) Nuclear mass and binding energy of a nucleus

(OR)

b) Explain semi-empirical mass formula.

25. a) Explain Liquid drop model.

(OR)

b)Explain shell model of Nucleus.

26. a)Explain what is Collective model of Nucleus.

(OR)

b) What is Gamow's theory of α particles.

******ALL THE BEST******

Register No. -------------

[18PHP203]

KARPAGAM ACADEMY OF HIGHER EDUCATION,
COIMBATORE – 641 021
DEPARTMENT OF PHYSICS
I M. Sc. PHYSICS
II-Internal Examination (March 2019)
NUCLEAR PHYSICS

Date:12.03.2019 (FN) Marks: 50
Duration: 2 Hrs.

PART – A (20 × 1 = 20 Marks)

Objective Type Questions:

1) In Fermi Gas model, the neutron is in a potential well of depth
a) 8 MeV b) 16 MeV c) 38 MeV d) 38 keV

2) Which of the following statements is correct?
a) Liquid drop model could nto give atomic masses and binding energy accurately
b) Liquid drop model could not predict alpha and beta emission properties
c) Liquid drop model could give atomic masses and binding energy accurately, but could not predict alpha and beta emission properties

d) Liquid drop model not could give atomic masses and binding energy accurately, but also could predict alpha and beta emission properties

3) Bohr-Wheeler theory of nuclear fission is based on
a) shell model b) Fermi gas model
c) collective model d) Liquid drop model

4) The property of nuclear isomerism is attributed to
a) different nuclear energy states
b) different nuclear size c) different number of nucleons d) all the above

5) When a particle is incident on a nucleus, scattering can be of ----- types
a) 2 types b) only 1 types c) 3 types d) 4 types

6) Interaction in which parity is not conserved
a) strong interaction b) weak interaction
c) electromagnetic interaction d) gravitational interaction

7) A particle bombarded on a nucleus is absorbed by the nucleus and a new nucleus is formed, with the emission of gamma ray. This process is
a) photo disintegration b) radioactive capture
c) elastic scattering d) disintegration

8) The quantum number used to describe the quantum states of nucleons is
a) magnetic quantum number b) parity
c) nuclear quantum number d) isospin

9) The general equation a + X ==> Y + b, is an example of -----
a) elastic scattering b) inelastic scattering
c) nuclear reaction d) none of the above

10) Total interaction cross section is
a) the sum of scattering cross section and reaction cross section
b) the nuclear reaction cross section itself
c) scattering cross section itself d) any of the above

11) In heavier nuclei, the levels are
a) closely spaced b) continuous
c) well separated d) none of the above

12) Compound nucleus is formed in
a)elastic scattering b) inelastic scattering
c) optical model d) direct reaction

13) Baryons have spin
a) integral b) zero
c) half integral d) 1/2

14) Which of the following statements is correct?
a) baryons are subject to strong interaction only
b) baryons are subject to weak interaction only
c) baryons are subject to strong, weak and electromagnetic interactions
d) baryons are subject to strong and weak interaction only

15) Baryons and mesons together are termed as
a) bosons b) fermions c) leptons
d) hadrons

16) Nucleons belong to the class
a) hyperons b) baryons c) bosons d) leptons

17) Characteristic time scale of gravitational interaction is of the order of

a) 10^16 s b) 10^-16 s c) 10^10 s d) 10^-10 s

18) Characteristic time of electromagnetic interaction is of the order of

a) 10^16 s b) 10^-16 s c) 10^10 s d) 10^-10 s

19) The characteristic time scale of strong interaction is of the order of

a) 10^16 s b) 10^-16 s c) 10^-23 d) 10^-10 s

20) Gravitational interaction is

a) always attractive b) always repulsive

c) can be attractive or repulsive, depending on its charge

d) can be attractive or repulsive, depending on its mass

PART – B (3 × 2 = 6 Marks)

Short Answer Type Questions:

21. Give the Properties of beta decay.
22. What is applications of nuclear energy
23. What are the intrinsic parity of pions.

PART – C (3 × 8 = 24 Marks)

Answer ALL questions:

24. a) Describe the Fermi's and Gamow teller transition.

(OR)

b) Explain Interaction of gamma rays with matter.

25. a) Explain DuMont bent crystal Spectrometer.

(OR)

b)What are the types of interactions in Nucleus.

26. a)Explain in detail the classifications of elementary particles..

(OR)

b) Explain GellMann Nisijima Formula in detail..

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