M.Sc. Physics

(4^{th} Semester)

Class notes

For students

Subject – Nuclear Physics

Government Postgraduate College Datia

Datia (M.P)

Atomic Nuclei:-

The atomic nucleus is composed of protons and neutrons. Protons and neutrons have approximately the same mass, but protons carry one unit of positive charge and neutrons carry no charge. These particles are packed together into an extremely small space at the center of an atom. According to scattering experiments, the nucleus is spherical or ellipsoidal in shape, and about 1/100,000th the size of a hydrogen atom. If an atom were the size of a major league baseball stadium, the nucleus would be roughly the size of the baseball. Protons and neutrons within the nucleus are called nucleons.

he number of protons in the nucleus is given by the atomic number, *Z*. The number of neutrons in the nucleus is the neutron number, *N*. The total number of nucleons is the mass number, *A*. These numbers are related by

$$A = N + Z$$

A nucleus is represented symbolically by

$$_{Z}X^{A}$$

where X represents the chemical element, *A* is the mass number, and *Z* is the atomic number. For example, $_{6}C^{12}$ represents the carbon nucleus with six protons and six neutrons (or 12 nucleons with 6 protons and 6 neutrons.

Nuclear Force:-

There are 4 kind of known forces in the nature

Gravitational

Electromagnetic

Weak interaction, and

Nuclear forces

Out of these forces nuclear forces are strongest and responsible for keeping nucleons together in the nuclei.

This is short range force with maximum range upto 10^{-15}m. It has following properties.

1. Spin dependent:- nuclear force is spin dependent. This has been found that when spin of nucleons are parallel then force between them is repulsive and they are found in less favourable energy state (Shell Model).
2. Charge Independent:- force between the nucleons are charge independent and does not distinguished between proton- proton and neutron-proton.
3. Saturated nature:- forces between nucleons are saturated in nature.
4. Non-central:- Nuclear force are non-central in nature.

5. Nuclear force are attractive in nature with repulsive in core.

(Kindly read Bohr's atomic model before going to the electron proton model, as this serves the basis of e-p model. A gist is as)

**The Bohr theory of atomic spectra and atomic structure. In epoch-making papers written between 1913 and 1915, Bohr developed a theory of the constitution of atoms which accounted for many of the properties of atomic spectra and laid the foundations for later research on theoretical and experimental atomic physics. Bohr applied the quantum theory of radiation as developed by Planck and Einstein to the Rutherford nuclear atom. His theory is based on the following postulates.

1. An atomic system possesses a number of states in which no emission of radiation takes place, even if the particles are in motion relative to each other, although such an emission is to be expected according to ordinary electrodynamics. These states are called the stationary states of the system.

2. Any emission or absorption of radiation will correspond to a transi- tion between two stationary states. The radiation emitted or absorbed in a transition is homogeneous, and its frequency v is determined by the relation where h is Planck's constant and W1 and Wa are the energies of the system in the two stationary states.

3. The dynamical equilibrium of the system in the stationary states is governed by the ordinary laws of mechanics, but these laws do not hold for the transition from one state to another.

4. The different possible stationary states of a system consisting of an electron rotating about a positive nucleus are those for which the orbits are circles determined by the relation where p is the angular momentum of the electron, h is Planck's constant, and n is a positive integer, usually called the quantum number. These postulates are a combination of some ideas taken over.

The constituents of Nucleus

Proton-electron hypothesis:-

The fact that certain radioactive atoms emit ***alpha and beta*** rays, both of which are corpuscular in nature, led to the idea that atoms are built up of elementary constituents. As early as **1816,** on the basis of the small number of atomic weights then known, Prout suggested that all atomic weights are whole numbers, that they might be integral multiples of the atomic weight of hydrogen, and that all elements might be built up of hydrogen.

Prout's hypothesis was discarded when it was found that the atomic weights of some elements are fractional, as for example, those of chlorine (35.46) and copper (63.54). Nevertheless, so many elements have atomic weights which are very close to whole numbers that there seemed to be some basis for Prout's hypothesis. The idea that all elements are built up from one basic substance received new support during the early years of the 20th century when the study of the radioactive elements led to the discovery of isotopes. It was found that there are atomic species which have different masses in spite of the fact that they belong to the same element and have the same atomic number and chemical properties; the different species belonging to the same element are called ***isotopes.*** Although all have the same charge.

The proof of the existence of isotopes in the radioactive elements led to experiments to test whether some of the ordinary elements also consist of a mixture of isotopes. It was found that this is indeed the **case.** Most elements are mixtures of isotopes, and the atomic **masses** of the isotopes **are** very close to whole numbers. Chlorine, **as** found in nature, has two isotopes with atomic weights of 34.98 and 36.98, respectively; 75.4% of the chlorine atoms have the smaller **mass,** while **24.6%** have the greater **mass,** and this distribution explains the atomic weight 35.46 of chlorine.

Analogous results were obtained for copper. The different isotopes of an element have the same number and arrangement of extranuclear electrons, and consequently their spectra have the same general structure; they are distinguished from one another by their different atomic masses. The fact that the atomic masses of the isotopes of an element are close to whole numbers led Aston to formulate his ***whole number*** rule. According to this rule, which is really a modified form of Prout's hypothesis, all atomic weights are very close to integers, and the fractional atomic weights determined by chemical methods are caused by the presence of two or more isotopes each of which has a nearly integral atomic weight. Much of the experimental work on isotopes involved the analysis of the positive rays from different substances; and in all the work of thii kind the lightest positively charged particle that was ever found had the same mass **as** the hydrogen atom, and carried one positive charge equal in magnitude to the electronic charge, but of opposite sign. This particle is evidently the nucleus of a hydrogen atom and has a mass very close to one atomic mass unit. The combination of the whole number rule and the special properties of the hydrogen nucleus led to the assumptions that atomic nuclei are built up of hydrogen nuclei, and the hydrogen nucleus was given the name ***protun*** to indicate its importance as a fundamental constituent of all atoms. The whole number rule is actually an approximation, holding to an accuracy of about 1 part in 1000. The most precise experiments show that there are small but systematic departures from this rule over the whole range of elements.

To account for the mass of a nucleus whose atomic weight is very close to the integer A, it was necessary to assume that the nucleus contained A protons. But if this were the case, the charge on the nucleus would be equal to A, nearly the same **as** the atomic weight and not equal to the atomic number Z, which is half, or less, of the atomic weight. To get around this difficulty, it was assumed that in addition to the protons, atomic nuclei contained A - Z electrons; these would contribute a negligible amount to the mass of the nucleus, but would make the charge equal to + Z, **as** required. It was thus possible to consider the atom as consisting of a nucleus of A protons and A - Z electrons surrounded by Z extranuclear electrons. The number A is called the mass number and is the integer closest to the atomic weight.

The proton-electron hypothesis of the nucleus seemed to be consistent with the emission of ***alpha-*** andbeta particles b y the atoms of radioactive elements. The interpretation of certain generalizations about radioactivity in terms of the nuclear atom showed that both the alpha- and beta-particles were ejected from the nuclei of the atoms undergoing transformation; and the presence of electrons in the nucleus made it seem reasonable that under the appropriate conditions one of them might be ejected. It was also reasonable to assume that alpha-particles could be formed in the nucleus by the combination of four protons and two electrons. The alpha-particles could exist as such, or they might be formed at the instant of emission.

Discovery of neutron:-

The failure of the protonelectron hypothesis of the nucleus was related to the properties of the free electron. It was proposed, therefore, that the electrons **are** bound to the positively charged particles and have no independent existence in the nucleus. One possibility, which had been suggested by Rutherford **as** early **as 1920,** was that an electron and a proton might be **so** claeely combined as to form a neutral particle, and this hypothetical particle was given the name *neutron.* Now, all of the methods that have been discussed so far for detecting particles of nuclear size depend on effects of the particle's electric charge, as deflection in magnetic or electric fields and ionization. The presence of a neutron, which **has** no charge, would be very hard to detect, and many unsuccesdul attempts were made to find neutrons. Finally, in 1932, **as** one of the results of research on the disintegration or transmutation of nuclei by a-particles, Chadwick demonstrated the existence of neutrons. This discovery opened up a vast field for further experimental work and led to the presently accepted idea of the constitution ***of*** the nucleus: that it is built of protons and neutrons.

Proton-neutron Hypothesis :-

The discovery of a particle, the neutron, with an atomic weight very close to unity and without electric charge, led to the assumption that every atomic nucleus consists of protons and neutrons. Under the proton-neutron hypothesis, the total number of elementary particles in the nucleus, protons and neutrons together, is equal to the mass number A of the nucleus; the atomic weight is therefore very close to a whole number. The number of protons is given by the nuclear charge ***Z*,** and the number of neutrons is A - ***Z*.**

The new nuclear model avoids the failures of the proton-electron hypothesis. The empirical rule connecting mass number and nuclear angular momentum can be interpreted as showing that the neutron, **as** well as the proton, has a half-integral spin; the evidence is now convincing that the spin of the neutron is indeed $h/2\pi$. If both proton and neutron have spin 1/2 then, according to quantum theory, the resultant of the spins of A - elementary particles, neutrons and protons, will be an integral or half- integral multiple of $h/2\pi$ according to whether A is even or odd. **This** conclusion is in accord with all the existing observations of nuclear angular momenta. The value of the magnetic moment of the neutron is close to -2 nuclear magnetons; it is opposite in sign to that of the proton, but not very different in magnitude. The values for both the proton and neutron are consistent with those measured for many different nuclei. Finally, since the mass of the neutron is very close to that of the proton, the argument showing that protons can be contained within the nucleus is also valid for neutrons. The neutron-proton hypothesis is consistent with the phenomena of radioactivity. Since there are several reasons why electrons cannot be present in the nucleus, it must be concluded that in radioactivity, the electron is created in the act of emission. This event is regarded **as** the result of the change of a neutron within the nucleus into a proton, an electron, and a new particle called a ***neutrino,*** and both experimental and theoretical evidence offer strong support for this view. In radioactivity, then, the nucleus is transformed into a different one with one proton more and one neutron less, and an electron is emitted. An ***alpha*** particle can be formed by the combination of two protons and two neutrons. It may exist as such in the nucleus, or it may be formed at the instant of emission; the latter possibility is now regarded as more likely.

References:-

Many sources which includes personal efforts along with

MIT lectures, Nuclear Physic by Krane, (TMH e-books) and other similar source.

Regards

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Nuclear forces and Nuclear Structures

Introduction:-

A large amount of experimental information about atomic nuclei is now available, examples of which have been given in preceding chapters. Although the data and their interpretation are consistent with the idea that nuclei are built up of protons and neutrons, there is as yet no satisfactory explanation of how nuclei are held together. It has not yet been possible to analyze the forces which hold neutrons and protons together and the structure of nuclei is not understood. There is no picture or theory of the nucleus which can unite the available information about nuclei into a consistent body of knowledge like that of the quantum-mechanical theory of atomic structure. It is possible only to show how the problem of nuclear forces and nuclear structure has been attacked, to point to some successes, and to indicate some limitations and dilemmas.

The Binding Energy:-

The mass energy $m_n c2$ of a certain nuclide is its atomic mass energy $\boldsymbol{m_a c2}$ the total mass energy of *Z* electrons and the total *electronic* binding energy *:*

$$M_n c^2 = m_a c^2 + Z m_e c^2 + \sum B_i \quad (1)$$

where ***Bi*** is the binding energy of the ith electron. Electronic binding energies are of order 10-100 keV in heavy atoms, while atomic mass energies are of order ***A*** x 1000 MeV; thus to a precision of about 1 part in lo6 we can neglect the last term of Equation 1 . (Even this 10^{-6} precision does not affect measurements in nuclear physics because we usually work with *differences* in mass energies, such as in determining decay or reaction energies; the effects of electron binding energies tend to cancel in these differences.)

The *binding energy B* of a nucleus is the difference in mass energy between a nucleus *$XN* and its constituent *Z* protons and *N* neutrons:

$$B = \{Zm_p + Nm_n - [m(^{A}X) - Zm_{e]}\}c^2 \quad (2)$$

where we have dropped the subscript from mA-from now on, unless we indicate otherwise, we shall always be dealing with *atomic* masses. Grouping the *2* proton and electron masses into *2* neutral hydrogen atoms, we can rewrite Equation 3.24 as

$$B = [Zm(^1H) + N\, m_n - m(^AX)]\, c^2 \qquad (3)$$

With the masses generally given in atomic mass units, it is convenient to include the unit conversion factor in c^2, thus: c^2 = 931.50 MeV/u.

We occasionally find atomic mass tables in which, rather than $m(^AX)$, what is given is the *mass defect* **A** = $(m - A)c^2$. Given the mass defect, it is possible to use above Equation to deduce the atomic mass.

Other useful and interesting properties that are often tabulated are the neutron and proton separation energies. The *neutron separation energy* Sn is the amount of energy that is needed to remove a neutron from a nucleus $^A_zX_N$, equal to the difference in binding energies between $^A_zX_N$ and $^{A-1}_ZX_{N-1}$: In a similar way we can define the *proton separation energy* **Sp** as the energy needed to remove a proton:

$$S_p = B(^A_ZX_N) - B(^{A-1}_{z-1}X_N)$$

$$= [m(^{A-1}_{z-1}X_N) - m(^A_ZX_N) + m(^1H)]c^2 \qquad (4)$$

The hydrogen mass appears in this equation instead of the proton mass, since we are always working with *atomic* masses; you can see immediately how the *Z* electron masses cancel from Equations 3 and 4.

The neutron and proton separation energies are analogous to the ionization energies in atomic physics-they tell us about the binding of the outermost or valence nucleons. Just like the atomic ionization energies, the separation energies show evidence for nuclear shell structure that is similar to atomic shell structure. We therefore delay discussion of the systematics of separation energies until we discuss nuclear models in next . As with many other nuclear properties that we will discuss, we gain valuable clues to nuclear structure from a *systematic* study of nuclear binding energy.

Since the binding energy increases more or less linearly with *A*, it is general practice to show the average binding energy per nucleon, ***B/A,*** as a function of *A.* Figure shows the variation of *B/A* with nucleon number. Several remarkable features are immediately apparent. First of all, the curve is relatively constant except for the very light nuclei. The average binding energy of most nuclei is, to within lo%, about 8 MeV per nucleon. Second, we note that the curve reaches a peak near $A = 60$, where the nuclei are most tightly bound. This suggests we can “gain” (that is, release) energy in two ways-below $\boldsymbol{A} = 60$, by assembling lighter nuclei into heavier nuclei, or above $A = 60$, by breaking heavier nuclei into lighter nuclei. In either case we “climb the curve of binding energy” and liberate nuclear energy; the first method is known as *nuclear fusion* and the second as *nuclear fission.*

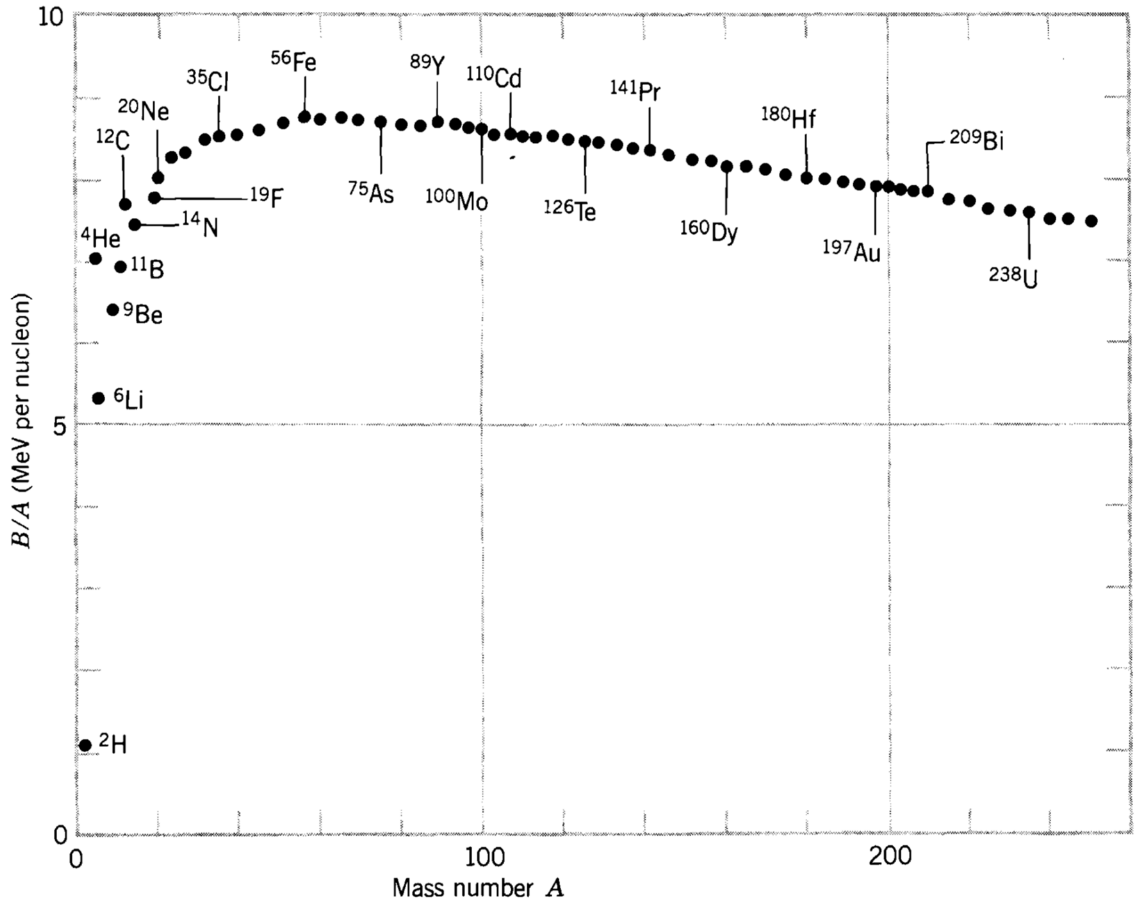

Figure:- Binding energy curve with mass number (*image taken from reference book)

References:-

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