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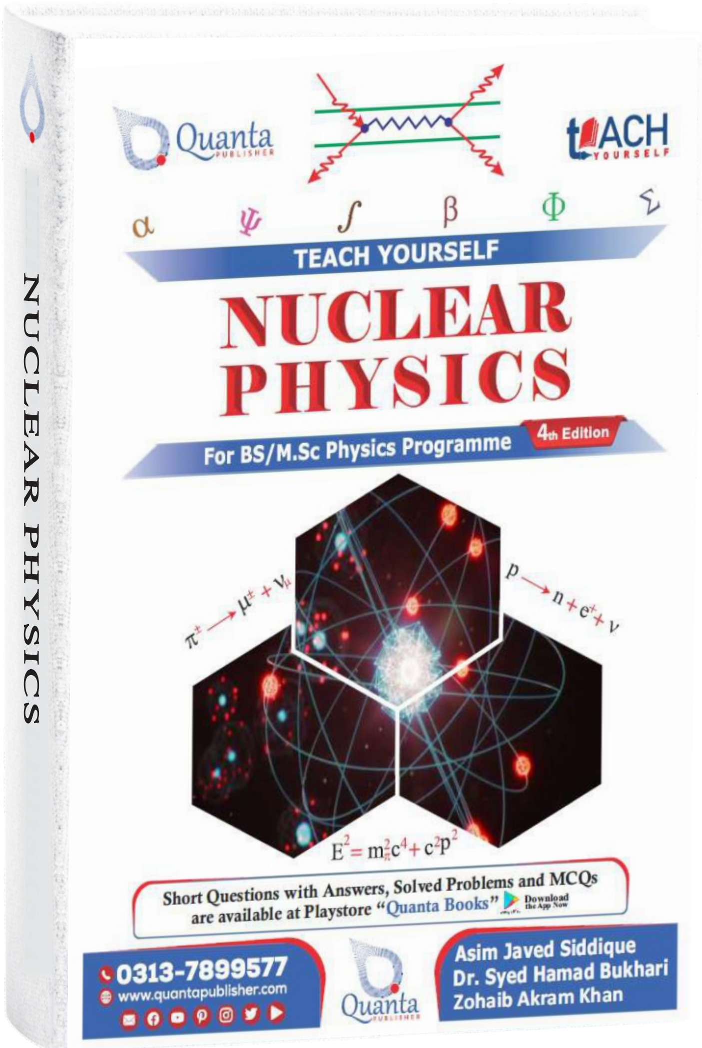

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Nuclear Physics

4th Edition

For **BS/M.Sc Physics** students of all Pakistani Universities

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Contents

Chapter 1

Basic Properties of Nucleus

In present chapter the different properties of the nucleus have been discussed such as mass, volume, density, size, mass defect, binding energy, magnetic moment, angular momentum etc. Before knowing the insight of the nucleus it is necessary to review the idea of atomic models presented by different scientists with the passage of time. Some of the models are enlisted below.

1. Daltons Atomic Model.

2. J. J Thomsons Model of Atom.

3. Rutherfords Atomic Model.

1.1 Models

Daltons Atomic Model

In 1803, Dalton presented his theory related to atom which was named by **Atomos** meaning indivisible has the following postulates as follows:

All the elements are composed of atoms which cannot be divided further by any means.

All atoms have the same identity of the same element. Atoms of different elements are different in weight and character.

Different atoms of different species can be combined to form a compound like B_2O_3, SiO_2 etc.

These famous postulates have been dominated till the end of 19th century and assumed to be the atom as a neutral. Later as the science developed by different scientists, this theory was discarded that atom cannot be subdivided.

Specially after the discovery of electron by J. J. Thomson in 1897 which revolutionized the world about the structure of atom. So, it was assumed that electron is the basic

Chapter 2

Nature of Nuclear Forces

AFTER the discovery of neutron, the mystery was solved that the nucleus contains proton and neutron. The forces known in the beginning of the twentieth century are gravitational and electromagnetic. Coulomb forces could not account for the stability of the nucleus. Protons carry positive charge and neutrons are neutral particles. The electrostatic force will be repulsive between two protons. So, this force will cause the nucleus to break and thus, it cannot account for the binding of the nucleus. The gravitational force of attraction between two nucleons is extremely weak; it also cannot explain the binding energy of the nucleus. This force is significant only on the macroscopic scale, such as for astronomical objects. The nuclear force is ten million times stronger than the chemical bonding that holds the atoms together in molecules. Gluons are responsible for holding quarks together.

2.1 Types Of Interactions

In order to understand the behavior of the elementary particles, i.e. their formation and decay, one needs to understand different types of fundamental interactions[1] among them. These interactions which fall into the following categories:

1. Gravitational interactions.
2. Electromagnetic Interactions.
3. Strong interactions.
4. Weak interactions.

In fact, all the known processes occurring in nature (starting from subnuclear to extragalactic levels) can be understood as manifestations of these four interactions. Note that in particle physics, the words force and interaction are used for the same purpose. Now we give brief introduction of these interactions.

[1] One also hears about many other interactions like chemical, electrical, mechanical, atomic forces, but all such interactions belong to the above-mentioned interctions.

Chapter 3

Nuclear Models

WHAT physicists have done so far is to propose model which can be used to interpret certain aspects of the behavior of the nuclei. Various model have been proposed for the detailed study of nucleus are the collective models, fermi gas model and the shell model, liquid drop model. There is detailed discussion about all the models.

3.1 Introduction

A variety of early experiments demonstrated that the character of the nuclear force differed markedly from any previously encountered in classical physics. However, a quantitative description of the nuclear force has turned out to be elusive. As we learned from atomic physics, where the correct level structure was found only after the classical Coulomb interaction between the nucleus and the electrons was extended to the atomic domain through quantum mechanics, knowing the properties of a force is only the first step in developing a theory of structure. Although neutrons and protons were known to be the nuclear constituents, the absence of a fundamental understanding of the nuclear force made it difficult to determine the structure of the nucleus. It is not surprising therefore that, instead of a theory, phenomenological models of the nucleus were constructed to accommodate the many remarkable experimental findings. In the following, we describe only a few such models. We should also keep in mind that, unlike the case of atomic physics, most of these nuclear models were proposed to explain only limited aspects of the data, which is precisely what they do.

Chapter 4

Theories of Radioactive Decay

RADIOACTIVE decays, also known as nuclear decay, is the process by which a nucleus of an unstable atom loses energy by emitting radiations. There are many different types of decay depending upon the particles emitting. The first decay process to be discovered were alpha decay, beta decay and gamma decay. Alpha decay occurs when a nucleus eject an alpha particle(Helium nucleus). Beta decay occurs when a nucleus emits an electron or positron and a type of neutrino. The detailed description of the mentioned topics are given in this chapter.

4.1 Introduction

Radioactivity was discovered in 1896 by the French scientist Henri Becquerel, while working on phosphorescent materials. These materials glow in the dark after exposure to light, and he suspected that the glow produced in cathode ray tubes by X-rays might be associated with phosphorescence. He wrapped a photographic plate in black paper and placed various phosphorescent salts on it. All results were negative until he used uranium salts. The result with these compounds was a blackening of the plate. These radiations were called Becquerel rays.

It soon became clear that the blackening of the plate had nothing to do with phosphorescence, because the plate blackened when the mineral was in the dark. Non-phosphorescent salts of uranium and metallic uranium also blackened the plate. It was clear that there was a form of radiation that could pass through paper and was causing the plate to become black. At first, it seemed that the new radiation was similar to the recently discovered X-rays. Further research by Becquerel, Ernest Rutherford, Paul Villard, Pierre Curie, Marie Curie, and others discovered that this form of radioactivity was significantly more complicated. Different types of decay occur, producing very different types of radiation.

Chapter 5

Nuclear Reactions

IN this chapter, general features of nuclear reactions are described. At higher incident energy particle, direct reactions become important. For heavy ion, direct reactions new features are seen reflecting the more classical behavior of ions. A nuclear reaction is a process which occur when a nuclear particle comes into contact with another during which exchange of energy and momentum takes place.

5.1 Introduction

We have discussed earlier, how Rutherford discovered the existence of the nucleus by bombarding fast moving -particles on thin gold foil. Similarly, Chadwick in 1932 bombarded fast moving -particles on ^{9}Be nucleus, which led to the discovery of neutrons. The question arises, what happens when we bombard fast moving, charged/neutral particles (also known as projectiles) on a stable nucleus (also called target nucleus). Experimentally, it has been observed that these particles can interact with the nucleus or can be captured by the nucleus. The nucleus so formed can be different from the initial nucleus and is invariably unstable. It decays by emitting -ray/a particle/a group of particles. The daughter nucleus so produced could be stable or unstable. In case it is unstable, it follows the laws of radioactive decay.

Nuclear Reaction

This process of bombarding a target nucleus by fast moving projectiles and the subsequent interaction between the two, which alters the composition, energy, etc. of the target nucleus is known as nuclear reaction. This is also known as transmutation of one element into another.

Suppose a target nucleus X is bombarded by particle a. During this process a new nucleus Y is formed and a particle (or -ray) b is emitted, then this nuclear reaction is written as:

$$a + X \qquad Y + b$$

Chapter 6

Elementary Particles

THE discovery of elementary particles, which form all the matter in the universe, has a long history. Scientists have often made claims to identify the basic building blocks of matter. Usually as elementary particle was thought to be point-like particle having no substructure. However, structure can be probed up to a given scale, which is decided by the available energy of probe.

6.1 Fundamental Interactions in Nature

The elementary particles (see Fig. (6.1)) which have been discovered so far are exceeding 200. The interactions amongst these particles may be considered as the source of the natural phenomena. There are four fundamental interactions known in nature, as follows;

1. Strong Interaction
2. Electromagnetic Interaction
3. Weak Interaction
4. Gravitational Interaction

1. Strong Interactions

This is the most dominant nuclear interaction in almost all nuclear phenomena, nuclear energy levels and so on. It is the interaction between neutron and proton having short range like the weak interaction (Range $10^{\ 15}$m). With this short range this interaction predominates over all other interactions. The quantum of the strong interaction is the pi-meson or pi-on (on).

The nuclear strong interaction is responsible for the formation of the so called meson and baryon resonances or excited states of the mesons and baryon particles. A term usually used for the strongly interacting particles is called hadrons.

Strong interaction is short range force ($10^{\ 15}$m) conserves Baryon number (B), charge number (Q), hypercharge (Y), parity (P), isospin (T) and its components (T_x). The

Chapter 7

Detectors and Accelerators

IN this chapter we shall discuss the interaction of heavily charged particle with matter and then particle accelerator and detectors will be discussed in detail. A particle accelerator is an instrument used to increase the Kinetic energy of charged particles i.e. electrons, protons, alpha particles and other heavy ions. The relation of particle accelerator to the nuclear Scientist is the same as that of microscope to a Biologist or telescope of Astronomer. If we perform any nuclear physics related experiment or apply nuclear science to any problem, nuclear radiation detector plays a vital role in such measurements. The development of nuclear reactor started with the discovery of Henry Becquerel in 1896.

7.1 Ionization Chamber

Ionization is a process in which neutral atoms gain or lose electrons. An ionization chamber uses this process to detect radiations *An ionization chamber is a device used to measure the ions which are produced by the passage of the charge particles through the gas.*

Principle

When charged particles pass through a gas, the ions are produced in the gas. These ions can be separated and collected by the electrodes. The resulting change of voltage on the electrodes is recorded.

Construction

It has a chamber filled of a gas. It has a window on one side which is usually made of glass or mica to allow the incident radiation to enter the chamber. The anode is fixed and is insulated with some material while the walls of the container act as cathode. The anode is connected to the +ve terminal and the cathode is

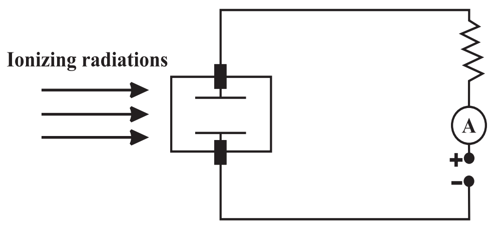

Fig. 7.1. A schematic picture of working of ionization chamber.

Chapter 8

Neutron Physics and Nuclear Fission

IN this chapter we shall first discuss the about the production and detection of neutron and then about the nuclear fission. Nuclear fission is a process of splitting a nucleus, generally heavy atom into when it is bombarded by neutrons fission releases large amount of energy along with neutrons.

8.1 Discovery of the Neutron

It is remarkable that the neutron was not discovered until 1932 when James Chadwick used scattering data to calculate the mass of this neutral particle. Since the time of Rutherford it had been known that the atomic mass number A of nuclei is a bit more than twice the atomic number Z for most atoms and that essentially all the mass of the atom is concentrated in the relatively tiny nucleus. As of about 1930 it was presumed that the fundamental particles were protons and electrons, but that required that somehow a number of electrons were bound in the nucleus to partially cancel the charge of A protons. But by this time it was known from the uncertainty principle and from particle-in-a-box type confinement calculations that there just wasnt enough energy available to contain electrons in the nucleus.

A rough scale of the energy required for the confinement of a particle to a given dimension can be obtained by setting the de-Broglie wavelength of the particle equal to that dimension. For example, if we presume that the dimension of a hydrogen atom is about 0.2 nm, then the corresponding confinement energy is about 38 eV, the correct order of magnitude for atomic electrons. But to confine an electron to a nuclear dimension of about 5 fermis requires an energy of about 250 MeV. The maximum available confinement energy from the electrical attraction to the nucleus is given by

Chapter 9

Thermonuclear Reactions

BINDING energy per nucleon in the lightest nuclei is less than that for nuclei of intermediate mass number. It implies that the sum of the masses of individual light nuclei is more than would be the mass of the nuclei formed by their fusion. Therefore, the combination of two of the lightest nuclei by a process of fusion is thus energetically advantageous. Moreover, nuclear fusion is responsible for the evolution of life on earth.

9.1 Fusion Process and its Mechanisms

The practical utilization of the energy released in nuclear fission both for beneficial and destructive purposes, is now an accomplished fact. Concentrated efforts are now being made all over the world for the practical use of the energy released in another type of nuclear reaction for peaceful purposes. This reaction is known as the fusion reaction. As the name implies, two (or more) light nuclei fuse together to produce a heavier nucleus with $A < 56$. For very light nuclei, such reactions are usually exoergic, which can be understood qualitatively from the binding fraction curve.

For very light nuclei, the binding fraction f_B is a rapidly rising function of A which means that a nucleus produced as a result of the fusion of two lighter nuclei may have greater binding energy than the combined binding energies of the latter.

For example, if we consider the fusion of two deuterons to produce an alpha particle according to the equation $H^2 + H^2 \quad He^4$, we get the Q value of the reaction as;

$$Q = B \quad 2B_d = 4f_B \quad 2 \quad (2f_{Bd}) \quad ; \quad Q = 28\ 3 \quad 2 \quad 2\ 225 = 23\ 84 \text{ MeV}$$

Thus the energy released per nucleon in this reaction is 23.84/4= 5.96 MeV. This is much larger than the energy released per nucleon in fission. The latter is about (200/238) or 0.84 MeV. So mass for mass, the fusion reaction usually gives more energy than the fission reaction.

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