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CHAPTER

The Perspective

1.1 EARLY HISTORY

The subject of Nuclear Physics has a very large range—both in concepts and techniques. Dealing with the smallest of the physical entities—nucleons and nuclei—interacting through the strongest forces available in nature; the subject requires the application of quantum mechanics in a particular manner—which is somewhat different from that required in atomic or solid state physics. Also the experimental techniques developed are special, because of the higher energies involved, by a factor of 10^3 to 10^6 compared to the problems of atomic or molecular physics. We will try to convey the perspective of both the concepts and techniques to the reader, in this chapter, before we plunge into the actual subject.

Nuclear Physics, like many other branches of physics, had a very humble beginning. In 1896, Becquerel[1], at the suggestion of Poincáre, was investigating the uranium salts to find out a relationship between the property of optical fluorescence and the newly discovered X-rays. While a search for this relationship proved illusory, he found, accidently, that the uranium salts emitted some penetrating radiation; which could fog the photographic plates even when they were covered with a good amount of wrapping material. Since then, a large number of experimental and theoretical developments, have brought the subject of nuclear physics to its present status where one is able to understand to a large extent, the various properties of nuclei in their ground as well as excited states.

In understanding the nature of the structure of the nucleus, first breakthrough came when Rutherford along with Geiger and Marsden[2] in 1913, performed the famous experiments on α-scattering from thin gold and platinum foils. They discovered that the number of α-particles scattered from a thin platinum foil at backward angles were one in 8000 compared to 1 in 10^{14} expected on the basis of the J.J. Thomson's[3] melon-seed model of the atom. Rutherford[4], successively explained these experiments on the basis of a model in which the positively charged heavy nucleus sits at the centre of the atom, surrounded by electrons. This model was supplemented by N. Bohr[5] in the same year, by the assumption of stationary orbits of electrons, thereby giving birth to the presently accepted, Bohr-Rutherford model of the atom or the more commonly called Bohr's Atomic Model.

The experiments on positive rays by J.J. Thomson[6], in 1912, and afterwards by Aston[7] in 1919 showed that hydrogen nuclei were protons and that nuclear masses were nearly the integral number of the proton mass. Aston also discovered that many nuclei consisted of more than one isotope, which had, the same amount of charge but different masses. Each isotope, however, consisted of the integral number of the proton masses approximately. The proper interpretation of the isotopes had, of course, to wait for some years. In the beginning, it was surmised that the nucleus consists of protons and electrons, with the number of protons about twice the number of electrons. This could account for the charge and the mass of both the nucleus and an atom. It seemed to be further supported by the observation that some radioactive nuclei emitted electrons. However, this hypothesis was rejected on the basis of statistics. Also the de Broglie wavelength of an electron inside a nucleus is expected to be of the same size as the nucleus. This requires the energy of electrons, emitted from nuclei (called β^--rays) to be of the order of more than 10 MeV; while the experimentally measured values of energies of beta rays are only of the order of a couple of MeV.

The above mystery was resolved in 1932, by the discovery of neutrons by Chadwick[8]. This discovery proved to be a landmark in the development of nuclear physics. Neutron was, at once, recognised as the 'other' particle, besides proton, which constituted the nucleus. Various isotopes were, then, understood to be as nuclei, with the same number of protons, but different number of neutrons. This neutron-proton model was later on confirmed by many observations on nuclear reactions. It also resolved the difficulties of the electron-proton model in a natural manner.

In the meantime, a lot of developments took place on the theoretical side. Especially quantum mechanics was developed from 1900 to 1928; by stalwarts like Planck, de Broglie, Schrödinger, Heisenberg and Dirac[9]. A theoretical framework for the understanding of the many-body microscopic structures like atoms and molecules was thus created. Application of these concepts to nuclei was a logical consequence. This meant development of the theoretical framework to explain the observed properties of nuclei in terms of the interaction between neutrons and protons (called nucleons) inside the nucleus, assuming that the same theoretical framework which explains atomic phenomena quite satisfactorily is also applicable to a nucleus which is a much smaller system.

The phenomenon of radioactivity, was quite well established by this time. It was known, for example, that there existed among heavier nuclei, a large number of naturally occuring radioactive isotopes which emitted nuclei of He^4 (called alpha particle), electrons (called β^--rays), and electromagnetic radiations of very short wavelengths (called gamma (γ) rays). Also, whereas the observed spectra of alpha and γ-rays were discrete, corresponding to the discrete excited states of the residual nuclei, the spectrum of β-rays was continuous. In the beginning, this gave rise to many speculations; one of them even envisaged a breakdown of the law of conservation of energy[10]. This paradox was, however, solved in 1933 by Pauli's hypothesis[11] of the existence of neutrino—a massless and a chargeless particle with an angular momentum (or spin) of $1/2\hbar$. Fermi[12] in 1934, gave his theory of β-decay, assuming the simultaneous emission of an electron and anti-neutrino (e– $\bar{\nu}$) in a negative beta (β^-) decay and the emission of positron and a neutrino (e^+–ν) in a positive beta decay (β^+). The two particles share their energies and give rise to a continuous spectrum of electrons or positrons (see Chapters 2 and 8).

The next relevant question which arose was: 'What is the nature of the nuclear forces, which bind the nucleons inside the nucleus?' For this purpose, it was necessary to study not only the properties of ground states of nuclei, but also those of the excited states; and the phenomenon of break up of nuclei. It had been earlier (1919) demonstrated by allowing α-particles from radioactive nuclei to fall on stable nuclei, that nuclei can be broken; emitting protons and neutrons. A frantic search was, therefore, started to find out artificial methods to excite or to break the nucleus, by artificial means.

1.2 ACCELERATORS

This resulted in designing and constructing different types of particle accelerators.

First accelerator was designed and fabricated in 1931 by R.J. Vande Graff at MIT, Cambridge[13] (U.S.A.). It was an electrostatic accelerator known after his name (Vande Graff Accelerator). Another accelerator around the same time was designed by J.D. Cockcroft and E.T.S. Walton at Cavandish Lab, Oxford (U.K.)[14], based on the principle of multiplying the voltage by charging the condensers in parallel and discharging them in series. As a matter of fact, the first nuclear reaction, by using any accelerator was conducted with the Cockcroft-Walton accelerator[15] in 1932, by accelerating protons to 300 KeV and allowing them to fall in Li^7. In the same year of 1932, E.O. Lawyence[16] built and tested the first cyclic machine called the Cyclotron at Berkley (U.S.A.) for protons. Later in 1945–46, Veksler and McMillan[17] modified the Cyclotron principle to include phase-stability to develop the so-called synchrocyclotron for higher energies, which can now go up to an energy of some 700 MeV for protons. These electrostatic and cyclic machines, with their variations, are now quite commonly[18] used for accelerating protons, deuterons, tritons, He^3, alpha particles and the heavier ions from Li^7 right upto uranium to several MeV per particle (say up to more than 50 MeV/A).

A combination of the principle of phase-stability and the application of alternating gradient was developed by Christophilos[19] (1950) and independently, by Courrant Livingston and Snyder[20] (1952) to apply to a doughnut type of cyclic machine called synchrotron. This machine has no apparent energy limits. Already energies of more than 10^6 MeV for protons have been achieved[25]. The synchrotrons are now being used also for heavy ions, as well as for electrons.

The acceleration of electrons, however, presented some special problems, because, their motion becomes relativistic even around one MeV of energy. Therefore, the cyclotron concept could not be easily adapted for them. D.W. Kerst[23], in 1941, used the principle of electromagnetic induction to develop the betatron. With this machine, it has been possible to accelerate electrons up to several hundred MeV's. Another important development in accelerator technology has been the evolution of the concept of linear accelerator. These are based on the principle of multiple acceleration on an approximate straight trajectory[21]. The first linear accelerator for protons was developed by D.H. Sloan and E.O. Lawrence[22] in 1931. Energies of 20 GeV for electrons; and 10 GeV for protons and greater than 10 MeV/A for heavier ions has been achieved using the principle of linear accelerators, especially using the technology of superconducting linear accelerators.[21,26]

Some very recent interesting developments in the cyclotron[24] (including synchrotrons) technology have opened up new ranges of intensities and energies. The concept of pulsed storage rings has increased the intensity of protons at the highest energy enormously[25]. The protons from synchrotron are injected into a ring, to which more and more protons are added at regular intervals from the main synchrotron. They are, then, ejected from the storage ring by applying a pulsed electric field at suitable times. Also new ion-sources *(e.g.* E.C.R. type) and the use of superconducting[24] magnets has made it possible to design very high energy cyclotrons for heavy ions. These developments have now made it possible to have electrons up to 10–20 GeV; protons for more than 1000 GeV; and heavy ions for more than 500 MeV/A[25,26]. Many accelerators are under development in the world, in these energy ranges.[25,26]

Recently[27] heavy ions, as projectiles have become very much popular for experiments on nuclear reactions or nuclear structure. Energies up to 10 MeV per nucleon have already been achieved for uranium and up to about 50 MeV/A for lighter nuclei. Still higher energies are expected from the new accelerators under development. The heavy ion induced nuclear reactions may be the major activity in nuclear physics in the near future.

The latest entry[28 (a)] into this field in accelerators (linear accelerators and (or plus) cyclotrons), accelerating exotic beams, *e.g.* radioactive ions or cluster-molecules, resulting in very new research fields in nuclear physics and material sciences.

The nuclear studies, with which we are concerned in this book; are generally carried out with accelerators up to say a few hundred MeV per particle. Still higher energy accelerators are, in general, employed for the production of fundamental particles like mesons, etc.

1.3 REACTORS

Another phenomenon, in nuclear physics, which has gained importance since 1939, was 'fission'. The phenomenon of fission of nuclei induced by thermal neutrons was discovered, experimentally by O. Hahn and F. Strassman[28] in 1939 and is one of the great discoveries in nuclear physics (Chapter 9). Afterwards[28], in fifties and sixties, the phenomenon of spontaneous fission was discovered for very heavy nuclei, beyond uranium. This principle of nuclear fission was used by Enrico Fermi[29] in 1942, for designing the first nuclear reactor. Later this principle resulted in the first nuclear explosion in 1945. Apart from their use as a source of power; the reactors form a major category of machines used extensively for research in nuclear physics. They are a copious source of thermal or fast neutrons and are used not only for producing new species of nuclei through neutron-capture but also for studying neutron reactions at these low energies and the structure of materials through neutron diffraction. At present[30], there are many research reactors in the world with neutron flux of the order of 10^8 to 10^{14} neutrons/cm^2/sec. Apart from these research reactors, there are several power reactors for providing electric power. The power reactors may range from a few megawatts to many hundred megawatts.[30]

1.4 COMPLEX NUCLEI

Various properties of complex nuclei have been studied using these instruments and machines, *e.g.*, (1) The masses and the binding energies of various nuclei in their ground state (2) Nuclear radii (3) Energies of the excited states (4) Angular momenta (spins), parities, magnetic moments and quadrupole moments of the ground and excited states of nuclei (5) Transition probabilities between the various excited states; and (6) The various cross-sections involving elastic and inelastic scattering and reactions leading to states of different nuclei.

The experimental techniques involved, for the measurement of the various properties of both the ground states and excited states of nuclei are:

1.4.1 The Ground State

(*i*) Mass spectrometry for measuring the masses of various nuclear species and hence their binding energies[31] (*ii*) Various atomic-beam methods as developed by Rabii and Coworkers[32], for measuring angular momenta and magnetic moments (*iii*) Nuclear magnetic resonance (NMR) and nuclear quadrupole resonance (NQR) for the measurement of the magnetic and quadrupole moments[33], respectively (*iv*) Some techniques based on atomic spectroscopy[34] for angular momenta and other properties of nuclei, and (*v*) The various scattering techniques for the measurements of nuclear radii[35] [Chapter 2].

1.4.2 The Excited States

(*i*) Nuclear spectrometry[36] using magnetic spectrometers, scintillation crystals, and solid state detectors like Ge-Li, Si-Li and surface-barrier detectors; along with sophisticated electronics like multi-channel and multi-parameter analysers or online computing systems for measuring energies of particles or gamma rays. (*ii*) Various techniques of angular distribution, angular correlation or polarisation for measuring the spins, parities, magnetic moments and quadrupole moments of the excited states[37] [Chapter 2].

These techniques combined with the techniques of accelerators and reactors have made experimental nuclear physics as one of the most challenging and exciting subjects of physics. A large amount of data has now been collected and published from time to time[38], in Nuclear Data Sheets, etc.

1.5 NUCLEAR FORCES

Any theoretical attempt to correlate these experimental facts and to understand them in terms of the motion of nucleons in the nuclei, requires the knowledge of nuclear forces operating between proton-neutron, proton-proton and neutron-neutron. The study of two-nucleon system of deuteron, and *n-p* or *p-p* scattering up to about 100 MeV provides information on free nucleon-nucleon interaction. Information about nuclear forces between *n-n* has been obtained either from *n-d* scattering or from comparison of the mirror nuclei. Analysis of the three-body systems like He^3, H^3, or *n-d* or *p-d* scattering has further contributed a great deal to the detailed knowledge about the nuclear forces. As a result, it has been possible to draw the following conclusions about the nuclear forces. (1) They have a short-range, of the order of 2 Fermis (2) They are predominantly central, but with a small, though significant, tensor term (3) The nuclear potential has a hard repulsive core of the range of $\approx$ 0.5 fermis, and an attractive part of the range of about a couple of fermis (4) Central forces are spin-dependent (5) The nuclear forces have an exchange character, which gives rise to the property of saturation of nuclear forces, which explains in a natural manner, the property of binding energy per nucleon being independent of number of nucleons in the nucleus; and the constant nuclear density. (6) They are charge-independent, *i.e.* they are intrinsically the same for *n-p, p-p* or *n-n* interaction. This property has given rise to a new concept of isotopic spin. (7) They depend on the spin-orbit coupling of a nucleon. (8) A detailed study of the complex nuclei exhibits, many-body character of the nuclear forces. (9) They may also depend on relative angular momenta and hence on relative velocities. (see Chapters 3–6).

Though the broad features of the nuclear forces, as mentioned above, are established, the exact quantitative expression for nuclear potential which should be applicable to the free nucleon-nucleon scattering as well as to nuclear structure problems is still, less than settled. Based on two-body interactions, certain effective nucleon-nucleon interactions have been proposed[39] whose application to real complex nuclei have shown limited successes (Chapter 10). Three-body forces have also been considered[40]. Discovery of mesons and latter on quarks, and their relationship with nuclear forces, has brought the subject to the present status.[40]

1.6 NUCLEAR DECAY

The nuclear structure problems based on our understanding of nuclear forces, can be studied either through nuclear decay using radioactive nuclei, or through nuclear reactions.

Nuclear decay, in radioactive nuclei involves three modes: (*i*) β-decay, (*ii*) γ-decay and (*iii*) α-decay. Out of these three modes, β-decay corresponds to 'Weak' interaction; γ-decay to electromagnetic interaction; and α-decay to 'nuclear' and coulomb-interaction. The strength of the β-decay is governed by weak interaction constant – $\left[(g_\beta c^2/\hbar^2)\, m_\pi^2)/\hbar c\right]^2 \approx 10^{-13}$, that of γ-decay, intrinsically by electromagnetic interaction constant $(e^2/\hbar c) = 1/137$, which is called the fine structure constant; and that of α-decay by nuclear interaction constant $(g_N^2/\hbar c) \approx 1$, and the Coulomb interaction.

The interest in α-decay arises, both because of its relationship with nuclear structure; as well as for the mechanism of decay. The characteristics of α-decay were explained by Gamow's theory[41] which proved to be one of the earliest successes of the quantum mechanics. This explained the phenomenon of tunnelling of α-particles through coulomb barrier on the basis of W.K.B. approximation, as discussed in Chapter 9.

The electromagnetic transitions, also include internal conversion, apart from γ-decay. In these cases, the form of the interaction is very well understood. The interest in this decay process basically arises because of the information that one gets about the properties of the various nuclear levels and the transitions, *e.g.* the spins and parities of levels. The mixing ratios of the transitions help in understanding the detailed wave functions of the nuclear states (Chapter 7). The beta decay includes electron (β^-) and positron (β^+) emission; as well as electron capture (EC). In this case, the interest is not only in the problem of nuclear structure but also in the basic interaction itself, because it represents one of the less understood fundamental interactions. The theory of beta decay was earlier developed by Fermi and Gamow-Teller.[12] The discovery of non-conservation of parity in β-decay has created a lot of interest among physicists because of its effect on weak interactions in particle physics. Detailed theory of beta decay; and its implications for nuclear structure are developed in Chapter 8.

Apart from the studies of decay of radioactive nuclei, a lot of information about nuclear structure has come from the excitation and de-excitation of nuclei involved in various reactions.

Because of the still existing ambiguities in the knowledge of nuclear forces, the solution to the problem of a nuclear structure-involving the complex nuclei, has not been an easy one. It gets further complicated by the fact that for obtaining the theoretical solution of these problems, one has actually to solve a many-body problem with strong internucleon forces, which do not lend easily to the various perturbation techniques, used, say in atomic physics.

1.7 NUCLEAR STRUCTURE MODELS

Historically, the problem was circumvented by postulating various models of nuclear structure. The first nuclear structure model extensively developed was the liquid drop model. This model was inspired by Neil Bohr's ideas of the compound nucleus, according to which, once a nucleon enters a nucleus, it loses the properties of its individual motion; because of the extremely strong nucleon-nucleon interaction inside the nucleus. Because of this reasoning, it was assumed in the liquid drop model, that the motion of individual nucleons in a nucleus are not important. Rather the whole nuclear matter in the nucleus, behaves like charged liquid drop, and one should consider the general motion of the liquid for calculating the various properties of the nucleus. The nuclear drop model was developed by Weiszãcker[42] for obtaining the nuclear masses and the binding energies in terms of macroscopic parameters like volume energy, surface energy, coulomb energy and pairing energy, etc. of the nucleons, considering the nucleus as a liquid drop. This model was later come handy in explaining the phenomenon of nuclear fission. Its latest version, *i.e*. collective model as developed by Rainwater[43] and by A. Bohr and B. Mottleson[44] has helped us in understanding the vibrational and rotational motions in nuclei. This is described in Chapter 11.

The collective and the liquid drop models, however, could not explain the properties of nuclei which exhibited the extra stability, for nuclei having neutrons or protons equal to the magic numbers of 2, 8, 20, 50, 82 and 126. This was successfully explained by the shell model, as developed by Mayor and Jensen[45] and later on modified by many other workers. This model requires that the nucleons in a given nucleus arrange themselves in groups of energy states—shells—so that the magic number nuclei correspond to the closed shells in the same manner as the closed shells in atoms correspond to noble gases. For creating such a shell structure, each nucleon is supposed to move in the common potential, $[- V(r)]$ created by other nucleons to which is added a spin-orbit coupling term $\mathbf{1.S}\ V_{ls}$. In this model, the magic numbers are explained in a natural manner, as well as the spins of the ground state of almost all nuclei. This simple shell model, also called, extreme single particle model, is, however, incapable of explaining, the magnetic moments, quadrupole moments, and the binding energies of nuclei in the ground state and also many properties of the excited states of nuclei. For this purpose, many extended versions of the simple shell model, have been used and developed in Chapter 10.

Basically the various modifications take into account the nucleon-nucleon interactions of 'loose' nucleons, outside the closed shells. The shape of the common potential itself has been modified in the case of the deformed nuclei, so that the loose nucleons move in an ellipsoidal common potential, rather than in a spherical potential, of the simple shell model. The introduction of ellipsoidal potential corresponds to the recognition of the collective effect of the 'loose' nucleus. This 'marriage' between the shell model and collective model, as developed by Nilsson and others[46], especially Davidov and Filipov, has helped in explaining the properties of excited states in deformed nuclei and has been in use for quite some time in nuclear structure calculations (Chapter 12). Core excitation and core polarisation imposed in the above mentioned conditions, are other sophistications, which have proved very useful in explaining the many anamalous moments and transition rates. Attempts have also been made to develop microscopic theories to take into account the fact that a nucleus is a many-body system, with a large number-(ranging from a few to many hundred) of nucleons which interact with each other strongly. Two approaches have been made in this direction.

1.8 MICROSCOPIC THEORIES

(*i*) *Theory of nuclear matter:* In this approach, developed by Brüeckner et al. and Bethe[47], the properties of nuclear matter (the infinite nucleus) were investigated assuming that the nuclear wave functions could be taken as plane-waves for infinite matter. One attempts to derive, in a self-consistent manner, the common potential in which each nucleon moves in an infinite matter, using the two-body interaction in accord with the scattering experiments as an input data, in the form of the reaction matrix (K matrix). Application to finite nuclei was developed by Brüeckner, Gammel and Weitzner[48] and others, where the effect of the boundary conditions of a finite nucleus was taken into account by appropriately modifying the K-matrix, so that it corresponds to the local density (which is uniform and independent of space-coordinates in infinite nuclear matter) which will vary as a function of radius in a finite nucleus. Calculations of binding energies, etc. for some nuclei on the basis of this theory have yielded results of the right order but the success is limited.

(*ii*) *The Hartree-Fock self-consistent theory:* Essentially this method reduces the problem of many interacting particles to one of non-interacting particles in a field, which is obtained in a self-consistent Hartree-Fock procedure[49], using the two-body nuclear potential as the input parameter. For light nuclei, with a few nucleons of say, up to $A \approx 20$, the method can be used to treat the whole nucleus in this manner. For medium and heavy nuclei, however, one uses this method to take into account only the interactions of 'loose' nucleons outside a 'Core' which may be assumed to be unperturbed in the excitation under consideration. This method, though very useful in simplifying the problems is, however, an approximation and neglects a large part of the long range internucleon-forces, called the 'residual interaction'. Various attempts of the recent calculations are essentially directed towards the inclusion of these residual interactions to better approximation. Notable among these attempts is the quasi-particle or BCS theory[50], which directly takes the short range part of the nuclear forces (the pairing energy) into account and the long range part is treated by perturbation methods. This theory has been borrowed from the theory of superconductivity as developed by Bardeen-Cooper-Schrieffer (BCS).[50] TamDancoff Approximation (T-D)[51] is a fancy name for about the simplest realistic microscopic treatment of nuclear excitations, based on H-F approximation. A variation of the Hartree-Fock (H-F) theory is the time dependent HF theory, and is called the Time Dependent Hartree-Fock-Approximation Theory (TDHF)[51]. This is used for calculating the time dependent phenomenon, involving excited states, and is designed to take into account the long range part of the residual interactions. The Random-phase Approximation theory (RPA)[52] is an alternative formulation of the time dependent Hartree-Fock theory and is borrowed from the theory of plasma oscillation as developed by Bohm and Pines.[53] This theory gives a lower order solution (and hence is a better approximation), than TDHF[51] theory for time dependent phenomena. Another model, applied to the description of quadrupole collective properties of low lying states in nuclei, is termed as Interaction Boson Model (IBM)[53] where bosons are assumed to be made up of correlated pairs of valence nucleons, carrying even angular momenta $l = 0, 2, 4$, etc. These and still more generalised theories have been developed and applied to deformed nuclei in a limited manner.[53] We have, however, not dealt these topics in this book.

Interacting Boson Approximation (IBA) Model has been a major tool for calculating energies, the transition probabilities and quadrupole moments of even-even nuclei and has been used extensively. Recently an extensive work was reported for even-even $Cd^{110,\,112,\,114}$, $Pd^{100-116}$ and Pu^{94-114} chains[54], using IBA model, where values of energies, B (M1), mixing ratios and magnetic dipole moments was calculated and compared with experimental data, with reasonable agreement. An extension of this model was used, where IBA model plus broken pair description was used for high spin dipole in ten bands[55], especially applying to $_{60}Nd^{136}$ nucleus, up to $l > 20$. For odd nuclei, or odd-odd nuclei, an Interacting Boson-Fermion model, with or without broken pair has been[56] used say for $_{39}Y^{97}$, or $_{51}Sb^{117}$ or $_{29}Cu^{62, 64, 66}$ nuclei.

Similarly extensive use of Hartree-Fock calculation have been combined with large basis shell model. A recent[57] calculation is that of $_{20}Ca^{47–60}$ where detailed comparison in made for $_{20}Ca^{48}$ to give the parameters. A detailed review of this method is given in Annual Review nuclear and particle Sciences[58].

A modification of this method, *i.e*. Cranked Hartree-Fock Bogoliubov model has been applied for a large number (more than forty) of even-even nuclei from Xe to Ba recently.[59]

1.9 NUCLEAR REACTION MODELS

Theoretically, the problems in nuclear reactions contain two basic components (*i*) The reaction mechanism (*ii*) The nuclear structure associated with the properties of nuclear states involved in the reaction. The problem of nuclear structure will, in principle, be the same as discussed earlier, except that in cases where highly excited states are involved, the states are so close to each other, that one may use the statistical model[60], rather than the individual properties of the levels. The statistical model deals with the nuclear level-density on the basis of statistical considerations. For the low excited states, however, the detailed properties of individual states can be taken into account, and dealt with in the manner discussed earlier. On the other hand, the reaction mechanism requires specific models or theories. One adopts either the compound nucleus model[61] or the direct reaction model[62] or some intermediate mechanism[63], depending on the type of the projectile, the target nucleus, and the incident energy. These are macroscopic models. As for example, in the compound nucleus models, one assumes that in entering the nucleus, the incident particle shares its energy with other nucleons and forms an intermediate state called the compound nucleus. In this case, the decay of the nucleus depends on the properties of the compound nuclear state rather than on the mode of the production of that state. These assumptions are based on the existence of very strong nuclear forces between nucleons. The decay time involved in this case is of the order of 10^{-14} to 10^{-16} seconds and corresponds to the time of many traversals of the incident particle in compound state of the nucleus. The compound and the statistical models have been dealt with in Chapter 13.

The direct reaction corresponds to the condition where the incident nucleon interacts with the nucleons in such a manner that the emitted particle comes out as a result of a single direct encounter of the projectile with a nucleon in the nucleus. In this case the time of interaction is shorter, of the order of 10^{-22} seconds, which is approximately the time taken by the incident particle to travel the incident nucleus, once. Typical examples of direct reaction are (*d, p*), (*d, n*), (H^3, *d*), (He^3, *d*), etc. In practice, the reaction may go through both the direct and the compound (and also through some intermediate processes) where the energy of the incident particle is shared by two or three particles in contrast to one particle in direct reaction or many particles in the compound nucleus. This topic has also been discussed in Chapter 14.

Another model is the optical model[64] in which one replaces the nucleus by a potential which is complex. The real part of the potential gives rise to elastic scattering and the imaginary part produces the absorption through reaction and inelastic scattering. This model has been extensively used for elastic and non-elastic scattering of particles, in cases where only the average properties of the scattering nucleus are involved and not the properties of any individual levels: Chapter 15.

Recently[63, 65], there have been carried out many studies of nuclear reactions experimentally and theoretically—where reaction mechanism corresponds to an intermediate status; between compound nucleus formation and single-hit direct reaction. This reaction mechanism, called the pre-compound, or pre-equilibrium model of nuclear reactions, assumes that the incident projectile, interacts with nucleons inside the nucleus successively in such a manner; that either the ejectile is emitted comparatively with high energy, leaving behind low energy projectile which shares its energy with other nucleons forming a compound nucleus, which then decays through statistical process. Or if the first ejectile is of low energy; the projectile then proceeds to either come out directly; or hits another nucleon; and again starts a reaction with low energy and high energy particles sharing energy. In this manner, after a few such encounters, say about 4 to 6; the energy shared between the two particles is low enough, that only compound nucleus is formed. The ejected particles then have an energy spectrum or angular distribution, which is a combination of these successive steps. A lot of experiments with both light and heavy incident particles have been carried out, at somewhat higher energies—10 to 100 MeV/nucleon—which can be understood on the basis of pre-compound or pre-equilibrium reaction model[65]; and have been analysed with theoretical models, developed in the last two decades. These are described in Chapter 16.

Analysis of the nuclear reactions based on these macroscopic models, yields broadly, the nuclear parameters like (*i*) the nuclear level densities (*ii*) nuclear radii (*iii*) the real and imaginary parts of the potential in the optical model (*iv*) the level widths or decay rates in the compound nucleus (*v*) the orbital angular momenta of the various levels in direct reaction and (*vi*) the spectroscopic factors which basically determine the strength of the direct reaction involving the particular level. These parameters and models are only indirectly related to the basic two-body nuclear forces and one requires a more detailed analysis to connect them directly to the nuclear forces. Attempts have been made to develop the generalised theories of nuclear reactions. As for example, a general theory, based on the collision or scattering matrix (called *S*-matrix) theory has been developed.[66] The reaction or scattering cross-sections in this general theory are expressed in terms of *S*-Matrix which gives the asymptotic forms of the wave functions of the system. To determine *S*-matrix, however, one requires to know the properties of the system, in the interaction region, where the two particles collide, so that the asymptotic wave functions of *S*-matrix can be connected with this region through the use of the continuity properties of the wave function. The wave function in the interaction region are expressed in the formalism of *R*-Matrix which, essentially involves various quantities evaluated in or just outside the region, within which the particles may interact, and outside which there is no further reaction. Kapur and Pierls[66] gave the basic form of the rigorous theory of nuclear reaction on the basis of *S*-Matrix and *R*-Matrix. Wigner[67] has given another representation which is very generally used. The inputs to the theory are the properties of the various states of the interaction system in the interaction region which provide *R*-Matrix. For understanding the basic features of these theories, the reader should refer to the above mentioned references; and 'Nuclear Theory V.I, II and III, J.M. Eisenberg and W. Greiner, North Holland Publishing[68] Co. Again, these generalised theories of nuclear reactions have not been dealt in this book.

1.10 HEAVY-ION REACTIONS

Reactions with heavy projectiles like ^{12}C, ^{16}O, ^{40}Ca, ^{84}Kr, ^{132}Xe, and many other heavy ions, up to even ^{238}U have opened a new vista in nuclear physics[68]. Many new phenomena are observed and many theoretical suggestions are advanced. As for the reaction mechanism involved in heavy ion collision, many authors have looked at heavy-ion physics as a playground for nuclear physicists to distinguish amongst, distant collisions, grazing collisions, hit-and-run, formation of two-body system, formation of a composite system and finally the formation of a compound system. Different degrees of contact can be classified by studying the density overlaps and interaction times between the two colliding nuclei. For energies well below coulomb energies, only Coulomb scattering takes place, and Rutherford scattering model holds good. As the energy is somewhat increased, the diffraction phenomena occur from the edges. So Fresnel and Fraunhauffer diffraction are observed. Inelastic scattering at higher energies, through Coulomb excitation, yields a lot of information about collective modes of excitement. Because of the transfer of high angular momenta by heavy ions, one observes very high spin states. Next comes one or two-nucleon transfer reactions, and one observes an interplay of nuclear structure and reaction mechanism like direct reaction or deep inelastic scattering. The latter is especially significant, for cluster-transfer by heavy ions-induced reactions. Fusion-fission and compound nucleus reaction mechanisms are observed at higher energies. At very high energies, the shock-waves or nuclear matter density isomers may be observed.

Heavy-ion nuclear physics, therefore, tends to become a very interesting subject (Chapter 17). As a matter of fact, a large amount of work is being conducted these days—both experimentally and theoretically—on the various aspects of heavy-ion reactions. One of the important fields, which has opened up because of these activities is, the availability of high spin states in nuclei at higher energies, because of the collective excitations. States of angular momenta up to $I \geq 50\ \hbar$ have been observed. The excitation of these states offers interesting insight into the excitations of many deformed and super deformed nuclei.[69]

With the availability of Tandem accelerators, superconducting linear accelerators and cyclotrons; heavy-ion projectiles are increasingly being made available in many laboratories. This has led to the experimental and theoretical[70] studies of heavy-ion reactions in the energy range from 2–3 MeV/A to 35 or 40 MeV/A, depending on the heavy nucleus in the projectile and using synchrotrons, sometimes going to greater than 10 GeV/A.

In a typical experiment, using $_{62}Sm^{152}$ ($_{3}Li^{7}$ 4n)$_{65}$ Tb,^{155} at 45 MeV and $_{50}Sn^{124}$ ($_{15}P^{35}$, 4n)$_{65}$ Tb^{155} at 165 MeV; using a Tandem accelerator[71], nuclear states up to angular momenta $I = 95/2\hbar$ were excited. This is an example of fusion-evaporation, at a medium incident energy.

At very high energies of 2 GeV protons and 3 GeV. He^3-induced reactions on Ag, Bi and U, one observed the phenomenon of nuclear cascade process of classical step by step evaporation and fission. At still higher energies, *i.e*. 11–6 GeV/A, for central, Au + Au reaction, the proton rapidity distribution, showed the possibility of formation of state of matter with baryon density substantially greater than normal nuclear matter.[72]

At lower energies, one observes the phenomenon of fission fragments as was investigated[73] by a group at Bombay using 14 UD tandem, using C^{12}, O^{16} and F^{19} projectiles on Th^{232} target.

The subject of nuclear physics, thus, provides a large field of interplay of theory with physical phenomenon, in nuclear interactions, using many fascinating experimental and theoretical techniques. It gives an insight into systems (Nuclei) of a limited number of constituents (Nucleons), governed by strong short-range forces.

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