Chapter 1

# Introduction

## 1.1 Background

Though the concept of the nucleus and the subsequent evolution of nuclear physics are credited to Rutherford, the earlier discovery of radioactivity by A. Henri Becquerel, Pierre and Marie Curie (1896–1898) played the most crucial role in these developments. The discovery of radioactivity opened up the way to new techniques of exploring subatomic systems – for example, by bombarding them with fast moving charged particles, a technique which is still in use, and used more vigorously now, even after hundred years.

In 1898, Pierre and Marie Curie succeeded in isolating significant amounts of two new elements from pitchblende, a uranium ore. They named the two elements polonium and radium. These new elements were found to undergo spontaneous self-destruction by emitting mysterious radiations. Passing of the collimated beam of these radiations through electric and magnetic fields revealed that they are made up of three components: negatively charged components, called beta particles; neutral components of electromagnetic waves of very short wavelength or gamma rays and a third component of positively charged particles. The negatively charged beta particles were identified as electrons, while the Curies established that the positively charged particles were doubly-ionized helium atoms, called alpha particles. The average kinetic energies of these alpha particles, beta particles and neutral gamma rays had different values for different radioactive sources. Radium and polonium, the two natural radioactive sources, emit alpha particles of energies in the range of 5 to 7 MeV. Rutherford, in his famous alpha scattering experiments, actually carried out by Geiger and Marsden[1], bombarded thin metallic foils by a collimated beam of alpha particles obtained from radium. In these experiments, it was observed that, on an average, one to five alpha particles out of about 20,000 particles, get scattered by more than 90°. Rutherford[2] concluded that this is possible only if the target atoms

have very small volumes at their centres where total positive charge and almost all mass of the atom are concentrated. Rutherford named this small volume as the nucleus of the atom, a term he borrowed from biological science. The layout of the experimental setup used by Rutherford is shown in Figure 1.1. The alpha particle source (radium) was kept in a lead box with a small hole to get the collimated beam. A ZnS painted screen placed in front of the microscope served as the detector. The target metallic foil was placed normal to the alpha beam. The scattered alpha particles, on hitting the ZnS painted screen, produced tiny flashes of light, which were measured by looking through the microscope. The microscope was capable of rotating in the horizontal plane.

The technique of bombarding a specimen with charged particles in order to explore the charge structure of the specimen's nuclei and nucleons has been used by R. Hofstadter et al.[3] Earlier experiments using neutron scattering have indicated that the radius $R$ of an atom's nucleus ${}^{A}_{Z}X$, where $A$ is the atomic mass number and $Z$ is the atomic number, is proportional to $A^{1/3}$ or $R = r_0 A^{1/3}$, where $r_0$ is a constant independent of $A$. Hofstadter used fast electrons of around 200 MeV energy and bombarded gaseous targets of many elements. He measured the angular distribution of scattered electrons with the help of a double-focusing electron spectrometer. Since electrons of energy less than 1 GeV do not split the target nucleus and interact with the target nucleus only through electromagnetic interaction, Hofstadter's experiments were best suited for studying the charge distribution of the nucleus. The analysis of the data showed that nuclei have a Fermi-type charge distribution described by two parameters – the radius $c$, which depends on the number of nucleons $A$ in the nuclei and a surface thickness $t$, which is nearly

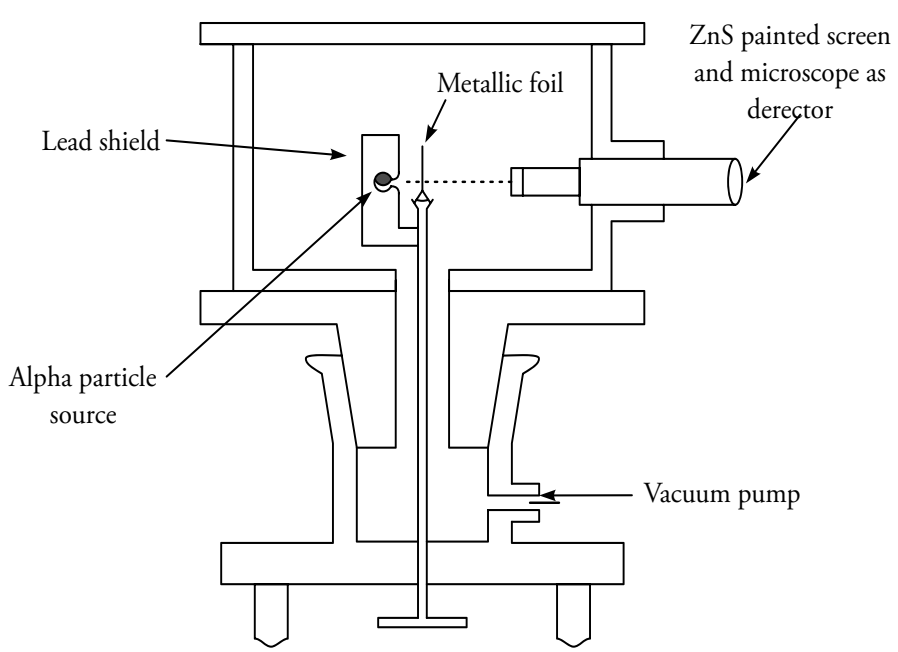



**Figure 1.1** Side view of the experimental setup used by Rutherford for alpha scattering

constant for all the nuclei. Accordingly, the charge density $\rho(r)$ at a distance $r$ from the centre of the nucleus is related to its value $\rho(0)$ at the centre by the relation,

$$\rho(r) = \frac{\rho(0)}{e^{\left(\frac{r-c}{0.23\,t}\right)} + 1} \tag{1.1}$$

where, $c = \left(1.07 \mp 0.02\right) A^{1/3}$ fm and $t = \left(2.4 \mp 0.10\right)$ fm (1.2)

This means that all nuclei, big or small, have the same charge density at the centre and the charge density falls off smoothly for all nuclei within the same distance, but they differ in the radius of the central core of uniform charge density as shown in Figure 1.2. It may be observed from Figure 1.2 that the *y*-axis scale is highly magnified.

In this technique of exploring a given target using highly charged particles, the resolving power of the incident charged particle increases with the decrease of the de Broglie wavelength of the particle. The same incident particle will distinguish finer details of the target if it has a smaller wavelength, i.e., relatively higher energies. Hofstadter also estimated the size of protons and neutrons using electrons of higher energies. Since both protons and the neutrons are spin-½ particles, and the incident electron is also a spin-½ particle, the electron interacts with nucleons through its charge as well through its magnetic moments. Hofstadter obtained the values of 0.75 fm and 0.00 fm for the charge radii of proton and neutron respectively; the corresponding magnetic radii were estimated to be 0.97 fm and 0.76 fm respectively. Hofstadter got the 1961 Nobel Prize in Physics for his work on electron scattering.

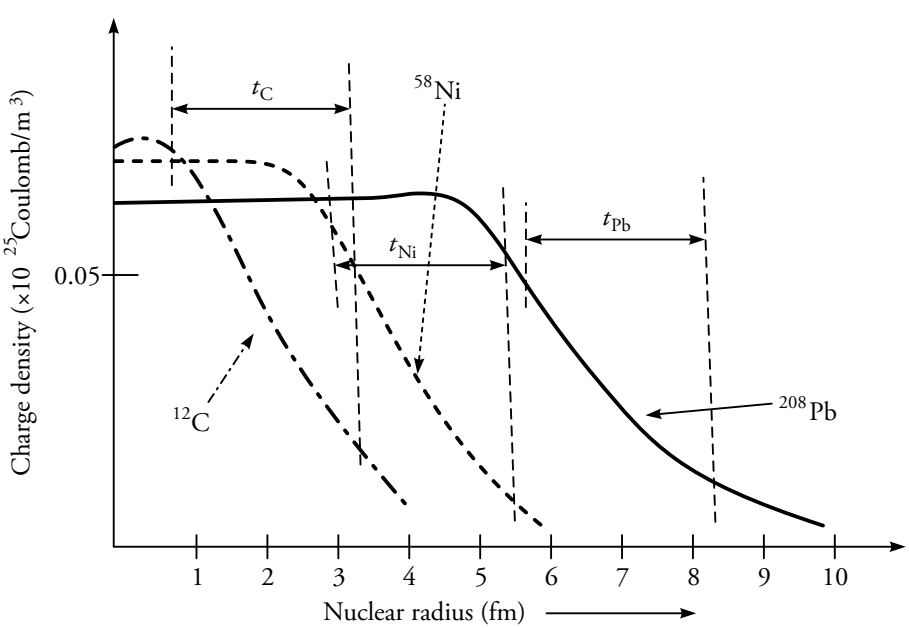



**Figure 1.2** Nuclear Charge Distribution and surface thickness *t* for some nuclei

### 1.1.1 Artificial radioactivity

The alpha ($\alpha$) particles provided by naturally radioactive sources like polonium and radium have energies of the order of 6 MeV, which is enough to overcome the Coulomb barrier between the alpha particle and a light nucleus. These alpha particles were extensively used to investigate nuclear reactions initiated by them in light nuclei. In January 1934, Irene Joliot-Curie, daughter of the Curies, and her husband, Frederic Joliot[4] carried out an experiment in which they bombarded a thin aluminium (Al) foil with a collimated beam of 5.3 MeV $\alpha$ particles obtained from a $^{210}$Po source. A thin window Geiger–Müller (GM) counter was used to detect the charged particles, if any, emitted from the Al foil in the process. It was found that positively charged particles are emitted when the foil was bombarded by $\alpha$ particles and these particles keep coming from the foil even when the polonium source is taken away from the foil. It was further observed that the number of counts per unit time in the GM counter decreased exponentially with time, like that in the case of natural radioactivity, with a half life of 2.34 min. They attributed these observations to the formation of a new unknown isotope $^{30}$P formed according to the following reaction,

$$^{4}_{2}\mathrm{He} + ^{27}_{13}\mathrm{Al} \rightarrow ^{30}_{15}\mathrm{P} + ^{1}_{0}n \tag{1.3}$$

Later, Curie and Frederic confirmed it by chemically separating phosphorous from the irradiated aluminium foil within a few minutes of irradiation and observing that the activity comes from the separated phosphorous. The isotope $^{30}$P was found to undergo the following radioactive decay:

$$^{30}_{15}\mathrm{P} \rightarrow ^{30}_{14}\mathrm{Si} + ^{0}_{1}e + \nu \tag{1.4}$$

Curie and Frederic's experiment demonstrated for the first time that radioactive isotopes may be produced artificially by nuclear reactions. At the same time, it also showed that the isotope $^{30}$P decays via a new mode, called $\beta^+$ decay, which was unknown till then. The experiment led to the search of new radioactive isotopes for medical and other applications.

### 1.1.2 Neutron era

After establishing the presence of a nucleus at the centre of each atom, Rutherford focussed his attention on the composition of the nucleus. Since only the proton and the electron were known at that time, it was assumed that the nucleus is also made up of only these two particles. However, in 1920, Rutherford, based on the fact that the actual mass of a nucleus is much larger than what is expected from the 'proton + electron' theory, proposed that there are heavy neutral particles of the type (P + $e^-$) present in the nucleus. He called them neutrons. The task of tracking and identifying these heavy and neutral 'Rutherford' particles was assigned to Chadwick.

In an experiment carried out in 1930, it was observed that when a sheet of beryllium was bombarded by $\alpha$ particles from a polonium source, a stream of highly penetrating radiations is emitted. Since the stream was made up of electrically neutral particles, it was assumed

to be made up of gamma rays. However, unlike gamma rays, these penetrating radiations did not discharge a charged electroscope or produce ionization. It was obvious that these radiations were different from gamma rays. Frederic and Irene Curie used these mysterious radiations to hit a layer of paraffin wax (Figure 1.3), which is rich in protons, and found that a large number of protons is ejected from the wax, which would not have been possible if the radiations were gamma rays. In 1932, Chadwick, using reaction kinematics and the principle of linear momentum conservation, calculated the mass of mysterious particles emitted from the beryllium foil and found it almost equal to the mass of a proton. Thus, Chadwick established the presence of neutrons, the neutral particle ($P + e^-$) suggested by Rutherford. However, from quantum mechanical reasoning, it was concluded that the electron cannot be a constituent of the nucleus. Thus, the neutron could not have the ($P + e^-$) structure as suggested by Rutherford. However, Heisenberg, using the quantum mechanical reasoning, had already predicted a neutral particle of a mass nearly equal to the mass of a proton. This gave rise to the proton–neutron model of the nucleus. Chadwick explained the production of neutrons in his experiment by the following equation;

$$ {}^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}C + {}^{1}_{0}n \tag{1.5} $$

It may be seen that the technique of hitting the target with energetic $\alpha$ particles and analyzing the emitted radiations led to the establishment of the presence of neutrons.

Neutrons, having no electrical charge, face no Coulomb barrier when impinging on a nucleus. Therefore, they enter the target nucleus with relative ease. Even very low energy neutrons, like thermal neutrons with energies $\approx 0.025$eV, can initiate nuclear reactions on entering a target nucleus. Taking advantage of this fact and taking a cue from Frederic and Irene Curie's experiment that new elements produced in a nuclear reaction may be identified through their radioactive properties or by the method of chemical separation, Fermi[5] carried out a large number of experiments in which he bombarded elements of successively higher atomic numbers with neutrons and produced hitherto unknown isotopes. The nuclear reaction

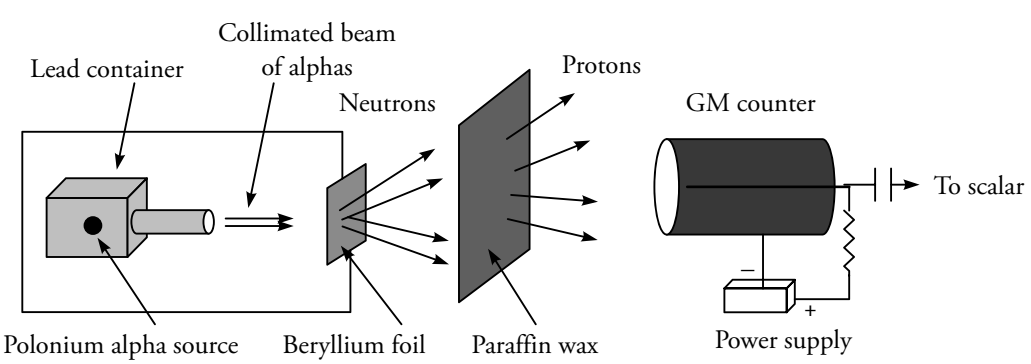



**Figure 1.3** Frederic and Irene Curie's experimental setup to discover the nature of 'Rutherford particles' – neutrons

initiated by the absorption of an incident neutron by a target nucleus ${}^{A}_{Z}X$ may be written as follows:

$$ {}^{A}_{Z}X + {}^{1}_{0}n \rightarrow {}^{A+1}_{Z}X + {}^{0}_{0}\gamma \tag{1.6} $$

The new isotope ${}^{A+1}_{Z}X$ is, generally, unstable and undergoes $\beta^-$ decay leading to the formation of the isotope of the next higher element $Y$ of atomic number (Z+1);

$$ {}^{A+1}_{Z}X \rightarrow {}^{A+1}_{Z+1}Y + \beta^- + \overline{\nu} \tag{1.7} $$

With this method, Fermi's group in Italy produced more than 40 new isotopes in a few months.

Using heavier and heavier targets, Fermi's group bombarded the heaviest nucleus, uranium, with neutrons in May 1934. The result of their experiment surprised them – instead of producing the nucleus of the heavier element, radio nuclides of elements having mass almost half of the uranium nucleus were found in the reaction products. Fermi and his collaborators could not unravel the mystery and it took three years for other European laboratories to understand the process. Finally, in 1938, German chemists Otto Hahn and Fritz Stresemann, discovered the phenomena of nuclear fission and published their findings in 1939[6]. The discovery of fission not only proved the mass energy equivalence proposed by Albert Einstein for the first time but also led to a new method of producing huge amounts of energy both for peaceful uses and for nuclear armament.

## 1.2 Classification of Ions and Research with Accelerated Light Ions

As far back as the late 1920s, the need for machines that may impart higher kinetic energies to charged particles, much more than the energies available with natural radioactive sources, was felt. Higher energy charged particles can overcome larger Coulomb barriers of nuclei of heavy elements, making it possible to initiate more nuclear reactions. Moreover, they have shorter de Broglie wavelengths, and therefore, higher power of resolution to distinguish the finer details of the target. Fusion of accelerated charged nuclear particles with the target nucleus may also produce new elements. In 1927, Rutherford asked scientists to develop systems or machines that may give 'copious supply' of particles more energetic than the $\alpha$ and $\beta$ particles available from natural radioactive sources. Several scientists responded to his call and undertook projects to build machines that may accelerate light ions. In general, charged particles with atomic mass number A < 4, like ${}^{1}_{1}$H, ${}^{2}_{1}$D, ${}^{3}_{1}$H and ${}^{3}_{2}$He are classified as light ions. At Rutherford's Cavendish Laboratory, Cambridge, England, John Cockcroft and E.T.S Walton produced high energy protons by accelerating them using a high-voltage transformer coupled to a voltage multiplier. Robert Van de Graaff built an electrostatic high-voltage generator that could generate up to 1 MV potential. This machine was used to accelerate protons up to 1 MeV energy.

The first cyclotron was conceived at Berkeley (USA) by Ernest Lawrence in 1929 and accelerated protons to 80 keV energies in 1930. In spite of its very small size (its acceleration chamber could be taken in one hand), this apparatus was a very important realization, and the first of an impressive series of machines of increasing power and diameter (4 inches, 11 inches, 27 inches, 37 inches, 60 inches ...). In 1938, E. Lawrence was already building his sixth cyclotron with a diameter of 184 inches (4.70 m). It aimed to accelerate protons to 100 MeV energies. This project was stopped by the Second World War. Just after 1945, magnets were used to build the Berkeley synchrocyclotron with which mesons were artificially produced for the first time. After the Second World War, powerful cyclotrons were built at several places and considerable research, using these machines and high energy light ions, were carried out to study nuclear reactions and the nuclear structure. However, to overcome the relativistic increase in the mass of the ion, cyclotrons were replaced by synchrocyclotrons. In the late 1950s, a 150 MeV proton synchrocyclotron was built at Orsay, France and a 600 MeV one at CERN. This was when the study of high energy interactions became separated from nuclear physics and came to be known as 'particle physics'.

Availability of accelerated light ions opened an era of focused attempts to study the nuclear reaction mechanism in detail. Since nuclear reactions occur in a very short time ($\approx 10^{-22}$ to $10^{-16}$s), and also because the true nature of a nuclear force is not known, it is not possible to look, in real time, at what transpires during the rearrangement of nucleons, etc., when the incident light ion enters the nuclear field of the target nucleus. A possible solution is to make some simplified assumptions regarding nuclear force and based on this, develop a theory for the reaction mechanism. The first such attempt was made by N. Bohr in 1936, and it is called the 'compound nucleus reaction mechanism'. Bohr assumed that a nuclear reaction proceeds in two steps – the formation of the compound nucleus by the absorption of the incident ion by the target nucleus that continues till a thermodynamic equilibrium is established in the compound system, and the subsequent decay of the equilibrated compound nucleus into the final products. The most important assumption of Bohr's theory, called 'the independence hypothesis' was that the two steps – the formation and the decay of the compound nucleus are independent of each other. This essentially means that a compound nucleus in a given quantum state decays to a given final state with a fixed probability that does not depend on the specific way it was formed. The first comprehensive test of the independence hypothesis was carried out by Ghoshal[7] in 1950, using accelerated beams of proton and $\alpha$ particles. In his experiments, Ghoshal produced the same compound nucleus $^{63}$Zn at the same excitation energy using two different channels and measured the excitation functions for three different decay channels in each case. The input and decay channels in Ghoshal's experiment are shown in Figure 1.4, and the measured excitation functions for the decay channels in Figure 1.5

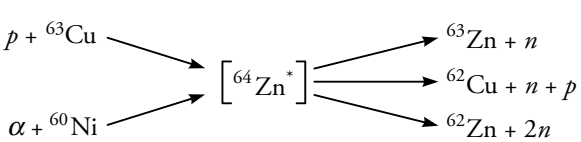



**Figure 1.4** Two input and three decay channels in Ghoshal's experiment

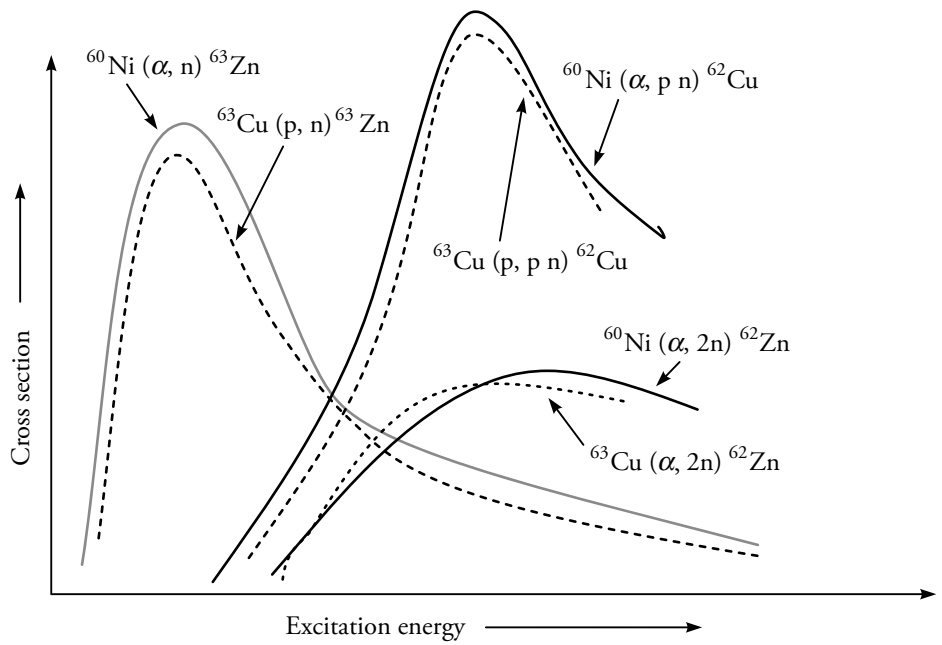



**Figure 1.5** Experimental excitation functions for the three decay channels

It may be observed in Figure 1.5 that the excitation functions for the same exit channel from two different input channels are similar to each other, as expected from compound reaction mechanism, but are not exactly identical. This discrepancy may be attributed to the fact that the excited compound system $^{64}$Zn produced via proton and $\alpha$ channels had the same excitation energy but different spin and isospin distributions. Several groups including that of J. R. Wiley[8] carried out detailed studies of the effects of isospins in compound statistical reactions. Wiley produced nine compound systems – $^{49}$V, $^{52}$Cr, $^{55}$Mn, $^{56}$Fe, $^{60}$Ni, $^{63}$Cu, $^{64,66}$Zn and $^{69}$Ga by 14 MeV proton bombardments of appropriate targets and also by bombarding various targets with 12–19 MeV $\alpha$ particles. The energy of $\alpha$ particles in each case were chosen to match the excitation energy of the compound system formed by proton bombardment. In the in-beam experiment, energy spectra and angular distributions of protons and $\alpha$ particles emitted from each compound system were measured. These spectra were used to deduce integrated cross-sections for each channel, which in turn were used to obtain the fraction of mixing of $T_<$ and $T_>$ isospin states. Neutrons cannot be accelerated in an accelerator; however, high energy neutrons may be obtained from nuclear reactions initiated by accelerated charged particles. For example, the following reaction

$$^{3}_{1}\mathrm{T} + {}^{2}_{1}\mathrm{D} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}n \tag{1.8}$$

which has a Q-value of ≈ 17 MeV, has often been used to generate neutrons of ≈ 14 MeV energy. Since the threshold energy of the reaction is low and peaks around 120–130 keV deuteron energy, small Cockcroft–Walton type accelerators, which may have 150 kV high

voltage terminals, may be used for this. A Cockcroft–Walton accelerator was built at Aligarh Muslim University, India in 1960[9] for producing 14.8 MeV neutrons and has been extensively used[10] for the study of neutron-induced nuclear reactions at moderate energies. Interesting results about shell effects in statistical nuclear reactions etc., have been obtained from these studies.

The Bohr compound nuclear reaction theory assumes that the composite excited system formed by the absorption of the incident particle by the target nucleus, lives long enough till a thermodynamic equilibrium is established in the composite system, i.e., the composite system forgets all about the history of its formation. Both intuition and experimental evidences suggest that light particle like n, p, $\alpha$ etc., may be emitted from the composite system while it is undergoing equilibration. These particles emitted during the process of equilibration are termed as pre-equilibrium or pre-compound particles and the process is termed as pre-equilibrium or pre-compound emission. Information of considerable value on the dynamics of pre-equilibrium emission has been obtained from the analysis of measured excitation functions[11] of reaction residues, and the energy and angular distributions of emitted light particles[12].

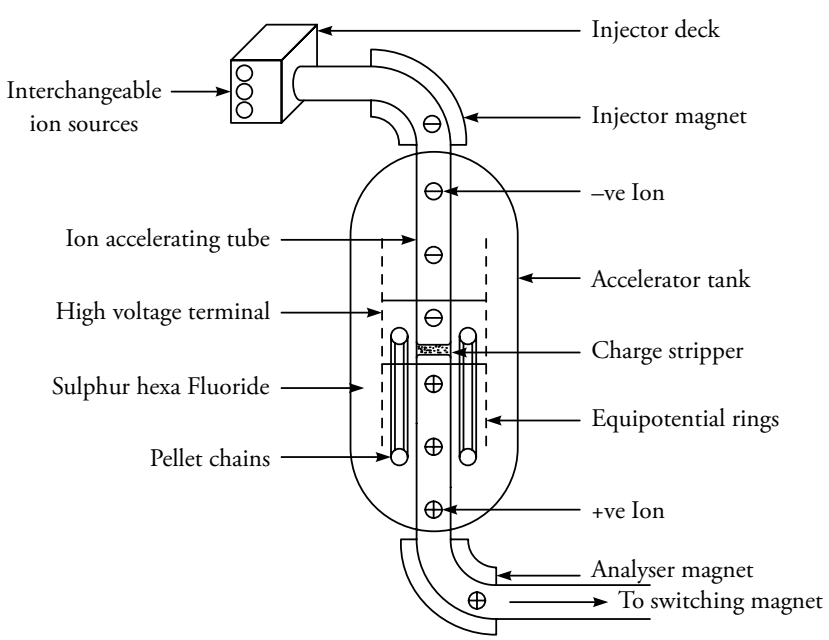
Accelerated light ion beams have also been used in medical applications, i.e., for radiation therapy as well as for producing radioisotopes.

## 1.3 Accelerated Heavy Ions

As has already been mentioned, atomic ions with mass number $A > 4$ are called heavy ions. It is generally not possible to remove all the electrons of atoms of heavy elements. At best, a few electrons may be removed by the ionization process. If $n$ electrons from a neutral heavy atom are removed, an ion with positive charge $Q = ne$, where $e = 1.6 \times 10^{-19}$ Coulomb, is formed. Similarly, if by some method, $n$ extra electrons are added to the neutral atom, a negatively charged ion with charge $Q$ is formed. If such an ion of charge Q is accelerated by electrostatic potential $V$, the energy $E$ gained by the ion will be $QV$ eV. The energy gained by an ion of charge $Q$ and mass number $A$ in a cyclotron of radius $R$ is given by $K\frac{Q^2}{A}$, where $K$ is a constant that depends on the cyclotron. In order to have higher values of $Q$, new multiple charged ion sources, particularly, penning ionization gauge (PIG) type sources[13] were developed. Though, historically the first accelerated heavy ion beam was carbon produced by Alvarez[14] way back in 1940, the real breakthrough was achieved by Walker et al.[15] at Birmingham, who introduced a small amount of argon gas in the accelerating column. The stripping process in the accelerating chamber increased the charge state of the ion resulting in an internal beam of high energy with a continuous spectrum of lower energies. Taking a cue from this work, two accelerating stage machines, called 'heavy ion linear accelerators' (HILACs), capable of accelerating ions up to neon to energies ≈ 10 MeV per nucleon (10 MeV/A) were built at many places including Manchester (UK), Yale and Berkeley (USA)[16]. These machines used a gas stripper cell between the two accelerating stages. Later, in 1965, a variable energy heavy ion cyclotron, called 'CEVIL' was commissioned under the supervision of Lefort[17] at Orsey,

France. With the view to accelerate ions heavier than neon, R. Basile[18], on a suggestion by Irene Joliot Curie, studied the process of stripping in detail and found that heavier ions of higher charged states may be produced if they are pre-accelerated up to about 1 MeV/A energy before undergoing stripping. This opened a new era of coupled machines for accelerating heavy ions. A linear accelerator (LINAC) with PIG ion source was used to inject pre-accelerated heavy ions into the variable energy heavy ion cyclotron (CEVIL) at Orsey, which, for the first time, could accelerate ions up to krypton to energies higher than the Coulomb barrier for uranium. This coupled machine is called ALICE. Two linear accelerators – SuperHilac at Berkeley, USA and Unilac at Darmstadt, Germany – could accelerate all ions up to uranium to energies ≈ 10 MeV/A. The French GANIL uses a combination of three cyclotrons to accelerate carbon to xenon ions to 20–100 MeV/A energies. Machines at RIKEN, Japan and Lanzhou at China can also accelerate heavy ions up to uranium to about 10 MeV/A energies. With the availability of superconducting magnets, cyclotrons of larger K ≈1200 were assembled at some places like Michigan State University and are used for heavy ion acceleration.

The Inter University Accelerator Centre (IUAC) at New Delhi, India, established specifically for users from the university system has a 15 UD Pelletron accelerator (see Figure 1.6). The accelerator which is a tandem Van de Graaff accelerator in vertical configuration can sustain a maximum terminal voltage of 16 MV. The accelerator can provide ion beams of energies from a few MeV to several hundred MeV, depending on the ion and its charge state. The energy range of the Pelletron accelerator has been further enhanced by installing a superconducting linear accelerator (LINAC) booster made up of eight niobium quarter wave resonators, which




A schematic figure showing the principle of acceleration of ions in pelletron

**Figure 1.6** Layout of IUAC heavy ion accelerator