CHAPTER I

INTRODUCTION

The nucleus is the positively charged heavy central part of the atom. Nuclear research is aimed at obtaining an understanding of the properties of the nucleus, as well as the nature of forces that exist between the subnuclear particles. The knowledge of nuclear reaction mechanism and the behaviour of the products of nuclear reaction renders a wealth of information regarding the nucleus. The discoveries of neutron and of the nuclear fission are among the noble achievements of nuclear reaction studies.

Lord E. Rutherford opened the door for the present nuclear era upon whose threshold the world now stands. The historic nuclear experiment\(^{(1)}\), named 'Nuclear Transmutation', is normally expressed as -

\[
\frac{14}{7}N + \frac{4}{2}{He} \rightarrow \left[ \frac{18}{9}{F} \right] \rightarrow \frac{17}{8}O + \frac{1}{1}{H} \quad \ldots \ldots \quad (I-1)
\]

The symbol in brackets stands for the unstable nucleus formed as a result of the capture of incident \(\alpha\)-particle by the target nitrogen nucleus. This kind of nucleus is often called a 'Compound Nucleus'. Further, this way of representing a nuclear change is usually used to express a nuclear reaction.
A nuclear reaction may be defined as the nuclear change brought either in the number of constituents of a nucleus or in the arrangement of subnuclear particles within the nucleus. The nuclear reactions generally involve large energy exchange of the order of few MeV. The products of the reaction may be one, two or more nuclear particles/nuclei leaving the nucleus in various directions. The strength of a particular nuclear reaction is often expressed in terms of a quantity called the 'Cross-Section' measured in units of $10^{-24}$ cm$^2$, called 'Barn'.

In absence of an adequate description of the physical phenomenon of nuclear reaction, two extreme theoretical approaches have been used to explain the reaction mechanism. These two extremities may conveniently be classified according to the time scale on which the reactions occur. There is compound nucleus picture$^{(2)}$ on one hand, in which the compound nucleus is expected to exist as a separate entity for a period of $\approx 10^{-16}$ sec. The other extremity is identified as the fast or direct reaction$^{(3,4)}$. The time scale for the latter class is of the order of $10^{-22}$ sec. The compound reaction mechanism is more likely to take place at relatively lower energies, while the direct process is more probable at higher excitations. At moderate excitation energies, both intuition and the results of experiments$^{(5-7)}$ indicate the inadequacy of pure compound mechanism as well
Fig. I.1 Typical energy spectrum of emitted particles in a nuclear reaction at moderate energy.
as that of the direct reaction mechanism. This may be explained with the help of figure 1.1, in which the general nature of observed energy spectrum of particles emitted at a given angle in a nuclear reaction at moderate energy is shown. The spectrum consists of a broad peak in its lower energy part, while there are sharp peaks towards the end of the high energy tail. The broad peak may be ascribed to the compound reaction mechanism, while occurrence of sharp peaks, corresponding to low lying states in the residual nucleus, can be explained on the basis of direct reaction mechanism. The smooth distribution in between the broad peak and the sharp peaks has no explanation in these two approaches. It seems natural to attribute this portion to some intermediate processes called hereafter 'Pre-equilibrium or Pre-compound' process\(^{(5,7)}\). In recent years, there is increasing interest to look into nuclear reaction mechanism via pre-equilibrium emission of particles followed by equilibrium decay\(^{(5-11)}\). In compound nucleus model\(^{(2,12)}\), the decay of the compound nucleus is considered independent of the specific way of its formation and is treated by the laws of statistics. This results in symmetrical distribution of evaporated particles about 90° in the centre of mass frame. The compound reaction mechanism has often been used to get the order of magnitude for reaction cross-sections. On the other hand,
the excitation of particular levels of the residual nucleus
and the diffraction structure of angular distributions,
usually forward peaked, are the important features of direct
reactions (6).

The pre-equilibrium concept may be considered as a
bridge between the two extremities (5-11). A series of two-body
collisions inside the nucleus is assumed to follow the
initial interaction and there is a finite probability that
a particle be emitted after each one of these collisions.
The high selectivity of direction is lost on one hand and
only a few degrees of freedom are involved on the other. The
participants, those share the excitation energy of the
intermediate system, are small in number.

Various models, e.g., Intranuclear cascade model
(ICM) (13), Harp-Miller-Berne model (HMB) (14), Exciton model (15),
Hybrid (16) and Geometry dependent hybrid (17) models, have
been developed for treating the pre-equilibrium emission of
particles. Though these models differ in specific and even
at important points, but they all are based on certain common
hypotheses, i.e.,

(i) the projectile interacts possibly with a small number
of nucleons of the target nucleus and populates states
of relatively simple configuration,

(ii) the successive two-body interactions follow the initial
interaction and give rise to states of ever increasing
complexity. Fast particles may be emitted preferably in the direction of incident projectile during these two-body interactions, i.e. the angular distribution of emitted particles is asymmetric (forward peaked). These emissions are called pre-equilibrium emissions, and

(iii) the thermodynamic equilibrium is finally reached among all the constituents of the system and subsequent decay of the system is governed by the well known laws of statistical evaporation mechanism.

The major difference among the various models lies in the treatment of successive two-body interactions. In the ICM model, the interaction cascade is calculated explicitly by following the trajectories of the excited nucleons inside the nucleus, while in other models the probability of every successive configuration is estimated and is expressed in terms of decay rates.

To test these pre-equilibrium theories, it is desirable to have extensive data on excitation functions, energy and angular distributions etc. of particles emitted in nuclear reactions at moderate excitation energies. The knowledge of excitation functions has served as a powerful tool for the study of nuclear reaction mechanism, in the past also (6,12,18-20). Further, the experimental excitation functions for the
reactions, like \([(i,xn), x = 1 \ldots k]\), may be used to evaluate critically a reaction theory, as the theory has to reproduce the excitation functions for several reactions, \([(i,n), (i,2n)]\), simultaneously. Alpha-particle has been used as a nuclear probe from the very beginning of the Nuclear Physics and alpha induced reactions are still of special interest. Since \(\alpha\)-particle carries larger angular momentum, higher spin states in the compound system are populated. Thus, using \(\alpha\)-induced reactions, these high spin states can be studied, which are otherwise not possible to study using nucleons as projectiles. The study of excitation functions for \(\alpha\)-induced reactions also give considerable information about nuclear structure effects\(^{(19-21)}\). The excitation functions for \(\alpha\)-induced reactions are of interest in understanding the nucleosynthesis process in a stellar evolution\(^{(22,23)}\). The study of nucleosynthesis process requires the knowledge of large number of thermonuclear reaction rates (TNRR) in the temperature range \(10^9-10^{10}\) K. The TNRRs can be calculated using experimentally measured excitation functions\(^{(22,23)}\). These studies are also required for the better understanding of the production of radionuclides from the interaction of solar cosmic rays with extraterrestrial matter, e.g., lunar surface\(^{(24)}\). The cross-sections for \(\alpha\)-induced reactions are also needed in reactor physics\(^{(25)}\). Besides, these investigations are imperative for various
non-energy applications\(^{(25)}\). The \((\alpha,n\gamma p)\) type reactions produce nuclei which are far away from the line of stability. These nuclei are generally short lived and only very little information about their level schemes and decay modes etc. is known at present. With the knowledge of the excitation functions for \((\alpha,n\gamma p)\) reactions, optimum production of these exotic nuclei can be achieved for the study of their nuclear properties.

Though, excitation functions for \(\alpha\)-induced reactions are available for many target nuclides\(^{(26)}\), but there are large discrepancies in the reported values\(^{(26)}\). Moreover, the data are incomplete and contain large errors. The analysis of excitation functions for \(\alpha\)-induced reactions, in the past, has often been carried out only on the basis of statistical equilibrium model. In general, this mechanism of reaction could not account for the high energy tails of the excitation functions. With this view, excitation functions for \(\alpha\)-induced reactions are measured experimentally in the energy range from \(\approx 10-40\) MeV for eighteen reactions covering a relatively wide mass region from 59 to 197. With the availability of improved detectors of high resolution and better quality beams, one expects to obtain more reliable experimental data. Out of many possible methods of measuring cross-sections, the activation analysis is of considerable importance because of its high selectivity, sensitivity and
simplicity. Therefore, stacked foil technique is used to measure these excitation functions. The stacks of samples were irradiated at the Variable Energy Cyclotron Centre (VECC), Calcutta (India). The post-irradiation measurements were done using either a HPGe or Ge(Li) detector in conjunction with a multichannel analyser. The measured excitation functions are analysed to study the relative contributions of the pre-equilibrium and equilibrium parts of the reaction and to investigate the dependence of pre-equilibrium fraction on incident ion energy. Excitation functions are calculated theoretically employing two different computer codes, e.g., ALICE/LIVERMORE 82(27) and ACT(28). These computer codes are able to perform calculations with and without pre-equilibrium emission of particles. The pre-equilibrium contributions are simulated by a hybrid model(16)/ exciton model(15) formalism, while for the equilibrium calculations, Weisskopf-Ewing(29)/Häuser-Feshbach(30) model is used. The present analysis clearly indicates the presence of significant contributions from pre-equilibrium process. Moreover, the pre-equilibrium fraction is found to depend strongly on the excitation energy per nucleon of the compound system. To the best of our knowledge excitation functions for the $^{59}$Co($\alpha$,n$\alpha$), $^{63}$Cu($\alpha$,2n$\alpha$), $^{123}$Sb($\alpha$,n) and $^{123}$Sb($\alpha$,3n) reactions are measured for the first time.
Details of the experimental measurements, theoretical models and computer codes are given in chapter II, III and IV of the thesis respectively. In chapter V, the results of these measurements are discussed.
REFERENCES

26. EXFOR Library, Nuclear Data Section, IAEA, Vienna.