EQUILIBRIUM AND PRE-EQUILIBRIUM EMISSION IN SOME REACTIONS INDUCED BY LIGHT AND HEAVY IONS

ABSTRACT

Doctor of Philosophy thesis

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ABSTRACT

The nuclear reaction mechanism, particularly at moderate excitation energies, is not well understood. At relatively lower excitation energies the observed features of nuclear reactions can be well explained by assuming the formation of compound nucleus (CN) which decays by statistical particle evaporation. On the other hand at considerably higher energies the reaction products show the characteristics of direct reactions. However, at moderate excitation energies neither the compound nucleus nor the direct reaction mechanisms could explain the experimental data. The observed continuous particle spectra, the high energy tails in the excitation functions, forward peaked angular distribution of emitted charged particles, stretched particle distribution in angular momentum space, relatively larger emission of higher energy particles than predicted by the CN mechanism, are some of the clear deviations from the compound and direct reaction mechanisms. As such, at moderate excitation energies, both the intuition and results of recent experiments indicate that the nuclear particles may also be emitted after the first projectile-target interaction but prior to the establishment of statistical equilibrium in the compound system. The
particles which are emitted during the equilibration of the compound system are termed as pre-equilibrium or precompound particles and the process is called the pre-equilibrium (PE) emission. In the semiclassical approach the reaction may be assumed to proceed through successive two-body nucleon-nucleon interactions of increasing complexity. Each stage of the interaction may be characterised by the particle hole pair \((p,h)\), together called excitons. A brief general introduction of the subject is presented in Chapter-I of the thesis.

The measurement of the reaction time may be the most direct method of determining the reaction mechanism, but the time scales involved in the nuclear reactions are extremely short, of the order of \(10^{-22}\) to \(10^{-16}\) sec., which the presently available electronics cannot measure. Models are, therefore, proposed to explain the reaction mechanism. While the compound nucleus and the direct reaction theories are more or less well established, various semiclassical as well as quantum mechanical theories have been proposed to explain the intermediate pre-equilibrium process. A brief description of the semiclassical and quantum mechanical theories is given in
Chapter-II of the thesis.

With a view to study the PE-emission, the excitation functions for the following light (proton and alpha) and heavy ions induced reactions in light, medium and heavy nuclei covering a wide range of periodic table from $A=51$ to $A=197$ in the incident energy range up to $\approx 20$ MeV for protons, $\approx 40$ MeV for alpha and $\approx 80$ MeV for $^{12}$C heavy ion are measured and analysed.

$^{51}$V(p,n)$^{55}$Cr, $^{58}$Ni(p,$\alpha$)$^{60}$Co, $^{60}$Ni(p,n)$^{60}$Cu, $^{60}$Ni(p,$\gamma$)$^{64}$Cu, $^{64}$Ni(p,n)$^{64}$Cu, $^{62}$Ni(p,2n)$^{64}$Cu, $^{63}$Cu(p,n)$^{68}$Zn, $^{69}$Cu(p,2n)$^{69}$Zn, $^{65}$Cu(p,n)$^{65}$Zn, $^{60}$Y(p,n)$^{80}$Zr$^{m,g}$, $^{98}$Nb(p,n)$^{98}$Mo$^{m}$, $^{119}$In(p,n)$^{119}$Sn, $^{115}$In(p,3n)$^{115}$Sn, $^{121}$Sb(p,n)$^{121}$Te$^{m,g}$, $^{121}$Sb(p,n)$^{120}$Sb, $^{128}$Sb(p,n)$^{123}$Te$^{m}$, $^{129}$Sb(p,np)$^{122}$Sb, $^{190}$Te(p,n)$^{190}$I, $^{197}$Au(p,n)$^{197}$Hg$^{m,g}$, $^{197}$Au(p,np)$^{196}$Au, $^{58}$Ni(\alpha,n)$^{64}$Zn, $^{58}$Ni(\alpha,p)$^{64}$Cu, $^{58}$Ni(\alpha,2n)$^{64}$Cu, $^{58}$Ni(\alpha,2n)$^{57}$Ni, $^{60}$Ni(\alpha,n)$^{63}$Zn, $^{60}$Ni(\alpha,2n)$^{62}$Zn, $^{60}$Ni(\alpha,p2n)$^{64}$Cu, $^{64}$Ni(\alpha,2n)$^{69}$Zn, $^{64}$Ni(\alpha,3n)$^{62}$Zn, $^{62}$Ni(\alpha,3n)$^{69}$Zn, $^{141}$Pr(\alpha,n)$^{144}$Pm, $^{144}$Pr(\alpha,2n)$^{147}$Pm, $^{165}$Ho(\alpha,3n)$^{174}$Ta, $^{165}$Ho(C,4n)$^{173}$Ta, $^{165}$Ho(C,5n)$^{172}$Ta.

Light ion experiments were carried out at the Variable Energy Cyclotron Centre (VECC), Calcutta, India, employing stacked foil activation technique. The heavy ion induced reactions
were studied at the Nuclear Science Centre (NSC), New Delhi. Details of the experimental technique and measurements are given in Chapter-III of the thesis.

In order to analyse the measured excitation functions computer codes ALICE-91, ACT, EXIFON and CASCADE are used. The code ALICE-91 uses the Weisskopf-Ewing model for equilibrium and Hybrid/Geometry dependent hybrid model for PE calculations. In the code ACT the equilibrium component is calculated using Hauser-Feshbach model and the PE contribution is simulated using Exciton model. The code EXIFON is based on analytical model for statistical multistep compound and multistep direct (SMC/SMD) mechanisms. The codes CASCADE and ALICE-91 are used for calculations in case of heavy ion induced reactions. Code CASCADE is a purely statistical code for heavy ion reactions and does not take into account pre-equilibrium emission. A brief description of these computer codes and their parameters is presented in Chapter-IV of the thesis.

The results of the present measurements and the analysis of the experimental data are presented in Chapter-V of the thesis. Experimentally measured and theoretically calculated
excitation functions are compared and, in general, satisfactory agreement between them is found only when pre-equilibrium emission is taken into consideration. The initial exciton number, the matrix element for two body residual interaction, the level density parameter and the mean free path multiplier are important parameters for the pre-equilibrium calculations. In the present analysis the initial exciton number \( n_0 = 3 \) \((2p + 1h)\) for nucleon induced reactions and \( n_0 = 6 \) \((5p + 1h)\) for alpha induced reactions is found to give a satisfactory representation of experimental data. For reactions induced by \(^{12}\)C ions, \( n_0 = 3 \) gives good fit to the measured data. Considerable PE-component is observed in all reactions including the heavy ion \(^{12}\)C induced reactions. An attempt is made to determine the relative strength \( R \) of pre-equilibrium contribution in these reactions. Interesting trends in \( R \) values are observed and are discussed in Chapter-V.

In some of the reactions both the metastable and the ground states of the residual nucleus are populated. Since the isomeric states differ largely in spin and only slightly in energy, isomeric cross-section ratios give information about
the spin distribution of the intermediate systems. Isomeric cross-section ratios for some reactions are measured over a range of \( \%12-28 \) MeV excitation energy and are compared with the values theoretically calculated. The results of this analysis are presented in Chapter-V.
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Doctor of Philosophy thesis

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CERTIFICATE

Certified that the work presented in this thesis entitled "Equilibrium and pre-equilibrium emission in some reactions induced by light and heavy ions" is the original work of Mr. Mohamed Musthafa M. done under my supervision.

(Prof. Rajeshwari Prasad)
Professor of Experimental Nuclear Physics
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CHAPTER I
INTRODUCTION

The aim of nuclear physics research is to study the properties of nucleus as well as the behaviour of nuclear forces that bind the nucleons inside the nucleus. The nuclear research started with the discovery of radioactivity by Henry Becquerel[1] in 1898. The existence of a nucleus at the centre of each atom was established by Rutherford[2] through his alpha particle scattering experiments. In 1932 James Chadwick[3] established the presence of neutron which was earlier proposed by Rutherford[4] on theoretical ground. The fundamental step in the exploration of nuclear force was taken by Wigner[5] who showed that it has a very short range of action. Heisenberg[6] and Majorana[7] showed the saturation property of nuclear force. The invention of electrostatic generator by Van de Graaff[8], accelerators by Cockcroft and Walton[9] and cyclotron by Lawrence[10] opened an altogether new branch of artificial transmutation and gave a big boost to the study of nuclear reactions at higher energies. The discovery of fission[11] and fusion[12] are other major contributions to the nuclear physics research.
Since it is not possible to explore a nucleus directly, nuclear reaction is often considered as the best tool to understand the phenomenon of nuclear interactions and the nuclear structure. A nuclear reaction is one in which an atomic nucleus interacts with some nuclear projectile resulting in the emission of nuclear particles, heavy ions and/or radiations leaving behind the residual nucleus. Most of the known nuclear reactions are produced by exposing different materials to a beam of accelerated nuclear particles. In 1909 Rutherford and Royds identified alpha particle as helium nucleus[13] and achieved the first artificial transmutation in 1919[14].

Macroscopically, in a nuclear reaction, one may have the information of the reaction process before and after the reaction has taken place. However, what exactly happens during the reaction itself is not well known. To explain the reaction mechanism, Bohr[15] proposed the compound nucleus(CN) mechanism. According to him, as the incident particle comes in close contact with the target nucleus it is absorbed in it forming a compound system, the energy and angular momentum of the projectile are shared by all the
nucleons in the compound system and a thermodynamic equilibrium is established. The CN so formed is assumed to exist for a period of \( \approx 10^{-16} \) sec, which corresponds to the time taken for the equilibration of the compound system. It then decays independent of its mode of formation. This is called the independent hypothesis. Since, the decay of the compound nucleus is considered independent of its mode of formation and is treated by the laws of statistics, it results in symmetrical distribution of evaporated particles about \( 90^\circ \) in the centre of mass frame. In 1950, S.N. Ghoshal\[16\] carried out experiments using accelerated particle beams and established the validity of Bohr's independent hypothesis. The CN reaction mechanism is likely to be valid at lower excitation energies\[16\]. On the other hand, at considerably higher excitation energies the reaction is generally described by direct reaction mechanism, which is expected to take place within a time of \( \approx 10^{-22} \) sec i.e., the time required for the incident particle to pass through the nucleus. The direct reaction may be further classified into knockout, stripping or pick-up reactions\[17-19\]. The excitation of particular isolated levels of the residual
nucleus and the diffraction structure of angular distributions, usually forward peaked, are important features of direct reactions. With the advancement in nuclear electronics and the development of new more efficient detectors with better resolving power, more detailed experiments on nuclear reaction studies have been done. A typical energy spectra of charged particles emitted in a nuclear reaction at moderate excitation energy is shown in Fig. 1.1. The broad peak towards the lower excitation energy side can be ascribed to the compound nucleus mechanism while the sharp isolated peaks towards the end of the high energy tail represents the contribution from the direct reaction mechanism. The smooth distribution of particles between the two extremes of the spectrum cannot be explained either by the compound nucleus or the direct reaction mechanisms. Both the intuition and the results of recent similar experiments indicate that the emission of particles, in a nuclear reaction at moderate excitation energy, may also take place during the equilibration of compound system. The particles which are emitted during the equilibration of the CN are called pre-equilibrium particles, or pre-compound particles
Fig. I.1. Typical particle spectrum emitted in a nuclear reaction at moderate excitation energy
and the reaction mechanism is termed as pre-equilibrium (PE)
emission[20-22]. The PE mechanism serves as a bridge between
these two extreme approaches, namely, the compound and direct
reaction mechanisms. In semiclassical approach a series of
two-body collisions inside the nucleus is assumed to follow
the initial interaction, with a finite probability of
particle emission after each collision. The participants
sharing the excitation energy of the intermediate system, are
small in number. As a result, only a few degrees of freedom
are involved on one hand and the selectivity of direct
reaction is lost on the other. The PE emission is featured by
slowly descending tails of excitation functions, forward
peaked angular distribution of emitted particles and
relatively large number of higher energy particles than
predicted by the CN mechanism.

Various semiclassical models, like Intranuclear Cascade Model
(ICM)[23], Harp Miller and Berne model (HMB)[24], Exciton
model (EM)[25], Hybrid model[26] and Geometry Dependent
Hybrid model (GDH)[27] and recently quantum mechanical
models, like Feshbach Kerman Koonin model (FKK)[28] and
Hydelberg model[29], are proposed for treating the PE
emission of the particles. These models are discussed in Chapter-II of the thesis.

A theoretical model may be evaluated on the basis of its power to predict the experimental data. In order to test these pre-equilibrium models, it is desirable to have extensive data on excitation functions, energy and angular distributions etc., of emitted particles 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.

The study of excitation functions for proton, alpha and heavy ion induced reactions is important from the point of view of nuclear physics, reactor physics, astrophysics, material, biological and medical sciences. In the primary cosmic rays proton contributes ≈90% and thus it may help to study the production of radioactive nuclides and pions on interaction with extra terrestrial bodies like lunar surface and the surfaces of other planets and their atmosphere. This also gives adequate information about the nucleosynthesis in the stars. A comparatively new field of heavy ion reactions has
opened new dimensions to the study of nuclear physics. Since heavy ions carry larger angular momentum, higher spin states in the compound nucleus are populated. Particularly, heavy ion reactions produce nuclei far from the line of stability, which are generally short lived and only very little information about these exotic nuclei is available at present. Also, with the knowledge of excitation function, optimum production of these exotic nuclei can be achieved for the study of their nuclear properties. The study of excitation functions for heavy ion induced reactions gives considerable information on the nucleosynthesis and structure effects. The probabilities of fission and fusion of heavy ions are also important from the point of reactor design. In medical science the optimum production of radioactive isotopes used for radiation therapy and treatment of cancer etc. is required. In biological science the study of mutation breeding and the biological effect of heavy ion radiations are important studies of research.

Though, the excitation functions for α-induced reactions and a few proton induced reactions are available for many target nuclides, but there are large discrepancies in the reported
values\[16,30-35\]. Further, the data are incomplete as they cover a small energy range and contain large errors. Also, in most of the literature data, the error analysis is not discussed in detail. Most of the analysis of excitation functions for alpha and proton induced reactions, in the past, were carried out only on the basis of statistical equilibrium model which could not account for the high energy tails of the excitation functions. In the case of heavy ion induced reaction, only very few measurements are available. With these factors in view, excitation functions for some proton induced reactions upto \( \leq 20 \) MeV, alpha induced reactions upto \( \leq 40 \) MeV, and heavy ion induced reactions upto \( \leq 80 \) MeV, from the threshold energy, are measured covering a relatively wide mass region of \( A=51-197 \).

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 selectivity, sensitivity and simplicity. Further, cross sections for several reactions can be measured in a single irradiation
using activation technique and thus considerable economy of accelerator beam time can be achieved. Activation technique may also be used to measure the angular distribution and range of the recoil nuclei in heavy ion reactions[36]. Present measurements are done using activation technique.

Experiments on the light ion reactions were carried out at the Variable Energy Cyclotron Centre (VECC), Calcutta, India, while heavy ion reactions were studied at the Nuclear Science Centre (NSC), New Delhi, India. Further details of these experiments and measurements are given in Chapter-III. Excitation functions for some 38 reactions are measured and analysed, using semiclassical and quantum mechanical theories, out of which measurement for nearly 23 reactions are being reported for the first time.

In order to analyse the experimental data, theoretical calculations are generally done using computer codes. In the present analysis semiclassical codes ALICE91[37] and ACT[38] alongwith quantum mechanical code EXIFON[39] are used for calculating the excitation functions for light ion induced reactions while codes ALICE91[37] and CASCADE[40] are used
for heavy ion reactions. Chapter-IV deals with the details of these computer codes used for the theoretical calculations. The results of the present measurements and analysis are discussed in Chapter-V. In order to make a consistent analysis of the experimental data, an attempt is made to fix the adjustable parameters of the reaction models. Further, the relative contributions of pre-equilibrium and equilibrium processes are separated and their dependence on several parameters is studied. Interesting trends in the pre-equilibrium fraction are observed.
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CHAPTER II
NUCLEAR REACTION MODELS

In a nuclear reaction an atomic nucleus interacts with the nuclear projectile, emitting nuclear particles and/or radiations leaving behind the residual nucleus. Macroscopically we know the system before and after the reaction but what exactly happens during the reaction process is not known. Since it is not possible to look into the reaction process directly, models for reaction mechanism are proposed in order to explain the yield, angular and energy distributions of the reaction products. The first attempt to model a reaction was made by Niels Bohr[1] in 1936, who proposed the compound nucleus (CN) mechanism, in which it is assumed that the projectile is absorbed by the target nucleus forming a compound nucleus (CN). It is further assumed that the CN lives till a thermodynamic equilibrium is established. It then decays by emitting particles and/or radiations. It is assumed that the decay of the CN depends only on the excitation energy and other good quantum numbers of the compound nucleus and is totally independent to its formation. This is called 'independent hypothesis'. Compound nucleus
mechanism accounts well the isotropic distribution of emitted particles in the centre of mass frame at lower excitation energies. However, at relatively higher excitation energies, the forward peaked angular distribution of particles indicates the presence of direct reaction mechanism [2,3]. In CN mechanism the whole system is involved while in direct reaction mechanism only a few nucleons take part in the evolution of the reaction process.

Both the intuition and the results of some recent measurements indicate the presence of reaction process which is intermediate between these two extreme reaction mechanisms. It is called pre-equilibrium mechanism (PE) [4-7]. In PE mechanism it is assumed that the nuclear reaction develops as a result of successive interaction of the projectile and the nucleons of the target nucleus and particle emission may take place at any stage even before the establishment of thermodynamic equilibrium. In reactions initiated by few tens of MeV the continuous particle spectra indicate the presence of such multistep process. It is possible that the particles may be emitted during the first
few projectile target interactions but prior to the establishment of statistical equilibrium in the compound system. The particles which are emitted during the equilibration are called pre-compound or pre-equilibrium particles.

While the compound nucleus and direct reaction theories are more or less well established, recently several semiclassical and more recently, quantum mechanical theories are proposed to explain pre-equilibrium reaction mechanism. A brief description of compound nucleus and PE mechanisms is presented in the following sections.

II.1. Compound nucleus model

Weisskopf and Ewing[8] developed theoretical calculations of reaction cross-sections according to the Bohr's model[1] using partial wave analysis. In this model[8] the conservation of angular momentum and parity for each partial wave is not taken into account, nevertheless, it provides a good estimate for the magnitude of the cross-section. On the other hand Hauser and Feshbach[9] treated the problem in a
more detailed way and have explicitly taken into account the conservation of angular momentum and parity. Further, the Hauser-Feshbach (HF) formalism[9] uses the optical model potentials for nucleon interactions.

According to Weisskopf-Ewing (WE) statistical model the average cross-section ($\bar{\sigma}$) is given by

$$ \bar{\sigma}_{jk} = \sigma_{\text{comp}}(j) [Q / G] \quad \text{...(II.1)} $$

where, the incident and the outgoing particles are denoted by the symbols $j$ and $k$ respectively. $\sigma_{\text{comp}}(j)$ is the cross-section for the formation of compound nucleus which may be computed using the transmission coefficients for partial waves. The term in the square brackets is called the branching ratio for the decay resulting in the emission of particles of type $k$. It may be evaluated using the level density $\omega(E)$. In literature several prescriptions for the level densities are available and different authors used different formulae in their calculations[10-16].

In Hauser-Feshbach model[9], which explicitly takes into account conservation of parity and angular momentum, the
average cross-section \( \bar{\sigma}_{jk}^{\mu \nu}(E_j) \) for the reaction \( I^\mu(j,k)L^\nu \) is given by,

\[
\bar{\sigma}_{jk}^{\mu \nu}(E_j) = \frac{\hbar^2}{(2M E_j^I)} \sum_{j \neq j'} (2J_{I}^{J_{I}^{j}+1})(2J_{I}^{J_{I}^{j}+1}) \sum_{\pi l',s'} T_{j}^{\mu}(J_{I}^{I},1,s) \times \sum_{l',s'} \frac{T_{k}^{\nu}(J_{I}^{I},1',s')/T_{total}(J_{I}^{I})}{(...II.2)}
\]

Notations used in eqn.(II.2) are due to Woosley et al.[17].

Here, \( \mu \) and \( \nu \) refer to the discrete energy states of the target nucleus \( I \) and the residual nucleus \( L \) respectively. \( E_j^I \) is the energy of the \( (I^\mu+j) \)th compound nucleus in c.m. frame and \( M \) is the reduced mass. \( J_{I}^{j} \) and \( J_j \) are respectively the spins of the nucleus \( I \) in state \( \mu \) and of particle \( j \). \( J \) and \( \pi \) refer to the spin and the parity of resonance states in compound nucleus, \( l, s \) and \( l', s' \) respectively the orbital angular momentum and channel spins in \( (I^\mu+j) \) and \( (L^\nu+k) \) systems. \( T_{j}^{\mu}(J_{I}^{I},1,s) \) and \( T_{k}^{\nu}(J_{I}^{I},1',s') \) are the transmission functions for the \( (I^\mu+j) \) and \( (L^\nu+k) \) systems respectively. \( T_{total}(J_{I}^{I}) \) is the sum of transmission functions for all channels from resonance states. The target is generally in its ground state (in real experiment) and hence \( \mu \) is taken as zero. The total cross-section \( \sigma \) averaged over all energy
states may then be given by,

$$\bar{\sigma} = \sum_{\nu} \bar{\sigma}_{\nu} = \frac{n\hbar^2/(2M E)}{(2J+1)(2J+1)} \sum_{J, \pi} \frac{T_j(J^\pi) T_k(J^\pi)}{T_{\text{total}}(J^\pi)} ...(\text{II.3})$$

The transmission functions are related to the respective partial widths $\Gamma_x$ as follows,

$$T_x(J^\pi) = \sum_{J, \pi} T_x(J^\pi, 1, s) = \frac{2\pi \langle \Gamma_x(J^\pi) \rangle}{D(J^\pi)} ...(\text{II.4})$$

Where $D(J^\pi)$ being the mean spacing between states of spin $J$ and parity $\pi$. Eqn. (II.3) results from the averaging over single resonance cross-sections according to the relation,

$$\bar{\sigma}_{jk} = \frac{n\hbar^2/(2M E)}{(2J+1)(2J+1)} \sum_{J} \frac{2\pi \langle \Gamma_j(J^\pi) \Gamma_k(J^\pi) \rangle}{D(J^\pi) \Gamma(J^\pi)} \frac{\Gamma_j(J^\pi) \Gamma_k(J^\pi)}{\Gamma(J^\pi)} ...(\text{II.5})$$

The width fluctuation correction for Hauser-Feshbach formula was introduced by Moldauer[18] through a correction term,

$$W_{jk}(J^\pi) = \frac{\Gamma_j(J^\pi) \Gamma_k(J^\pi)}{\Gamma(J^\pi)} \frac{\langle \Gamma_j(J^\pi) \rangle <\Gamma_k(J^\pi)>}{\langle \Gamma(J^\pi) \rangle} ...(\text{II.6})$$

Though width fluctuation correction is important, particularly near the reaction threshold and when the number
of channels is small[19], however, at moderate excitation energies more channels open up and, therefore, width fluctuation correction becomes less important[20].

II.2. Pre-equilibrium models

Nuclear reaction models based on semiclassical and totally quantum mechanical theories are proposed for PE emission mechanism. Some of the important semiclassical models, like Intranuclear Cascade Model, Harp Miller and Berne Model, Exciton model, Hybrid/Geometry Dependent Hybrid model and Index model, along with quantum mechanical treatments of PE emission given by Feshbach, Kerman and Koonin and Nishioka, Verhaarshot, Weidenmuller and Yoshida (NVWY or Hydelberg model) are briefly outlined in the following sections.

II.2.1. Intranuclear cascade model

A diagrammatic representation of intranuclear cascade (INC) model[21] is shown in Fig.II.1. As is indicated the trajectories of particles after two-body interactions inside the nucleus are followed, one at a time, in three dimensional co-ordinate space, using the Monte-Carlo method, till some
Fig. II.1. Pictorial representation of INC model
arbitrary energy (generally considerably above the average equilibrium value) is attained by the nucleon. Experimental free nucleon-nucleon scattering cross-sections and angular distributions are generally used in these calculations. Particle emission is assumed to occur whenever nucleon follows a trajectory out of the composite nucleus without undergoing another collision. Different forms for the nuclear potential and nuclear density distribution are used[22]. Till mid 80s the INC model was the only pre-compound model which could predict the angular distribution of emitted particles. However, INC model underestimates, by an order of magnitude, cross-sections at backward angles. With the evolution of computer the INC model has become more intricate with respect to the physics going into the calculations. The model also shows complexity while dealing with large number of collisions.

II.2.2. Harp-Miller-Berne Model

A schematic representation of Harp-Miller-Berne (HMB)[23] model is shown in Fig. II.2. In this model the reaction is assumed to start at some time $t_0$. The energy scale (total
excitation) is divided into bins of some suitable size (say 1 MeV) and occupation number of each bin is calculated and stored. During the evolution of reaction the occupation numbers of these bins change due to the scattering into other bins or into continuum. The two-body transition rates in this model are computed using free nucleon-nucleon scattering cross-sections. The relative occupation number of each bin as a function of time is computed by a set of coupled differential equations. Though following the energy bin population with time is an intricate problem this model is simple in approach. However, it cannot predict angular distributions. Another practical disadvantage of this model is its computational complexity. To deal with this difficulty additional assumptions are to be made. This is done in the Exciton and the Hybrid models.

II.2.3. Exciton model

The exciton model (EM) which originated from the work of Griffin[24] is most extensively used for calculating the pre-equilibrium contributions[7,25-27]. In this model a nuclear state is characterised by the excitation energy $E$ and
Fig. II.2. Pictorial representation of HMB model
the exciton number $n$ which is the sum of $p$-particles above and $h$-holes below Fermi surface. As the incident particle enters the nucleus a series of two-body interactions is assumed to give rise to states of increasing complexity as shown in Fig. II.3. A basic assumption of the model is that all possible ways of sharing the excitation energy between different particle-hole configurations with the same exciton number $n$, have equal probability. A two-body interaction with an initial state of $p$-particles and $h$-holes may lead to (i) another configuration of the same state, (ii) a state of $(p+1)$ particles and $(h+1)$ holes or (iii) a state of $(p-1)$ particles and $(h-1)$ holes. Thus a two-body interaction changes the exciton number $n$ by $\pm 2$ or zero. Since the level density of states is an increasing function of exciton number, the system will predominantly proceed towards higher exciton number. Finally, the system will attain equilibrium value $\bar{n}$ of the exciton number such that the decay rates for $\Delta n = 2$ and $-2$ become equal. Particle emission into continuum may take place after each two-body interaction. The development of the exciton number $n$, which changes in time as
Fig. II.3. Pictorial representation of exciton model
a result of intranuclear collisions, is followed. As exciton number increases towards the equilibrium value the probability of particle emission having high energy decreases exponentially. The level densities of the intermediate states play an important role in the exciton model. The particle-hole state densities in the uniform spacing model are given by Williams[26] as,

\[ \rho = g \frac{(gE-A_{p,h})^{n-1}}{p! h! (n-1)!} \]  ...(II.7)

where \( g \) is the single particle density, \( E \) is the excitation energy of the compound nucleus and \( A_{p,h} \) the correction for Pauli's exclusion principle given by,

\[ A_{p,h} = \frac{1}{4}(p^2 + h^2 + p - 3h) \]  ...(II.8)

The fraction of \( n \)-exciton state in which one particle is at an energy \( \epsilon + B \) above the Fermi energy is given by the ratio,

\[ \frac{\rho_n(U,\epsilon)}{\rho_n(E)} = \frac{\rho_{p,h}(U,\epsilon)}{\rho_{p,h}(E)} \]  ...(II.9)

where \( U \) and is the excitation energy of the residual nucleus and \( \epsilon \) is the channel energy of the emitted particle.
Statistical and phase space considerations finally lead to the following expressions of the total decay probability for the emission of a particle with channel energy $\epsilon$,

$$ P(\epsilon) d\epsilon = \frac{(2s+1)ma\epsilon}{n^2 \hbar^2 g E} \sum_{n=n_0}^{n_{\max}} \left[ \frac{U}{E} \right]^{n-2} \rho(n-1) \epsilon \, d\epsilon \quad \text{(II.10)} $$

The lifetime $\tau_n$ may be evaluated on a relative basis by \cite{24},

$$ \lambda_{n,n'} = \frac{1}{\tau_n} = \frac{2n}{\hbar} |\overline{M}|^2 \rho_n(E) \rho_{n'}(E) \quad \text{(II.11)} $$

where, $\rho_{n}(E)$ is the density of accessible final states and $\lambda_{n,n'}$ is the transition rate from a given initial $n$ exciton state to any of the accessible $n'$ exciton state, $|\overline{M}|^2$ being the square of average two-body residual interaction matrix element. Williams\cite{28} proposed the following expressions for the internal transition rates.

$$ \lambda_+ = \frac{2n}{\hbar} |\overline{M}|^2 \frac{g^3 U^2}{(n+1)} $$

$$ \lambda_- = \frac{2n}{\hbar} |\overline{M}|^2 \frac{g p \hbar (n-2)}{(n-2)} $$

$$ \lambda_0 = \frac{2n}{\hbar} |\overline{M}|^2 \frac{g^2 U \left( \frac{1}{4} (3n-2) \right)}{(n-2)} \quad \text{(II.12)} $$
here, $\lambda_+^\prime$, $\lambda_-'$ and $\lambda_0$ are the relative internal transition rates for $\Delta n=+2$, -2 and 0 respectively. It can be seen from the above expressions, as expected $\lambda_+^\prime \gg \lambda_-'$ if $n\langle \bar{n} \rangle$. Assuming that $\lambda_+^\prime = \lambda_-'$ at equilibrium ($n=\bar{n}$) one may get $\bar{n} = \sqrt{2gE}$. In order to evaluate internal transition rates it is necessary to calculate $|\bar{M}|^2$. In the absence of any microscopic description Kalbach-Cline[29] proposed the energy dependent matrix element as $|\bar{M}|^2 = F A^{3-4} E^{-1}$ where $A$ is the atomic mass number and $E$ is the excitation energy of the compound system.

II.2.4. Hybrid and Geometry Dependent Hybrid model

Hybrid model[30] was proposed by Blann. It maintains the physical transparency and simplicity of the exciton model while permitting the calculation of absolute spectral yield as in the HMB model. The continuum decay rates are computed from the partial state densities while the intranuclear transition rates are calculated from the mean free path (MFP) of the nucleons in the nuclear matter. The MFP, in turn, may be evaluated either from free nucleon-nucleon scattering cross-sections or from the imaginary part $W$ of the optical
potential\textsuperscript{[30]}. The total particle emission probability in a given range of channel energy \( \varepsilon \) and \( \varepsilon + \Delta \varepsilon \) may be given as the sum over the contribution of the intermediate states. The probability of emission of a particle of type \( \nu \) with channel energy \( \varepsilon \) to \( \varepsilon + \Delta \varepsilon \) is given by the expression\textsuperscript{[30]},

\[
P(\varepsilon) d\varepsilon = \sum_{n=0}^{\infty} nP_{\nu} \left[ \frac{\rho_n(U, \varepsilon)}{\rho_n(E)} \right] \frac{\lambda_c(\varepsilon)}{\lambda_c(\varepsilon) + \lambda_{n+2}(\varepsilon)} D_n \quad \ldots (\text{II.13})
\]

Where, \( nP_{\nu} \) is the number of particles of type \( \nu \) in an \( n \) exciton state with \( n (=p+h) \) excitons, one of which has an energy such that if emitted, the residual nucleus would have excitation energy \( U (=E-B_\nu - \varepsilon) \) and the particle would have channel energy \( \varepsilon \). \( B_\nu \) is the binding energy of the emitted particle and \( \rho_n(E) \) is the state density of \( n \)-exciton state with excitation energy \( E \). \( \lambda_c(\varepsilon) \) is the decay constant for transition into the continuum for a particle at excitation \( (B_\nu + \varepsilon) \) above Fermi energy and \( \lambda_{n+2}(\varepsilon) \) is the corresponding decay rate for creating another particle-hole pair, leading to the final state of \( (n+2) \) excitons. \( D_n \) is the population surviving the particle emission. The emission rate \( \lambda_c(\varepsilon) \) into the continuum is given as,
where, \( \sigma(\xi) \) is the inverse cross-section, \( \rho_c(\xi) \) the density of transitional state of a particle in the continuum and \( \Omega \) the volume in which the free phase space is normalised.

The non-uniform distribution of nucleons in the nucleus may affect the decay rates as the mean free path in the diffused surface region will be larger as compared to the mean free path in the interior of the nucleus. To take into account this effect Blann proposed Geometry Dependent Hybrid (GDH) model[31]. Nuclear geometry effects may be taken into account through Fermi energy of two regions. Following Fermi density distribution is generally used to include geometry effects,

\[
d(R) = d_s[\exp(R - C)/Z + 1]^{-1} \quad \ldots(II.15)
\]

where, \( d(R) \) is the density at radius \( R \), \( Z=0.55\text{fm} \) and \( d_s \) is the saturation density of the nuclear matter in the interior of the nucleus. The charge radius \( C \) is given by[32],

\[
C = 1.18A^{1/2} \left[ 1 - \left( \frac{1}{1.18\Lambda^{1/2}} \right)^2 \right] + \Lambda \quad \ldots(II.16)
\]
where, $\lambda$ is the de Broglie wavelength of the projectile. The dependence of Fermi energy and single particle level density ($g_x$) on nuclear matter density are taken as follows,

$$E_F(R) = E_F[(d(x)/ds)^{2/3} \text{ MeV}] \quad \text{(II.17)}$$

$$g_x(R) = [E_f(R)](A/28) \quad \text{...(II.18)}$$

where, $E_F$ is the Fermi energy at the saturation density and $x$ represents particle type.

II.2.5. Index Model

All pre-equilibrium models assume that the reaction proceeds through a series of binary collisions, each of which leads to either scattering into more complex configuration or particle emission into the continuum. During equilibration the compound system passes through a series of intermediate states each of which is characterised by the number $n$ of excited particles plus holes. Different and sometimes divergent viewpoints about the treatment of intermediate states are adopted in hybrid and exciton models. In hybrid model a single particle view is taken and energy dependent
but stage independent single particle life times are used for intermediate states. In the exciton model, on the other hand, a collective view point is taken and energy independent but stage dependent life times are taken. In exciton model complete and thorough configuration mixing within state of a given exciton number \( n \) is due to collective view point, while in hybrid model each exciton interacts independently from the other. In view of these divergent approaches, the predictions of the two models for the same reaction are likely to be divergent. This is sometimes cited as the plausible reason for adjusting parameters for matching experimental data.

Ernst et al.\[33\] developed Index model, of independently interacting excitons, for pre-equilibrium emission which unifies the exciton and hybrid models. The basic assumption of the Index\[33\] model is that all excited particles which survive emission undergo two-body collisions and create further particle-hole pairs independently from each other. Thus the energy of each exciton is shared by the three excitons of the following stage. The average nucleon-nucleon collision rates and the internal energy in this model are
taken from the interaction rate of nucleons inside the nuclear matter. In Index model it is possible to include the multiparticle emission and it is shown that for light ion induced reactions below 100 MeV, emission of more than three PE nucleons is not important[33].

II.3. Quantum mechanical theories

Several quantum mechanical theories of pre-equilibrium reactions are also proposed[34-47]. The quantum mechanical calculations, at present are mostly being done for the nucleon induced reactions. It is because for a complex particle, like \( \text{He}^4 \), the quantum mechanical treatment of initial projectile-target interaction becomes very much complex. Further, the multiparticle emission in such cases has to be treated using approximations, therefore, approaching the philosophy of the semiclassical models. Considering the above facts, it may be concluded that for reactions initiated by complex particles the quantiative calculations, if not impossible, are impractical as mentioned by Gruppelaar et al[42]. However, some calculations for complex incident particles are referred[43]. A brief outline
of quantum mechanical theories of precompound emission is presented in the following sections.

II.3.1. Feshbach-Kerman-Koonin model

Feshbach, Kerman and Koonin[34] proposed a statistical theory which applies to the entire spectrum based on statistical multistep compound and multistep direct reaction mechanism. The distinction between the reaction process is made on the basis of angular distribution of emitted particles. As one moves away from the evaporation regime towards higher energies, first the angular distribution of emitted particles becomes anisotropic but remains symmetric around 90° in centre of mass and eventually at still higher energies this symmetry around 90° is also lost. The processes which produce isotropic angular distributions symmetrical around 90° are called multi-step compound (MSC) reactions and processes giving forward peaked angular distribution, like the angular distribution characteristics of direct reactions, are termed as multi-step direct (MSD) processes. Like exciton model, the reaction is considered to proceed through a set of stages. The excitation of nth stage is more complex than (n-1)th
stage and less complex than \((n+1)\)th stage. Both MSD and MSC processes are involved in these stages of complexity. In each stage assumed to be the multistep direct, at least one particle is in the continuum. On the other hand, in the case of multistep compound stage all the particles are bound. The reaction may be terminated at any stage by a transition to the final stage, a process which competes with (i) the excitation of the next stage of complexity and (ii) the de-excitation back to a less complex stage. This is schematically represented in Fig. II.4, where P and Q chains represent the successive MSD and MSC stages respectively with a finite probability of shifting the channels. It is assumed that the residual interaction can induce transitions from the \(n\)th stage only to the \((n+1)\)th stage. This is referred to as chaining hypothesis. In MSD the matrix elements involving different total angular momentum, parity and other quantum numbers required to specify a channel, are assumed to have random relative phases, so that no interference term remain upon averaging. The angular distribution generated by the multistep compound process is therefore, symmetric around 90°.
Fig. II.4. Pictorial representation of FKK model
P-chain represents MSD process and
Q-chain represents MSC process
in the centre of mass frame. MSD assumes that only matrix elements which will interfere constructively upon averaging are those involving the same change in the momentum of the particle in the continuum. The memory of initial direction is thus preserved and an anisotropic angular distribution results. Further, it is assumed that the width $\Gamma_{n+1}$ of the appropriate state in the $(n+1)$th stage is larger compared to the spacing $D_n$ of levels in the $n$th stage. The predictions of MSC analysis are sensitive to the density of states $\rho_n$ associated with each stage. These densities increase very rapidly as $n$ increases till the chain is terminated. The termination stage contains all configurations which are not being included in all stages upto $(n-1)$th stage. The component of the wave function in the terminating stage is assumed to be statistically distributed among all these configurations. Thus the wave function of the nuclear state is composed of components from each stage, including the terminating stage.

The reaction cross-section $\sigma_{fi}$ for a reaction proceeding from an initial two-body channel $f$ to a different final channel $f$
is given by,
\[ \sigma_\text{fl} = \frac{4\pi^3}{k^2} |T_{\text{fl}}|^2 \] ...\(\text{(II.19)}\)

Where, \(|T_{\text{fl}}|^2\) is the square of the transition matrix element. Accordingly, the \(T_{\text{fl}}\) will be composed of MSD and MSC components contributing the two types of cross-sections namely MSD and MSC cross-sections. Thus,
\[ T_{\text{fl}} = T_{\text{fl}}^{(\text{direct})} + T_{\text{fl}}^{(\text{MSC})} \] ...\(\text{(II.20)}\)

II.3.1.1. Multistep Direct reaction

The transition matrix element for direct reaction \(T_{\text{fl}}^{(\text{direct})}\) is obtained from the solution of Schrodinger equation.
\[ (E-H_{\text{opt}})|\psi^*_l\rangle = 0 \] ...\(\text{(II.21)}\)

\(H_{\text{opt}}\) is decomposed into a diagonal part \(H^D\) and a coupling interaction \(v\) with respect to an appropriate set of wave functions. The transition amplitude associated with \(H_{\text{opt}}\) can be obtained by Lippman Swinger function,
\[ T_{\text{fl}}^{(\text{direct})} = V_{fl} + \langle \phi_{\text{f}}^* | v \frac{1}{E^*-H_{\text{opt}}} v | \phi_{\text{l}}^* \rangle \] ...\(\text{(II.22)}\)
Here, \( v \) gives the single step Distorted Wave Born Approximation (DWBA) direct transition amplitude while the second term is the multistep direct contribution. Partitioning into subspace \( p \) and using the chaining hypothesis leads to the result,

\[
T_{f_1}^{(dir)} = v_{f_1} + \sum_{\nu} T_{f_1}^{\nu} ... (11.23)
\]

\[
T_{f_1}^{\nu} = \langle \psi_{f_1}^- | v | \nu \rangle \frac{1}{E - H_{opt}} \langle \psi_{f_1}^- | \phi_{f_1}^+ \rangle ... (11.24)
\]

and

\[
v_{f_1} = p_{f} v_{p_{f}}
\]

where, \( p_{f} \) and \( p_{i} \) are the final and initial channel wave functions respectively. Using the propagator, one may obtain,

\[
T_{f_1}^{\nu} = v_{f_1} G_{\nu} v_{f_1} G_{\nu-1} v_{f_1} G_{\nu-1} v_{f_1} G_{\nu-2} ....... v_{f_1} G_{\nu} v_{f_1} ... (11.25)
\]

The multistep cross-section is proportional to \( \sum (T_{f_1}^{\nu})^* T_{f_1}^{\nu} \).

Invoking the random phase hypothesis, only \( \mu = \nu \) terms survive and hence,
\[
\sum_{\nu \nu'} (T_{ll}^{\nu})^* T_{ll'}^{\nu'} = \sum_{\nu \nu'} \langle \nu, \nu' | v_{m\nu} G_{\nu-1} G_{\nu} v_{l2} | \nu, \nu', \nu' \rangle \\
\sum_{\nu \nu'} G_{\nu-1} \nu, \nu' G_{\nu}^* v_{l1}^* | \phi^*_{l1} \rangle 
\]

Now the eigen state, \( \chi_{\nu \alpha} \) of the effective Hamiltonian \( H_{opt} \) associated with each Green function is introduced such that,

\[
\left[ H_{\nu \nu}^D + v_{\nu, \nu+1} G_{\nu+1} \nu, \nu+1 \right] \chi_{\nu \alpha} = (\hbar^2/2mk^2 + \epsilon_{\nu \alpha}) \chi_{\nu \alpha} \quad \text{...(II.27)}
\]

where, \( \chi_{\nu \alpha} \) is asymptotically the product of wave function for the residual nucleus in a state \( \alpha \) and a distorted wave describing the particle of momentum \( k_{\nu} \). \( \epsilon_{\nu \alpha} \) and \( \hbar^2/2mk^2 \) are respectively the energies of the residual nucleus and of the particle in the continuum. The average cross-section may then be obtained as,

\[
\left\langle \frac{d\sigma_{(k_{1},k_{2})}}{d\Omega_{f} d\Omega_{l}} \right\rangle = \sum_{m_{l},l} \frac{dk_{l}}{(2\pi)^3} \cdots \frac{dk_{\nu}}{(2\pi)^3} \\
\times \left[ \frac{dw_{m\nu}(k_{1},k_{2})}{d\Omega_{f} d\Omega_{l}} \right] \left[ \frac{dw_{\nu-1}(k_{1},k_{2})}{d\Omega_{f} d\Omega_{l}} \right] \\
\cdots \\
\cdots \left[ \frac{dw_{2l}(k_{1},k_{2})}{d\Omega_{2} d\Omega_{2}} \right] \left[ \frac{d\sigma_{l1}(k_{1},k_{2})}{d\Omega_{l1} d\Omega_{l1}} \right] 
\]

\quad \text{...(II.28)}
with
\[ \frac{d\gamma_{11}}{d\gamma_{11}^2} = \frac{2\pi m}{\hbar^2 k_1} \rho(k_1) \rho(U_{11}) |v_{11}(k_1, k_1)|^2 \] ...(II.29)

II.3.1.2. Multistep Compound Reaction

Corresponding to the partition of the \( Q \) space into subspaces \( Q \) a the transition amplitude becomes,

\[ T_{f_l}^{(\text{fluct})} = \sum_{n=1}^{\infty} T_{f_l}^n \] ...(II.30)

Applying chaining hypothesis and using Green function propagator

\[ T_{f_l}^n = \langle \psi_f | V_{n,n} V_{n-1,n-1} \cdots V_{1,1} | \psi_i \rangle \] ...(II.31)

\[ V_{n,n-1} \equiv Q_{Q_n} \]

Here, \( G_k \) is the projected propagator of \( h_{QQ} \) in the subspaces \( Q_k \) allowing for the influence of all the subspaces further along the chain terminating at the \( r \)th stage and is defined by,

\[ G_k = \frac{1}{E - h_{kk} - V_{k,k+1} G_{k+1} V_{k+1,k}} Q_k \] ...(II.32)

and
\[ V_{k,k+1} G_{k+1,k} V_{k+1,k} = w_{kk} \]

\( V_{k,k+1} \) is the potential that allows for the coupling and consequent damping of \( Q_n \) into the more complex subspaces, \( w_{kk} \) being the effective potential that allows for the coupling and damping of \( Q_k \) to the reaction channels. Diagonalising \( h_{kk} + w_{kk} \) and performing expansion of these eigen states \( h_{rr} |\alpha\rangle \) which satisfies

\[(e_{r\alpha} - h_{rr}) |\alpha\rangle = 0, \quad (e_{r\alpha}^* - h_{rr}^*) |\alpha\rangle = 0, \quad \ldots (11.33)\]

and

\[ e_{r\alpha} = E_{r\alpha} - i \Gamma^+/2 \quad \ldots (11.34) \]

One gets

\[ W_{r-1,r-1}(E) = \sum_{\alpha} V_{r-1,r} \left| \frac{1}{E - e_{r\alpha}} \langle \alpha | V_{r,r-1} \right| \ldots (11.35) \]

It follows that the matrix element of \( W_{kk} \) will vary smoothly with energy if average of the escape width is greater than the average level spacing of \( Q_{r-1} \) space.

\[ \langle \Gamma^+ \rangle \equiv \langle \Gamma^+ \rangle_{r_{r-1}} \]

The operator \( W_{r-1,r-1} \) is complex but essentially energy independent. Since many states \( |n\alpha\rangle \) contribute to the sum \( T_n \), it depends on the correlation between the matrix
elements coupling $Q_n$ to $Q_{n-1}$ and $Q$ to $P$. Such a correlation is assumed to be vanishingly small in accordance with the random phase assumption. Thus each $T^n_{f_i}$ is self averaging and averages to zero. Hence $\langle T^n_{f_i} \rangle = 0$. Now,

$$|T^n_{f_i}|^2 = \sum_{n,n'=1}^r T^{n*}_{f_i} T^n_{f_i} \approx \sum_{n=1}^r T^n_{f_i}^2$$

$$= \sum_{\alpha} \langle \psi_f^- | \psi_{p_n} | n\alpha \rangle \frac{1}{|E - e_n\alpha|} \langle n\tilde{\alpha} | \psi_{n,n-1}^Q \psi_i^+ \rangle^2 \quad \text{...(II.36)}$$

so that

$$|T^n_{f_i}|^2 = \frac{\Gamma^n_{f_i}}{\Gamma_n} \frac{\langle |n\tilde{\alpha}| \psi_{n,n-1}^Q \psi_i^+ \rangle}{\mathcal{D}_n} \quad \text{...(II.37)}$$

$$\Gamma^n_{f_i} \equiv 2\pi \langle \langle \psi_f^- | \psi_{p_n} | n\alpha \rangle \rangle^2 \quad \text{...(II.38)}$$

where, average is taken over all states $\alpha$. Inserting a complete set of eigen states for $G_{n,n-1}$ and using the statistical assumptions, one may get,

$$\langle |T^n_{f_i}|^2 \rangle = \frac{\Gamma^n_{f_i}}{\Gamma_n} \frac{\langle |n\tilde{\alpha}| \psi_{n,n-1}^Q \psi_i^+ \rangle^2}{\mathcal{D}_{n-1}} \quad \text{...(II.39)}$$

$$= \frac{\Gamma^n_{f_i}}{\Gamma_n} \left[ \prod_{k=1}^{n-1} \frac{\Gamma_k}{\Gamma'_k} \right] \frac{1}{2\pi} \frac{\Gamma^4_{f_i}}{\mathcal{D}_1} \quad \text{...(II.40)}$$

where,
\[ \Gamma^i_s = 2m \langle |\nabla \psi_s \rangle^2 \] ...(II.41)

and the product in the brackets is defined to be one when \( n=1 \). Thus,

\[ q_{i1}^{(\text{fluc}')} = \frac{2m\Gamma^i_s}{D_i} \] ...(II.42)

The cross-section for a given reaction is then expressed as the sum of \( r \) partial cross-sections each associated with one of the \( Q \) spaces in the chain up partition. The factor \( 2m\Gamma^i_s/D_i \) is the probability for formation of the first stage of compound system \( Q \) from the entrance configuration. The product of depletion factor \( \Gamma_k^{\uparrow} / \Gamma_k \) expresses the propagation through the intermediate spaces of partition upto some final space \( Q \). \( \Gamma_k^{\downarrow} / \Gamma_k \) is the escape width from the \( Q \) space into the final channel.

II.3.2. NVWY MSC Model

A new quantum mechanical approach based on multistep compound and multistep direct reactions is proposed by Hydelberg group[38-40]. It is assumed that the matrix elements of the Hamiltonian have Gaussian probability distribution[38].
Averaging over this distribution yields a transport theory for the nuclear cross-section. In this model weak coupling is considered when the time of mixing of states within the same class is much shorter than the mixing time for states in different classes. The level density is taken equal to the inverse average spacing of quasibound states. The transmission coefficient carries a class index \( n \), in addition to other quantum numbers. The transmission coefficient \( T^{(a,n)} \) in the channel \( a \) is split into three contributions corresponding to the population of the classes \( n-1 \), \( n \) and \( n+1 \). The relative weights of these three contributions are determined by the accessible state densities. The structure of the calculation is similar to the master equation approach so that the equilibrium limit arises naturally.
References:

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CHAPTER III
EXPERIMENTAL TECHNIQUES AND MEASUREMENTS

The interaction of a nuclear projectile with a target nucleus is generally described in terms of the cross-section, which essentially is a measure of the probability of occurrence of a nuclear reaction. The cross-section, usually denoted by \( \sigma \), is expressed in units of barns which is equal to \( 10^{-24} \text{ cm}^2 \) and is of the order of the size of a nucleus. The cross-section for a nuclear reaction can be measured experimentally on one hand and can be calculated theoretically on the basis of an assumed reaction mechanism on the other. Cross-section \( \sigma_{X(a,b)Y} \) for a nuclear reaction,

\[
X + a \rightarrow Y + b \quad \text{...(III.1)}
\]

in which an incident particle \( a \) interacts with a target nucleus \( X \) (generally at rest) producing a residual nucleus \( Y \) with the emission of particle (and/or radiation) \( b \), is defined as the number of events of the given type \( X(a,b)Y \) per target nucleus per incident particle per unit area in unit time. If \( N \) be number of initial target nuclei irradiated for a time \( t \) with a particle beam of flux '\( \phi \)', then the cross-section for the event \( X(a,b)Y \) may be given by,
\[
\sigma_r = \frac{\text{Number of events of type } X(a,b)Y \text{/ unit area}}{N_0 \frac{1}{t}} \quad \text{(III.2)}
\]

In the above equation, the quantities in the denominator are known. Therefore, in order to determine the cross-section, the quantities in the numerator i.e., the number of events of given type per unit area, is to be determined. It can be determined either, by counting the emitted particles and/or the residual nucleus either in-beam or off-beam. In the in-beam experiments the outgoing particles are recorded in a particle telescope and/or the residual nuclei are identified through their characteristic gamma rays or detecting the residual nucleus itself. On the other hand, in an off-beam experiment the yield of the residual nuclei can be determined either by radiochemical separation[1] or by following the activities induced in irradiated samples from their characteristic gamma rays, in case of radioactive residual nuclei of measurable half-lives. This is called the Activation technique[2]. The activation analysis is simple and quite accurate. Obviously, the in-beam experiments are more involved and complicated due to the large background at the detector. To measure the excitation functions stacked
foil or spinning wheel technique[3] of activation analysis, is generally used.

III.1. Activation technique and formulation

The discovery of artificial radioactivity[4] initiated this type of analytical approach. With time, the activation technique has established itself as a powerful and sensitive tool in the field of pure nuclear research as well as in applied science[2-6].

Activation method is defined as a method of measuring the concentrations of radioactive nuclei in a given sample by detecting their characteristic radiations. The unique decay mode of each radioactive isotope provides a specific way for its identification and measurement. The activities in samples can be induced by their bombardment with elementary particles, radiations or nuclei. In general, several activities due to various reaction products are produced in samples after irradiation. Thus cross-section for more than one reaction, several in case of heavy ions, can be determined in a single irradiation[7-9]. Relatively simple, nondestructive and less expensive set-ups are special merits
of this analysis. Further, the analysis sometimes become complicated due to the presence of interfering reactions which produce the same residual nucleus. In case of mixing of $\gamma$-rays due to different isotopes, the contribution from each isotope can be separated on the basis of their half-lives, by following the measurement of the induced activity for a considerably longer period. Proper choice of target material, projectile type and energy, duration of irradiation, half-lives of induced activities and the detecting system etc., are imperatives for good activation measurements.

III.1.1. Formulation

Irradiation of a sample by a projectile particle like proton, alpha and heavy ions may initiate various reactions in it producing various isotopes. When a sample having $N_0$ number of target nuclei is irradiated by a beam of flux $\phi$, then the rate of formation of particular activation product is given by,

$$N = N_0 \phi \sigma_r \quad \ldots(III.3)$$

where, $\sigma_r$ is the reaction cross-section for that particular
channel. If some of the isotopes formed are radioactive, some of the product nuclei will decay out. If the sample is irradiated for a time $t_1$, the activity in the sample is recorded for a time $t_2$ after a time lapse of time $t_3$, then the number of nuclei decayed in time $t_2$ to $t_2+t_3$ is given by,

$$ C = N_0 \frac{[1-\exp(-\lambda t_1)][1-\exp(-\lambda t_3)]}{\lambda \exp(\lambda t_2)} \quad ...(III.4) $$

If the induced activity is recorded by a detector of geometry dependent efficiency $G_e$, then the absolute counting rate $C$ and the observed counting rate $A$ are related as,

$$ C = A/(G_e \cdot \theta \cdot K) \quad ...(III.5) $$

Where '$\theta$' is the branching ratio of the particular radiation and $K$ is the self absorption correction for the material of the sample for gamma rays and is given by,

$$ K = \frac{[1-\exp(-\mu d)]}{(\mu d)} \quad ...(III.6) $$

where, $\mu$ is the gamma-ray absorption coefficient for the sample and $d$ is the thickness of the sample. Thus, $a_r$ can be written as,
Radio-isotopes at any time \( t \) and \( \gamma \) being their decay
and \( N \) be the number of nuclei of the parent and the daughter.

\[ N \] for the number of nuclei of the parent and the daughter. Let \( N \) in such cases may be separated using the following.

In such cases, the activities of the individual reactions depend on the half-lives of the intermediate and the contributions from both the reactions. The relative contributions from both the reactions. The relative

the characteristic \( \gamma \)-ray of the residual nucleus has
to the ground state. In such cases, the measured intensity of
\( \Delta \) emission, electron capture (EC) or decay of isomeric state
to \( \beta \)-irradiation and the decay of a precursor nucleus through
by two different reaction chains, i.e., by the activation due

sometimes the same residual radio-active nucleus is populated.

\[
(III)\ldots \quad \mathcal{C}^{0} N \phi^{\alpha} F_{0}(\gamma) \#_{x}(\gamma) \cdot \alpha x_{d} \cdot \alpha x_{e} = \mathcal{C}^{0} N \phi^{\alpha} F_{0}(\gamma) \#_{x}(\gamma) \cdot \alpha x_{d} \cdot \alpha x_{e}
\]

Stop of \( \Delta \)-irradiation can be calculated as,

cross-section. Also the count rate \( \mathcal{C}^{0} \) at the time of the

This is the final expression for the calculation of reaction

\[
(III)\ldots \quad \mathcal{C}^{0} N \phi^{\alpha} F_{0}(\gamma) \#_{x}(\gamma) \cdot \alpha x_{d} \cdot \alpha x_{e} = \mathcal{C}^{0} N \phi^{\alpha} F_{0}(\gamma) \#_{x}(\gamma) \cdot \alpha x_{d} \cdot \alpha x_{e}
\]
constants respectively. Also let \( N_1^0 \) and \( N_2^0 \) be the number of nuclei of each kind at time \( t=0 \), then the number of daughter nuclei at any time \( t \) is given by,

\[
N_2 = \frac{N \exp(\lambda_1 t) - \exp(-\lambda_2 t)}{\exp(-\lambda_2 t) - \exp(-\lambda_1 t)} ...
\]

The above expression has been used for separating the contributions in case of successive decay.

III.2. Measurements

In the present measurements cross-sections for the following reactions

\[ ^{51}V(p,n)^{51}\text{Cr}, ^{58}\text{Ni}(p,\alpha)^{55}\text{Co}, ^{60}\text{Ni}(p,n)^{60}\text{Cu}, ^{60}\text{Ni}(p,\gamma)^{61}\text{Cu}, ^{61}\text{Ni}(p,n)^{61}\text{Cu}, ^{62}\text{Ni}(p,2n)^{62}\text{Cu}, ^{63}\text{Cu}(p,n)^{69}\text{Zn}, ^{63}\text{Cu}(p,2n)^{62}\text{Zn}, ^{65}\text{Cu}(p,n)^{65}\text{Zn}, ^{69}\text{Y}(p,n)^{69}\text{Zr}^{m+g}, ^{69}\text{Nb}(p,n)^{69}\text{Ho}^{m}, ^{113}\text{In}(p,n)^{113}\text{Sn}, ^{115}\text{In}(p,3n)^{115}\text{Sn}, ^{124}\text{Sb}(p,n)^{124}\text{Te}^{m+g}, ^{124}\text{Sb}(p,np)^{122}\text{Sb}, ^{130}\text{Te}(p,n)^{130}\text{I}, ^{129}\text{Sb}(p,n)^{129}\text{Te}^{m}, ^{129}\text{Sb}(p,np)^{127}\text{Sb}, ^{127}\text{Te}(p,n)^{127}\text{I}, ^{127}\text{Au}(p,n)^{127}\text{Hg}^{m+g}, ^{147}\text{Au}(p,np)^{146}\text{Au}, ^{58}\text{Ni}(\alpha,n)^{64}\text{Zn}, ^{58}\text{Ni}(\alpha,\alpha,n)^{59}\text{Ni}, ^{58}\text{Ni}(\alpha,\alpha,n)^{57}\text{Ni}, ^{60}\text{Ni}(\alpha,n)^{63}\text{Zn}, ^{60}\text{Ni}(\alpha,2n)^{62}\text{Zn}, ^{60}\text{Ni}(\alpha,2n)^{64}\text{Cu}, ^{61}\text{Ni}(\alpha,2n)^{63}\text{Zn}, ^{61}\text{Ni}(\alpha,3n)^{62}\text{Zn}, ^{62}\text{Ni}(\alpha,3n)^{63}\text{Zn}, ^{144}\text{Pr}(\alpha,n)^{144}\text{Pr}, ^{144}\text{Pr}(\alpha,2n)^{149}\text{Pr}, ^{105}\text{Ho}(C,3n)^{174}\text{Te}, ^{105}\text{Ho}(C,4n)^{173}\text{Te}, \text{ and} \]
\( ^{195} \text{Ho}(C, 5n)^{172} \text{Ta} \), are experimentally determined employing stacked foil activation technique. The excitation functions for proton induced reactions are measured for energy ranges from threshold up to \( \approx 20 \) MeV, for alpha induced reactions up to \( \approx 40 \) MeV and for heavy ion induced reactions up to \( \approx 80 \) MeV.

III.3. Sample preparation and irradiation

III.3.1. Light ion irradiation

The samples for irradiation were prepared from spectroscopically pure (99.99%) natural vanadium, nickel, copper, yttrium, niobium, indium, antimony, praseodymium and gold and enriched isotope of \( ^{190} \text{Te} \) (61%). The Yttrium samples were prepared by centrifuging on Al backing, gold samples were prepared by rolling while other samples were prepared by vacuum evaporation on Al backing of 6.75 mg/cm\(^2\) thickness, except for copper which was deposited on mylar of 800 \( \mu \)g/cm\(^2\). The thickness of the samples varied from 0.32 gm/cm\(^2\) for vanadium to 30.0 mg/cm\(^2\) for gold. The samples of 1.2x1.2 cm\(^2\) size were fixed on identical aluminium holders having concentric holes of 1 cm in diameter. The aluminium target holders are used for rapid heat dissipation. In order to achieve wide energy variation aluminium foils of suitable
thicknesses were interposed between the samples in the stack so that the desired energy is incident on each sample which was calculated from the energy degradation of the initial beam using the stopping power values (Table of Northcliffe and Schilling[11]) of different materials. The stack containing seven to ten samples was fixed on a flange. Keeping in view the half-lives of interest, the stacks were irradiated for optimum times ranging from 15 minutes to 12 hours. The arrangement for irradiation is shown in Fig. III.1. The charge collected in the Faraday cup was used to calculate the beam flux. Separate samples of vanadium, nickel, copper, yttrium, niobium, indium, antimony, tellurium and gold were irradiated with proton beams, each individually, using diffused proton beam of energy ≈12-20 MeV of current ≈100nA and nickel and praseodymium samples by beams of alpha particles (≈100 nA) at the Variable Energy Cyclotron Centre (VECC), Calcutta, India.

III.3.2. Heavy ion irradiation

The samples for heavy ion irradiation were prepared by rolling natural holmium, of purity better than 99.99%, to a thickness of the order of 2 mg/cm$^2$. Taking into account the
Fig. III.1. Experimental set up for light ion irradiation
rapid energy loss of heavy ions, individual samples were separately irradiated with carbon beams of energies 55, 62, 71 and 80 MeV having beam currents of \( \approx 30 \) nA and the charge state \( 5^+ \) available from the 15 UD Pelletron accelerator of the Nuclear Science Centre (NSC), New Delhi, India. The experimental set-up for the heavy ion irradiation is shown in Fig.III.2. The samples, along with 1 mg/cm\(^2\) thick Al catcher foil, for irradiation were fixed in an aluminium ladder which was irradiated in a 1 metre scattering chamber. The transfer of samples to and from the chamber was done without disturbing the vacuum. The Al catcher foil was kept in order to collect nuclei recoiling out of the target during the reaction. Two silicon surface barrier detectors, D1 and D2 (Rutherford monitors) in the figure, were kept at an angle of 30\(^\circ\) on either side behind the sample for monitoring the incident beam. The incident flux of \(^{12}\text{C} (5^+\) charge state) was determined from the charge collected in the Faraday cup as well as from the counts of the two Rutherford monitors.

III.4. Post irradiation analysis
The activities in the irradiated samples were followed using high resolution HPGe detectors, of 100 c.c active volume
Fig. III.2. Experimental set up for heavy ion irradiation
$D_1$ and $D_2$ are detectors monitors
coupled to the multichannel analyser. Reaction products were identified by their characteristic $\gamma$-rays. The detectors were calibrated using various standard $\gamma$-sources i.e., $^{22}\text{Na}$, $^{54}\text{Mn}$, $^{57}\text{Co}$, $^{60}\text{Co}$, $^{137}\text{Ba}$, $^{137}\text{Cs}$ and $^{152}\text{Eu}$ of known strength. These standard sources were also used for determining the geometry dependent efficiency $G\gamma$, of the detectors. A typical geometry dependent efficiency curve for gamma rays of different energies and for different source-detector distances are shown in Fig. III.3. The $\gamma$-ray spectrum of each sample was analysed in order to identify the photo peaks of interest produced due to various residual nuclei. A typical $\gamma$-ray spectrum observed from the sample of enriched $^{180}\text{Te}$ irradiated by 18 MeV proton beam is shown in Fig. III.4. As a check, the relative intensities of prominent $\gamma$-rays from this sample are also measured and are compared with their literature values in Table III.1. As can be seen from this table, the presently measured intensities are, in general, in good agreement with the literature data\cite{12,13} which ensures proper calibration of the detecting system. The residual nucleus of a particular reaction may, in general, emit $\gamma$-rays of more than one energy. Thus the cross-section for the same
Fig. III.3. Typical geometry dependent efficiency curves for gamma rays at different source-detector distances.

- 4.6 cm
- 2.6 cm
- 6.4 cm
Fig. III.4. Observed gamma ray spectrum from $^{130}$Te irradiated with 18 MeV proton
reaction may be determined separately from the observed intensities of $\gamma$-rays of different energies originating from the same residual nucleus. The identified residual nuclei formed in different reactions, their half-lives and characteristic $\gamma$-rays with branching ratios are listed in Table III.2. The weighted average of cross-sections is taken as the final experimental value. The following formula[14] is used to calculate the weighted average.

If $X_1 \pm \Delta X_1$, $X_2 \pm \Delta X_2$, $X_3 \pm \Delta X_3$,..... are n different measured values of the same quantity $X$, then the weighted average is given by:

$$\overline{X} = \frac{\sum W_i X_i}{\sum W_i}$$  \hspace{1cm} \text{(III.10)}

here, $W_i = 1/(\Delta X_i)^2$. The internal error (I.E.) is calculated as,

$$I.E. = [\sum W_i]^{-1/2}$$  \hspace{1cm} \text{(III.11)}

while the external error (E.E.) is,

$$E.E. = \left[ \frac{\sum W_i (X_i - \overline{X})^2}{n(n-1)\sum W_i} \right]^{1/2}$$  \hspace{1cm} \text{(III.12)}

Eqn III.11 depends entirely on individual observations,
whereas equation III.12 depends upon the differences between the observations from the mean value. External error is, therefore, a function of, what might be called, the external consistency of observations whereas, the internal error depends on internal consistency. A computer programme based on the above formulation is used to compute the cross-sections and their errors at different energies. As a typical example, the calculated cross-section for $^{190}\text{Te}(p,n)^{190}\text{I}$ reaction at $\approx 14.0$ MeV incident energy, from various identified $\gamma$-rays along with their count rates, efficiency etc., is given in Table III.3. Some typical cases involving interfering chains leading to the same residual nuclei are discussed further in Chapter-V.

III.5. Experimental errors

In the present measurements following factors are likely to introduce errors[15],

1) The uncertainty in determining the number of target nuclei. Errors in the number of target nuclei may come up due to inaccurate estimate of the foil thickness and non-uniform deposition of target material. To estimate the number of target nuclei and to check the thickness of
sample deposition and their uniformity, the pieces of sample foils of different dimensions were weighted on an electronic microbalance and thickness of each piece was determined. It is estimated from this analysis that the error in the thickness of the sample material is expected to be <1%.

2) Errors due to fluctuations in beam current. Often during the long irradiation runs, beam current fluctuates which results in the variation of incident flux. Care was taken to keep the beam current constant within 10%. In some typical runs the duration (>1 min) and the amount of change in beam current were noted during the irradiation time and flux was individually calculated for each duration of fluctuation. These varying fluxes were then used to calculate cross-sections according to the following formula[16],

\[
\sigma = \frac{A\lambda \exp(\lambda t_2)}{N_o \Theta K(Gc)[1-\exp(-\lambda t_{1})][\phi_1(1-\exp(-\lambda t_{A})) + \phi_2(1-\exp(-\lambda t_{B}))...]
\]

...(III.13)

where, \(\phi_1, \phi_2, \ldots\) are fluxes during the time \(t_A, t_B, \ldots\) respectively and \(t_A + t_B + \ldots = t_1\) (the total
irradiation time). It is estimated that beam fluctuation may introduce errors <3%.

3) Dead time correction. Dead time of counting in all the cases studied presently was kept less than 10% by suitably adjusting the sample-detector distance and the correction for it was applied in the counting rate.

4) The measured detector efficiency of the γ-ray spectrometer may be inaccurate on account of the following. (a) The statistical errors of counting of standard source, which was minimised by accumulating large number of counts for comparatively larger time (>3000 sec.). (b) The uncertainty due to the fitting of the efficiency curve by power graph. This was estimated to be <3%. (c) Uncertainty may also come up in determining the efficiency on account of the solid angle effect, since the irradiated samples were not point sources like the standard sources, instead had a diameter of 5 mm. A detailed analysis of solid angle effect is given in ref.[17]. Using this formulation the error in the efficiency due to solid angle effect is estimated to be <3%. Thus the overall error in the efficiency is found to be <6%. 
5) In irradiation of the stack, as the beam traverses the thickness of the stack material, the initial beam intensity reduces. This decrease in beam intensity may introduce certain errors. The beam intensity I after traversing a thickness x (cm) of the stack material may be given by[18],
\[ I = I_0 \exp(-10^{-27} \cdot \sigma \cdot \rho \cdot N_{av}/A) \] ...(III.18)

here, 'I₀' is the initial beam intensity, 'σ' the absorption cross-section in mb, 'ρ' the density of stack material, 'N_{av}' is the Avogadro number and 'A' the mass number of the stack material. Assuming a constant cross-section of σ=2 barns (say) the maximum beam loss at the end of the antimony stack was calculated to be <2%. Further, it has been pointed out by Ernst et al. [18], that large number of low energy neutrons which may be released as the beam traverses through the stack material may in turn disturb the yield, however, such disturbing yields are also negligible.

6) Losses due to recoiling nuclei. The product nuclei recoiling out of the target may introduce large errors in the measured cross-sections. In the present measurements
both the sample and the catcher foil or degrader foil were counted together and hence the loss due to recoiling is avoided.

The above mentioned errors do not include the uncertainty of the nuclear data like branching ratio, decay constants etc. which were taken from the Nuclear Data Tables, Nuclear Data sheets and Tables of Isotopes. The presently measured cross-sections at different incident energies are tabulated in Table III.4.
Table III.1. Measured and literature values of the intensities of $\gamma$-rays emitted by $^{130}$I.

<table>
<thead>
<tr>
<th>$\gamma$-ray energy (keV)</th>
<th>Measured value of literature</th>
<th>Branching ratio (%)</th>
<th>Branching ratio (%)</th>
<th>Statistical error of counting</th>
<th>Overall error of counting</th>
</tr>
</thead>
<tbody>
<tr>
<td>418.00</td>
<td>34.2±0.1</td>
<td>33.02</td>
<td>±0.08</td>
<td>±2.72</td>
<td></td>
</tr>
<tr>
<td>536.10</td>
<td>99.9±0.5</td>
<td>99.00</td>
<td>±0.20</td>
<td>±8.12</td>
<td></td>
</tr>
<tr>
<td>668.56</td>
<td>96.1±0.6</td>
<td>91.19</td>
<td>±0.20</td>
<td>±7.50</td>
<td></td>
</tr>
<tr>
<td>739.48</td>
<td>82.3±0.7</td>
<td>78.2</td>
<td>±0.19</td>
<td>±6.45</td>
<td></td>
</tr>
<tr>
<td>1157.49</td>
<td>11.3±0.1</td>
<td>9.21</td>
<td>±0.06</td>
<td>±0.75</td>
<td></td>
</tr>
</tbody>
</table>

†Ref. 12

Table III.2. Reactions, Residual nuclei and their identified $\gamma$-rays

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Residual nucleus</th>
<th>Half life</th>
<th>Energy of $\gamma$-ray (keV)</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{51}$V(p,n)</td>
<td>$^{51}$Cr</td>
<td>27.7 d</td>
<td>320.2</td>
<td>9.8</td>
</tr>
<tr>
<td>$^{58}$Ni(p,α)</td>
<td>$^{55}$Co</td>
<td>17.5 h</td>
<td>477.2, 931.2</td>
<td>20.2, 75.0</td>
</tr>
<tr>
<td>$^{60}$Ni(p,n)</td>
<td>$^{60}$Cu</td>
<td>23.2 min</td>
<td>826.3, 1332.5</td>
<td>21.9, 88.0</td>
</tr>
<tr>
<td>$^{60}$Ni(p,γ)</td>
<td>$^{61}$Cu</td>
<td>3.4 h</td>
<td>283.0, 656.0</td>
<td>12.5, 10.7</td>
</tr>
<tr>
<td>$^{64}$Ni(p,n)</td>
<td>$^{61}$Cu</td>
<td>3.4 h</td>
<td>283.0, 656.0</td>
<td>12.5, 10.7</td>
</tr>
<tr>
<td>$^{62}$Ni(p,2n)</td>
<td>$^{61}$Cu</td>
<td>3.4 h</td>
<td>283.0, 656.0</td>
<td>12.5, 10.7</td>
</tr>
<tr>
<td>$^{63}$Cu(p,n)</td>
<td>$^{63}$Zn</td>
<td>38.1 min</td>
<td>669.86, 926.27</td>
<td>8.4, 6.6</td>
</tr>
<tr>
<td>65 Cu(p,2n)</td>
<td>$^{65}$ Zn</td>
<td>9.3 h</td>
<td>548.4</td>
<td>15.2</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------</td>
<td>--------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>90 Cu(p,n)</td>
<td>$^{90}$ Zn</td>
<td>244.1 d</td>
<td>1115.5</td>
<td>50.7</td>
</tr>
<tr>
<td>80 Y(p,n)</td>
<td>$^{80}$ Zr</td>
<td>3.3 d</td>
<td>909.1</td>
<td>99.0</td>
</tr>
<tr>
<td></td>
<td>$^{80m}$ Zr</td>
<td>4.2 min</td>
<td>587.7</td>
<td>89.5</td>
</tr>
<tr>
<td>99 Nb(p,n)</td>
<td>$^{99}$ Mo</td>
<td>6.8 h</td>
<td>263.1</td>
<td>56.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>684.8</td>
<td>99.7</td>
</tr>
<tr>
<td>119 In(p,n)</td>
<td>$^{119}$ Sn</td>
<td>115.1 d</td>
<td>391.7</td>
<td>64.0</td>
</tr>
<tr>
<td>115 In(p,3n)</td>
<td>$^{115}$ Sn</td>
<td>115.1 d</td>
<td>391.7</td>
<td>64.0</td>
</tr>
<tr>
<td>124 Sb(p,n)</td>
<td>$^{124}$ Te</td>
<td>16.8 d</td>
<td>573.1</td>
<td>80.3</td>
</tr>
<tr>
<td></td>
<td>$^{121m}$ Te</td>
<td>154.0 d</td>
<td>212.2</td>
<td>81.4</td>
</tr>
<tr>
<td>124 Sb(p,np)</td>
<td>$^{120}$ Sb</td>
<td>5.8 d</td>
<td>197.3</td>
<td>88.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1171.4</td>
<td>99.9</td>
</tr>
<tr>
<td>123 Sb(p,n)</td>
<td>$^{123m}$ Te</td>
<td>119.7 d</td>
<td>159.0</td>
<td>84.0</td>
</tr>
<tr>
<td>129 Sb(p,np)</td>
<td>$^{122}$ Sb</td>
<td>2.7 d</td>
<td>564.37</td>
<td>70.0</td>
</tr>
<tr>
<td>190 Te(p,n)</td>
<td>$^{130}$ I</td>
<td>12.4 h</td>
<td>418.0</td>
<td>34.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>536.1</td>
<td>99.0</td>
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<tr>
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<td></td>
<td></td>
<td>668.6</td>
<td>96.1</td>
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<td></td>
<td></td>
<td></td>
<td>739.5</td>
<td>82.3</td>
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<td></td>
<td></td>
<td></td>
<td>1157.5</td>
<td>11.3</td>
</tr>
<tr>
<td>107 Au(p,n)</td>
<td>$^{107g}$ Hg</td>
<td>2.7 d</td>
<td>80.4</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>$^{107m}$ Hg</td>
<td>23.8 h</td>
<td>134.0</td>
<td>47.2</td>
</tr>
<tr>
<td>107 Au(p,np)</td>
<td>$^{107m}$ Au</td>
<td>9.7 h</td>
<td>147.8</td>
<td>47.2</td>
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<td></td>
<td></td>
<td></td>
<td>188.2</td>
<td>34.4</td>
</tr>
<tr>
<td>58 Ni(α,p)</td>
<td>$^{61}$ Cu</td>
<td>3.4 h</td>
<td>283.0</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>656.0</td>
<td>10.7</td>
</tr>
<tr>
<td>Reaction</td>
<td>nuclide(s)</td>
<td>Energy (MeV)</td>
<td>Half-life (sec)</td>
<td>Q-value (MeV)</td>
</tr>
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<td>---------------</td>
<td>------------</td>
<td>-------------</td>
<td>----------------</td>
<td>--------------</td>
</tr>
<tr>
<td>$^{58}\text{Ni} (\alpha, \text{pn})$</td>
<td>$^{60}\text{Cu}$</td>
<td>23.2 min</td>
<td>826.3</td>
<td>21.9</td>
</tr>
<tr>
<td>$^{58}\text{Ni} (\alpha, \text{an})$</td>
<td>$^{57}\text{Ni}$</td>
<td>1.5 d</td>
<td>122.1</td>
<td>85.5</td>
</tr>
<tr>
<td>$^{60}\text{Ni} (\alpha, \text{n})$</td>
<td>$^{69}\text{Zn}$</td>
<td>38.1 min</td>
<td>669.86</td>
<td>8.4</td>
</tr>
<tr>
<td>$^{60}\text{Ni} (\alpha, 2\text{n})$</td>
<td>$^{62}\text{Zn}$</td>
<td>9.3 h</td>
<td>548.4</td>
<td>15.2</td>
</tr>
<tr>
<td>$^{60}\text{Ni} (\alpha, p\text{2n})$</td>
<td>$^{64}\text{Cu}$</td>
<td>3.4 h</td>
<td>283.0</td>
<td>12.5</td>
</tr>
<tr>
<td>$^{61}\text{Ni} (\alpha, 2\text{n})$</td>
<td>$^{63}\text{Zn}$</td>
<td>38.1 min</td>
<td>669.86</td>
<td>8.4</td>
</tr>
<tr>
<td>$^{64}\text{Ni} (\alpha, 3\text{n})$</td>
<td>$^{62}\text{Zn}$</td>
<td>9.3 h</td>
<td>548.4</td>
<td>15.2</td>
</tr>
<tr>
<td>$^{62}\text{Ni} (\alpha, 3\text{n})$</td>
<td>$^{69}\text{Zn}$</td>
<td>38.1 min</td>
<td>669.86</td>
<td>8.4</td>
</tr>
<tr>
<td>$^{141}\text{Pr} (\alpha, \text{n})$</td>
<td>$^{144}\text{Pm}$</td>
<td>363.0 d</td>
<td>476.8</td>
<td>42.2</td>
</tr>
<tr>
<td>$^{141}\text{Pr} (\alpha, 2\text{n})$</td>
<td>$^{149}\text{Pm}$</td>
<td>265.0 3</td>
<td>742.0</td>
<td>38.5</td>
</tr>
<tr>
<td>$^{149}\text{Ho} (\text{C}, 3\text{n})$</td>
<td>$^{174}\text{Ta}$</td>
<td>1.2 h</td>
<td>90.9</td>
<td>15.9</td>
</tr>
<tr>
<td>$^{150}\text{Ho} (\text{C}, 4\text{n})$</td>
<td>$^{179}\text{Ta}$</td>
<td>3.6 h</td>
<td>172.2</td>
<td>17.0</td>
</tr>
<tr>
<td>$^{150}\text{Ho} (\text{C}, 5\text{n})$</td>
<td>$^{172}\text{Ta}$</td>
<td>38.8 min</td>
<td>214.0</td>
<td>52.0</td>
</tr>
</tbody>
</table>
Table III.3. Cross-sections calculated from different $\gamma$-rays for the $^{130}$Te(p,n)$^{130}$I reaction at $\approx$14 MeV incident energy

<table>
<thead>
<tr>
<th>Identified Gamma (kev) at zero time</th>
<th>Count rate</th>
<th>Branching ratio</th>
<th>Detection efficiency</th>
<th>Cross-section cross-section</th>
<th>Error in</th>
</tr>
</thead>
<tbody>
<tr>
<td>418</td>
<td>82.13</td>
<td>0.342</td>
<td>0.009</td>
<td>100.88</td>
<td>2.42</td>
</tr>
<tr>
<td>536</td>
<td>136.78</td>
<td>0.990</td>
<td>0.0067</td>
<td>103.05</td>
<td>1.13</td>
</tr>
<tr>
<td>668</td>
<td>93.50</td>
<td>0.961</td>
<td>0.0052</td>
<td>93.53</td>
<td>0.94</td>
</tr>
<tr>
<td>739</td>
<td>70.78</td>
<td>0.823</td>
<td>0.0046</td>
<td>93.43</td>
<td>0.93</td>
</tr>
<tr>
<td>1157</td>
<td>5.29</td>
<td>0.113</td>
<td>0.0027</td>
<td>86.71</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Weighted average cross-section = 94.85 mb at 14 MeV energy

- Internal error = 0.546 mb
- External error = 1.798 mb

Table III.4. Cross-sections for various reactions at different incident energies.

<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>03.70 ±0.53</td>
<td>25.21 ± 5.6</td>
</tr>
<tr>
<td>05.23 ±0.53</td>
<td>237.93 ±31.2</td>
</tr>
<tr>
<td>06.51 ±0.52</td>
<td>275.33 ±35.8</td>
</tr>
<tr>
<td>07.89 ±0.52</td>
<td>322.47 ±45.2</td>
</tr>
<tr>
<td>09.33 ±0.51</td>
<td>429.29 ±15.4</td>
</tr>
<tr>
<td>10.57 ±0.51</td>
<td>432.89 ±42.5</td>
</tr>
<tr>
<td>11.97 ±0.51</td>
<td>400.95 ±52.8</td>
</tr>
<tr>
<td>12.92 ±0.50</td>
<td>357.24 ±50.0</td>
</tr>
<tr>
<td>13.98 ±0.50</td>
<td>309.10 ±43.2</td>
</tr>
<tr>
<td>15.00 ±0.50</td>
<td>251.03 ±33.7</td>
</tr>
<tr>
<td>Incident Energy (MeV)</td>
<td>Cross section (mb)</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>07.08 ±0.56</td>
<td>2.82 ±0.8</td>
</tr>
<tr>
<td>09.00 ±0.56</td>
<td>1.20 ±0.2</td>
</tr>
<tr>
<td>10.65 ±0.55</td>
<td>0.65 ±0.1</td>
</tr>
<tr>
<td>12.10 ±0.55</td>
<td>0.59 ±0.1</td>
</tr>
<tr>
<td>13.50 ±0.54</td>
<td>0.08 ±0.1</td>
</tr>
<tr>
<td>15.00 ±0.54</td>
<td>0.95 ±0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>Cross section (mb)</th>
<th>Cross section (mb)</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06.68 ±0.54</td>
<td>57.25 ± 7.8</td>
<td>---</td>
<td>278.63 ±36.1</td>
</tr>
<tr>
<td>09.00 ±0.53</td>
<td>385.42 ±50.1</td>
<td>---</td>
<td>515.36 ±66.9</td>
</tr>
<tr>
<td>11.53 ±0.53</td>
<td>565.26 ±73.6</td>
<td>---</td>
<td>652.69 ±85.6</td>
</tr>
<tr>
<td>13.74 ±0.52</td>
<td>437.32 ±56.8</td>
<td>---</td>
<td>474.37 ±88.9</td>
</tr>
<tr>
<td>16.06 ±0.52</td>
<td>279.28 ±44.8</td>
<td>20.70 ± 3.3</td>
<td>256.52 ±35.9</td>
</tr>
<tr>
<td>18.00 ±0.52</td>
<td>89.31 ±11.7</td>
<td>45.30 ± 6.3</td>
<td>93.32 ±15.4</td>
</tr>
<tr>
<td>20.00 ±0.51</td>
<td>63.20 ± 8.9</td>
<td>98.32 ±12.7</td>
<td>47.15 ± 7.2</td>
</tr>
</tbody>
</table>
| Energy (MeV) | \( ^{89}\text{Y}(p,n)\) 
|-------------|-----------------
| 5.24 ±0.55  | 72.63 ±10.1    |
| 6.50 ±0.55  | 173.42 ±22.6   |
| 7.48 ±0.54  | 217.26 ±28.2   |
| 8.10 ±0.56  | 294.32 ±40.2   |
| 9.17 ±0.56  | 322.28 ±43.9   |
| 10.25 ±0.56 | 320.31 ±42.8   |
| 11.62 ±0.55 | 326.21 ±43.2   |
| 13.28 ±0.57 | 323.74 ±44.6   |
| 15.02 ±0.56 | 177.63 ±23.1   |

<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{89}\text{Y}(p,n)) ( ^{85}\text{Zr} )</td>
<td>( ^{89}\text{Y}(p,n)) ( ^{89}\text{Zr} )</td>
</tr>
<tr>
<td>5.24 ±0.55</td>
<td>72.63 ±10.1</td>
</tr>
<tr>
<td>6.50 ±0.55</td>
<td>173.42 ±22.6</td>
</tr>
<tr>
<td>7.48 ±0.54</td>
<td>217.26 ±28.2</td>
</tr>
<tr>
<td>8.10 ±0.56</td>
<td>294.32 ±40.2</td>
</tr>
<tr>
<td>9.17 ±0.56</td>
<td>322.28 ±43.9</td>
</tr>
<tr>
<td>10.25 ±0.56</td>
<td>320.31 ±42.8</td>
</tr>
<tr>
<td>11.62 ±0.55</td>
<td>326.21 ±43.2</td>
</tr>
<tr>
<td>13.28 ±0.57</td>
<td>323.74 ±44.6</td>
</tr>
<tr>
<td>15.02 ±0.56</td>
<td>177.63 ±23.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{93}\text{Nb}(p,n)) ( ^{99}\text{Mo} )</td>
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<td>05.41 ±0.70</td>
<td>5.83 ± 0.7</td>
</tr>
<tr>
<td>06.81 ±0.67</td>
<td>17.26 ± 2.5</td>
</tr>
<tr>
<td>08.76 ±0.65</td>
<td>28.26 ± 3.8</td>
</tr>
<tr>
<td>10.39 ±0.63</td>
<td>42.68 ± 5.5</td>
</tr>
<tr>
<td>11.15 ±0.62</td>
<td>59.31 ± 9.3</td>
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<tr>
<td>12.00 ±0.61</td>
<td>85.02 ±11.5</td>
</tr>
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<td>Incident Energy (MeV)</td>
<td>Cross section (mb)</td>
</tr>
<tr>
<td>-----------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>06.10 ±0.54</td>
<td>28.00 ± 4.3</td>
</tr>
<tr>
<td>07.48 ±0.53</td>
<td>244.25 ±33.8</td>
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<td>09.31 ±0.53</td>
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<td>14.65 ±0.52</td>
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<td>16.50 ±0.51</td>
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<td>18.31 ±0.51</td>
<td>122.12 ±15.8</td>
</tr>
<tr>
<td>20.00 ±0.50</td>
<td>88.92 ±11.1</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>Cross section (mb)</th>
<th>Cross section (mb)</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04.41 ±0.53</td>
<td>74.18 ±10.6</td>
<td>85.01 ± 8.6</td>
<td>---</td>
</tr>
<tr>
<td>04.57 ±0.53</td>
<td>94.63 ±12.5</td>
<td>74.96 ±10.5</td>
<td>---</td>
</tr>
<tr>
<td>05.21 ±0.53</td>
<td>121.82 ±15.8</td>
<td>95.31 ±13.5</td>
<td>---</td>
</tr>
<tr>
<td>05.96 ±0.53</td>
<td>173.39 ±22.6</td>
<td>157.59 ±22.1</td>
<td>---</td>
</tr>
<tr>
<td>08.08 ±0.52</td>
<td>318.64 ±41.6</td>
<td>262.83 ±34.8</td>
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</tr>
<tr>
<td>09.48 ±0.52</td>
<td>346.25 ±44.8</td>
<td>407.28 ±53.5</td>
<td>---</td>
</tr>
<tr>
<td>10.74 ±0.52</td>
<td>228.42 ±29.6</td>
<td>323.34 ±43.5</td>
<td>---</td>
</tr>
<tr>
<td>12.53 ±0.52</td>
<td>204.27 ±26.6</td>
<td>320.36 ±42.6</td>
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</tr>
<tr>
<td>14.56 ±0.51</td>
<td>127.32 ±16.6</td>
<td>166.83 ±21.7</td>
<td>1.1 ±0.2</td>
</tr>
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<td>54.28 ± 7.1</td>
<td>79.70 ±10.2</td>
<td>3.0 ±0.4</td>
</tr>
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<td>64.29 ± 9.2</td>
<td>5.5 ±0.8</td>
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<td>36.20 ± 4.9</td>
<td>61.03 ± 8.5</td>
<td>8.5 ±1.13</td>
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<tr>
<td>Incident Energy (MeV)</td>
<td>Cross section (mb)</td>
<td>Cross section (mb)</td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------</td>
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<td></td>
</tr>
<tr>
<td>04.41 ±0.53</td>
<td>64.68 ±10.6</td>
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<td></td>
</tr>
<tr>
<td>04.57 ±0.53</td>
<td>78.63 ±12.5</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>05.21 ±0.53</td>
<td>101.82 ±14.4</td>
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<td></td>
</tr>
<tr>
<td>05.96 ±0.53</td>
<td>130.39 ±17.5</td>
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<td></td>
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<tr>
<td>08.08 ±0.52</td>
<td>282.64 ±41.8</td>
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<tr>
<td>09.48 ±0.52</td>
<td>296.25 ±40.8</td>
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<td>10.74 ±0.52</td>
<td>178.42 ±25.2</td>
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<td>4.31 ±0.5</td>
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<tr>
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<td>109.32 ±15.6</td>
<td>16.07 ±2.2</td>
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<td>16.21 ±0.51</td>
<td>77.28 ±12.1</td>
<td>19.91 ±2.6</td>
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<td>18.16 ±0.51</td>
<td>76.31 ±11.7</td>
<td>24.30 ±2.9</td>
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</tr>
<tr>
<td>20.00 ±0.50</td>
<td>74.80 ±11.6</td>
<td>38.32 ±4.5</td>
<td></td>
</tr>
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<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04.87 ±0.54</td>
<td>8.76 ± 0.1</td>
</tr>
<tr>
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<td>282.34 ±41.9</td>
</tr>
<tr>
<td>09.65 ±0.53</td>
<td>262.61 ±38.4</td>
</tr>
<tr>
<td>11.90 ±0.52</td>
<td>132.15 ±16.8</td>
</tr>
<tr>
<td>13.98 ±0.52</td>
<td>94.85 ±13.6</td>
</tr>
<tr>
<td>16.04 ±0.52</td>
<td>74.91 ±12.2</td>
</tr>
<tr>
<td>18.00 ±0.50</td>
<td>100.24 ±12.7</td>
</tr>
<tr>
<td>Incident Energy (MeV)</td>
<td>Cross section ( ^{197}\text{Au(p,n)}^{197}\text{Hg} ) (mb)</td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>08.43 ±0.53</td>
<td>7.49 ±1.4</td>
</tr>
<tr>
<td>10.13 ±0.52</td>
<td>63.38 ±0.9</td>
</tr>
<tr>
<td>12.30 ±0.52</td>
<td>65.72 ±9.1</td>
</tr>
<tr>
<td>14.17 ±0.51</td>
<td>41.18 ±5.9</td>
</tr>
<tr>
<td>16.27 ±0.51</td>
<td>40.26 ±5.6</td>
</tr>
<tr>
<td>18.15 ±0.51</td>
<td>28.69 ±4.2</td>
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<tr>
<td>20.00 ±0.50</td>
<td>27.94 ±4.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>Cross section ( ^{58}\text{Ni(a,n)}^{61}\text{Zn} ) (mb)</th>
<th>Cross section ( ^{58}\text{Ni(a,p)}^{61}\text{Cu} ) (mb)</th>
<th>Cross section ( ^{60}\text{Ni(a,an)}^{60}\text{Cu} ) (mb)</th>
<th>Cross section ( ^{60}\text{Ni(a,an)}^{57}\text{Ni} ) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.90 ±1.04</td>
<td>2.10 ±0.3</td>
<td>27.26 ±3.6</td>
<td>406.91 ±56.8</td>
<td>30.51 ±4.4</td>
</tr>
<tr>
<td>13.90 ±0.92</td>
<td>27.51 ±3.6</td>
<td>105.32 ±13.9</td>
<td>400.10 ±58.3</td>
<td>110.26 ±15.6</td>
</tr>
<tr>
<td>16.51 ±0.88</td>
<td>130.47 ±16.9</td>
<td>400.75 ±52.6</td>
<td>250.83 ±35.0</td>
<td>25.34 ±3.8</td>
</tr>
<tr>
<td>23.07 ±0.82</td>
<td>112.63 ±14.6</td>
<td>211.36 ±27.5</td>
<td>110.83 ±15.4</td>
<td>---</td>
</tr>
<tr>
<td>25.35 ±0.80</td>
<td>70.26 ±9.3</td>
<td>95.28 ±12.5</td>
<td>406.91 ±56.8</td>
<td>30.51 ±4.4</td>
</tr>
<tr>
<td>29.08 ±0.75</td>
<td>17.41 ±2.8</td>
<td>31.53 ±4.3</td>
<td>400.10 ±58.3</td>
<td>110.26 ±15.6</td>
</tr>
<tr>
<td>35.65 ±0.72</td>
<td>2.63 ±0.4</td>
<td>7.26 ±1.3</td>
<td>250.83 ±35.0</td>
<td>25.34 ±3.8</td>
</tr>
<tr>
<td>40.00 ±0.70</td>
<td>0.53 ±0.1</td>
<td>0.95 ±0.4</td>
<td>110.83 ±15.4</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>Cross section ( ^{60}\text{Ni(a,n)}^{63}\text{Zn} ) (mb)</th>
<th>Cross section ( ^{60}\text{Ni(a,2n)}^{62}\text{Zn} ) (mb)</th>
<th>Cross section ( ^{60}\text{Ni(a,p2n)}^{61}\text{Cu} ) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.35 ±0.80</td>
<td>92.41 ±12.9</td>
<td>43.30 ±6.1</td>
<td></td>
</tr>
<tr>
<td>29.08 ±0.75</td>
<td>47.81 ±6.8</td>
<td>162.53 ±22.8</td>
<td>43.30 ±6.1</td>
</tr>
<tr>
<td>35.65 ±0.72</td>
<td>30.23 ±4.4</td>
<td>160.28 ±21.9</td>
<td>110.27 ±15.5</td>
</tr>
<tr>
<td>40.00 ±0.70</td>
<td>17.17 ±2.6</td>
<td>29.84 ±4.3</td>
<td>233.62 ±31.2</td>
</tr>
<tr>
<td>Incident Energy (MeV)</td>
<td>$^{\alpha}$Ni(α,2n)$^{69}$Zn</td>
<td>$^{\alpha}$Ni(α,3n)$^{69}$Zn</td>
<td>$^{\alpha}$Ni(α,3n)$^{69}$Zn</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>29.08 ±0.75</td>
<td>100.42 ±14.7</td>
<td>----</td>
<td>----</td>
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<tr>
<td>35.65 ±0.72</td>
<td>208.35 ±28.1</td>
<td>14.61 ±2.1</td>
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</tr>
<tr>
<td>40.00 ±0.70</td>
<td>73.36 ±10.6</td>
<td>65.27 ±9.6</td>
<td>55.62 ±8.2</td>
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<table>
<thead>
<tr>
<th>Incident Energy (MeV)</th>
<th>$^{144}$Pr(α,n)$^{144}$Pm</th>
<th>$^{144}$Pr(α,2n)$^{143}$Pm</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.2 ±1.2</td>
<td>24.30 ± 4.45</td>
<td>----</td>
</tr>
<tr>
<td>16.5 ±1.0</td>
<td>123.90 ±18.96</td>
<td>----</td>
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<tr>
<td>18.6 ±0.9</td>
<td>126.80 ±19.28</td>
<td>122.8 ±21.59</td>
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<tr>
<td>21.9 ±0.9</td>
<td>55.22 ± 9.05</td>
<td>350.77 ±55.36</td>
</tr>
<tr>
<td>27.2 ±0.8</td>
<td>25.21 ± 4.23</td>
<td>572.82 ±84.48</td>
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<tr>
<td>31.9 ±0.7</td>
<td>14.69 ± 3.35</td>
<td>541.59 ±82.92</td>
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<tr>
<td>36.1 ±0.6</td>
<td>10.13 ± 2.25</td>
<td>257.39 ±41.48</td>
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<tr>
<td>40.0 ±0.6</td>
<td>7.88 ± 1.97</td>
<td>113.89 ±19.15</td>
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<tr>
<th>Incident Energy (MeV)</th>
<th>$^{165}$Ho(C,3n)</th>
<th>$^{165}$Ho(C,4n)</th>
<th>$^{165}$Ho(C,5n)</th>
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<td>55.00±0.50</td>
<td>46.51 ± 6.0</td>
<td>13.1 ± 1.7</td>
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<tr>
<td>62.00±0.50</td>
<td>62.10 ± 8.1</td>
<td>200.4 ±26.4</td>
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<tr>
<td>71.00±0.50</td>
<td>13.40 ±1.7</td>
<td>336.0 ±43.7</td>
<td>93.3 ±12.1</td>
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<tr>
<td>80.00±0.50</td>
<td>2.00 ±0.3</td>
<td>137.2 ±17.8</td>
<td>426.3 ±55.4</td>
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References
5. I. Curie and F. Joliot, Nature, 133(1934)201


CHAPTER IV
COMPUTER CODES

The measured excitation functions are analysed using both the semiclassical as well as the quantum mechanical models of pre-equilibrium emission. For semiclassical calculations computer codes ALICE91[1] and ACT[2] are used while code EXIFON[3] is used for quantum mechanical analysis. For Heavy ion induced reactions calculations are done using codes ALICE91[1] and CASCADE[4]. Brief details of these computer codes are given in the following sections.

IV.1. ALICE91

This computer code can perform calculations for both the equilibrium and the pre-equilibrium emission cross-sections upto 300 MeV excitation energy employing Weisskopf-Ewing[5] evaporation model for the former and the hybrid/geometry dependent hybrid model[6,7] for the latter. Statistical fission calculation can also be done in this code with Bohr-Wheeler approach[8,9]. The physics and the organisation of the code is reviewed in ref.[10,11].

Though in the Weisskopf-Ewing (WE) formalism, conservation of angular momentum is not taken into account explicitly, an
approximate treatment of angular momentum effects is incorporated using s-wave approximation[12,13]. The fission barriers in this code are estimated either from the rotating liquid drop model of Cohen et al.[14] or using the results of rotating finite range model of A.J.Sierk[15]. Incident particle may be a nucleon or a nucleus and the emitted particle may be n, p, d and/or alpha particle. Sequence of emission is not taken into account and hence the calculations cannot distinguish, for example, between np and pn emissions.

Various parameters like the Q-values and the binding energies for all the nuclei in the evaporation chain are calculated in this code using Myers-Swiatecki/Lysekil mass formula[16]. Pairing term for various nuclei may be given as the input data and in default it is taken either (i) zero for odd-even nuclei, $\delta$ for even-even nuclei and $-\delta$ for odd-odd nuclei with $\delta = 11/4A$, [16] or (ii) zero for even-even nuclei, $-\delta$ for odd-even and $-2\delta$ for odd-odd nuclei assuming backshifted level density/pairing treatment[17]. A table of known experimental masses[18] is called for default options. Inverse reaction cross-section for all emitted particles may be calculated using optical model[19] subroutines, if not
supplied. The transmission coefficients are calculated using parabolic model of Thomas[20]. Pre-equilibrium emission can be calculated either by hybrid[6] or geometry dependent hybrid (GDH)[7] models. Initial exciton number is one of the input parameters that must be given. The mean free path (MFP) for intranuclear transition rates may be calculated either from optical potential parameters of Becchetti and Greenlees[21] or from Pauli corrected nucleon-nucleon cross-sections[22,23]. To account for the difference, if any, between the calculated MFP and the actual MFP for two-body residual interactions, the MFP is multiplied by an adjustable parameter COST which may be varied to adjust the nuclear mean free path in order to reproduce the experimental data. Since most of the parameters, in default option, are internally generated only very few input parameters are to be supplied for calculation by this code.

Level densities of nuclides involved in the evaporation chain play crucial role in the statistical nuclear reactions. It can be calculated from the Fermi gas model or from the constant temperature form. The Fermi gas model gives[10]
\[ \rho(u) \sim (u-\delta)^{-5/4} e^{2(\alpha(u-\delta)/u)} \quad \text{(IV.1)} \]

where, \( \delta \) is the pairing term and \( U \) is the excitation energy of the nucleus. The level density parameter \( \alpha \) is taken as \( A/K \), \( A \) being the mass number of the nucleus and \( K \) an adjustable parameter. The constant temperature form gives

\[ \rho(u) \propto \frac{1}{T} \left( \frac{U}{T} \right)^{\alpha} \quad \text{(IV.2)} \]

Option is available to use level density expressions of Kataria/Ramamurthy[24] or Ignatyuk[25].

The differential cross-section for emitting a particle with channel energy \( \varepsilon \) may be written as,

\[ \left( \frac{d\sigma}{d\varepsilon} \right) = \frac{\pi}{\lambda} (2I+1) T \sum_{l=0}^{I} (2S_{\lambda}+1) \sum_{l=0}^{l=0} T_{\lambda}^{l}(\varepsilon) \sum_{J=I-1}^{I+1} \rho(E,J)/D \]

\[ = \sum_{l=0}^{\alpha} \sigma_{\lambda}^{2}(2S_{\lambda}+1) \sigma_{\lambda}(\varepsilon) m \varepsilon \rho(E,J)/D \quad \text{(IV.3)} \]

where, \( \lambda \) denotes the reduced de Broglie wavelength of the incident ion, \( T_{I} \) the transmission coefficient of the \( I^{th} \) partial wave of the incident ion, \( \rho(E,J) \) the spin dependent
level density for the residual nucleus, \( D \) the integral of numerator over all particles and emission energies, \( E \) the excitation energy of the compound nucleus, \( \sigma_i \) the partial reaction cross-section for the incident \( i^{th} \) partial wave, \( S_\nu \) the intrinsic spin of particle \( \nu \), \( T_\nu^I(c) \) the transmission coefficient for particle \( \nu \) of total angular momentum \( I \), \( \sigma_i^{-1} \) the inverse reaction cross-section and \( m \) the mass of the emitted particle. The logic flow diagram of the code is shown in Fig.IV.1, while further details are given elsewhere[1].

IV.2. ACT

The code ACT[2] is a nuclear reaction code developed on the lines of code STAPRE[26]. In this code Hauser-Feshbach[27] statistical model is used for CN calculations while Exciton model[28] is employed for PE emission. Sequential evaporation of upto six particles may be considered. The code ACT may, therefore, differentiate, for example, between the np and pn reaction paths. The pre-equilibrium emission of particles is considered only in the first step of de-excitation where the excitation energy is sufficiently large.

A simple diagrammatic representation of the nuclear reaction
Fig. IV.1. Representation of logic flow of code ALICE
T(x₀, x₁, x₂, x₃)ₚₐₐₚₐₚ is shown in Fig.IV.2. The target nucleus
T(Eₙ, I₀, π₀), with energy E₀, spin I₀ and parity π₀, is
essentially in ground state. As shown in this figure, before
reaching the final residual nucleus F, the compound system
passes through many intermediate steps. The system formed by
the combination of projectile x₀ and target T is termed as
the first compound nucleus (CN). The residual nuclei formed
in the sequential emission of particles (x₁, x₂, x₃, ....., xₙ)
are then identified as (i+1)th CN. The projectile may be a
nucleon or any other complex nucleus while the emitted
particle(s) may be n, p, d and(or) α-particle. Level
densities in the code are calculated within the framework of
back-shifted Fermi gas model[29]. The level density parameter
a, the back-shifted energy Λ and the effective moment of
inertia ¹¹ₑ₁, for all the nuclei of the evaporation chain are
to be given as input data. The single particle state density
⁹ is taken as ⁶m²/a. In order to enhance the emission of
complex ejectiles like α-particles, it is assumed that these
clusters exist preformed in the compound nucleus and the
preformation probability is to be given as input parameter.
Fig. IV.2. Different ways of populating final state 
$(E_f, l_f, \Pi_f)$ for a reaction $T(x_0, x_1, x_2, \gamma)$
The PE emission is considered in the decay of 1st CN and the configuration of compound nucleus during PE emission is identified by the exciton number. Initial exciton number $n_0$ is supplied as input data. No distinction is made between a neutron and a proton. The internal transitions compete with the decay into the continuum. The PE contribution $\frac{\partial a^\text{pre}}{\partial \xi}$ to the differential cross-section is calculated employing the following expression,

$$\frac{\partial a^\text{pre}}{\partial \xi} = a^\text{non}_x \sum \sum b(n) \frac{\lambda^*(n,\xi)}{\lambda(n)} \, d\xi \quad \ldots(IV.4)$$

and

$$q^\text{pre} = 1 - \sum \sum \frac{b(n)}{\lambda(n)} \frac{\lambda^*(n)}{\lambda(n)} \quad \ldots(IV.5)$$

where, $q^\text{pre}$ is the fraction of initial population surviving the pre-equilibrium emission, $a^\text{non}_x$ is the non-elastic cross-section for the formation of 1st CN by the projectile $x_0$, and is obtained from the optical model formulations. $K$ is the upper limit for the internal transitions to be determined from the ratio $b^{(k+1)}(n)/b^{(k)}(n)$, $b(n)$ being the probability of the state of a given $n_0(p+h)$ configuration, $\lambda^*(n,\xi)$ is
the particle emission rate while $\lambda(n)$ is the sum of internal decay and particle emission rates.

The internal transition rates $\lambda_+(n)$, $\lambda_0(n)$ and $\lambda_-(n)$ defined as the average rates for internal transition change the exciton number $\Delta n$ by +2, zero or -2. These internal decay rates are calculated as\[30-31],

$$
\lambda_\pm = (p, h, E) = \frac{2m}{\hbar} |M|^2 \omega_\pm(p, h, E) \quad ...(IV.6)
$$

where $|M|^2$ is the square of averaged two-body residual interaction and $\omega_\pm(p, h, E)$ is the density of $p$ particle and $h$ hole state at energy $E$. In the absence of any microscopic description, Kalbach proposed $|M|^2 = F_M A^{-3} E^{-1}$, where $F_M$ is an adjustable parameter which may be varied to match the experimental data and $A$ is the mass number of the nucleus. Fraction of the population of the compound system that survive pre-equilibrium decay is calculated using Hauser-Feshbach formalism[27]. The pre-equilibrium emission results in the reduction of population of states that reach the equilibrium stage. This loss is accounted for by the
factor $q_{\text{pre}}^\text{p}$,

$$WB_2(E, I, \Pi) \Delta E = \left( q_{\text{pre}}^\text{p} \frac{\partial \sigma_{\text{HF}}^{x, y}}{\partial E} (E, I, \Pi) \right) \Delta E + \left( \frac{\partial \sigma_{\text{HF}}^{x, y}}{\partial E} (E', I, \Pi, I') \right) \Delta E \quad \ldots \ldots \text{(IV.7)}$$

The differential cross-section for first chance de-excitation is obtained from the population of states of second CN using following relation,

$$\frac{\partial \sigma}{\partial E}(E', I', \Pi') \Delta E = WB_2(E', I', \Pi') \Delta E \quad \ldots \ldots \text{(IV.8)}$$

where, $WB_i(E', I', \Pi') \Delta E$ is the population of the $i^{\text{th}}$ compound nucleus resulting from the population of $(I-1)^{\text{th}}$ compound nucleus. Other terms used in the expressions have their usual meaning.

In the evaporation chain $\gamma$-emission is also considered. Excitation energy, spin and parity of each discrete level for all residual nuclei are to be given in the input data. The number of these levels may be taken up to a maximum of 20. The $\gamma$-ray transmission coefficients are generated within the code employing Weisskopf's estimate, however, Brink-Axel model[32]...
is used for the dominant E1 transitions. The average s-wave neutron radiation width $\Gamma_\gamma$ which is required for final normalisation is to be given as input data. The maximum multipolarity of $\gamma$-radiations may be taken up to octupole transitions for both electric and magnetic types. A schematic representation of the sequence of calculation for $\gamma$-emission in this code is shown in Fig.IV.3. The population of levels by $n$ successive $\gamma$-transitions can be obtained by the following formula,

$$WB'^{ni} (E',I',\Pi') \Delta E' = \sum_{I,\Pi} \int_{E'}^{E_{\text{max}}} dE' \cdot WB^{n-1} (E,I,\Pi)$$

$$\sum_{I,\Pi} \int_{E'}^{E_{\text{max}}} dE' \cdot WB^{n-1} (E,I,\Pi)$$

$$\times \frac{\Gamma_\gamma (E,I,\Pi;E',I',\Pi')}{{\Gamma_\gamma (E,I,\Pi)}} \rho_\gamma (E',I',\Pi') E' \quad \text{(IV.9)}$$

where $E^{\text{max}}$ is the maximum energy up to which $I\hbar$ compound nucleus is populated and $\Gamma_\gamma /{\Gamma_\gamma}$ is the branching ratio for photon emission. Optical model transmission coefficients and separation energies for incident as well for the emitted particles are given as input data. Further details of the code are given elsewhere[2].
Fig. IV.3. Sequence of calculation in code ACT
IV.3. EXIFON

The code EXIFON[3] is based on a pure statistical multistep approach assuming the division of the reaction into multistep direct and multistep compound (MSD/MSC) parts[33,34]. This approach is based on many body theory (Green's function formalism)[35,36] and random matrix physics[37,38]. It predicts angular distribution, emission spectra and activation cross-sections which include contributions from equilibrium, pre-equilibrium as well as direct (collective and non-collective) processes. The code uses a standard global set of parameters. Multiparticle emission is considered up to three decays of the compound system. The code takes into account the neutron, proton and the alpha particle in the entrance channel and the same particles plus photons in the exit channel.

In the statistical multistep model the total emission spectrum of the process \((a,xb)\) is divided in three main parts,

\[
\frac{d\sigma_{a,xb}(E_a)}{dE_b} = \frac{d\sigma_{a,b}^{MSD}(E_a)}{dE_b} + \frac{d\sigma_{a,b}^{MSC}(E_a)}{dE_b} + \frac{d\sigma_{a,xb}^{WPE}(E_a)}{dE_b} \quad \text{...(IV.10)}
\]

The multistep direct part, the first term on the R.H.S. of
the equation (IV.10), contains contributions up to five single steps. Besides, particle-hole excitations and collective phonon excitations are also considered. The multistep compound part, the second term in the R.H.S. of the equation (IV.10), is based on master equation approach. MSD and MSC together represents the first chance emission. The third term of the equation corresponds to the multiparticle emission (MPE) which includes the second, third and higher chance emissions.

\[
\frac{d\sigma_{\text{MPE}}}{dE_b} = \frac{d\sigma_{a,cb}}{dE_b} + \frac{d\sigma_{a,cbd}}{dE_b} + \ldots \quad \text{(IV.11)}
\]

The activation cross-section is calculated as,

\[
\sigma_{a,b} = \sum_{c} \sigma_{a,cb} - \sum_{d} \sigma_{a,cbd} \quad \text{(IV.12)}
\]

The simple analytical expression for mean squared matrix element between bound configurations is given as

\[
\bar{I}_{bb}^2 = 2^{-5}(F_0/A)^2(k_F R)^2 \quad \text{...(IV.13)}
\]

with \(h k_F\) and \(E_F\) being the Fermi momentum and Fermi energy respectively and \(F_0\) the strength of the surface-delta
interaction. All other types of mean squared matrix elements between bound and/or unbound configurations are simply related to $I_{BB}^2$ as,

$$I_{BU}^2(E_a) = \left[ \delta_{nn} + \delta_{ca} + 2F_{13}(E_b)\delta_{bc} \right] (2S_b + 1) \frac{\rho(E_b)}{2} I_{BB}^2$$

...(IV.14)

$$I_{UB}^2(E_a) = (4\pi)^{-1} \frac{\rho(E_a)}{2} \frac{E_F}{E} I_{BB}^2$$

...(IV.15)

$$I_{UU}^2(E_a) = (4\pi)^{-1} \frac{(2S_b + 1) \rho(E_a) \rho(E_b)}{2} \frac{E_F}{4} I_{BB}^2$$

...(IV.16)

Single particle density of particle c (c=n,p,a) with mass $\mu_c$ is given by,

$$\rho(E_c) = 4\pi V \mu_c (2\mu_c E_c)^{1/2} / (2\mu_h)$$

...(IV.17)

where, $V$ is the nuclear volume. The single particle state density of bound particle at Fermi energy is given as,

$$g = 4\rho(E_F)$$

IV.3.1. MSD Cross-section,

The MSD differential cross-section is a sum over s-step direct processes,

$$\frac{d\sigma_{MSD}^{(s)}(E_a)}{dE_b} = \sum_{a,b} \frac{d\sigma_{MSD}^{(s)}(E_a)}{dE_b}$$

...(IV.18)
Besides the particle hole excitation \([\text{ex}]\), the transition probability also includes collective excitations \([\text{vib}]\). The probability for particle-hole excitation is given by,

\[
W_{ab}^{(\text{ex})}(E_a, E_{\text{b}}) = \frac{1}{\Omega} |\langle E_{\text{a}} | E_{\text{b}} \rangle|^2 \rho_2^B(U) \quad \text{...(IV.19)}
\]

while the \(s\)-step direct non-collective contribution is given as,

\[
\frac{d\omega_{a,b}^{(s)}(E_a)}{dE_b} = \frac{\mu_a \mu_b V^2}{(2\pi)^2} \frac{2\pi}{k_b} \left[ 2^{\alpha} (F/A)^2 \right]^2 \frac{x q^2}{(s!)} \rho_{2s}^B(U) \quad \text{...(IV.20)}
\]

where, \(q = (n/2)(\rho(E)/kR)^2\) and \(\rho_{2s}^B\) is the final state density. The particle-phonon coupling is given by,

\[
V_{\lambda}(r) = -\beta_{\lambda} V_{0,0} R_0 (r-R) Y_{\lambda_0,0}(r) \quad \text{...(IV.21)}
\]

which leads to the transition probability,

\[
W_{ab}^{(\text{vib})}(E_a, E_{\text{b}}) = \delta_{ab} \sum_{\lambda} |\langle E_{\text{b}} | V_{\lambda}(r) | E_a \rangle|^2 \delta(U - \omega_\lambda) \quad \text{...(IV.22)}
\]

where \(\omega_\lambda\) and \(\beta_\lambda\) denote the energy and deformation parameters of a phonon with multipolarity \(\lambda\).
IV.3.2. MSC cross-section

The MSC cross-section is given as,

\[ \frac{d \sigma_{MSC}^{a,b}(E)}{dE_b} = a^SMC_a(E_o) \sum_{N=N_0}^{N} \frac{\tau_N(E)}{h} \sum_{(\Delta N)} \Gamma_N^{(\Delta N)}(E,E_v) \]  \hspace{1cm} \text{(IV.23)}

where \( \tau_N(E) \) satisfies the time integrated master equation.

\[-\hbar^2_{\Delta N} = \Gamma^{(+)}_{N-2}(E) \tau_{N-2}(E) + \Gamma^{(-)}_{N+2}(E) \tau_{N+2}(E) - \Gamma_N(N) \tau_N(E) \]  \hspace{1cm} \text{(IV.24)}

for each exciton number \( N=N+\Delta N \). The sum from \( N_0 \) to \( N \) includes the equilibrium stage \( N \approx (1.4gE)^{1/2} \). The initial exciton number \( N_0 = 2, 3, \) or \( 6 \) is assumed for photon, nucleon and \( a \) induced reactions. The damping widths are defined by,

\[ \Gamma_N^{(\Delta N)}(E) = 2\pi I_{BB}^{(\Delta N)}(E) \]  \hspace{1cm} \text{(IV.25)}

The MSC formation cross-section in equation (IV.23) is given by

\[ \sigma_{a}^{MSC}(E) = a^{OM}_a(E_o) - \sum_c^{MSC} \sigma_a^{c}(E) \]  \hspace{1cm} \text{(IV.26)}

It acts as normalisation constant. To consider the isospin conservation, eqn. (IV.23) is modified to include the isospin
quantum number and hence contains two parts

$$\frac{d\sigma_{\alpha,\beta}^{\text{MSc}}(E_a)}{dE_b} = \frac{d\sigma_{\alpha,\beta}^{\text{MSc}}(T_a;E_a)}{dE_b} + \frac{d\sigma_{\alpha,\beta}^{\text{MSc}}(T_a';E_a)}{dE_b} \quad \ldots(IV.27)$$

where \( T_+ = T_0 + 1/2 \), \( T_- = T_0 - 1/2 \), and \( T_0 = (N-Z)/2 \) is the target isospin. Thus the isospin dependent cross-sections are given respectively by,

$$\sigma_{\alpha}^{\text{MSc}}(T_+;E_a) = \frac{2T}{2T+1} \sigma_{\alpha}^{\text{MSc}}(E_a) \quad \ldots(IV.28)$$

and

$$\sigma_{\alpha}^{\text{MSc}}(T_-;E_a) = \frac{1}{2T+1} \sigma_{\alpha}^{\text{MSc}}(E_a) \quad \ldots(IV.29)$$

The \( \gamma \)-emission is considered as a pure E1 process. The photo absorption cross-section is given by,

$$\sigma_{\alpha}^{\text{Obs}}(E_\gamma) = \frac{4\pi^2}{k^2} \rho(E_\gamma) \mathcal{D}^2(E_\gamma;E_R) = \frac{2n\nu}{\hbar c} \mathcal{D}^2(E_\gamma;E_R) \quad \ldots(IV.30)$$

with

$$\rho(E_\gamma) = \frac{4\pi\nu k^2}{(2n)^3 \chi}, \quad \ldots(IV.31)$$

$$\mathcal{D}^2(E_\gamma;E_R) = (2L+1) \frac{e^2}{2} \frac{4n}{3V} S f(E_\gamma;E_R) \quad \ldots(IV.32)$$

$$S = \frac{\hbar^2}{2m} \frac{NZ}{A} (1+0.8x),$$
and \( f(E, E_R) = \frac{2}{\pi} \frac{E^2 \Gamma_R}{(E^2-E_R^2)^2 + E^2 \Gamma_R^2} \) \( \ldots \text{(IV.33)} \)

The escape width for the MSC \( \gamma \)-emission is given by,

\[
\Gamma^{\Delta N}_{N, \gamma}(E_E) = \frac{D^2(E, E_R)}{(2L+1)} \frac{\rho^{\Delta N}_N(E, U)}{\rho^+(E)} \quad \frac{2\rho(E)}{\rho} \quad \ldots \text{(IV.34)}
\]

The MPE are calculated in a pure MSC concept, for second-chance process \((a,cb)\) and \(c = \gamma\),

\[
\frac{d\nu}{dE} = \sum_{N=0}^{\infty} \sum_{\Delta N} \Gamma^{\Delta N}_{N-1, b}(E_1, E_2) \quad \ldots \text{(IV.35)}
\]

The master equation has to be solved for each intermediate excitation energy. The pair effects are considered by using the binding energy \(B_{n,p}^{\text{eff}}\).

\[
B^{\text{eff}}_n = B_n + \Delta \quad \text{for } n \text{ odd} \quad \text{and} \quad B^{\text{eff}}_p = B_p + \Delta \quad \text{for } n \text{ even}
\]

\[
B^{\text{eff}}_\gamma = B_\gamma \quad \text{and} \quad B^{\text{eff}}_\gamma = 0 \text{ are taken.}
\]

where \(B_x\) is the experimental binding energy for particle \(x\).

The pairing shift \(\Delta\) is calculated using, \(\Delta = 12.8 A^{1/2}\) MeV.
In MSD processes effective binding energies are used in the outgoing channel only.

Pauli-blocking effect is considered by replacing $E$ and $U$ by $E - A_{ph}$, $U - A_{ph}$ (for particle emission) and $U - A_{ph}$ (for $\gamma$-emission) respectively. The energy shift $A_{ph}$ is given by,

$$ A_{ph} = \frac{N_p^2 + N_p + N_h^2 - 3N_h}{4g} \quad \text{...(IV.36)} $$

In order to consider the Shell structure effects in MSC processes, the single particle state density $g$ is multiplied by

$$ \left[ 1 + \frac{\delta W}{E_x} \left[ 1 - \exp(-\gamma E_x) \right] \right] \quad \text{...(IV.37)} $$

with $\gamma = 0.05 \text{ MeV}^{-1}$, $E_x = E$ or $U$ and $\delta W$ as shell correction energy taken from tables[39]. The Coulomb effect and threshold effects are considered by multiplying the cross-sections by $P_a(E_a)P_b(E_b) \leq 1$ where, $P_c(E_c)$ is given by,

$$ P_c(E_c) = \frac{\alpha_{cw}(E_c)}{\alpha_{nw}(E_c)} \frac{4k'K}{(k'+K)^2} \left[ 1 \right] \quad \text{...(IV.38)} $$

for $(k'R)_c^2 \leq 1$ for the ingoing and outgoing channels $(c=n,p,a)$. For $\gamma$-emission $P_{\gamma}(E_{\gamma}) = 1$. The second term, in the
equation (IV.41), is for Coulomb effects. It takes the value 1 for neutron \(c=n\). Analytical expressions for the optical model reaction cross-sections \(\sigma_{cc}^{OM}(E)\) are taken from [40], where \(K = [2\mu(E + V_0)]^{1/2}\) and \(k'_c = [2\mu(E - E_{coul})]^{1/2}\) are the wave numbers of particle \(c\) inside the nucleus and above the Coulomb barrier respectively.

Standard global set of parameters used in the code is:

**Strength of surface-delta interaction**

- \(F_0 = 27.5\) MeV

**Radius parameter**

- \(r_0 = 1.21 + 4.0A^{1/2} - 15A^{-1/3}\) fm.

**Potential depth**

- \(V_0 = 52 - 0.3E_{F}\) MeV

**Fermi energy**

- \(E_F = 33\) MeV

**Pairing shift**

- \(\Delta = 12.8A^{-1/2}\) MeV

**Phonon (Breit-Wigner) width**

- \(\Delta_\omega = 1.4\) MeV

**Optical model potential**

- Wilmore-Hodgson (for neutron)[41]
- Perey et al. (for proton)[42]
- Huizenga-Igo (for alpha)[43]

**IV.4. CASCADE**

The computer code cascade[44] is a pure statistical code to calculate evaporation mass residue and \(Z\) distribution for...
heavy ion reactions. It starts with an excited nucleus, the spin distribution for which is to be specified and calculates the relative decay widths for neutron, proton, α-particle and γ-ray emission. It generates matrices containing the population of the daughter nuclei as function of excitation energy and angular momentum. The sequence of emission continues till the excitation energy falls below the particle threshold.

The partial cross-section for the formation of a compound nucleus of spin $J$ and parity $\pi$ from a projectile and a target nucleus (spins $J_p$, $J_T$) at c.m. energy $E$ is given by,

$$
\sigma(J,\pi) = \frac{2J+1}{2J_p+1}(2J_T+1) \sum_{J_p} \sum_{J_T} T_{J_p, J_T} J^* |T(E)|^2
$$

The transmission coefficients $T_{J_p, J_T}$ are assumed to be dependent only on the energy and the orbital angular momentum $L$. The particle emission rate from a nucleus excited to energy $E_1$ leading to the residual nucleus with energy $E_2$ is given by,
where $\xi_x$ is the kinetic energy of the particle $x$, $J_x + s$ is the channel spin. The $\gamma$-ray emission rate from the same nucleus is given by,

$$R_{\gamma} d\xi = \frac{1}{\hbar} \Gamma_{\gamma}(\xi_{\gamma})$$

$$= \frac{\rho(E, J, \eta_1, \eta_2)}{2n^2 \rho(E, J, \eta_1, \eta_2)} \sum_{J - s \geq 0} \sum_{J = s} \sum_{J = s} T_L^{\gamma}(\xi_{\gamma}) d\xi_{\gamma}$$

where $L$ denotes the multipolarity of the $\gamma$-ray, and $T_L^{\gamma}(\xi_{\gamma})$ are energy dependent strengths. The level density is calculated as,

$$\rho(E, J) = \omega(E, M = J) - \omega(E, M = J + 1)$$

with the state densities

$$\omega(E, M) = \frac{1}{\exp(2\sqrt{aU})}$$

and the equation of state

$$U = E - \Delta = at^2 - \frac{9}{2}t.$$
The spin dependence is determined by the parameter \( a R = \frac{2J}{\hbar^2} \)
where \( J \) is the effective moment of inertia. The level density formula implies a yrast line,

\[
E_{\text{rot}}(J) = \frac{J(J+1)}{2aR} + A = \frac{J(J+1)\hbar^2}{2J} + \Delta \quad \text{(IV.47)}
\]

The entire region is divided into three regions. Region I (Low excitation energy \( E < 4 \text{ MeV} \)), here the experimentally known levels are used. Region II. (Medium excitation energy \( 4 < E < 10 \text{ MeV} \)) Analytical level density formula is applied. \( a \) and \( \Delta \) are determined empirically for each nucleus as was done by Vonach et al.\[28\] and Dilg et al.\[45\]. Region III. (High excitation energy \( E > E_{\text{LDW}} \)). Here it is assumed that at a sufficiently high excitation energy all nuclei behave as predicted by liquid-drop model. Analytical form of Fermi gas model is used here and both parities are assumed equally probable. \( a = A/K \) is taken where \( k \) is constant. The pairing shift \( \Delta_{\text{LDW}} \) is calculated assuming the virtual ground state. Further the level density in this region should coincide with the ground state energy of a spherical liquid drop which can be calculated from one of the following options. (1) Myers-Swiatecki mass formula\[16\], (2) Dilg et al.\[44\]
(3) Kataria[24]. The moment of inertia is taken to be that of a deformable liquid drop with gyrostatic motion. The angular momentum l-deformation is taken from the work of Cohen et al[14].
References:

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The presently measured cross-sections at different incident energies for the reactions $^{51}V(p,n)^{51}Cr$, $^{58}Ni(p,\alpha)^{55}Co$, $^{60}Ni(p,n)^{60}Cu$, $^{60}Ni(p,\alpha)^{64}Cu$, $^{64}Ni(p,n)^{64}Cu$, $^{62}Ni(p,2n)^{62}Cu$, $^{69}Cu(p,n)^{69}Zn$, $^{63}Cu(p,2n)^{63}Zn$, $^{65}Cu(p,n)^{65}Zn$, $^{80}Y(p,n)^{80m}Zr$, $^{80}Y(p,n)^{80}Zr$, $^{93}Nb(p,n)^{93}Mo$, $^{119}In(p,n)^{119}Sn$, $^{115}In(p,3n)^{113}Sn$, $^{121}Sb(p,\alpha)^{121m}Te$, $^{121}Sb(p,n)^{121}Te$, $^{123}Sb(p,\alpha)^{123m}Te$, $^{123}Sb(p,n)^{123}Te$, $^{180}Te(p,n)^{180}I$, $^{197}Au(p,n)^{197m}Hg$, $^{197}Au(p,n)^{197}Hg$, $^{197}Au(p,\alpha)^{197}Au$, $^{58}Ni(\alpha,n)^{61}Zn$, $^{58}Ni(\alpha,p)^{61}Cu$, $^{58}Ni(\alpha,\alpha)^{58}Ni$, $^{60}Ni(\alpha,2n)^{62}Zn$, $^{60}Ni(\alpha,p2n)^{64}Cu$, $^{61}Ni(\alpha,2n)^{63}Zn$, $^{64}Ni(\alpha,3n)^{67}Zn$, $^{62}Ni(\alpha,3n)^{65}Zn$, $^{141}Pr(\alpha,n)^{144}Pm$, $^{141}Pr(\alpha,2n)^{143}Pm$, $^{165}Ho(C,3n)^{174}Ta$, $^{165}Ho(C,4n)^{173}Ta$, and $^{165}Ho(C,5n)^{172}Ta$ are tabulated in Tables III.3 in Chapter-III and are plotted in Figs. V.1-18. The energy spread shown by horizontal bars in these figures represents the sum of the energy loss of the projectile in the half thickness of the sample foil and the inherent beam energy uncertainty. Presently measured excitation functions are also compared with literature data wherever available. Detailed analysis
Fig. V.1. Measured excitation function for $^{51}\text{V}(p,n)$ reaction along with theoretical and literature data.
Fig. V.2. Measured excitation functions for $^{58}$Ni(p,$\alpha$) and $^{60}$Ni(p,n) reactions along with theoretical and literature data.

Fig. V.3. Measured excitation functions for $^{60}$Ni(p,$\gamma$), $^{62}$Ni(p,n) and $^{62}$Ni(p,2n) reactions along with theoretical and literature data.
Fig. V.4. Measured excitation functions for $^{63}\text{Cu}(p,n)$ and $^{65}\text{Cu}(p,2n)$ reactions along with theoretical and literature data

Fig. V.5. Measured excitation function for $^{65}\text{Cu}(p,n)$ reaction along with theoretical and literature data
Fig. V.6.
Measured excitation function for $^{80}$Y(p,n) reaction along with theoretical and literature data. Dark circle and triangle represent population of metastable and ground states respectively. Open circle shows the sum.

Fig. V.7.
Measured excitation function for $^{99}$Nb(p,n) reaction (isomeric) along with theoretical and literature data.
Fig. V.8.
Measured and theoretically calculated excitation functions for $^{113}\text{In}(p,n)$ and $^{115}\text{In}(p,3n)$ reactions.
Fig. V.9.
Measured excitation functions for $^{121}$Sb(p,n) and $^{122}$Sb(p,np) reactions along with theoretical data. Dark circle and triangle represent the population of metastable and ground states respectively. Open circle shows the sum.
Fig. V.10. Measured excitation functions for $^{129}$Sb(p,n) (isomeric) and $^{129}$Sb(p,np) reactions along—with theoretical data.
Fig. V.11. Measured excitation function for $^{130}$Te(p,n) reaction along with literature and theoretical data.

Fig. V.12. Measured excitation functions for $^{197}$Au(p,n) and $^{197}$Au(p,np) reactions along with literature and theoretical data. Dark circle and triangle represent the population of metastable and ground states respectively. Open circle shows the sum of metastable and isomeric cross-sections.
Fig. V.13.
Measured excitation functions for $^{58}$Ni($\alpha$,n), $^{60}$Ni($\alpha$,2n) and $^{62}$Ni($\alpha$,3n) reactions along with theoretical and literature data.

Fig. V.14.
Measured excitation functions for $^{60}$Ni($\alpha$,n), $^{61}$Ni($\alpha$,2n) and $^{62}$Ni($\alpha$,3n) reactions along with theoretical and literature data.
Measured excitation functions for $^{141}\text{Pr}(\alpha,n)$ and $^{141}\text{Pr}(\alpha,2n)$ reactions alongwith theoretical data.
Fig. V.18.
Measured excitation functions for $^{165}\text{Ho}(C,3n)$, $^{165}\text{Ho}(C,4n)$ and $^{165}\text{Ho}(C,5n)$ reactions along with the theoretical calculations using the codes ALICE and CASCADE.

(—— ALICE with PE,
- - - ALICE pure CN
— — — CASCADE)
of likely errors in present measurements is already presented in Chapter-III.

V.1. Literature Survey

To the best of our knowledge, the excitation functions for the reactions $^\text{60}\text{Ni}(p,n)^{60}\text{Cu}$, $^\text{62}\text{Ni}(p,2n)^{62}\text{Cu}$, $^\text{86}\text{Y}(p,n)^{86}\text{Zr}$, $^\text{6}\text{Y}(p,n)^{6}\text{Zr}$, $^\text{113}\text{In}(p,n)^{113}\text{Sn}$, $^\text{115}\text{In}(p,3n)^{113}\text{Sn}$, $^\text{121}\text{Sb}(p,n)^{121}\text{Te}$, $^\text{121}\text{Sb}(p,n)^{121}\text{Te}$, $^\text{121}\text{Sb}(p,\text{np})^{120}\text{Sb}$, $^\text{123}\text{Sb}(p,n)^{123}\text{Te}$, $^\text{123}\text{Sb}(p,\text{np})^{122}\text{Sb}$, $^\text{197}\text{Au}(p,n)^{197}\text{Hg}$, $^\text{58}\text{Ni}(\alpha,n)^{58}\text{Zn}$, $^\text{58}\text{Ni}(\alpha,\text{np})^{60}\text{Cu}$, $^\text{61}\text{Ni}(\alpha,2\text{n})^{63}\text{Zn}$, $^\text{69}\text{Ni}(\alpha,3\text{n})^{62}\text{Zn}$, $^\text{62}\text{Ni}(\alpha,3\text{n})^{63}\text{Zn}$, $^\text{60}\text{Ni}(\alpha,p\text{2n})^{61}\text{Cu}$, $^\text{141}\text{Pr}(\alpha,n)^{144}\text{Pm}$, $^\text{141}\text{Pr}(\alpha,2\text{n})^{143}\text{Pm}$, $^\text{165}\text{Ho}(\alpha,\text{3n})^{174}\text{Ta}$, $^\text{165}\text{Ho}(\alpha,4\text{n})^{173}\text{Ta}$, and $^\text{165}\text{Ho}(\alpha,5\text{n})^{172}\text{Ta}$ are being reported for the first time and hence no comparison with the literature data is possible.

The presently measured excitation functions for the reactions $^\text{51}\text{V}(p,n)^{51}\text{Cr}$, $^\text{58}\text{Ni}(\alpha)^{55}\text{Co}$, $^\text{6}\text{Ni}(\beta)^{64}\text{Cu}$, $^\text{6}\text{Ni}(\alpha,\text{np})^{64}\text{Cu}$, $^\text{6}\text{Cu}(p,n)^{63}\text{Zn}$, $^\text{6}\text{Cu}(p,2\text{n})^{62}\text{Zn}$, $^\text{6}\text{Cu}(p,n)^{65}\text{Zn}$, $^\text{86}\text{Y}(p,n)^{86}\text{Zr}$, $^\text{9}\text{Nb}(p,n)^{69}\text{Mo}$, $^\text{13}\text{Te}(p,n)^{130}\text{I}$, $^\text{16}\text{Au}(p,n)^{167}\text{Hg}$, $^\text{16}\text{Au}(p,\text{np})^{166}\text{Au}$, $^\text{6}\text{Ni}(\alpha,\text{p})^{64}\text{Cu}$, $^\text{58}\text{Ni}(\alpha,\text{np})^{64}\text{Cu}$, $^\text{58}\text{Ni}(\alpha,\text{np})^{64}\text{Cu}$, $^\text{60}\text{Ni}(\alpha,n)^{63}\text{Zn}$ and $^\text{60}\text{Ni}(\alpha,2\text{n})^{62}\text{Zn}$ are compared with the
literature data[1-21] as shown in the corresponding figures. In general, the literature data agree reasonably well with the present measurements. It may, however, be pointed out that in most of the earlier data detailed analysis of errors in cross-section values and in incident beam energies is not reported. Further, most of the earlier measurements were done with a view to study the compound nucleus (CN) reaction mechanism and, therefore, measurements were done up to the peak of the excitation functions, generally employing chemical separation method and/or using low resolution detectors. The experimental data reported by different workers, some times, also differ from each other by large amount[2,3,,10,12,13]. The present measurements are done with the view of studying the pre-equilibrium emission which is hidden in the higher energy tail portion of the excitation functions, using high resolution (2 keV at 1.33 MeV γ-ray of 60Co) HPGe detector. For example, in Figure V.1, the presently measured excitation function for 51V(p,n)54Cr reaction is compared with the literature values[1-3]. Although there is reasonable agreement between the presently measured and literature values, the literature values are
slightly higher than the present ones. As is already mentioned, the measurement of Wing and Huizenga[1] was carried out to study the CN mechanism up to 10.5 MeV with about 10% error. The measurement of Hontzeas and Yaffe[2] was done using chemical separation of isotopes with an error of about 17%. Further, they used cross sections of $^{63}\text{Cu}(p,n)^{63}\text{Zn}$ and $^{65}\text{Cu}(p,n)^{65}\text{Zn}$ reactions as standard for monitoring the flux of proton beam. However, the cross-section values for these standard reactions reported by different authors differ from each other. Further, no detailed discussion of errors is made by these authors. In Figures V.2 and V.3 the presently measured excitation functions for the reactions $^{58}\text{Ni}(p,\alpha)^{55}\text{Co}$, $^{60}\text{Ni}(p,\gamma)^{64}\text{Cu}$ and $^{64}\text{Ni}(p,n)^{64}\text{Cu}$ up to 15 MeV are compared with the literature data[6-9]. As can be observed from these figures there is satisfactory agreement between the present measurement and literature data. In the case of $^{197}\text{Au}(p,n)$ reaction both the metastable and ground states of $^{197}\text{Hg}$ are formed. In the literature compilation of excitation functions[17,22], it is not clear whether the measured data is for the production of metastable state, the ground state or the sum of the two. However, it may be
observed from Fig. V.12, that the literature data[12,17] is comparable to the presently measured excitation function for $^{197}$Au(p,n)$^{190}$mHg reaction.

V.2. Theoretical Analysis

The presently measured excitation functions are analysed using both semiclassical and quantum mechanical models for Pre-equilibrium (PE) emission. The computer codes ALICE91[23], ACT[24] and CASCADE[25] are used for semiclassical calculations while code EXIFON[26] is used for quantum mechanical calculations. Details of the theoretical models and computer codes are already discussed in Chapters II and IV respectively.

All the theoretical codes have some parameters which may be adjusted to match the experimental data. As such, different groups of workers use different values of these adjustable parameters in order to reproduce their data. However, a consistent analysis demands that a given set of adjustable parameters should reproduce a large amount of data, taken consistently using the same method. This requirement becomes more stringent for the cases of sequential emission of
particles, as in reactions of the type \((x,n), (x,2n), (x,3n),\) etc. A chosen value of the parameter set should be such that it reproduces the measured excitation functions for all the reactions of the chain. In the present analysis an effort is made to fix the values of some adjustable parameters of the different theoretical codes.

In code ALICE the level density parameter \(a\), the mean free path multiplier \(C0ST\) and the initial exciton number \(n_o\), are the three important parameters which may be varied to reproduce the experimental data. The level density parameter affects both the CN and the PE components while \(C0ST\) and \(n_o\) changes only the PE component. The level density parameter \(a\) is given by \(a=A/K\) where, \(A\) is the mass number of the nucleus and \(K\) is a parameter which can be varied to match the experimental data. In the present calculations \(K=10\) and \(C0ST=3\) are, generally, taken. These values for \(K\) and \(C0ST\) are obtained from our earlier analyses of proton and alpha induced reactions[27-31] and, except for the two cases of \(^{119}\text{In}(p,n)^{119}\text{Sn}\) and \(^{190}\text{Te}(p,n)^{190}\text{I}\) reactions, reproduce satisfactorily the presently measured experimental data for light ion induced reactions. In order to see the effect of
level density parameter $a$ and mean free path multiplier $\text{COST}$ on the calculations done with the code ALICE, for example, the excitation functions for the reaction $^{119}\text{In}(p,n)^{113}\text{Sn}$ with different values of $K$ and $\text{COST}$ are shown in Fig. V.19. As may be seen, $K=18$ and $\text{COST}=3$ gives the best fit to the experimental data. This relatively larger value of $K$, which means a smaller value for $a$, may be due to the fact that the compound and the residual nuclei $^{50}\text{Sn}$ have a closed proton shell with magic number 50. Similarly, a value of $K=10$ and $\text{COST}=9$ reproduces well the presently measured excitation function for $^{190}\text{Te}(p,n)^{190}\text{I}$ reaction[27], as shown in Fig. V.20. For the heavy ion induced reactions, $K=13$ and $\text{COST}=3$ is found to give satisfactory reproduction of the experimental data. The initial configuration, determined by $n_0$, is an important parameter for pre-equilibrium emission. A smaller value of $n_0$ means a less complex initial state and, therefore, the system is likely to undergo a large number of intermediate interactions to reach the equilibrium, hence a relatively large contribution of PE emission. On the other hand, large value of $n_0$ reflects a more complex initial state, only a few residual interactions to bring about
Fig. V.19.
Excitation functions for $^{119}$In(p,n) reaction calculated using code ALICE with different values of parameter $K$ and COST.
Fig. V.20.
Excitation functions for $^{130}$Te(p,n) reaction calculated using code ALICE with different values of parameter COST.
equilibrium, and hence relatively smaller contribution of PE emission. For nucleon induced reactions a value of \( n_0 = 3 \) gives satisfactory reproduction of the presently measured excitation functions. This value of \( n_0 (=3) \) may mean that the incident nucleon in its first interaction excites one particle creating a hole. Similarly for alpha induced reactions \( n_0 = 6 \) is found to give satisfactory matching with the experimental data. The six exciton state may be created as a result of the excitation of one particle creating a hole and the breakup of alpha particle itself. In cases of heavy ion reactions \( n_0 = 3 \) gives a good fit to the experimental data. It may be argued that the incident heavy ion (Carbon) does not breakup in the initial interaction on account of its large binding energy and only two particle one hole initial state is involved. As is already mentioned, binding and separation energies etc, in the code ALICE are internally calculated using the mass tables[32].

In code ACT, apart from the level density parameter \( a \) and initial exciton number \( n_0 \), the other adjustable parameters are the fictive ground state energy \( \Delta \), the effective moment of inertia \( \Theta_{\text{eff}} \), and the parameter \( F_M \) that is related to the
matrix element for two-body residual interactions. Though several formulations, tables etc. are available in literature, the level density parameter $a$ and fictive ground state energy $\Delta$, in the present calculations, are taken consistently from the tables of Dilg et al.[33]. In case of some nuclei for which these are not available in Dilg tables,[33] their values were obtained by extrapolating the nearby values. The effective moment of inertia $I_{eff}$, in calculations by ACT, is kept equal to the rigid body value for all cases. The particle separation energies, needed in these calculations are taken from the tables of Wapstra and Gove[34]. Decay schemes and energy levels etc., of the various nuclei are taken from the Table of Isotopes[35] and Nuclear Data Sheets. $F_M$ is another adjustable parameter, values for which in the range of 95 to 7000 MeV$^3$ have been used in the literature[36,37]. In the present analysis a value of $F_M = 430$ MeV$^3$ is taken. This value of $F_M (=430$ MeV$^3$) is obtained from our earlier analyses of proton, neutron and alpha induced reactions[27-31,38] and is found to reproduce the present data satisfactorily. Kalbach[39] also indicated a value of $F_M \approx 430$ MeV$^3$. However, in the case of $^{190}$Te(p,n)
reaction the value of \( F \) is varied to have a better agreement with the experimental data. In order to see the effect of parameter \( F \), as a typical case, excitation functions calculated with different values of \( F \) for the reaction \(^{130}\text{Te}(p,n)^{130}\text{I}\) are shown in Fig.V.21. As may be seen in this figure, \( F = 140 \text{ MeV} \) along with initial exciton number \( n_0 = 3 \) gives best fit to the experimental data. Analysis of the data further shows that variation in the level density parameter \( a \) changes the cross-sections by a considerable amount in the peak region and not so much in the tail part as shown in Fig. V.19, which is very much affected by the value of parameter \( F \). No straightforward argument for the low value of \( F \) in the case of \(^{130}\text{Te}\) is presented, however it is to be noted that this system is very near to a doubly magic region of \( Z=50 \) and \( N=80 \). The effect of initial exciton number \( n_0 \) on the excitation function, particularly in the high energy tail part is also shown in figure V.21.

The code EXIFON calculates the excitation function using a standard global set of parameters\([26,40]\). In the global set the radius parameter \( r_0 = 1.21 - 4.0A^{2/3} - 15A^{4/3} \text{fm} \), the Fermi energy \( E_F = 33 \text{ MeV} \) and the pairing shift term \( \Delta = \)
Fig. V.21. Excitation functions for $^{190}$Te(p,n) reaction calculated using code ACT with different values for $F_M$ and $n_0$.

Fig. V.22. Excitation functions for $^{119}$In(p,n) reaction calculated with different parameter sets of code EXIFON.
12.8A$^{-1/2}$ MeV are taken. Further, angular momentum and parity conservations are not taken into account in these calculations\cite{41}. Excitation functions for the reactions $^{51}$V(p,n)$^{54}$Cr, $^{58}$Ni(p,$\alpha$)$^{55}$Co, $^{60}$Ni(p,n)$^{63}$Cu, $^{60}$Ni(p,$\gamma$)$^{64}$Cu, $^{64}$Ni(p,n)$^{67}$Cu, $^{62}$Ni(p,2n)$^{64}$Cu, $^{63}$Cu(p,n)$^{67}$Zn, $^{63}$Cu(p,2n)$^{69}$Zn, $^{65}$Cu(p,n)$^{69}$Zn, $^{89}$Y(p,n)$^{92}$Zr, $^{113}$In(p,n)$^{116}$Sn, $^{121}$Sb(p,n)$^{124}$Te, $^{130}$Te(p,n)$^{133}$I, $^{197}$Au(p,n)$^{200}$Hg, $^{58}$Ni($\alpha$,n)$^{61}$Zn, $^{58}$Ni($\alpha$,$\alpha$)$^{61}$Cu, $^{60}$Ni($\alpha$,n)$^{63}$Zn, $^{60}$Ni($\alpha$,2n)$^{62}$Zn, $^{64}$Ni($\alpha$,2n)$^{67}$Zn $^{144}$Pr($\alpha$,n)$^{147}$Pm, and $^{144}$Pr($\alpha$,2n)$^{147}$Pm are also calculated using the code EXIFON. In general, excitation functions calculated with global parameter set do not agree well with the experimental data. As a typical case, the calculated and measured excitation functions for $^{113}$In(p,n)$^{116}$Sn reaction are shown in Fig. V.22. The global set of parameter underestimates the measured cross-sections particularly at higher energies. In order to match the experimental data the Fermi energy $E_F$ is changed to 40 MeV instead of 33 MeV. This value of $E_F = 40$ MeV is also suggested by Chadwick et al\cite{42}, Avrigeanu et al.\cite{43} and Oblozinsky\cite{44}. Kalka (author of this code) also used the same value in some calculations\cite{40}. The pairing energy $\Delta$ is
taken equal to \(\Delta = -3.0\) MeV and \(-2.5\) MeV for \(^{113}\)In(p,n)^{113}\)Sn and \(^{130}\)Te(p,n)^{130}\)I reactions. These values of \(\Delta\) are in the range of values used in the literature\([33,37,45]\). Excitation functions calculated using \(E_F = 40\) MeV for all the above measured reactions are in better agreement with the experimental data. It may be mentioned that the Fermi energy \(E_F\) is related to the single particle state density \(g\) and through it to the level density parameter \(a\). For \(E_F = 40\) MeV one gets a value of \(a = 16\) for \(^{130}\)Te and \(^{130}\)I nuclei with a radius parameter 1.4 fm. This value of \(a\) for \(^{130}\)Te and \(^{130}\)I agree well with other literature data. In these calculations the optical model parameters of Becchetti and Greenlees\([46]\) are used for the nuclei V, Cu, In and Te, that of Menet et al.\([47]\) for Ni, Sb, and Au, whereas that of Perey\([48]\) for all other nuclei.

The codes ALICE and CASCADE are used to calculate the excitation functions for reactions induced by heavy ion \(^{12}\)C. Excitation functions for the reactions \((C,3n)\), \((C,4n)\) and \((C,5n)\) calculated using the code ALICE are shown in Fig. V.23. It may be seen that the peaks of the measured excitation functions for all the three reactions lie at
Excitation functions for $^{165}$Ho(C,3n), $^{165}$Ho(C,4n) and $^{165}$Ho(C,5n) reactions using the code ALICE without considering energy shift. The dashed lines to guide the eye along the experimental points.
energies higher than the corresponding peaks of the calculated ones. This is expected, since CN calculations in code ALICE are done using the Weisskopf-Ewing model which does not take into account the angular momentum effects. In heavy ion induced reactions incident particle gives relatively larger angular momentum to the compound system and if during the last stages of de-excitation particle emission from higher momentum states is inhibited, the excitation functions for particle emitting mode will show peaks at higher energies [49-51]. An estimate of the energy shift can be made from the rotational energy $E_{\text{rot}}$. The rotational energy for the $^{12}\text{C}+^{169}\text{Ho}$ system around $\approx 80$ MeV incident energy is about $\approx 6$ MeV. The ALICE calculations shifted by the corresponding rotational energies are plotted in Fig. V.18. It may be seen that, in general, there is good agreement between the measured excitation function and the ALICE predictions with the shift of energy by $E_{\text{rot}}$. Since light ion induced reactions do not impart large angular momentum, the rotational energy shift is not so predominant in nucleon and alpha induced reactions.
The code CASCADE is a purely statistical code and hence the level density parameter and the angular momentum limit are the two important parameters of the code. In the present calculations the level density formula of Kataria/Ramamurthy[52] is used and the angular momentum limit is taken as 40ℏ in order to optimise the agreement between the measured and calculated excitation functions in the peak region. Calculations done with code CASCADE are also plotted in Fig. V.18. As is clear from this figure, the calculation done using the code CASCADE do not match with the experimental data for all of the three reactions. CASCADE calculations for the (C,3n) reaction, in particular, underestimate the measured cross-sections by a large amount. This may be due to the PE emission which is not taken into account in the CASCADE code. Further, the PE emission is more likely in (C,3n) reaction than in (C,4n) and (C,5n) reactions, the relatively large discrepancy between the CASCADE calculations and the experimental data for (C,3n) reaction is expected.
V.3. Special cases

V.3.1. Isomeric populations

Though general details of measurements are given in Chapter-III, some cases need further elaboration on account of the complexity involved. Sometimes both the metastable (m) and the ground (g) states of the residual nucleus are populated in the reaction but only one of them is of measurable half life. In such cases theoretical calculations are done using the code ACT, since the codes ALICE and EXIFON calculate the total cross-sections and not the partial cross-sections. However, when both the isomeric and the ground states are of measurable half-lives, for example, in case of $^{88}\text{Y}(p,n)^{60}\text{Zn}$, $^{121}\text{Sb}(p,n)^{121}\text{Sn}$ and $^{197}\text{Au}(p,n)^{197}\text{Hg}$ reactions, measurements are done for both the isomeric and ground states separately and are individually compared with the calculations of code ACT. In such cases, the sum of the measured cross-sections for the metastable and ground states at each energy are also compared with the calculated values from code ALICE and EXIFON.

In reactions where metastable (m) state is of short half-life and decays into the relatively longer lived ground (g) state,
the observed intensity of the ground state activity taken after several isomeric state half-lives, contains the full contribution of the metastable activity. The cross-section calculated from the intensity of the long lived ground state activity is, therefore, the sum of the cross-sections for the metastable and the ground states ($\sigma_m + \sigma_g$). However, if the half-life of the metastable and ground states are either comparable or if measurements are done before the complete decay of the metastable state, the observed intensity of the ground state decay contains some contribution from the metastable state. For example, in the case of $^{90}\text{Y}(p,n)^{90m}\text{Zr}$ (4.18 min.) and $^{90}\text{Y}(p,n)^{90q}\text{Zr}$ (78.43 h) reactions, the cross-section for the population of the metastable state is determined from the intensity of the gamma-ray of $^{90m}\text{Zr}$ (587.7 keV). The observed intensity of the gamma rays of $^{90q}\text{Zr}$ (909.1 keV) is corrected, using the formulation given in Chapter-III, to remove the contributions of the metastable state, and from the corrected intensity, the cross-section for only the ground state population is determined. Using this method, cross-sections for the ground state and isomeric states are determined for the reactions $^{90}\text{Y}(p,n)^{90m, g}\text{Zr}$,
\[ ^{121}\text{Sb}(p,n)^{121\text{m}}\text{Te} \text{ and } ^{197}\text{Au}(p,n)^{197\text{m}}\text{Hg}. \]

In the case of reactions \[ ^{93}\text{Nb}(p,n)^{93\text{m}}\text{Mo} \text{ and } ^{121}\text{Sb}(p,n)^{121\text{m}}\text{Te} \]

cross-sections for only the metastable states are measured as the ground states are either stable or very long lived.

The isomeric cross-section ratios \[ \frac{\sigma_{m}}{\sigma_{g}} \]
determined from the measured cross-sections, are compared with the values calculated from the code ACT. The results are plotted in Fig. V.24. It can be seen from this figure that the isomeric cross-section ratio for the reaction \[ ^{80}\text{Y}(p,n)^{80}\text{Zr} \]

first increases up to \( \approx 12 \) MeV excitation energy, then slowly decreases and finally levels off. In the case of reactions \[ ^{121}\text{Sb}(p,n)^{121}\text{Te} \text{ and } ^{197}\text{Au}(p,n)^{197}\text{Hg}, \]

\[ \frac{\sigma_{m}}{\sigma_{g}} \]

increases slowly with the excitation energy and becomes constant beyond some particular energy. Such behaviour of isomeric ratio may be understood in terms of average spin \( \langle I_{c} \rangle \) imparted to the compound system, and the average spin \( \langle I_{r} \rangle \) of the residual nucleus. \( \langle I_{c} \rangle \) increases with the incident angular momentum which itself increases with increase in incident energy. On the other hand \( \langle I_{r} \rangle \) is also expected to increase with increase in incident energy. As such beyond a certain excitation energy the relative populations of the metastable
Fig. V.24.
Measured and theoretically calculated isomeric cross-section ratios for $^89\text{Y}(p,n)$, $^{121}\text{Sb}(p,n)$ and $^{197}\text{Au}(p,n)$ reactions as a function of excitation energy. Lines show the theoretical calculations using code ACT.
and ground states remains unchanged. In the case of $^{80}$Zr nucleus produced in the reaction $^{80}$Y(p,n), the ground state has a spin $9/2^+ \hbar$ whereas the metastable state has a spin $1/2^- \hbar$ and hence $\alpha_m/\alpha_{in+g}$ first increases sharply with excitation energy and then decreases. In the cases of $^{125}$Te and $^{197}$Hg the metastable states are of higher spin ($11/2^- \hbar$ and $13/2^- \hbar$) than their respective ground states ($1/2^+ \hbar$ and $1/2^- \hbar$), the ratio $\alpha_m/\alpha_{in+g}$ increases rather slowly before leveling off. The theoretical values of $\alpha_m/\alpha_{in+g}$ for each case, are also plotted in Fig.V.24. The experimental and theoretical isomeric ratios show similar behaviour with energy.

V.3.2. Residual nuclei formed through multichannels

In some cases the same residual nucleus is produced through different reaction channels and hence the observed count rate is the sum of contributions from different reaction paths. In such cases the individual contributions may be separated using the theoretically calculated cross-section ratios for different paths. While calculating these cross-section ratios proper care is taken for the threshold of each channel, isotopic abundance, half-life of the residual nucleus and the
branching ratio for the observed gamma rays. In Table III.3 in Chapter-III, such cases where the cross-sections are deduced in this way are marked by asteric (*) symbol. For example, the residual nucleus $^{64}$Cu, observed in the nickel sample irradiated by 15 MeV proton beam, may be produced through $^{60}$Ni(p,$\gamma$)$^{64}$Cu, $^{64}$Ni(p,n)$^{64}$Cu and $^{64}$Ni(p,2n)$^{64}$Cu reactions. Therefore, the observed intensity of the $\gamma$-rays of $^{64}$Cu nucleus is the sum of contributions from all these channels. The relative contributions for different reaction paths are separated using the theoretical estimates as mentioned above. Similarly, the residual nucleus $^{64}$Cu, observed in the decay of nickel sample irradiated by 40 MeV $\alpha$-particle, may be produced through $^{58}$Ni($\alpha$,p)$^{64}$Cu, and $^{60}$Ni($\alpha$,p2n)$^{64}$Cu reactions. Further, the residual nucleus $^{64}$Zn, produced in the reactions Ni($\alpha$,n)Zn and $^{58}$Ni($\alpha$,3n)$^{64}$Zn, will decay to $^{64}$Cu with a half-life of 89 sec. by $\beta^+$ emission (62%) and electron capture (38%). As such the observed intensity of the $^{64}$Cu activity in this case contains the contributions from all these reactions. In all these cases, the individual contributions are separated using the methodology earlier discussed.
V.4. Pre-equilibrium fraction

Excitation functions calculated without PE emission are also shown in Figs. V.19-21. From the comparison of the theoretically calculated and experimentally measured excitation functions, it has clearly come out that pre-equilibrium emission must be taken into account to reproduce the experimental data, particularly in the case of first chance emission. The pre-equilibrium fraction FR, defined as the ratio of the pre-equilibrium to the total reaction cross-section, reflects the relative importance of equilibrium and pre-equilibrium processes. The pre-equilibrium fraction FR, calculated from the best theoretical fits to the experimental excitation functions, are plotted against the excitation energy of the compound nucleus for the presently measured cases in Figs. V.25 and V.26. It is interesting to note that pre-equilibrium contributions start building up from the excitation energy of $\approx$10 MeV for all the cases of proton induced reactions. Further, as expected, the pre-equilibrium fraction increases with the increase in excitation energy. In general, the probability of pre-equilibrium emission at a given energy is larger in
Fig. V.25. Variation of pre-equilibrium fraction FR, as a function of excitation energy for proton induced reactions on different targets.

Fig. V.26. Variation of pre-equilibrium fraction FR, as a function of excitation energy for alpha induced reactions on different targets.
lighter nuclei than in the heavier ones.

In case of nickel, excitation functions for both the proton and alpha induced reactions on $^{58,60,61,62}$Ni isotopes are measured, while for antimony target only proton induced excitation functions for $^{121,123}$Sb isotopes are measured. In order to see how the pre-equilibrium fraction varies with the isotope mass number, the pre-equilibrium fractions are plotted against the excitation energy above Coulomb barrier $(E-E_{CB})$ in Fig.V.27. From this figure, it may be seen that, in general, at a given excitation energy, proton induced reactions have larger values of $FR$ and hence higher probability of PE emission. This is expected, as at the same excitation energy above Coulomb barrier, energy per exciton in the proton induced reactions is higher than for the alpha induced reactions. As is already mentioned, in the present calculations done using codes ALICE and ACT, the initial exciton number $(n_o)_p$ for proton induced reactions and $(n_o)_\alpha$ for alpha induced reactions is taken respectively as 3 and 6. The ratio of the pre-equilibrium fraction $(FR)_p$ for proton induced reactions and $(FR)_\alpha$ for alpha induced reactions in the same isotope, as a function of $E-E_{CB}$ is plotted in
Fig. V.27.
Comparison of FR's for proton and alpha induced reactions on various nickel isotopes, as a function $E-E_{CB}$. 
Fig. V.28, where it may be seen that the ratio has a nearly constant value $\approx 2$ which is also the ratio of \( \frac{n_o}{n_p} \).

In reactions induced by heavy ion \( ^{12}\text{C} \), effect of PE-emission is quite predominant. PE-fraction \( (FR)_c \) for these reactions is plotted against the excitation energy in Fig. V.29. \( (FR)_c \) has much larger values, as compared to the lighter ion induced reactions. It may be largely due to the higher excitation energies involved in these reactions. However, in heavy ion induced reactions also the initial exciton number \( n_o \) is taken equal to 3, which is also the value used for proton induced reactions. If the PE emission process for both the light and heavy ion induced reactions is similar, \( (FR)_p \) and \( (FR)_c \) at the same excitation energy are likely to be of the same order of magnitude for reactions in which the same compound system is formed. In the present measurements proton induced reactions are studied upto 15 MeV incident energy, while the \( ^{12}\text{C} \) induced reactions upto a considerably higher energy $\approx 80$ MeV. However, if \( (FR)_p \) values for \( ^{197}\text{Au} \) are extrapolated, as an example, to the excitation energy range of \( ^{12}\text{C} \) reactions, (35 MeV say), it is found to be of the same order of magnitude as \( (FR)_c \), as shown in Fig. V.29. It may,
Fig. V.28. Ratio of FR for proton induced reaction to that of alpha induced reaction, \((FR)_p/(FR)_{\alpha}\), as a function of \(E-E_{CB}\).

Fig. V.29. Comparison of FRs for proton \(^{197}\text{Au}+p\) and heavy ion \(^{165}\text{Ho}+^{12}\text{C}\) systems as a function of excitation energy.
however, be mentioned that the compound system formed in the above reported reactions are different.

Finally, from the present analysis it may be concluded that pre-equilibrium emission, as expected, plays very important role in nuclear reactions at moderate excitation energies. Excitation functions calculated without the inclusion of PE emission do not reproduce the measured excitation functions both for light and heavy ion induced reactions. The pre-equilibrium component is found to be dependent on both the excitation energy and initial exciton number. Further, both the semiclassical as well as the quantum mechanical models for PE emission may reproduce the experimental data with the proper choice of the various parameters of these two models. In Exciton model $n_o=3$ and $F_W=430$ MeV are found to give reasonably good fit to the experimental data for almost all the cases of proton induced reactions. However, for alpha induced reactions $n_o=6$ gives satisfactory agreement with the data. On the other hand, in case of the hybrid model the experimental data can be reproduced satisfactorily by taking the parameters $K=10$, and $COST=3$. The $n_o$ in this case also is taken equal to 3 for proton induced reaction and 6 for alpha
induced reactions. For the reactions induced by the heavy ion carbon, K=13, COST=3 and n 0 =3 gives a good fit to the experimental data. Calculations done with the code EXIFON using the global parameter set do not give a good representation of the experimental data. However, if the Fermi energy $E_F$ is changed to 40 MeV and minor adjustment, within physically justified limits, is done in the value of the pairing energy $\Delta$, the code EXIFON may also reproduce the experimental data for some proton and alpha induced reactions satisfactorily. Further, it is observed that a single set of optical model parameters for all nuclei can not be used to reproduce the experimental data by this code. In some cases where both the isomeric and ground states are populated variation of isomeric cross-section ratio with the excitation energy depends, as expected, on the spins of the metastable and ground states and follow the trends expected from the theoretical calculations.
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1. Semiclassical and quantum mechanical analysis of excitation function for $^{130}$Te(p,n)$^{130}$I reaction
   M.M.Musthafa, B.P.Singh, M.G.V.Sankaracharyuly, H.D.Bhardwaj and R.Prasad
2. Measurement and analysis of excitation functions for proton induced reactions in Vanadium and Indium
   M.M.Musthafa, B.P.Singh and R.Prasad
3. Trends in pre-equilibrium emissions in proton induced reactions on copper isotopes
   M.M.Musthafa, B.P.Singh and R.Prasad
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4. Measurement and analysis of excitation function in monoisotopic praseodymium
   B.P.Singh, M.M.Musthafa, H.D.Bhardwaj and R.Prasad
5. Excitation functions and isomeric cross-section ratios for proton induced reactions on natural Niobium, Antimony and Gold
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6. Investigation of preequilibrium emission in proton induced reactions
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7. Measurement and analysis of excitation functions for alpha induced reactions on $^{141}$Pr
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8. Study of preequilibrium emission in proton induced reactions on Indium
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Proceedings of DAE Nuclear Physics, Dec. 20-24, 1996, G.B.Pant University of Agriculture and Technology, Pant Nagar, U.P., India

M.M.Musthafa, Sunita Gupta, B.P.Singh and R.Prasad.
Semiclassical and quantum mechanical analysis of the excitation function for the $^{109}$Te($p,n$)$^{105}$I reaction

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We report excitation function for the reaction $^{109}$Te($p,n$)$^{105}$I in the energy range 4–18 MeV. The measurements were done employing stacked foil activation technique. To the best of our knowledge this excitation function has been reported for the first time. The theoretical analysis of the excitation function has been done employing both the semiclassical as well as quantum mechanical descriptions of the pre-equilibrium emission. In general, the theoretical calculations agree well with the experimental data.

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I. INTRODUCTION

Pre-equilibrium (PE) emission, as a reaction mechanism at moderate excitation energies, has attracted considerable attention from both the experimental as well as the theoretical viewpoints [1]. Initially, semiclassical models [2–6] were successfully used to describe the experimental data on PE emission. Recently, however, the stress has been laid on the systematic study of trends with a view to finding a consistent set of input parameter of that can describe the large amount of experimental data. Lastly, totally quantum mechanical (QM) theories for PE emission have also been developed and have been used to analyze mostly the data on nucleon-induced reactions [7–11].

In the present work the excitation function for the reaction $^{109}$Te($p,n$)$^{105}$I has been measured using the stacked foil activation technique. The analysis has been performed within the framework of both the semiclassical and QM models. The computer codes ALICE/LIVEMORE [12] and ACT [13] have been used for the semiclassical treatment while the code EXIFON [14] has been employed for the QM calculations involving the multisep compound (MSC) and the multisep direct (MSD) formulation [7]. The details of the measurements are presented in Sec II and the analysis of the data is discussed in Sec III.

II. EXPERIMENTAL DETAILS

In the present measurements the stacked foil activation technique [15] has been employed. An enriched isotope (61%) of selenium (mass number = 130) was used for preparing the samples, which were made by vacuum evaporation, of 1 mg cm$^{-2}$ thickness on aluminum backing of 6.75 mg cm$^{-2}$. The square pieces of targets of size 1.2 × 1.2 cm$^2$ were used as samples in the stack. Each target was mounted individually on a conducting metal frame for heat dissipation. A stack for irradiation was made by taking seven targets with Al foils of suitable thickness as degraders, in between, to have the desired energy at each target. The stack was irradiated by an unresolved diffusion proton beam with an energy uncertainty of 0.5 MeV at the Variable Energy Cyclotron Centre (VECC), Calcutta, India. A tantalum collimator was used just before the sample stack to restrict the size of the beam to 8 mm diameter. The incident energies on the first and last foils were ~18 and ~10.87 MeV, respectively. The charge accumulated in the Faraday cup during the irradiation was measured using an ORTEC current integrator device. Further details of the experiment and the measurements are described elsewhere [16].

The $\gamma$ counting of the irradiated samples was carried out using conventional Ge(Li) $\gamma$-ray spectroscopy. The detector was calibrated using various standard $\gamma$ sources including a $^{133}$Cs source of known strength which was also used for determining the geometry-dependent detector efficiency for $\gamma$ rays of different energies at different source-detector distances. A typical efficiency curve at a source detector distance of 6.4 cm is shown in Fig 1. The $\gamma$ rays of energies 418.0, 536.1, 668.56, 739.48, and 1157.49 keV emitted in $^{105}$I produced in the reaction $^{109}$Te($p,n$) were identified in

![Figure 1: Geometry-dependent efficiency of Ge(Li) detector at 6.4 cm source detector distance.](image-url)
order to check the calibration of the detecting system, the energies of these γ rays were measured and are listed in Table I. Literature values [17] of the branching ratio for the same are also shown in this table. The errors in the literature data are only the statistical error of γ counting. The branching ratios were measured relative to the γ ray of $536\, \text{keV}$ and may contain errors due to the following factors: (i) The statistical errors of counting which are tabulated in column 4 of Table I. (ii) Uncertainties in the absolute calibration of the geometry-dependent efficiency of the γ-ray detector. Since for the standard $^{152}\text{Eu}$ source the counts were accumulated for a relatively larger time ($\approx 3000\, \text{sec}$) the uncertainty in the measured γ intensity of the standard source was negligible. The uncertainty due to the fitting of the measured efficiency by a power law graph was found to be $<4\%$. Uncertainties may also come up in the efficiency on account of the solid-angle effect since the irradiated samples were not point sources but instead had a diameter of $1\, \text{mm}$ A detailed analysis of the solid-angle effect is given in Ref. [18]. Using this formula, the errors on the efficiency due to the solid-angle effect were estimated to be $<4\%$. Thus the overall errors in the measured branching ratio are $<5\%$ and are given in column 5 of Table I. From Table I it may be seen that there is a reasonable agreement between the measured and the literature values [19–21] of the branching ratios for all the γ rays except for the $1157 \, \text{keV}$ γ ray for which we could not assign any reason.

The experimentally measured intensities of these γ rays have been used for calculating the cross sections according to the formula mentioned in Ref. [16]. The measured cross sections for the reaction of $^{152}\text{Eu}(p,n)^{155}\text{Eu}$ at different incident proton energies ($E_p$) are given in Table II. The first column in this table lists the incident energy on the foil while the second column lists the corresponding measured cross section values. The errors in the energy in the first column represent the energy spread in half of the sample thickness along with the inherent energy uncertainty in the proton beam energy. The measured cross section values at each energy reported in Table II in column 2 are the weighted averages of the cross sections calculated from the measured intensities of γ rays of different energies emitted by the residual nucleus $^{155}\text{Eu}$. In this table column 3 contains the statistical error of counting only. However, in column 4 the overall errors are given which may be due to the following factors: (i) The statistical error of γ counting. (ii) The uncertainty in the determination of the number of target nuclei in the sample due to inaccurate determination of the sample thickness and nonuniform deposition of the target material. To estimate the uncertainty in the number of target nuclei, and to check the thickness and uniformity of the samples, pieces of different dimensions of the sample foils were weighed on an electronic microbalance and the thickness of each piece was calculated. In this way the errors in the estimation of the number of target nuclei were analyzed and are estimated to be $<1\%$. (iii) During the irradiation the beam current often fluctuates, which results in variation of the incident flux. Care was taken to keep the beam current fluctuations $<10\%$. In some typical irradiation runs the duration ($>1\, \text{min}$) and the amount of change in the beam current were noted during the irradiation and the flux was individually calculated for each duration of fluctuation. It is expected that the beam flux fluctuation may introduce errors of $<3\%$. (iv) The measured detector efficiency of the γ-spectrometer may be inaccurate on account of the statistical errors in the counting of the standard source and the nonreproduction of identical geometry for the standard source and the sample. As already mentioned the statistical errors in the counting of the standard source were minimized by accumulating a large number of counts for a comparatively larger time ($\approx 3000\, \text{sec}$). The uncertainties in the efficiency of the detector are estimated to be $<5\%$. (v) Beam intensity loss may occur as the beam traverses the thickness of the stack material. In the present experiment the total stack thickness reduces the incident proton energy from $\approx 18$ to $\approx 5\, \text{MeV}$. The error in the measured cross section due to the maximum beam intensity loss at the end of the stack was estimated to be $<1.5\%$. (vi) The product nuclei recoiling out of the thin target may introduce errors in the measured cross sections. In the present measurements the targets were oriented parallel to the beam normal. The table lists the corresponding measured cross section values.
beam with sample deposition facing the beam. This avoided the loss of recoiling nuclei which were stopped in the relatively thick (6.75 mg/cm²) Al backing and were counted along with the sample. In this way the error due to recoiling nuclei has been eliminated (v). Errors may be introduced due to dead time, particularly for cases where the intensity of the induced activities in the sample was large. In such cases the sample-detector distance was suitably adjusted to minimize the dead time which was kept <10% and correcions for which were applied in counting rates. The total error due to all the factors is expected to be <15% of the measured cross-section values.

III. ANALYSIS OF THE DATA

The analysis of the excitation functions has generally been carried out using the semi-classical theories [2-6]. However, in recent years the QM theories have also been applied extensively for nucleus-induced reactions [7-11]. In the present work, we have analyzed the measured excitation function for the reaction \(^{90}Zr(p,n)\) using both the semi-classical as well as QM theories with the so-called global set of parameters. The parameters for the semi-classical approach were obtained from our earlier analysis of neutrons and \(^{90}Zr\)-induced reactions [13,16,22,23]. The computer codes ALICE [12] and ACT [13] have been used for the semi-classical analysis, while the code EXFOR [14] has been used for the QM description of the data. Brief details of these codes and the parameters are summarized in the following sections.

A. Analysis with code ALICE

In the code ALICE the compound nucleus (CN) calculations are performed using the Weisskopf-Ewing model [24] and the PE component is simulated employing the hybrid/geometry-dependent hybrid model [25]. The hybrid model is based on a combination of the exciton model [4] and the Hug-Miller-Berne model [3]. In the geometry-dependent hybrid model a decompositon is made according to incoming angular momentum in order to account for the effects of the nuclear density distribution, leading to increased emission of high energy particles. The binding energies are calculated using the Myers-Smith/Mylett mass formula [26] and the pairing energy \(E_p\) is calculated from the backshifted Fermi gas model [27]. The optical model parameters of Becchetti and Greenlees [28] are used for optical model (OM) calculations of the transmission coefficients. The mean energy leaving behind a hole in the excited state resulting in the excitation number, needed in these calculations is taken equal to \(A'\) equal to \(3\). Values of \(E_p\) equal to \(A'\) and \(A''\) were applied in counting rates. The total error due to dead time which was kept <10% and corrections for which were applied in counting rates. The total error due to all these factors is expected to be <15% of the measured cross-section values.

FIG 2 Excitation functions calculated using the code ALICE. Solid curves show the calculations done using different values of the parameter \(C\). The dotted curve shows the pure CN component. **(a)** shows the experimental data.

parameter \(a\) in this code is calculated from the expression \(a = A'K\), where \(A\) is the atomic mass number of the compound system and \(K\) is a constant which can be varied to match the excitation functions. In the present calculations the value of \(K\) equal to 10 is kept. The same value of \(K\) was used in our earlier analyses of \(^{90}Zr\)-induced reactions [22]. The initial configuration of the compound system, i.e., the initial excitation number, needed in these calculations is taken equal to 3 with two particles and one hole. It may be assumed that the first interaction of the proton with the target nucleus may give rise to the excitation of one particle above the Fermi energy leaving behind a hole in the excited state resulting in the two particle and one-hole state.

B. Analysis with code ACT

In computer code ACT [13], the CN calculations are performed using the H"{u}s"{a}n-Feshbach (HF) [29] model, while the PE emission is simulated using the exciton model [4] of Griffin. In the HF formalism the angular momentum effects are explicitly considered at each step of deexcitation. The transmission coefficients needed in these calculations are generated using the optical model code TSL [13] which uses the OM potentials of Blann and Young [30]. The level density which determines the shape of the equilibrium and pre-equilibrium components is an important parameter in these calculations. The level density parameter \(\alpha_{\text{effective}}\) and the effective ground state energy \(\varepsilon_{\text{ground}}\) are taken from the tables of Dilg et al. [31]. The effective moment of inertia \(I_{\text{eff}}\) is taken equal to the rigid body value. The particle separation energies needed in the calculation are taken from the table of Wapstra and Gove [11].

The initial particle hole configuration \(n_i\) is also needed in these calculations. Here, \(n_i = 3\) (\(n_i = 2\) and \(n_i = 1\)) is taken similar to the one taken in the code ALICE. In the excitation
model the intranuclear transition rates depend directly on the square of the matrix element for two-body residual interactions $|M|^2$. Its value in generally computed from the expression $|M|^2 = F_{ru} U^{-2} r_{li}$, where $A$ and $U$ are the mass number and the excitation energy of the compound system, respectively, and $F_{ru}$ is generally treated as an adjustable parameter to match the measured and calculated excitation functions. $F_{ru}$ values ranging from 95 to 7000 MeV have been proposed in the literature. Excitation functions calculated with different values of $F_{ru}$ and $r_{li}$ are shown in Fig. 3. In some of our earlier analyses of ($p,p$) and $(\alpha,n)$ reactions, a value of $F_{ru} = 430$ MeV was found to give satisfactory reproduction of the experimental excitation functions. However, in the present case the value of $F_{ru} = 140$ MeV and $r_{li} = 3$ reproduces the measured excitation function satisfactorily, both in the peak as well as the tail portions for the reaction. The dotted line in Fig. 3 shows the calculation for the CN component alone. In the exciton model, it is assumed that the PE cross section is distributed among the levels with different spins and parity in the same proportion as the equilibrium contribution. This limitation may have important consequences for isomeric cross sections, but not for the total cross sections as presented in this paper.

C. Analysis with code EXIFON

The code EXIFON [14] is based on an analytical model for statistical multistep direct and multistep compound reactions (SMISD/SMC model) [7]. It predicts the activation cross section including the equilibrium and pseudoequilibrium as well as the direct (collective and noncollective) processes within a parameterized multistep reaction model. This approach is based on many body theory (Green's function formalism) [32,33] and random matrix physics [34,35]. The code EXIFON predicts the cross section from a standard set of parameters. In these calculations, the initial excitation number in this code is taken equal to 3 for nucleon induced reactions, similar to the one taken in semiclassical calculations. The calculation with the code EXIFON takes into account the pairing correction, Pauli blocking, shell structure, and the Coulomb effects. Figure 4 shows the excitation functions calculated using the code EXIFON with different sets of parameters. In this figure, curve 1 shows the excitation function calculated using the code EXIFON with a standard set of parameters. As can be observed from this figure, the calculation using the standard set of parameters underestimates the experimental data, particularly in the tail portion. In order to match the experimental data the values of some of the parameters have been changed from that of the standard set. The value of the pairing correction term $\Delta$ has been changed from $-1.12$ to $-2.5$ which is in agreement with the value used by Kalbach, Cline, Huizenga, and Vonach [16] and Covey [36]. The Fermi energy $E_F$ is related to the single particle state density $g$ and through it to the level density parameter $\alpha$. For $E_F = 40$ MeV using the formulation of Kalbach [38-41], Oblozinsky [42], and Avergeen et al. [43,44] one gets the value of $\alpha = 1$ for $^{185}$Re and $^{197}$Os with radius parameter $r_F = 1.4$ fm. These values of $E_F = 40$ MeV and $r_F = 1.4$ fm are used in the present calculations with a residual interaction of 32 MeV.

From the above analyses it may be concluded that both the semiclassical as well as the QM codes each with suitable choice of parameters reproduce the experimental excitation function. As such there is no specific advantage in using the QM code over the semiclassical one. This is important since the QM calculations for complex particles in the incident channel are more intricate as mentioned by Kalbach, Quim, and Molla [45].

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The study of excitation functions (EF) provide information of considerable value about the pre-equilibrium (PE) emission in nuclear reactions \cite{1}. However, only few measurements of EFs induced by heavy-ions (HI) are available. In the present work, the activation technique has been used to measure the reaction cross-sections in $^{12}$C+$^{16}$O system at incident energies 55, 62, 71, and 80 MeV. To the best of our knowledge EFs for these reactions are reported for the first time.

The experiments were performed at the Pelletron accelerator of the Nuclear Science Centre (NSC), New Delhi. Self supporting targets of $^{16}$O (12 mg/cm$^2$) and Al catcher foils (12 mg/cm$^2$) downstream each target, were bombarded with a beam of $^{12}$C (charge state 5$^+$) ions. The flux of the $^{12}$C beam was monitored by the two Rutherford detectors as well as by the charge collected in the Faraday cup. Irradiated $^{16}$O targets and the Al catcher foils, transferred in vacuum, were counted by a 100 c.c. HPGe detector which was precalibrated for the efficiency and the $\gamma$-ray energy. Gamma-rays, due to several residual nuclei produced by the complete and incomplete fusion of $^{12}$C ion, were identified in the targets and the catcher foils. However, measurement and analysis for $^{16}$O($^{12}$C,3n), $^{16}$O($^{12}$C,4n), and $^{16}$O($^{12}$C,5n) reactions are presented here. The measured and calculated EFs for the above mentioned reactions are shown in Fig.1.

The theoretical calculations of the EFs are done employing the codes CASCADE/2 and ALICE-91/3. The code CASCADE is based on Hauser-Feshbach/4 theory. As may be seen from the Fig., CASCADE
calculations agree with the experimental EFs except for the reaction $^{186}_{185}$Ho(C,3n). The large discrepancy for $^{186}_{185}$Ho(C,3n) reaction is an indication of considerable PE-component in it, which is not taken into consideration in CASCADE calculations.

The code ALICE/3/, employs Weisskopf-Ewing/5/ model for compound and Hybrid model for PE calculations. In Fig. 1, the peaks of the EFs calculated with ALICE are shifted towards the lower energy side as compared to the experimental data. This may be due to the rotational energy $E(\text{rot})/6$, which is not taken into account in ALICE. The ALICE calculations satisfactorily reproduce the EFs on shifting the energy scale by $E(\text{rot})$. Further, substantial PE-contribution is present in $^{186}_{185}$Ho(C,3n) reaction at higher energies as expected. The analysis of the other reactions is underway.

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References:
The study of pre-equilibrium (PE) emission in nuclear reactions has attracted considerable attention recently. The slowly descending tails of the excitation functions is one of the important signatures of PE emission. As part of an ongoing project on PE studies we report, here, the measurement and analysis of excitation functions for the reactions $^{121}\text{Sb}(p,n)^{121}\text{Te}$, $^{121}\text{Sb}(p,n)^{121}\text{Te}$, $^{121}\text{Sb}(p,np)^{120}\text{Sn}$, $^{123}\text{Sb}(p,n)^{123}\text{Te}$, and $^{123}\text{Sb}(p,np)^{122}\text{Sb}$. These measurements, to the best of our knowledge are reported for the first time. The experiment was performed at the Variable Energy Cyclotron Centre (VECC), Calcutta, India using the stacked foil activation technique. A stack containing 10 samples of Sb (1 mg/cm$^2$) on Al backing (6.75 mg/cm$^2$) along with degrader foils was irradiated for two hours by 20 MeV proton beam of 100 nA current. Further details of the measurements are given elsewhere/1/. As a typical example the measured excitation function for the reaction $^{121}\text{Sb}(p,n)^{123}\text{Te}$ is shown in Fig. 1.

The theoretical calculations of the excitation functions have been performed using the code ACT which is based on the lines of code STAPRE/2/. This code uses Hauser-Feshbach model for CN and exciton model for PE emission. The level densities required for these calculations are taken from the tables of Dilg et al/3/. The initial exciton number $n_0$ is taken equal to three, assuming that the first interaction generates a 2 particle 1 hole state. The strength of the two-body residual interaction matrix element $V_N$ is taken as 430 MeV from our earlier analysis. As may be seen from the Fig., there is reasonable agreement between the experimental and the theoretical calculations. The semiclassical calculation have also been done using the code ALICE/4/ which performs the CN calculations employing the Weisskopf Ewing model and PE calculations using the Hybrid model. Since this code
calculates only the total reaction cross-sections, the theoretical calculations are compared with the measured sum of cross-sections. As can be seen a satisfactory agreement is obtained with this code also.

The theoretical calculations have also been done using the quantum mechanical code EXIFON/S. This code is based on the random matrix physics and Green's function approach. However, the organisation of the code EXIFON allows the calculation of only the total reaction cross-sections. The calculated excitation function is compared with the sum of the measured cross-sections for the ground and metastable states. As can be seen from the Fig., the EXIFON calculations match the experimental data in the peak region around \( E \approx 10 \text{ MeV} \), but underestimates the measured cross-sections at higher energies. The PE fraction, \( P_E \), has also been calculated and found to be energy and mass number dependent, as expected. Similar trends are also observed for other reactions.

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It is well known that the measured cross-sections for sub-barrier fusion of heavy ions (with \( Z_1 Z_2 \geq 200 \)) are higher by up to several orders of magnitude as compared to the one dimensional barrier penetration calculations. It has also been observed that in general there is a strong isotopic dependence as far as the magnitudes of cross-sections as well as their energy dependence are concerned. However, according to a recent study, no significant enhancement as well as systematic isotopic dependence were observed in case of \(^{35}\text{Cl} + ^{50}\text{Ti}, \quad ^{51}\text{V}, \quad ^{52}\text{Cr}, \quad ^{54}\text{Fe}, \quad ^{54}\text{Cr} \) systems. We have measured sub-barrier fusion cross-sections for \(^{32}\text{S} + ^{48}\text{Ti} \) system, which falls in the above-mentioned mass region in order to see the extent of enhancement.

The experiment was carried out with pulsed \(^{32}\text{S} \) beam provided by the NSC 16 MV Pelletron at energies between 74 and 88 MeV. Isotopically enriched \(^{48}\text{Ti} \) target (105 \( \mu \)g/cm\(^2 \) thick with 99.13% enrichment) on 15 \( \mu \)g/cm\(^2 \)-carbon backing was used. A pair of Si(SB) detectors were placed at \( \pm 30^\circ \) deg with respect to the beam direction for the purpose of normalization. The evaporation residues recoiling in the forward direction were separated from the primary beam by HIRA/2/ and detected at its focal plane after mass dispersion by a 2D-position sensitive MWPPAC and a \( \Delta E-E \) ionization chamber. An HPGe detector was mounted close to target at 90 deg with respect to the beam using the re-entrant cup of the sliding seal chamber for measuring the absolute detection efficiency of HIRA. Typically a mass resolution of \( m/\Delta m \approx 300 \) was obtained for 5 msr.

From the observed mass spectra it turns out that the 3N- channel dominates the fusion cross-section while the 2N- and 4N- channels account for most of the remaining part. This is consistent with the observation of Szanto et al./1/ Figure 1 shows the measured fusion excitation function along with the theoretical calculations. In the coupled channels calculations (using CCFUS/3/), inelastic couplings to 2+...
and 3' states of the projectile and the target nuclei were included. We notice quite significant enhancement in the fusion cross-sections which was not observed in ref. 1. Our results clearly indicate the need of including the transfer couplings.

We thank the NSC-Pelletron personnel for an excellent operation of the accelerator and the associated beam pulsing system. We are grateful to Dr. H.J. Maier, University of Munich for providing us with the $^{48}\text{Ti}$ targets. The help in data analysis from Mr. L.T. Baby is thankfully acknowledged.

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Measurement and analysis of excitation functions in α-induced reactions has become an important tool for studying the pre-equilibrium phenomenon. The pre-equilibrium emission in nuclear reactions is characterised by the asymmetric angular distribution of emitted particles in centre of mass frame, enhanced emission of high energy particles than expected from the compound nucleus evaporation, slowly descending tails of the excitation functions etc. As part of the programme of precise measurement and analysis of excitation functions in α-induced reactions for a large number of nuclei, we report the excitation functions for the reactions $^{141}$Pr(α,n)$^{144}$Pm and $^{141}$Pr(α,2n)$^{143}$Pm measured in the energy range from threshold to $\approx 40$ MeV. To the best of our knowledge the excitation functions for these reactions have been measured for the first time. Measurements have been performed using stacked foil activation technique. Natural Praseodymium of spectroscopic purity better than 99.9% (SPECUPURE) has been used for making the samples of thickness $\approx 3.32$ mg/cm$^2$. The irradiation has been carried out at the Variable Energy Cyclotron Centre (VECC), Calcutta, India using the α-beam of $\approx 40$ MeV. During the irradiation the beam current was kept $\approx 100$ nA. The flux of the α-beam was $\approx 10^{11}$ α-(particles/sec)/cm$^2$. 

The post irradiation analysis has been carried out using the HPGe detector coupled to the
ORTEC's PC based multichannel analyser at the Inter University Consortium (IUC) for DAE facilities, Calcutta, India.

The presently measured excitation functions for the reactions $^{141}\text{Pr}(\alpha,n)^{144}\text{Pm}$ and $^{141}\text{Pr}(\alpha,2n)^{143}\text{Pm}$ are shown in Fig.1. The analysis of these excitation functions has been carried out using the computer code ACT/2/ which uses the Hauser-Feshbach formalism/3/ for CN calculation and exciton model of Griffin/4/ for simulating PE contributions. The level density parameter '$a$', and the fictive ground state energy '$\Delta$' for various nuclei under consideration have been taken from the tables of Dilg et al/5/. The initial exciton number $n_0=6(5p+1h)$ and the square of the average of two-body residual interaction matrix element $|M|^2=430 \text{ A}^{-3} \text{ U}^{-1}$ have been used in these calculations. Theoretically calculated excitation functions have also been shown in Fig.1. It may be observed that the inclusion of PE emission to the CN calculation reproduces the experimental data satisfactorily.

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STUDY OF PRE EQUILIBRIUM EMISSION IN PROTON INDUCED REACTION ON INDIUM

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Recent experiments have clearly indicated that in statistical nuclear reactions at moderate excitation energy particles may be emitted prior to the establishment of the thermodynamic equilibrium in the compound system. This process is generally known as pre-equilibrium (PE) emission/1/. With the aim of studying the PE emission in statistical nuclear reactions, the excitation functions (EFs) for a large number of proton, neutron and alpha-induced reactions have been studied over a wide range of the periodic table/2/.

In this paper the measurement and analysis of EF for \(^{113}\text{In}(p,n)^{113}\text{Sn}\) reaction has been reported. To the best of our knowledge the EF for this reaction has been reported for the first time. The experiment has been carried out at the VECC, Calcutta, India using stacked foil activation technique. The samples have been prepared by vacuum evaporation of natural (purity 99.97%) Indium, (thickness \(\approx 4.22 \text{ mg/cm}^2\)) on Al foils of thickness \(\approx 6.75 \text{ mg/cm}\). A stack of nine samples with Al degraders was irradiated by \(\approx 20 \text{ MeV}\) proton beam of \(\approx 100 \text{ nA}\) at the VECC. Post-irradiation analysis has been performed using the HPGe detector coupled to the ORTEC's PC based MCA at ICU-DAEF, Calcutta Centre. Experimentally measured EF for \(^{113}\text{In}(p,n)^{113}\text{Sn}\) reaction is shown in Fig.1.

The theoretical analysis of the EF has been done using the quantum mechanical code EXIFON/3/.
which is based on an analytical model of Statistical multistep direct and multistep compound reaction mechanism (SMD/SMC models)/4/. The theoretically calculated EF employing the standard parameter set of code EXIFCN/3/ is shown as curve 1 in Fig.1. As can be seen from the comparison of theoretical calculations (curve 1) and the experimental data, the theoretically calculated EF underestimates the experimental data both in the peak region as well as in the tail portion of the EF. Calculations have also been performed by varying the various parameters and are shown as curves 2-4. From Fig.1, it may be observed that curve 3 reproduces the experimental data satisfactorily both in the peak region as well as in the tail portion.

However, at energies $E \geq 18$ MeV there is contribution from $^{115}\text{In}(p,3n)^{113}\text{Sn}$ reaction which has a threshold $\approx 18.13$ MeV. This may explain the rise of the experimental EF beyond 18 MeV.

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