CHAPTER - III

NUCLEAR REACTION THEORIES
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A nuclear reaction is an intricate process involving an atomic nucleus, several theories have been put forth to explain these complexities. The multifarious series of operations which occur in nuclear reactions of various intervals of time are presented in succession in Fig. 3.1. The incident beam of alpha particles come into contact with the target nucleus within the limits of nuclear forces, resulting in the scattering and/or absorption of the incident particle. This is the first step in the reaction process. Absorption of these incident particles leads to the formation of a complex system. This complex system decays further to produce certain emitted particles and the residual nucleus. Thus, one can ascertain indubitably that the second stage is the most complicated one. Theorists still continue their research to know what exactly happens during this stage.

Neils Bohr (1) propounded the principle of compound nuclear reaction mechanism in the year 1936, to explain the second stage of this chain mechanism. His theory has been extremely useful in the correlation and interpretation of nuclear reactions. According to Bohr, a nuclear reaction takes place in two distinct and independent stages. (i) Formation of a compound nucleus (CN) and (ii) the
Fig. 3.1 Diagramatic representation of nuclear reaction
disintegration of the compound nucleus into products of the reaction.

The compound nucleus which is a multi-body system of strongly interacting particles is formed by the amalgamation of an incident particle with a target nucleus. The compound nucleus survives to distribute the energy and momentum of the projectile among all the other nucleons. The new nucleus thus formed is in excited stage. This compound nucleus disintegrates further depending upon the incident energy and emits particles like neutrons, protons etc., or the γ-rays. Such a compound reaction mechanism take place at comparatively lower excitation energies. Recent research reveals the fact that particle emission may occur even at the time of establishment of thermodynamics equilibrium. Collisions continue to take place within the compound nucleus until a stage of equilibrium is established, leading to emission of particles. The particles which are emitted during the establishment of thermodynamic equilibrium are called pre-equilibrium particles and the reaction mechanism is called pre-equilibrium emission process. Generally, the particles which are evaporated during equilibrium have higher energies as compared to those which are emitted in the compound nucleus decay and the likelihood of pre-equilibrium emission increases with projectile energy.
In the recent past, many models have been unfolded to explain the pre-equilibrium emission of particles which may be broadly classified into two types: (i) Semi-classical models of pre-equilibrium emission and (ii) the quantum mechanical models.

The significant features of the compound nucleus model along with pre-equilibrium models \(^{(3-5)}\) are briefly elucidated in this chapter.

### 3.1 COMPOUND NUCLEUS THEORY

The compound nucleus model was first proposed in the year 1936, by Bohr. Soon after interaction, the target nucleus and the incident particle are combined to form a compound nucleus. This facilitates the interchange of energy and momentum among the two interacting forces resulting in the establishment of a thermodynamic equilibrium. Thus the compound system forgets the mode of its formation. As the reaction continues, accidentally, excess of energy may be concentrated or few nucleons which may get emitted resulting in the decay of the compound nucleus (CN). Thus it can be inferred that the formation and decay of the compound nucleus are independent processes. Weisskopf Ewing \(^{(6)}\) have based their theoretical calculations of partial wave analysis for the calculation of cross-sections on Bohr's model. According to
this model, for every partial wave, the conservation of angular momentum and parity are not reconed clearly, but it provides the magnitude of the nuclear cross-section. However, Hauser and Feshbach have analysed this problem thoroughly and have taken into consideration explicitly, the conservation of angular momentum and parity. Further, they use the optical model potentials for nucleon interactions.

According to the Weisskopf-Ewing statistical model, the average reaction cross-section \( \bar{\sigma}_{jk} \) is given by

\[
\bar{\sigma}_{jk} = [\sigma_{\text{comp}(j)}] [G_k/G]
\]

Where \( j \) and \( k \) stand for the incident and outgoing particles respectively. In the equation given above, \([\sigma_{\text{comp}(j)}]\) represents the cross-section for the formation of compound nucleus, which can be calculated by using the transmission Co-efficients for partial waves. The branching ratio \([G_k/G]\) which depends upon the final products to type \( k \), may be computed by applying the level densities. Generally, the level density for the nucleus is given by the expression

\[
W(E) = C \exp \left( \frac{2\Gamma}{\Theta} \right)
\]

Where \( C \) is the constant for the given nucleus and varies
with excitation energy \( E \) and the nuclear temperature \( T \). The cross-section for the reaction calculations are given below \((6)\).

In Hauser - Feshbach model\(^{(7)}\) the parity conservation and the angular momentum used in the optical model potential is utilised to understand the absorption cross-section. Using the symbols of Holmas et.al.\(^{(8, 9)}\). The average cross-section for the reaction \( \mathcal{I}^\mu \ (j, k)_L \) can be given as:

\[
\sigma_{jk}(E_j) = \frac{\prod H_j^2/(2 M_j E_j^\mu)}{(2J_j + 1)(2 J_j+1)} \sum_{J_n} (2 J+1) \sum_{\ell} \mu \left( \sum_{I^1, S^1} T_j(J_n^1, 1^1, s^1)/ T_{total} (J_n^1) \right)
\]

Where \( \mu \) and \( \gamma \) represent the discrete energy levels of the residual nucleus \( L \) and target nucleus \( I \) respectively. \( E_j^\mu \) represents the energy of \( (I^\mu + J) \) compound system in the centre of mass frame. \( M_j \) is the reduced mass. \( T_j(J_n^1, 1^1, s^1) \) and \( T_k(J_n^1, l^1, s^1) \) are transmission functions for \( (I^\mu + J) \) and \( (I^\gamma + k) \) systems. \( T_{total} (J_n^1) \) is the sum of transmission functions for all channels. Moldauer\(^{10-12}\) has given a detailed description of these calculations.

3.2 PRE-EQUILIBRIUM THEORIES

At excitation of few tens of MeV, the process of
equilibrium is expected to be complicated because of the possibilities of multiple collision. Recently, many theoretical models are proposed to account for the particles emitted in nuclear reactions. Some of the important semi classical models\(^{(13-18)}\) are:

3.2.1 Intranuclear Cascade Model (ICM).
3.2.2 Harp Miller and Berne Model (HMB).
3.2.3 Exciton Model, (EM).
3.2.4 Hybrid and Geometry Dependent Hybrid Model (GDH).
3.2.5 Quantum Mechanical Model (QM).

3.2.1 Intranuclear Cascade Model (ICM)

The Intranuclear Cascade model was proposed by Seber\(^{(13)}\) and modified by others\(^{(19-24)}\) to explain various experimental data. Seber\(^{(13)}\) pointed out that in this model interaction is treated as quasifree scattering process with the assumption that the incident nuclear wavelength is shorter than intranuclear distances within the nucleus. This assumption is valid for nucleon energies above 100 MeV.

In this model, mean free paths and energy transfers in the assumed two body scattering processes are based on experimental nucleon-nucleon (N-N) scattering cross-
Fig. 3.2 Representation of the equilibration process in the frame-work of HMB model. The shaded areas represent the occupied fraction of each bin, with occupations changing after each time interval.
sections and angular distributions. For each scattering events, the position of the collision within the nucleus, energies and directions of each particle are followed explicitly in three dimensional geometry. The behaviour of the cascade particles is described by the equation of state for the ideal gas. ICM is perhaps the only model which may give the angular distribution of emitted particles, but in medium energy range it does not predict them very well. The detailed cascade calculations have been performed with the Brookhaven "VPOT" code and the "ORNL" code due to Bertini.

3.2.2 Harp Miller & Berne Model (HMB)

This model was proposed by Harp et.al. The schematic representation of this model (Usually called as HMB model) is shown in Fig. 3.2. In this model the process of equilibrium is supposed to start at a time $T_0$. The total excitation of nucleus is divided into bins of suitable size (may be 1 MeV). The calculation for the number of available single particle levels in each bin can be done with a nucleus in its ground state. It is assumed that relaxation time of the residual nucleus is long, as compared to the life time of nuclear emission. For a given incident nucleon, the rate of allowed transitions with all nucleons in the nucleus is computed as also the
rate of emission of the excited particles into the continuum. The two processes that is the internal transition and the particle emission into the continuum are treated statistically and the cross-sections for each process are derived accordingly. Nucleon-nucleon scattering cross-sections are used for calculating the two-body transition rates. The computation of transition rates into the continuum is done using inverse cross-section and the free particle Phase-space factors. The calculations are repeated till all the possible ways of scattering out of each bin are considered. The rate of equilibrium is assumed to reach. The equilibrium problem is solved by the set of coupled differential equations.

3.2.3 Exciton Model (EM)

Exciton model proposed by Griffin is an improvement over the HMB model. This model uses densities of intermediate states characterised by particle hole (exciton) number and assumes a statistical population of these states in the equilibration sequence. The incident nucleon enters the nuclear potential where all the fermions are in their ground state. The first interaction gives rise to a 2plh (2 particle, 1 hole) state. Successive two body interaction could lead either to (3p 2h) state or back to a different (2p 1h) state.
The probability of each occurrence is assumed to be proportional to the density of accessible final state. The level density of intermediate states are rapidly increasing functions of particle-hole numbers. As a result, the system goes predominantly in the direction of equilibrium. At each intermediate configuration, characterised by the specific particle hole number, some functions will have at least one particle with energy in excess of its binding energy.

The following simple statistical expression given by Williams may predict the particle-hole state densities in the uniform spacing model\(^{(25)}\) as

\[
\rho_n(E) = \frac{q^g(A(p,h))^{(n-1)}}{p! h! (n-1)!}
\]

Where \(A(p,h) = \frac{1}{4} (p+h)^2 + \frac{1}{4} (p-h) - \frac{1}{2} h\) and \(n = p + h\)

It is generally assumed that the fraction of \(n\)-exciton states in which one particle is at energy \(E+B\) above the fermi energy is given by the ratio

\[
\frac{\int n(U,E) \, dE}{\int n(E) \, dE - \int p(h, U,E) \, dE}
\]

Where \(U\) is the exciton energy of the residual nucleus and \(p\) is the channel energy of the emitted particles. The probability of decay from \(n\)-exciton states is given by
\[ P_n(\epsilon) \, d\epsilon = \frac{(2S+1) \int n(U,E) \, d\epsilon}{\int n(E)} \, \frac{4\pi p^2 \, dp}{R^3} \cdot \frac{\sigma_v}{r_n} \, T_n \]

Where \( T_n \) is the mean life time of \( n \)-exciton state, the phase space and penetrability factors. The total decay probability is given by

\[ P(\epsilon) \, d\epsilon = \frac{(2S+1) m \epsilon}{\pi^2 \hbar^3} \sum_{n=0}^{\infty} \frac{n^{-2}}{n-1} \, p(n-1) T_n \, d\epsilon \]

The mean life time \( T_n \) may be evaluated on a relative basis, as follows

\[ \lambda_n, \, n^1 = 1/T_n \]

\[ = \frac{2\pi / \hbar}{|M|^2} \, \int n^1(E) \]

Where \( |M| \) is the matrix element for the two body interaction, \( n^1(E) \) is the transition rate from the initial exciton state \( (n) \) to the final state \( (n^1) \) at any particular energy \( E \).

### 3.2.4 Hybrid and Geometry Dependent Hybrid (GDH) Model

The hybrid model was proposed by Blann\(^{(16)}\) which the basic principles of the exciton model\(^{(15)}\) and those of the HMB model\(^{(26)}\) are incorporated. In this model the excited particle populations during equilibrium were calculated using partial state densities as in the excitation model and the intranuclear transition rates of the excited particles were determined from calculations of the mean free paths of nucleons in nuclear matter. In a later
formulation\(^{(17)}\), the effects of interaction in the diffuse nuclear surface were also included in the model, and it is known as the "Geometry Department Hybrid (GDH) model".

The hybrid and geometry dependent hybrid models have been successful in reproducing a broad range of data\(^{(3)}\). This was accomplished with several choices of parameter options giving rather similar results.

In a recent work Blann and Vonach\(^{(29)}\) attempted to test whether the hybrid and GDH models can predict an extensive data using a single set of parameters for all projectile energies. They used a part of the currently available data as an aid in selecting a single mode of calculation for the hybrid and GDH models, in order to see how well a single parameter set will globally reproduce these data. Optical model parameters were also modified to obtain better global results for inverse reaction cross-sections in the pre-equilibrium energy range up to 90 MeV.

A. GENERAL DESCRIPTION OF THE FORMULATIONS

The formulations of the hybrid and GDH models, as described below are mainly taken from Ref. 29. The formulations can be written as

\[
P_Y (\mathcal{E}) d\mathcal{E} = \sum_{n=0}^{\text{max}} x_n y_n (\mathcal{E}, U)/N_n (\mathcal{E}) \times \delta_{n+2}
\]
Where the symbols are defined in Table 3.1. The quantity in the first set of square brackets of Eqn. (1) represents the number of particles to be found (per MeV) at a given energy \( \varepsilon \) (with respect to the continuum) for all scattering processes leading to an "n" exciton configuration. The second set of square brackets represents the function of the \( \gamma \) type particles at energy which should undergo emission into the continuum, rather than making an intranuclear transition. \( D_n \) represents the average fraction of the initial population surviving decay prior to reaching the \( n \)-exciton configuration.

Analysis of nucleon-induced reactions at incident energies of 18 and 62 MeV gave evidence of major spectral contributions from the nuclear surface. To investigate the importance of nuclear density distribution in pre-equilibrium decay Blann(17) formulated the geometry dependent hybrid model. The hybrid model was reformulated with a geometry dependence based on the impact parameters for the partial waves initiating the reaction. It was assumed that the reaction initiated by each partial wave
Table 3.1

Definition of Symbols

\[ P_\gamma(\varepsilon) \, d\varepsilon \]  
Number of particles of type \( \gamma \) (neutrons or protons) emitted into the unbound continuum with channel energy between \( \varepsilon \) and \( \varepsilon + d\varepsilon \) (MeV).

\[ p(l,\varepsilon) \, d\varepsilon \]  
As for \( P_\gamma(\varepsilon) \) but evaluated for the \( l \)th partial wave.

\( \tilde{n} \) = Equilibrium (most probable) particle plus whole (exciton) number.

\( n_0 \) = Initial exciton number.

\( N_X^\gamma \) = Number of particles of type \( \gamma \) (proton or neutron) in an \( n \) exciton configuration.

\( E \) = Composite system exciton.

\( U \) = Residual nucleus excitation.

\( N(n,\varepsilon,U) \) = Number of ways that \( n \) exciton may be combined such that one, if emitted, would have channel energy \( \varepsilon \) and the remaining \( n-1 \) exciton would share exciton

\[ U = E - \varepsilon - \varepsilon_{\gamma} \]  
where \( \varepsilon_{\gamma} \) is the particle binding energy.
\[ N_n(E) = \text{Number of combinations with which } n \text{ excitons may share excitation energy } E. \]

\[ \lambda_c(\varepsilon) = \text{Emission rate of a particle into the continuum with channel energy } \varepsilon. \]

\[ \lambda_+ (\varepsilon) = \text{Intranuclear transition rate of a particle which would have channel energy } \varepsilon \text{ if it were emitted into the continuum.} \]

\[ D_n = \text{Fraction of the initial population which has survived decay prior to reaching the } n\text{-exciton configuration.} \]

\[ \sigma_R = \text{Reaction cross-section.} \]

\[ l = \text{Orbital angular momentum in units } \hbar. \]

\[ T_l = \text{Transmission coefficients for the } l\text{th partial wave.} \]

\[ d(l R_1) = \text{Nuclear density at radius } R_1 \text{ where } l \text{ denotes the entrance channel orbital angular momentum.} \]

\[ d_s = \text{Saturation density of nuclear matter.} \]

\[ \lambda = \text{Reduced de Broglie wave length.} \]

\[ \sigma_l = \text{Partial reaction cross-section for the incident } l\text{th partial wave.} \]

\[ g_y = \text{Single particle level density for particle type } y. \]
\[ N \] = Target neutron number.

\[ Z \] = Target proton number.

\[ \epsilon_f \] = Fermi energy.

\[ B_\gamma \] = Binding energy of particle type \( \gamma \).

\[ \epsilon \] = Channel energy.
proceeds in the spherical shell-shaped region of thickness with radius defined by the initial impact parameter. The diffuse surface properties sampled by the higher parameters were crudely incorporated in the pre-equilibrium decay formulation, in the GDH. The differential emission spectrum is given as

$$\frac{d\sigma}{d\epsilon} = \pi X^2 \sum_{\ell=0}^{\infty} (2\ell + 1) T_{\ell} P_{\ell}(1, \varepsilon)$$

Where the symbols are defined in Table 3.1. The intranuclear transition rates entering Eqn. (1) are evaluated for nuclear densities averaged over the entire nucleus, while for those in Eqn. (3) should be averaged over the densities corresponding to the entrance channel trajectories, at least for the contributions from the first projectile-target interaction.

B. PARAMETER EVALUATION AND MODIFICATION

(i) Nuclear Density Distribution

The nuclear density is given by a Fermi distribution as

$$\rho(R_L) = \frac{ds}{\pi} \left[ \frac{\exp (R_L - c)}{0.55 \text{ fm} + 1} \right]^{-1}$$

Where $\rho$ is the saturation density of nuclear matter and the charge radius $c$ is given by
\[ c = 1.18 \lambda^{1/3} \left[ 1 - \left( \frac{1}{1.18 \lambda^{1/3}} \right)^2 \right] + \lambda \]  

...[5]

Where \( \lambda \) is the reduced de-Broglie wave-length of the projectile. The radius of the lth partial wave is defined by

\[ R_l = \lambda \left( 1 + \frac{L}{2} \right) \]  

...[6]

In the hybrid model the average nuclear density is calculated by integration and averaging Eqn. [4] between \( R=0 \) and \( R= C + 2.75 \text{ fm} \). The Fermi energy (\( \varepsilon_f \)) has been taken as 40 MeV for saturation density, and is assumed to be proportional to the two third power of the average density. The value of \( f \) so evaluated is used in defining the single particle level density "g" for all calculations, hybrid and GDH. The single particle level densities have been defined by

\[ g_n = \frac{N}{20} \left\{ \left( \varepsilon_f + B_n + \varepsilon \right) / \left( \varepsilon_f \right) \right\}^{\frac{1}{3}} \]  

...[7a]

\[ g_p = \frac{N}{20} \left\{ \left( \varepsilon_f + B_n + \varepsilon \right) / \left( \varepsilon_f \right) \right\}^{\frac{1}{3}} \]  

...[7b]

In the hybrid model, the Pauli corrected nucleon-nucleon scattering cross-section are used to evaluate the \( \lambda^+(\varepsilon) \) of Eqn. [1], the average value of the Fermi energy (usually = 30 MeV) and density are used to define the nuclear mean free path (mfp). In the geometry dependent hybrid model the Fermi energies and nuclear densities are defined according to impact parameter via Eqn. [6]. Option have been employed using either the maximum density
along each targetory or an average. In the ALICE/LIVERMORE-82 code, the density average is used as the code default option. The $E_f$ values determined by the average densities also determine the maximum hole depth of the $2p - 1h$ and $1p - 1h$ configurations of hybrid or GDH calculations, which are used in the $N_n(E)$ functions of Eqn. [1].

(ii) Intranuclear transition rates

The hybrid and GDH models have employed intranuclear transition rates evaluated both from the imaginary optical potential and from Pauli corrected nucleon-nucleon scattering cross-sections. The optical model parameter set is valid only for projectile energies below 55 MeV. For treating the data at higher energies, the Pauli corrected N-N scattering evaluation is used as the standard default parameter.

(iii) Initial exciton numbers

Different values of this input parameters should be given for different types of projectiles. A default option is also available in the code. For $\alpha$-particle induced reactions, initial exciton numbers 4 and 5 are found to give better fits to the experimental data.

(iv) Pairing options

There are two choices for the pairing effect in the ALICE/LIVERMORE-82 code. The value of the pairing
correction is defined as
\[ \delta = \frac{11}{\sqrt{A^b}} \quad \ldots \ldots [8] \]
with a backshift or standard shift being applied. The standard shift uses true thermodynamic excitation for odd A nuclei, reduces the excitation by \( \delta \) for doubly even nuclei and increases it by \( \delta \) for doubly odd nuclei. The backshifted option uses true thermodynamic excitation for doubly even nuclei, and increases it by \( \delta \) for odd A nuclei and 2 \( \delta \) for doubly odd nuclei.

(v) Binding energies

The binding energies and Q-values used in the hybrid and GDH models are all based on experimental masses, which is included in the ALICE/LIVERMORE-82 code in the form of block data. A simple input parameter results in all Q-values and binding energies being internally generated from the experimental mass tables.

(vi) Reaction and inverse reaction cross-sections

The ALICE/LIVERMORE-82 code has a classical sharp-cutoff routine for inverse reaction cross-sections and an optical model routine. Either routine may be used for calculating inverse reaction cross-sections.

(vii) Multiple particle emission

The multiple pre-equilibrium decay processes must be
considered at high excitations (\( \geq 50 \) MeV). They are important in determining the contributions of terms after \( n = n_0 \) in Eqn. [1] in determining the cross-section surviving to the (equilibrium) compound nucleus, and in determining yields of products which require multiple pre-equilibrium emission for population e.g., a \((\alpha, 2p)\) reaction on a heavy element target. These are two types of multiple pre-equilibrium decay. In the first type a nucleus emits more than one exciton from a single exciton configuration. For example, in a \(2p - 1h\) configuration, upto two particles could be emitted, in a \(3p - 2h\) configuration upto three particles could be emitted.

The second type of multiple pre-equilibrium decay, the sequence is particle emission, one or more two-body intranuclear transitions in the daughter nucleus and lastly particle emission. This type becomes the first type if the intervening two-body transitions are emitted.

(viii) Evaporation calculation of level densities

The Fermi gas level density used in the code is of the form

\[
P(U) \propto (U - S)^{-5/4} \exp \left[2 \sqrt{a(U - S)} \right]
\]

where the pairing options are already described. The level density parameter \(a\) was given as an input parameter.

The hybrid and geometry dependent hybrid models were able to reproduce experimental particle spectra as well as
excitation functions of reactions induced by $\alpha$-particle. Blann\(^{(3)}\) calculated particle spectra for ($\alpha,p$) reactions in medium and heavy mass nuclei at an $\alpha$-particle energy of 55 MeV and compared the results with the experimental results of Chavarier et al\(^{(26)}\) and found good agreement between the two. The author also compared the experimental particle spectra\(^{(26-28)}\) for the $^{93}$Nb ($\alpha,p$) reaction at $\alpha$-particle energies of 30.5, 42 and 55 MeV with the calculated values obtained using the hybrid model and found a good agreement.

It was also shown\(^{(3,27)}\) that geometry dependent hybrid model was able to predict the excitation functions of the reaction $^{93}$Nb ($\alpha,XnYp$) for $X \leq 10$, $Y \leq 6$ and for $\alpha$-particle energies 16 to 171 MeV.

3.2.5 Quantum Mechanical Model

To understand the pre-equilibrium processes through nucleon-nucleon interaction, the quantum mechanical multi-step models have been developed\(^{(32)}\). Recently quantum mechanical models have been developed\(^{(33-38)}\) for reckoning the cross-section of pre-equilibrium processes. The quantum mechanical models have been divided into two categories. (i) Multistep compound (MSC) reaction and (ii) Multistep direct (MSD) reaction. The multistep description of the nuclear reaction has been illustrated in Fig. 3.3.
Fig. 3.3 Multi-step description of a nuclear reaction
The pre-equilibrium emission of particles is assumed to take place either directly from each stage of P-chain or indirectly from Q-chain. If the emission of particles before equilibration occurs from Q-chain then the emission goes through several stages of P-chain, in three different ways as represented in the above figure. The higher energy particles are emitted during the initial stages and particles of lower energy are emitted in the later stages. The multistep direct and compound reaction processes through P and Q chains are dominant in the high and low energy regions respectively. The MSD reactions occurring in the P-chain show forward peaked angular distribution and those occurring in the Q-chain are compound in nature producing symmetric angular distribution. The nuclear reaction goes through various stages as the incident nucleon interacts with the target nucleus. It is likely that the reaction proceeds to the next stage, returns to the earlier stage or goes to the continuum. The last probability is related to the pre-equilibrium emission $^{(4,18)}$.

(i) The Multistep compound (MSC) reaction

In this type of reaction, the transitions in a series of excitation can be made one at a time, similar to that of exciton model. This is termed as the chaining hypothesis, for example, from the $N_{th}$ stage, a reaction can proceed only either to $(N-1)_{th}$ stage or $(N+1)_{th}$ stage or to
the final stage. Jumping to the next stage leaving one in between is not possible i.e., from $N_{th}$ to $(N+2)_{th}$ stage leaving $(N+1)_{th}$ stage is not possible. The reaction between the exciton number $n$ and the stage number $N$ is given by $N = (n-1) / 2$. The likelihood of the transition is proportional to the level density in the final state.

(ii) The multistep direct (MSD) reaction

At higher excitation it is assumed, all through the course of reaction that at least one particle remains in the continuum. It is already assumed that the reaction passes through many stages of high complexity.

Semi-classical models and in recent years, totally quantum mechanical models have been developed to describe the non-equilibrium processes. However, it has not been possible to consider multiparticle emission in the light of quantistic approach as yet, and therefore measured excitation functions have been computed theoretically with and without the inclusion of pre-equilibrium emission using semi-classical models.
REFERENCES

1. N. Bohr; Nature 137 (1936) 344.


