STUDY OF ALPHA INDUCED REACTIONS ON IRIDIUM

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By

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The undersigned hereby certify that they have read and recommended to the Faculty of Science School of Graduate studies for acceptance of this thesis entitled "**Study of Alpha induced reaction on Iridium**" by **Chali Yadeta** in partial fulfillment of the requirements for degree of **Master of Science in Physics**.

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Abstract

Excitation function of (α, xn) reaction on Ir -191 (abundance 37.3%) and Ir -193 (abundance 62.7%) were studied for various energy range of alpha particle. The calculations were done using ALICE-91 computer code, which is based on Geometry Dependent Hybrid (GDH) model. Various parameters were changed to see the effect on the excitation functions. The calculated values were compared with experimental result obtained from available literature. This comparison gives the best-fit parameters viz pld, exciton number, etc. Further this confirms that at these energies compound nucleus theory does not satisfy experimental results. There is sufficient proof of pre-equilibrium decay of the system.

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Chapter –one

Introduction

The atomic nucleus was discovered almost a hundred years ago by Geiger and Marseden (1909) and then Rutherford (1911) postulated basic features of nucleus. During the following years the atomic nucleus was studied extensively through low energy reactions using different particles from radio active decay to study nucleus until Cockroft and Walton's invention of the electrostatic accelerators which generates high energy particles for higher and higher nuclear reactions.

The study of nuclear reactions is significant for its impact on related fields of investigations and for its rich variety of applications. Measurement and the calculation of the cross-sections of nuclear reactions and understanding of reaction mechanism are of great importance.

A nuclear reaction is a process that takes place when any projectile (a nucleon or combination of nucleons, or heavy ions) come in close contact with nucleon or a system of nucleons. It is a process in which a new system of new composition or a system of new energy or both are formed by bombarding a target nucleus by nuclear probe or with gamma ray. The study of nuclear reactions provides knowledge about the nature of nuclear forces and nuclear structure such as nuclear density, and nuclear reaction mechanism. The only way to delve the entire secretes of nucleus is to send in a probe particle and study the outcome. Practically we bombard the target nucleus by the beam of particles. The beam of particles can be from radioactive sources or from accelerating machines. The energy of particles from radioactive sources is distributed to its entire constituent and discrete in nature and hence it is inconvenient for bombardment of target nucleus with sufficient energy continuously, as it is required, to have nuclear reaction. But the accelerating machine such as Pelletron, Cyclotron, etc produces high energy particle beam, ranging from proton to ^{235}U, energies varying from few MeV/nucleon to many GeV/nucleons which are used for the bombardment of a variety of target to study various types of nuclear reactions in all elements of the periodic table. The alpha particle beam from accelerating machine is used to study the nuclear reactions produced on natural iridium isotopes. When alpha particle beam comes to iridium, nuclear reactions

takes place between the nucleus of the incoming alpha particle and the nucleons of the iridium gives an out going particle.

Presently studies have been made to compare the excitation functions of reactions in the isotopes of natural iridium (^{191}Ir and ^{193}Ir);

^{191}Ir(α , n), ^{191}Ir(α ,$2n$), ^{191}Ir(α ,$3n$), ^{191}Ir(α ,$4n$), ^{191}Ir(α ,$5n$)

^{193}Ir (α , $3n$), ^{193}Ir (α , $4n$), ^{193}Ir (α , $5n$)

Iridium is a silvery white metal named after the Latin word for rainbow because its salts are highly colored. It is quite dense, about twice as dense as lead, and occurs in nature as two stable isotopes. Natural iridium contains about 37% iridium-191 and about 63% of iridium-193.

In the last 100 years, scientists have been trying to probe deeper into the constituents of matter. Perhaps the first steps came with Thomson's investigations of the electron at the end of the 19th century. Then, in the early 1900s, Ernest Rutherford had fired alpha particle at atoms to probe. Alpha particle is a doubly ionized helium atom ($_2^4He^{++}$), that can be obtained when heavy nuclei like Uranium or Radium decay spontaneously or from accelerator machines, have high energy used to probe different atoms. The energy of alpha particles obtained from natural radio active nuclei distributes to all parts and discrete in nature and appreciably smaller than the coulomb barrier and they are not suitable to make nuclear reactions efficiently. But the alpha particle from the accelerator machines has continuous and higher energy and they are frequently used for study of the nuclear reaction mechanisms of different isotopes. The accelerators have out grown their structure. Nowadays, physicists use particle accelerators to take particles up to speeds close to the speed of light and smash them into other particles and study the out come. These accelerators led to the description of the structure of protons and neutrons because physicists developed the theory of the quarks to explain all the particles that have been made in them. Modern accelerators play an effective complementary role in nuclear reactions, for they produce radio active isotopes that have various applications in applied fields of science as a residue of nuclear interaction between projectiles and target. In my present case alpha particles from accelerators is used to produce nuclear reactions with natural iridium isotope and study its out come. When alpha particle makes nuclear

reaction with the isotopes of iridium we get gold (Au) isotopes of different mass number with different excitation energy and half-life and even with different properties.

When nuclear reaction takes place targets would be excited and the knowledge of excitation functions of nuclear reactions will enable us to produce selected isotopes that have ever-increasing demand in applied fields. From the physics point of view, the shape of the excitation functions reveals the reaction mechanism of nuclear reactions. Depending upon the time at which they occur, the nuclear reactions are of two types,

1. compound nucleus reactions, and
2. direct reactions.

In compound nucleus reactions the incident projectile fuses with the target forming a composite system, which is assumed to be fully in equilibrium. Originally Bohr proposed the compound nucleus hypothesis (**1**). In compound nucleus reaction the energy and angular momentum of the incident particle is distributed among the nuclear constituents before any particle is emitted from the nucleus, the excitation energy of the compound nucleus is distributed over numerous degrees of freedom of compound nucleus. Since the probability of finding all excitation energy in some individual particles that would be emitted, the life time of the compound nucleus is usually very large, 10^{-16}s. The direct reactions are supposed to be initiated and completed at the very first projectile target collision; and hence are thought to occur with in a time of 10^{-22}s.

Apart from the two extreme reactions direct reactions and compound nucleus reactions, an intermediate process, there is certain probability for a particle emission after each one of these collisions, are coming to be recognized basically from the complicated interactions that are observed in relatively short period of time from the original hypothesis of Bohr compound nucleus reaction. The process may be attributed to pre-compound or pre- equilibrium processes. There are different models of pre-compound or pre-equilibrium process (**2-5**) .These are;

i). Intra - Nuclear Cascade (INC) model,
ii). Harp - Miller- Berne (HMB) model,
iii). Exciton model,
iv). Hybrid/geometry dependent hybrid (GDH) models.

In Intra-Nuclear-Cascade model the trajectories of particles inside the nucleus are followed in co-ordinate space by means of Monte Carlo method. The numerical simulation of the scattering process is based on the experimental free n-n scattering cross - sections, and the angular distributions. Up to 1975, this was the only pre -equilibrium model capable to predict the angular distributions of the emitted particles. This model provides a classical approach to pre - equilibrium decay process.

In contrast to the intra-nuclear cascade model the HMB model permits a quantum mechanical treatment, though in practice; the transition rates are computed in the classical manner. It cannot predict the angular distributions of the emitted particles. In this model the total excitation energy of the nucleons is divided into bins. The average number of occupied single particle levels in each bin is computed in the framework of the Fermi gas model. The occupation of nucleons in each bin changes in time due to the intra-nuclear collisions. The evolution of this excited nuclear Fermi gas is followed through numerical calculation of the relative occupation of each bin as function of time, by solving a set of coupled differential equations. The two body transition rates are calculated using nucleon - nucleon scattering cross-sections and transition rates into the continuum are calculated by using inverse cross - sections and free particle phase space factors. The major disadvantage of HMB model is its computational complexity. In order to deal with such situations additional assumptions have been introduced in exciton model and hybrid models, which are the most popular pre-equilibrium models for applications in the nuclear data evaluation. The INC and HMB models are most widely used but more particularly the exciton model and GDH models.

The exciton model assume all possible ways of sharing the excitation energy between different particle-hole configurations, with the same exciton number ħ 'have equal prior probability. In this instead of tracing the evolution of the occupation of each energy bin, as in case of HMB model, one merely traces the temporal development of exciton number ħ 'which is as a result of intra-nuclear collisions changes in time. This assumption makes the pre - equilibrium theory amenable to practical calculations. The hybrid model is the combination of Griffin model and simplifying aspects of HMB model. In this, the intra-nuclear transition rates are calculated from the free n-n scattering cross - sections. Further, the geometry effects are also introduced in it and are named as

geometry dependent hybrid (GDH) model. In GDH model the variation of nuclear level density at nuclear surface is taken into account.

In this thesis work, theoretical calculations of excitation functions or cross-section (σ) for heavy isotopes, specifically for natural iridium, when induced by alpha particle is made using the ALICE-91 computer code which is based on compound and pre-equilibrium models. The compound nucleus calculations are due to Weisskopf-Ewing model (**6**) while the pre-equilibrium calculations are based on hybrid/geometry dependent hybrid models. The calculated values are compared with the experimental results which are obtained from different literatures and conclude about the alpha-induced reactions on natural iridium isotopes (^{191}Ir and ^{193}Ir).

Chapter Two

Nuclear Reaction Theories

Nuclear reactions are process that takes place between the projectile and nucleus of target, which may result a new system of different excitation energy and of different quantum mechanical parameters.

When energetic nuclear probe from a natural radioactive source or from a particle accelerator are allowed to fall up on bulk matter or target there is a possibility of nuclear reaction. Rutherford made the first nuclear reaction in 1919 using alpha particles from a natural radioactive source and transmutation of target was identified (**1**). He bombarded the alpha particle to nitrogen-14 nuclei and obtained a new nucleus that is oxygen-17 with proton as emitted particle.

$$\alpha + {}^{14}N \rightarrow {}^{17}O + p$$

Cockroft and Walton did the first transmutation reaction by using artificially accelerated particle in 1930 **(1)**. They bombarded high energetic proton, obtained from accelerator, on Li-7 nuclei and they obtained helium nuclei as out put and another helium nuclei as emitted particle.

$$p + {}^{7}Li \rightarrow {}^{4}He + {}^{4}He$$

The general and simplest expression for nuclear reaction is given by,

$a + X \rightarrow Y + b$, or

in short , $X(a,b)Y$

Where, a - is a projectile,

b - is emitted particle,

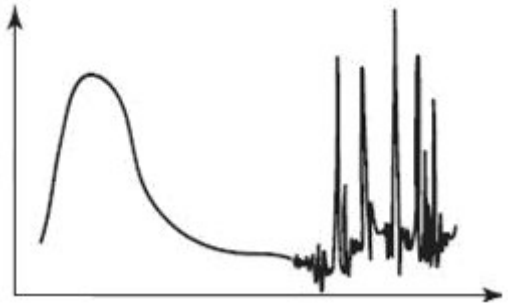
X - is target nucleus and

Y – is residual nucleus.

2.1 **Reaction mechanisms**

A nuclear reaction occurs when two nuclei are brought close enough to touch that is, when they are brought closer than the sum of their radii. Depending on the mechanism through which the reaction takes place the angular and energy dependency of out going fragments may vary significantly. As an example if we considers the variation of reaction cross section for inelastic proton scattering on a heavy target nucleus with the energy of out going proton, the reaction mechanism of the whole process can be given on cross-section verses particle energy graph as follows;

$$\frac{\partial^2\sigma}{\partial\Omega\partial\theta}$$



E_p (MeV)

Fig 2.1 a sketch of total reaction cross-section for varying energy of emitted particle from a nuclear reaction (3)

At the maximum energy of projectile (incoming proton) we observe discrete structures corresponding to the low lying states in the target nucleus and at low proton energy a Maxwellan peak from protons escaping just over the coulomb barrier in the proton plus target system. These two parts of the spectrum corresponds to direct reactions where the incoming proton only interacts with one or two or a few nucleons in the target, and compound nucleus reactions in which the projectile and the target combines to form a " long lived " compound nucleus which subsequently decays. Between the two structures is a flat, which is due to pre-equilibrium reaction mechanisms such as multiple scattering and resonance reactions. From the graph of spectrum above (Fig.2.1) we observe that

different reaction mechanisms contribute to different parts of the spectrum and makes easier to identify the reaction mechanisms involved in a given data. This may of course be very difficult if the incident energy is very low since the compound and direct reaction contributions may overlap. The graph shown in the figure depends on the energy of the incident proton but basically just expands/contracts the flat middle part for the higher/lower incident energy. The proton may leave the target unchanged (elastic scattering), or as above excite the target nucleus (inelastic scattering). Further transfer reactions occur when one or a few nucleons are transferred between the projectile and target nucleus or a neutron and proton can switch place in a charge exchange reaction.

The different reaction channels mentioned above can proceed via different reaction mechanisms such as direct, pre-equilibrium or compound nucleus reactions. The following figure shows the different reaction mechanisms lead to the same reaction channels.

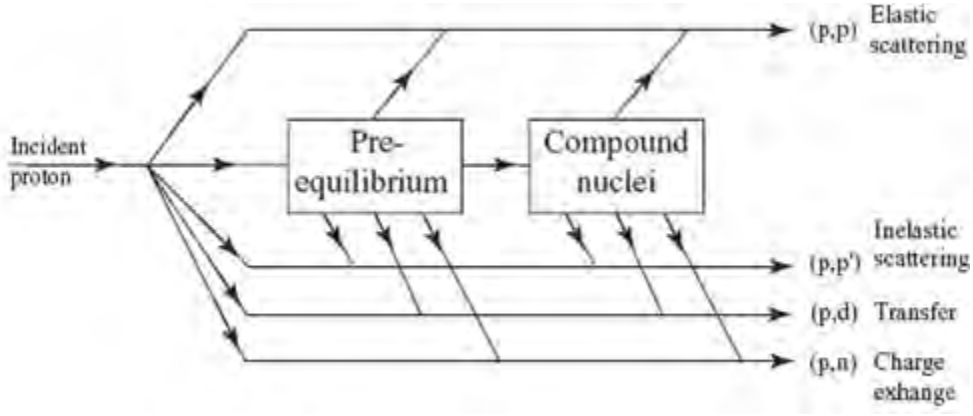


Fig.2.2 Diagram showing the different reaction products produced via different reaction channels exemplified with proton scattering (**3**)

2.1.1 Direct reactions

Direct reactions are the simplest reaction type since they normally only involve the interaction between two (or a few pair of) nucleons but can excite the nucleus into many different states. Over the years it has been found that inelastic scattering mainly excites collective states, one-nucleon transfer reactions excites single-particle states and multi-

nucleon transfer reactions and charge-exchange reactions excites cluster states in the nucleus probed in the reaction. For a reaction to be called direct it must occur fast, on the time scale of the transit time of the projectile through the target nucleus (about 10^{-21}s to 10^{-22}s), and with a minimum of rearrangement in the residual nucleus.

$$^{2}_{1}H + ^{63}Cu \rightarrow ^{64}Cu + ^{1}_{1}H \text{ .... (Stripping)}$$

$$^{1}_{1}H + ^{63}Cu \rightarrow ^{62}Cu + ^{2}_{1}H \text{ … (Pick-up)}$$

In many cases it is a requirement that the wave functions of the incident and exit channel have a large overlap for a reaction to occur via a direct mechanism. Another requirement on a direct reaction is that the de Broglie wavelength,

$$\lambda = \frac{h}{p} \text{ ……. (2.1)}$$

of the lightest particle involved is smaller or on the order of the size of one nucleon. If the de Broglie wavelength is larger (1 MeV proton λ in order of 4-5 fm) the projectile interacts with the nucleus as a whole and the reaction can hardly be called direct. This argument again proposes that direct reactions dominate for high-energy reactions whereas low energy is the regime of compound reactions. Thus particles with $A.E_{kin} \leq$ 9 MeV (corresponding to a de Broglie wave length of 1.5 fm) are more likely to react via compound reactions whereas particles with higher energy will tend to react via direct reactions. Since a direct reaction is a localized process with only a few nucleons participating in it is most likely to take place at the surfaces of the involved nuclei and not deep inside.

The common theoretical framework used for direct reactions is the so-called Distorted Wave Born Approximation (DWBA), which is a fairly precise and tractable model. The idea of the DWBA model is that the main part of the reactions are elastic scattering and that all other channels are weak perturbations governed by an imaginary potential which removes particles from the elastic channel. The potential used in DWBA is an optical potential consisting of a real and imaginary part. Optical potentials come in various versions and may also contain spin dependent terms. Apart from just using an optical potential the DWBA implements Coulomb distorted wave functions instead of just plane waves.

In direct reaction,

i). the emission of much larger number of high energy particle as compared with the particle emitted in compound nucleus reactions.

ii). angular distribution of emitted particles having forward peaking $\theta = 0^0$, no isotopic distribution, as observed in the compound nucleus formation.

iii). a mono-atomic change of cross-section with energy, no resonance is observed.

iv). direct reactions usually takes place at higher energies.

2.1.2 **Compound Nucleus theory**

In a compound nucleus (**7**) reaction a long-lived system consisting of the target and beam nuclei is formed. This system lives long enough for the incoming beam nucleons to spread their energy among the target nucleons, thus making a collective excitation in the system. The life time of a compound nucleus, ranges from 10^6 to 10^7 times the transit time of the beam nucleus through the target nucleus, is up to 10^{-16}s. The life time clearly depends very much on the incident energy, since higher incoming energy transfers more energy into the system and makes it easier to give one nucleon enough energy to escape, therefore giving compound systems created at higher energy a shorter life time. The decay mechanism in compound nuclei is of statistical nature, where eventually one nucleon, or a small group, by statistical fluctuations receives enough energy to escape the compound system. In most cases this leads to the evaporation of a low energy neutron or proton since this is more probable than emitting a composite particle. Since the energy is redistributed many times among the nucleons in the compound nucleus the decay of the system has no “memory” of its creation, thus giving a rather uniform angular emission of particles. The idea that the compound nucleus has no “memory” is of course not completely true since conservation of e.g. angular momentum must be fulfilled, but compared to direct reactions the angular distribution from compound reactions are much more isotropic.

The compound nuclear reaction can be given in short as,

$a + X \rightarrow C^*$, where,

a – is projectile

X - is target

C^* - is emerging compound nucleus.

Ex

$$p + {}^{63}Cu \rightarrow {}^{64}Zn^*$$

$$\alpha + {}^{64}Ni \rightarrow {}^{64}Zn^*$$

If E_c is the excitation energy of compound nucleus, then this excitation energy can be calculated from the following relations,

$$E_c = E_\alpha + E_\beta \ldots\ldots\ldots (2.2)$$

Where E_α -is projectile energy in alpha channel; E_β, - is its binding energy in the nucleus.

Since the compound nucleus is always at rest in the center of mass system, this energy at least must be available internally as excitation energy (i.e. as mass energy). In addition, the work done by the nuclear forces when the two particles come with in range must also be available internally; this is given in the second term of the equation. If we want to separate the projectile and the target again, for example, energy equal to E_β must be supplied from some where.

For the whole process of compound nucleus, Bohr gave two different assumptions;

i) Mode of formation of compound nucleus, and

ii) Independent decay of compound nucleus.

In mode of formation he generally identified that when incident projectile interacts with the target, compound nucleus of its own excitation energy and life time before it decays to some other nuclei is formed. The formation of compound nucleus takes a long time and hence the newly formed compound nucleus forgets the history its formation. It doesn't know from where it is formed. Its decay process is independent of the mode of formation, that is the decay doesn't depend up on the nature of incoming particle, but the decay process depends only on the quantum mechanical parameter of the compound nucleus such as energy of excitation, angular momentum and parity of the states.

The relation that can express the compound nucleus idea formally is,

$$\sigma(a,b) = \sigma_c(a)G_c(b) \ldots\ldots\ldots\ldots \quad (2.3)$$

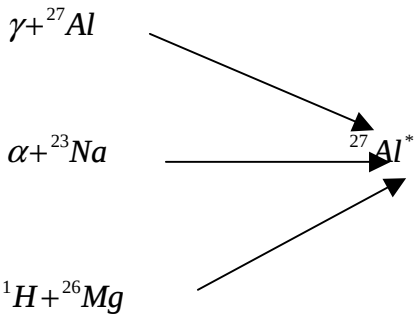
Where,

$\sigma(a,b)$ - is the cross-section for complete reaction X (a, b) Y.

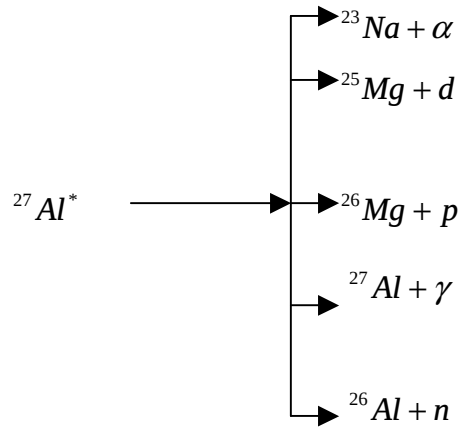
σ_c (a) - is cross-section for the formation of compound nucleus with excitation energy ε by absorbing 'a' with kinetic energy (E_a).

$G_c(b)$ - is the decay cross section of excited nucleus by emitting 'b'

It is assumed that $G_c(b)$ is independent of the mode of formation of the compound nucleus. The compound nucleus aluminum-27, at excited state, is formed in different channels in different targets.



The decay process takes place independent of the mode of formation of compound nucleus. The excited compound nucleus $^{27}Al^{*}$ will decay into different nuclei in different channels.



The probability of compound nucleus formation in α channel with emitted particle in channel β is given by,

$\sigma(\alpha,\beta) =$ (Cross-section in compound nucleus formation in α channel). (Cross-section of independent decay in channel β)

$$\sigma(\alpha,\beta) = \sigma_c(\alpha).G_c(\beta) \ldots\ldots\ldots (2.4)$$

The energy width of the whole reaction is calculated from the uncertainty principle,

$$\Delta E \Delta t \equiv \hbar ,$$

$$\Delta E_\beta \equiv \frac{\hbar}{\tau_\beta}$$

$$\Delta E_\beta = \Gamma_\beta, \ldots\ldots\ldots\ldots\ldots (2.5)$$

Where ΔE_β is the energy width in the reaction.

The decay of a reaction is given by the ratio of energy width in channel β to total energy width.

$$G_c(\beta) = \frac{\Gamma_\beta}{\Gamma} \ldots\ldots\ldots (2.6)$$

Then, the over all compound nucleus reaction can be given as

$$\sigma(\alpha,\beta) = \sigma_c(\alpha).\frac{\Gamma_\beta}{\Gamma} \text{.....(2.7)}$$

From reciprocity theorem we can say that,

$$k_\alpha^2\sigma(\alpha,\beta) = k_\beta^2\sigma(\beta,\alpha) \text{ ..... (2.8)}$$

Where, k_α^2 and k_β^2 are wave numbers in $\alpha, and \beta$ channels respectively.

$$\frac{k_\alpha^2\sigma_c(\alpha)}{\Gamma_\alpha} = \frac{k_\beta^2\sigma_c(\beta)}{\Gamma_\beta} = U(E_c) \text{ ..... (2.9)}$$

Using these relations, the decay cross-section will be,

$$G_c(\beta) = \frac{k_\beta^2\sigma_c(\beta)}{\sum k_\alpha^2\sigma_c(\alpha)} \qquad \text{..... (2.10)}$$

$$\sigma(\alpha,\beta) = \sigma_c(\alpha).\frac{k_\beta^2\sigma_c(\beta)}{\sum k_\alpha^2\sigma_c(\alpha)} \qquad \text{... (2.11)}$$

Bohr explained the compound nucleus reaction by using liquid drop model. The projectile is assumed to enter the nucleus and to share its energy rapidly with the other near by nucleons; it soon losses its identity. The interaction between the incident particle and the nucleus is not with one or two nucleon only but with the whole nucleons in the nucleus. Compound nucleus with its own excitation energy and half-life is formed. The mean free path of the collision of projectile should be very much smaller than the nuclear radius of the target nucleus, otherwise the projectile may come out in few (one or two) collisions and there is no through mixing that means no energy sharing.

Total excitation energy of compound nucleus is given by, $\varepsilon + B_E$ and this energy must be much less than the total separation energy (SA) of the nucleons.

$$\varepsilon + B_E << \text{SA},$$

Where, ε - excitation energy

B_E - Binding energy of nucleons

s - Separation energy of each nucleon

A - total number of nucleon /mass number

SA - total Separation energy all nucleons

For the separation energy per nucleon is the order of the binding energy of the nucleons, $S \approx B_E$ for a nucleon, the excitation energy relation according to bohor is given by,

$$\varepsilon << B_E(A-1) \text{ . ……. (2.12)}$$

From this relation one can infer that, the excitation energy relation is applicable only for nuclei's with medium or heavy mass with medium binding energy. It can be valid for light nuclei's at low energies only. This means Bohr's theory of compound nucleus reaction is valid only for medium or heavy nuclei's at medium energy but not for light nuclei at high or medium energy.

Shells model of nucleus considers very large mean free path in which the projectile will leave the nucleus by making one or two collisions, with out energy sharing between them. Shell model is often used in low -energy region, is taken as weak coupling. If one considers shell model, the Bohr's model is not an applicable and for very high-energy range (>10^3 eV), the incoming particle is moving very fast that target nucleus and the projectile will not interact but with this energy meson production will takes place.

2.1.3 **Pre-equilibrium decay in nuclear reactions**

Incident energies above about 10 MeV, it is possible for a particle emission to take place after the direct stage, the projectile may share its energy among a small number of nucleons which may further interact with other nucleons, and during this cascade of nucleon-nucleon interaction through which the energy of the incident particle is progressively shared among the target nucleons, a particle may be emitted long before the attainment of statistical equilibrium or compound nucleus formation. The process constitutes the third reaction mechanism that we call as pre-equilibrium or some times pre-compound reactions (**3**). The study of pre-equilibrium reaction is of great importance to investigate the mechanism of thermalization of nucleus, i.e. reaching of the statistical equilibrium states.

There are different evidences for the existence of pre-equilibrium decay in nuclear reactions. Some of them are,

i). at lower energies there is a component with an angular distribution symmetric about 90^0, that has a cross-section much greater than that is given by compound nucleus formation.

ii). at its higher energies, the angular distribution of these particles (PE), is forward peaked but lacks the diffraction structure and nuclear structure dependence characteristics of the particle emitted in direct process.

iii). additional evidence for the presence of pre-equilibrium reaction is provided by comparison between the cross-section for the compound nucleus formation (which in the case of proton induced reaction on a heavy nucleus may be estimated from the maxima of excitation function of the (P, *x*n) ; *x*=1, 2, 3... .Where compound nucleus evaporation dominates and the total cross-section calculated from the optical model.

iv). A pre-equilibrium reaction corresponds to the emission of un bound particle from one of the particle-hole states when a composite nucleus is not yet equilibrated. Most pre-equilibrium reactions take place at energies high enough for it to be no longer possible the individual final states.

v). In many other cases the cross-section of pre-equilibrium nuclear reaction is neither purely direct nor compound.

Several semi-classical model, have been proposed for the description of the above observations. These models are,

i. Intra-Nuclear-Cascade(INC) model,
ii. Harp-Miller-Berne(HMB) model,
iii. Exciton model, and
iv. Hybrid\Geometry Dependent Hybrid (GDH) model.

Among these models, the hybrid and geometry dependent hybrid models have been reasonably successful in reproducing a broad range of experimental data. Recently some complex quantum mechanical formalism such as multi-step direct and multi-step compound models has been proposed (**8**). These quantum-mechanical models provides in principle, a way of calculating the cross-sections of pre-equilibrium processes with out the uncertainties of the semi-classical approximations. At present, these models are applicable only for the nucleon induced reactions because, for a complex particle like the alpha - particle the quantum mechanical treatment of the initial projectile-target interaction becomes very complex, we use the computer code ALICE-91(**9**) to compute the excitation functions of the alpha-particle induced reactions for the comparison with the experimental values.

2.1.3.1 Intra-Nuclear-Cascade (INC) model

Intra-nuclear cascade (INC) model was first proposed by Serber in1947 (**10**) for explaining various experimental nuclear reaction data. The first calculation of pre-equilibrium angular distributions was performed with this model using the quasi-free scattering inside the nucleus.

The projectile enters the target nucleus with a given impact parameter "b", after traveling a certain distance inside the nucleus it interacts with a target nucleon and excites it above Fermi Sea. Each scattered particles then travel through the nucleus interacting with the other nucleons. The Intra-nuclear cascade model traces the individual nucleon-nucleon trajectories in three-dimensional geometry. The trajectory of an excited particle

is followed until some arbitrary energy generally considerably above the average equilibrium value has been attained by the nucleon. Particles reaching the nuclear surface with sufficient energy to be emitted are assumed to be emitted. When all particles of a given cascade have been traced, the total energy of the residual nucleus; its density, and the energies and angles of the emitted particles are shared, and a new cascade with new impact parameter is calculated. With the help of such an approach, the time evolution of the reaction can be generated but after few collisions the actual calculations becomes too much complicated. The intra-cascade model is a realistic model but in general, the predictions are not satisfactory at back ward angles and in some forward angles also.

2.1.3.2 Harp-Miller-Berne (HMB) model

The Harp-Miller-Berne model (**4**) is another pre-equilibrium decay model for describing nuclear interaction mechanisms. The nuclear single particle states are classified according to their energies in-group or 'bins' whose size $\Delta\varepsilon$ is chosen to be of some convenient dimension.

In the calculations the fractional occupation of each bin is taken as a function of time. This model calculates the occupation probability of the average state in the 'ith' bin as a function of time using Fermi gas distribution. At the initiation of the reaction, at the time τ_0 all the levels below Fermi energy are filled up (as the target is in ground state), and the projectile is in an excited state. This gives the fractional occupation probability at time $\tau = \tau_0$. Two body interaction the lead to a redistribution of probabilities.

Harp and Miller (**11**) suggested minor modification in the HMB model and they considered the nucleus to be composed of independent proton and neutron Fermi gases. Therefore, the proton and neutron occupation numbers for the single particle states of these gases completely specifies the internal configuration of the nucleus at any time. Further it is also assumed that the mechanism for the equilibrium of gases takes place through binary nucleon-nucleon collisions. Correspondingly a new set of master equation is obtained, the solution of which gives the proton and neutron occupation numbers.

2.1.3.3 Exciton model

The Exciton model was first proposed by Griffin (5) in 1966 for explaining various experimental nuclear reaction data. The equilibrium between target and projectile is achieved by the succession of two body interactions. An excited nucleus is considered, as a gas of quasi- particles that are particle-hole degree of freedom is included, taking into account residual hh, ph, and pp interactions. In Exciton model, the composite nucleus states are characterized by the number of excited particles and holes (the exciton) at any stage of the nucleon -nucleon cascade. The initial configuration is fixed by the nature of the projectile. For instance in the case of a nucleon- induced reactions, it is a two-particle, one-hole (2p,1h) configuration due to the interaction of the incident nucleon with a nucleon of target which is excited from a state below , forming hole at below, to a state above Fermi energy the Fermi energy. Additional two-body interactions give rise to a sequence of states characterized by increasing exciton numbers, eventually leading to a fully equilibrated residual nucleus. Restriction to two- body interactions leads to the following selection rules concerning the possible variation of number of particles (p), holes (h), and excitons (n), n = p + h , in the course of the cascade of interactions. The states that are excited in the course of this interaction cascade are unstable.

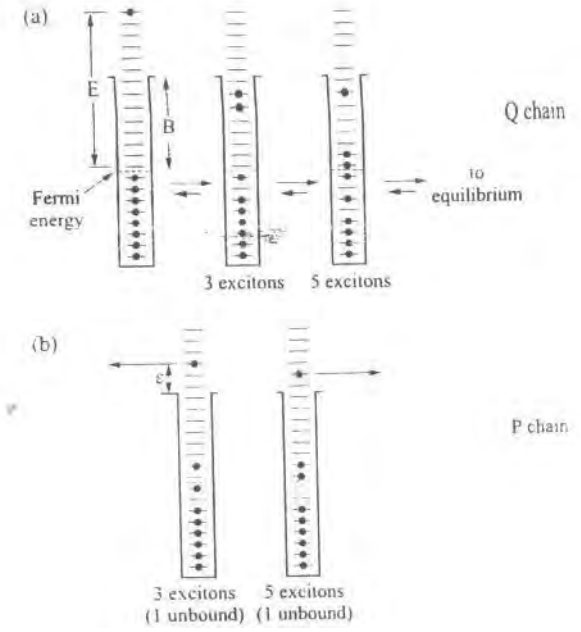


Fig. 2.3 Exciton model

The simple exciton model is illustrated in fig 2.3 above. The nuclear potential is equally spaced single particle levels, that is, levels whose occupancy is either 0 or 1; initially the target nucleus is in ground state. All the levels below the Fermi-energy E_f are filled and all the levels above are vacant. A nucleon is entering a nuclear potential with a given and form a (1p, 0h) state, that is, a state with exciton number, n =1. At this stage, the projectile has entered the nuclear force field but has not been absorbed by the target. It is still in the entrance channel and can leave the nuclear force field with out interacting with any individual target nucleon. Since all the levels below the Fermi energy are filled, the first interaction between the projectile and the target nucleon will raise the target nucleon (the later) above the Fermi energy and leave a hole below; a 2p-1h state is formed. The absorption of the projectile nucleon by the target leads to the formation of n=3 exciton state. After the formation of the n= 3 state, ether of the excited particles may be emitted if it has sufficient energy to escape. If however, particle emission doesn't takes place, the there will be a further two body interaction either between one of the two excited particles and a particle below the Fermi surface or between the two excited particles themselves. The first interaction will result in the formation of n = 5 exciton state, (3p-2h) state, and the second would lead to a new exciton state,(2p,1h) stat having different energy configuration of particles and holes, or back to the original state, (1p-0h) state. Hence a two body interaction will lead to transitions in which the change in the exciton number, delta n = 0, $\pm$ 2.

The exciton model assumes that,

1). at each stage of the cascade all the states with the same configuration and the same total energy are equiprobable, and

2). at each stage the cascade all the processes which may occur are also equiprobable.

2.1.3.4 **The Hybrid\ Geometry Dependent Hybrid (GDH) model**

The hybrid model was first proposed by Blann (**12**) in which some features of HMB model is incorporated. In this model, multi pre-equilibrium particle emission along with equilibrium decay is considered where as the spectra of emitted particles are calculated from each step in the energy dissipation process induced by the interaction between projectile and target nucleons. Through the hybrid model deals with the pre-equilibrium compound emission of nucleons only, pre-compound emission of clusters are out side the purview of this model. The pre-equilibrium emission cross-section of the type 'υ' (nucleon) in the hybrid model is given by

$$\sigma_{PEQ}(\varepsilon) = \sigma_{abs} \sum_{\substack{n=n_0 \\ \Delta n=2}}^{\bar{n}} D_n P_n^{\upsilon}(\varepsilon) \text{ …….(2.13)}$$

Where, $P_n^{\upsilon}(\varepsilon)$ - is the emission probability of' υ 'with energy ε from the n exciton states.

The pre-equilibrium decay probabilities in this model are given by

$$p_{\upsilon}(\varepsilon)d\varepsilon = \sum_{\substack{n=n_0 \\ \Delta n=2}}^{\bar{n}} \left[\frac{x_{\upsilon} N_n(\varepsilon,u)}{N_n(\varepsilon)} \right] g d\varepsilon x \left[\frac{\lambda_c(\varepsilon)}{\lambda_c(\varepsilon)+\lambda_+(\varepsilon)} \right] D_n \text{ ……(2.14)}$$

Where,

$p_{\upsilon}(\varepsilon)$ - is the number of the type υ emitted in to unbound continuum with Channel energy between ε and ε + dε

D_n - represents the average fraction of the initial population surviving to the exciton number being treated.

The quantity in the first set of square brackets represents the number of particles to be found (per MeV) at a given energy ε (with respect to continuum) for all scattering process leading to 'n' exciton configuration. The second set of square brackets represents the fraction of the type particles at energy ε, which should undergo emission in to the continuum, rather than making an intra-nuclear transition.

The hybrid model also calculates the rate of decay ($\lambda_+(\varepsilon)$) from the nucleon-nucleon scattering cross-section, but instead of the experimental cross-section it uses either Kikchi-Kawai calculations or the empirical expression for the two-body interaction rate giving by Blann (**13**) by simplifying the detailed Kikchi-Kawai calculations. The empirical expression is as follows,

$$\lambda_+^n = \left[1.4x10^{21}(\varepsilon+\beta) + 6x10^{18}(\varepsilon+\beta)^2\right]k^{-1} \ldots\ldots\ldots (2.15)$$

Where,

ε - the particle energy out side the nucleus, i.e. ejectile energy

β - its separation energy

K- is an adjustable constant, if K =1, the equation above represents the Kikchi-Kawai interaction rates.

The geometry dependent hybrid model is a variant of the hybrid model in which the nuclear geometry effects are considered. In the hybrid model calculations the nuclear matter density is taken as uniform through out the nucleus, but in geometry dependent hybrid model takes account the reduced matter density and hence also the shallow potential at the nuclear surface. In this way the diffused surface properties sampled by higher impact parameters were incorporated in to the pre-compound decay formation in the geometry dependent hybrid model. There fore differential pre-equilibrium cross-section for particle emission in the GDH model is give by,

$$\frac{d\sigma_\upsilon(E)}{dE} = \pi\lambda\!\!\!^{-2}\sum_{l=0}^{\infty}(2l+1)T_l P_\upsilon(l,\varepsilon) \ldots\ldots\ldots (2.16)$$

Where,

$P_\upsilon(l,\varepsilon)$ -is the same as $P_\upsilon(\varepsilon)$ but evaluated for the l^{th} partial wave.

T_l - is transmission co-efficient for the l^{th} partial wave.

$\lambda\!\!\!^{-}$ - is reduced de-broglie wave length. When the system is equilibrated, it de-excitation is followed by the Weisskopf-Ewing evaporation model,

$\rho(\upsilon)$ - is level density calculated using Fermi gas level density formula.

The nuclear level density distribution in the GDH is given by employing a Fermi density distribution function as,

$$d(R_L) = R_s\left(\frac{\exp(R_l - C)}{(0.55\,fm + 1)}\right)^{-1} \quad \text{..... (2.17)}$$

where,

R_s - is saturation density of nuclear matter

C - is the charge radius by,

C =1.7A$^{1/3}$ fm, taken from electron scattering results.

In the hybrid model the average nuclear density is calculated by the integration and averaging of

$$d(R_l) = R_s\left(\frac{\exp(R_l - C)}{(0.55\,fm + 1)}\right)^{-1}$$, between R=0 and R= C +2.75 fm..... (2.18)

The Fermi energy (ε_f) is assumed to vary as the average density to the third power. The value of ε_f so evaluated, is used in defining the single particle level density "g" for all calculations, hybrid and GDH, as this should be a property of average potential. The single level densities have been defined by (**14**)

$$g_n = \frac{N}{20}\left[\frac{\varepsilon_f + \beta_n + \varepsilon}{\varepsilon_f}\right]^{1/2} \quad \text{..... (2.19), and}$$

$$g_p = \frac{N}{20}\left[\frac{\varepsilon_f + \beta_p + \varepsilon}{\varepsilon_f}\right]^{1/2} \quad \text{..... (2.20)}$$

Chapter Three.
Computer Codes

Several models have been proposed to understand nuclear reaction mechanisms and nuclear structure. A variety of computer codes were developed for the prediction and analysis of various products of compound nucleus decay. These computer codes can now be used to verify the reaction mechanisms, to aid in the identification of compound nucleus formation and decay, to determine angular momenta and to search for non-statistical aspect of nuclear structure at higher excitation energies and higher angular momentum. The type of calculations and computer code may be classified as single-step (SS) calculations and multi- step (MS) calculations. In single-step calculations the excited nucleus has energy sufficient for one decay or it is only the emission of the first particle that is of interest. However, in the case of multi-step calculations the spectra of the gamma rays and high-energy particles contains contribution from successive decays and the distribution of heavy residues is arrived at through several or many successive decays.

I have used the ALICE- 91 computer codes out of various available statistical codes for the calculation of excitation functions and to compare the experimental values with the calculated ones. ALICE- 91 is based on multi-step girded (MSGR) method. In MSGR a grid is constructed in Z and A and, for each nucleus, a population distribution over a two dimensional grid in exciton energy and angular momentum. The size of the grid in Z and A continues to expand for successive daughter nuclei until further decay is energetically for-bidden. The multi-step Monte Carlo (MSMC) method follows the decay of individual compound nuclei in an initial ensemble by Monte Carlo techniques until the residual nucleus can no longer decay. The great advantage of the Monte Carlo method is that it can predict energy spectra, angular distributions and multi particle correlations in laboratory system. The advantage of the usage of multi-step grided method is that, the grid calculation is that the yield of very weakly populated residual nuclei may be calculated with precision. How ever such codes generally do not calculate the angular distributions of emitted particles or residues.

3.1 **ALICE- 91 Computer Code**}

The code ALICE - 91 employs the Weisskopf-Ewing model for the statistical component and hybrid \ geometry dependent hybrid (GDH) models of Blann for pre-equilibrium emission of particles in nuclear reactions. In the equilibrium calculations, the evaporation of proton, neutrons, deuterons, and binding energies for all nuclides of the interest in the evaporation chain have been calculated; using the Myers -wiatecki/Lyseki mass formula (**15**). In this code we have the facility of varying mesh size and there fore the cross-section up to 300Mev x ΔE (ΔE be the mesh size) can be calculated. The residual nuclei of a grid 11 mass units wide by 9 atomic members deep may be calculated. Particle spectra can be selected in the out put, in addition to individual product yields and fission cross sections. The inverse reaction cross-section is calculated from the optical model and some times from classical sharp cut off model. The level densities of nuclide involved in the evaporation chain can be calculated from the Fermi gas model (**12**) as

$$\rho(u) = (U-\delta)^{-5/4} \exp\left(2\sqrt{a(u-\delta)}\right) \ldots\ldots\ldots\ldots \quad (3.1)$$

Where, U- is excitation energy of the nucleus

δ - is pairing term

a - is level density parameter.

a = A/k, A- is nucleon number of the compound nucleus

k- is a constant for which values spread over a wide region.

The level density option due to Kataria/Ramamurthy (**16**) or due to Ignalyuk (**17**) may be selected. The Kataria/Ramamurthy option takes in to account the shell correction. Level density option due to Ignalyuk some work needs to be done on fine-tuning input; it has also shell correction in its operation. The systematic expressions for precompound angular distribution of C.kalbach are considered; these options are much faster than the option based on nucleon-nucleon scattering kinematics, and give better agreement with experimental results.

Precompound angular distributions may be calculated for nucleon induced reactions (input variables are, 'iadst, irfra, imxx'). Gamma ray spectra are given for reactions, and gamma rays compete with nucleon emission. This helps to minimize problems with trapped protons for very proton rich nuclei. The ALICE-91 may be used to calculate for isotopically mixed targets, e.g. natural isotopic compositions. The following summarizes input requirements for the full operation of the program and find best calculated values in order that it fits to experimentally observed results of alpha induced reactions.

ap- projectile mass number

at- target mass number

zp- projectile charge

zt- target charge

qval- reaction q value=ap+at-acn. d=calculated from Myers swiatecki lysek (msl) mass formula.

cld- ratio of single particle level densities åf/an. d =1.0

barfac - scales liquid drop or finite range fission barrier; d=1.

If input parms na, nz, mc, mp are all entered as blank or zero then default will set na =11, nz = 9, mc = 3, and on card(s) 3, jcal = 1(Weisskopf calculation) and geometry dependent hybrid (gdh) Precompound decay, these are suggested for beginners, in this mode, ike = 4 and inver = 2 are also selected.

isot- if isot is non zero, cld will be isotopic abundance; in this mode the isotopic abundances input must sum to 1.00

na - number of nuclides of each z to be included in calculation.

nz - number of z to be calculated in the emission process.

mc - mass option, for separation energies and level density ground state shifts (level density ground state (ldgs) together with mp.

mc = 0, myers swiatecki lysekil (msl) masses incl. shell correction

mc = 1, msl masses without shell correction term (with mp=0 only)

mc = 2, msl masses incl. shell correction, but separation energies and/or ldgs at least partly provided by user.

*** if mc increased by 10, Alice will substitute 1971 gove mass table masses for msl masses where available and (if so selected by mc =11 or mp = 0) subtract pairing or shell correction.

mp – is pairing option.

mp = 0, no pairing term in masses

mp = 1, pairing term in masses, ldgs calculated from msl formula and applied back shifted

mp = 2,as mp=1,but shell correction also included in ldgs

mp = 3, normal pairing shift, zero for odd-even nuclei, delta added to excitation for odd-odd nuclei, etc recommend values mc=10,mp=3

ldopt if zero, Fermi gas level density;

if ldopt = 1, Kataria Ramamurthy formula with shell correction due to difference of experimental mass and liquid drop correction;

if ldopt = 2, Ignalyuk level density.

if ldopt = 3, Gilbert-Cameron level density.

inver –is inverse cross section parameter.

= 0, results supplied by optical model sub-routine,

= 1, user supplies;

= 2, sharp cutoff values each z.

** Option inver = 2 greatly reduces total central Processing Unit (CPU) time.

ike - is energy bin mesh size in Mev

If = 0, no particle spectra will be printed;

If =1, equilibrium spectra for each nuclide will be printed;

If = 2, only pre- compound spectra printed;

If = 3, as 1+2;

If = 4, Precompound spectra will be printed as well as the sum (over all emitting nuclides and all partial waves) of Precompound plus equilibrium spectra.

****** to print gamma spectra, increase ike value Selected by 5.

ipch if ipch =1 or =2,fission barriers may be read in after card number 1 as bexp (ia,iz),one card for each barriers are independent of angular momentum for ipch=1, and are scaled as rldm barriers for ipch=2.

** this option should be used with care as abuses are not disallowed.

pld- is level density parameter ‘a’, a = acn/pld. a = acn/8, a = acn/9 and a = acn/10,

kplt- if kplt is 1 and the last energy input line is followed by -1.

in column 1-5, excitation functions will be plotted on standard output.

Note that kplt and m3 are not in five-column format. m3 – is number and type of particles to be emitted from each nuclide.

If m3 = 1 for neutrons only

= 2 for neutrons and protons

= 3 for neutrons, protons, and alphas

= 4 for neutrons, protons, alphas, and deuterons

When m3 = 3 is default value recommend pld = 0, kplt = 0, m3 = 0, blank = 0

Card 2 title card-80 columns

1. If mc=2 or 12 on card 1, read user supplied n, p, alpha, Deuteron binding energies and/or ldgs here, one line per nuclide, order ((ia=1,na+2),iz=1,nz+2)when ever non zero n binding energy is detected, alice will use user provided binding energies for this nuclide, same convention for ldgs.
2. If inver =1 on card 1, read n, p, alpha, deuteron inverse cross sections here, in ascending channel energy,1st value for 0.1 MeV channel energy, then up in 1 MeV steps, 48 values for each particle type, sequence n, p, alpha, deuteron.

Card. 3 energy/options card.

this card (and card(s)4 if selected)is repeated for each energy for a given target + projectile

If the na, nz, mc, mp = 0 default mode was used on card 1, enter only ex. on this card.

eq1. Projectile kinetic energy in the laboratory system.

if=0, a new problem will begin at card 1.

if=-1, previously calculated excitation functions will be plotted, if kplt = 1 was selected and if eq values were run in ascending order if eq = 0 on two successive cards, a normal exit will occur.

rcss- is reaction cross section. If left blank, the reactions cross section will be internally generated by the optical model subroutine for incident n or p, and by the parabolic model routine for all other projectiles. If rcss is read in, this value entered for rcss will be used. If a geometry dependent hybrid model and/or fission calculation is selected, and if one wishes to enter transmission coefficient for entrance channel, then the negative of the number of t(l) to be read must be entered for rcss; the t(l) will then be read on card(s)4

iadst If = 0, no angular distribution,

If = 1, yes-for neutrons;

= 2, yes for protons;

= 3, for neutrons using Kalbach systematics;

= 4, for protons using Kalbach systematics

irfr- choice for refraction with angular distributions

If irfr = 0, no refraction

If irfr = 1/2, entrance channel refraction

If irfr =3, Heisenberg entrance and exit refraction

If irfr = 2**,** std entrance refraction and Heisenberg exit channel

i3d – If = 0, three dimensional folding for angular distribution, else2-D

jcal- is i2 14 type of calculation option.

jcal = 1**,** weisskopf-ewing evaporation calculation

jcal = 2, s-wave approximation, liquid drop moment of inertia

jcal = 3, s-wave approximation, rigid body moment of inertia (only if entrance channel cross sections calculated by parap, i.e. zp.gt1.and.rcss.eq.0.)

jcal = 0, evaporation-fission competition, partial wave by partial wave

** If fission is to be calculated using zero barrier for all j.gt.jcrit, increase jcal by 10.

adist-energy increment for calculating angular distributions (f3.0) if adist =1**,** default value is 5 MeV.

Jfrac - if a fission calculation is to be only in a specified angular momentum range, this is the lower limit.

Jupper- is upper limit of angular momentum, if the range is to be restricted

jang - is option of emitted particles decreasing angular momentum. If = 1, yes; If = 0, no.

1. If jang is greater than 100 (less than 200) loop over angular momenta will be for increments of jang-100 and ħo 'option on removal of angular momentum holds. if jang is greater than 200, delta l ẏes 'option holds, and loop is incremented by jang-200, use jang.gt.100 with jcal = 0 and td = 0 only

All additional parameters on this card are for pre compound option, leave remaining columns blank if no pre compound calculation selected

1. If 'td' is positive and 'ex1' and 'ex2' are blank, default parameters will be selected. The gdo option may still be selected. for default pre compound hybrid model, use td =1, remaining variables zero for gdh calculation, enter td=1,tmx=1,and leave all other variables after td blank.

td-initial exciton number = p+h.

ex1-initial excited neutron number.

ex2-initial excited proton number.

tmx-if = 0 hybrid model, if eq.1, gdh.

av - If av = 0, optical model transition rates; these values should not be used above 55 MeV.

2. If av =1, nucleon-nucleon mean free paths are used.

'gav'-No longer used

3. Cost –is mean free paths are multiplied by cost+1.
4. gdo - If =1, 'gdh' calculation (if any) restricted to initial exciton number, hybrid calc. for higher exciton numbers.
5. ij- If ij=1, isospin pre compound option is selected.

if so, the next card ℨa 'will be containing (p,n)q values qpn (1),qpn (2),and qpnc, qpnc is (p,n) q value for making compound nucleus by a (p,n) reaction; qpn(i) is for nucleus populated by emission of particle i,1= n,2 = p.

qpnc = bp (at+ap+1,zt+zp)-bn (same),and

qpn (1) = (bp-bn) of (at+ap,zt+zp),and

qpn (2) = (bp-bn) of (at+ap,zt+zp-1)

Card. 4 entrance Channel

Transmission coefficients t (l), needed only, if rcss.lt.0, alice will try to read as many t(l) as indicated by the absolute value of rcss (i.e. it may expect several cards here).

In Alice-91 computer code to calculate all the calculations internally, so the core of the computer is divided in to chart of nuclides. The compound nucleus that is formed at some excitation energy and with some cross-section uses Weisskopf calculation with 1Mev grid size to perform the evaporation of neutron, proton, alpha and deuteron storing the residual nucleus population in to the appropriate bin.

The control then moves over to the A-1 bin if neutron emission, from the compound nucleus. This bin can also be resulted with the emission of proton, deuteron, and alpha particles. The residual nuclei obtained from the emission of aforesaid particles are stored in the respective bins. The code uses the number of mill barns in the highest energy in (A-1) and redistributes that cross-section in the same manner. After this the control comes down to the next residual excitation and the process continues up to the moment all the cross-sections redistributed and summed it in the appropriate bins of residual nuclides. This logic is repeated going across the A as far as requested by an input parameter. After this the control comes down in z to the nucleus A-1, z-1 and repeats the process till all calculations are not completed for each input parameter.

Chapter Four

Experimental techniques for measurement of excitation function

When we study about the alpha induced reactions, measuring the excitation function is its central idea. In order to measure the excitation function of the reactions we the stacked foil activation technique (**18**) can be used. The stacked foil activation technique makes use of stack target foils with aluminum degrader foils that are irradiated with alpha particle beam obtained from accelerator. The experimental result, that I used to compare with the theoretically calculated result, were taken from EXFOR, IAEA Vienna (**19**) measured using different accelerators viz Cyclotron, Pelletron etc. During the experiment numbers of reactions are observed by identifying the characteristic gamma rays obtained from the decay of the various residual nuclei produced. The principle of this technique is to analyze the activity of residual nucleus obtained from a particular reaction. This technique is OFF-Beam technique; similarly one can use In-Beam technique in which experiment is performed during irradiation of the sample.

4.1 **Formulation**

The expression for the cross-section of a nuclear reaction may be written from the consideration of decay rate equation governing the nuclear transformation and decay of the activated product. If a target is irradiated by a projectile of constant flux ϕ, then the rate of production R_p can be written as,

$$R_p = \sigma \phi N_0 \quad \ldots\ldots\ldots \quad (4.1)$$

Where,

σ - is activation cross-section,

N_0 - is the number of target nuclei of isotope under investigation present in the sample, in my case, 191-Ir and 193-Ir

The expression for N_0 can be given as,

$$N_0 = \frac{mNf}{A_0} \quad \text{…….. (4.2)}$$

Where,

m- is the mass of the sample,

N- is Avogadro's number, and

f- is the abundance of the isotope in the target.

Let t_1 – be the time of irradiation of the target by a constant flux incident beam to produce a radio active reaction product R. The equation that governs the growth of activity during production can be written as,

$$\frac{dR}{dt} = \sigma\phi N_0 - R\lambda \quad \text{……. (4.3)}$$

Where,

λ - is decay constant

R- type of activated nuclei, R is the number of radioactive atoms present.

The activity of R type nuclei at the instant of stopping the irradiation is given by,

$$W = R\lambda$$

$$W = \sigma\phi N_0\left[1 - \exp(-\lambda t_1\right] \text{……. (4. 4)}$$

The term $\left[1 - \exp(-\lambda t_1\right]$ is called the saturation factor of the reaction.

If the activity of radioactive nucleus R is measured after a time "t'" from the time stopping irradiation, then it will be given by,

$$\frac{dR}{dt'} = W\exp(-\lambda t')$$

$$dR = \sigma\phi N_0\left[1 - \exp(-\lambda t_1)\right]\exp(-\lambda t')dt' \text{,.....(4.5)}$$

If ‘D’ be the actual number of disintegrations of the sample during a time period of t_3 starting after a time t_2 from the stop of irradiation, then DA can be obtained by integrating ‘dR’ with respect to time limits of t_2 to $t_2 + t_3$.

$$DA = \int_{t2}^{t2+t3} dR$$

$$DA = \frac{\sigma\phi N_0 [1-\exp(-\lambda t_1)][(1-\exp(-\lambda t_3))]}{\lambda \exp(-\lambda t_2)}, \text{.....(4.6)}$$

If ‘A’ is the number of counts observed by the detector during the time interval ‘t_3’, ‘Gε’ is geometry dependent detector efficiency of the detector ,’θ’ is the absolute intensity of the particular gamma ray and ‘k’ is the self absorption correction factor of the gamma ray in disc shaped target, which is given as the

$$k = \frac{[1-\exp(-\mu d)]}{\mu d}, \text{ …… (4.7)}$$

Where,

μ - is gamma ray absorption coefficient

d - is thickness of target under investigation for my case, 191-Ir and 193-Ir

Then the actual number of disintegration DA will be given as,

$$DA = \frac{A}{G\varepsilon.\theta.k}, \text{……. (4.8)}$$

Relating equations (4.6) and (4.8), the activation cross-section of a nuclear reaction will be

$$\sigma = \frac{A\lambda \exp(-\lambda t_2)}{\phi N_0 [1-\exp(-\lambda t_1)][(1-\exp(-\lambda t_3))] G\varepsilon.\theta.k} \text{…….. (4.9)}$$

This expression has been widely used to calculate the activation cross-section for the alpha induced reactions on different isotopes (**18**).

4.2 **Experimental results**

The experimental value based on the EXFOR data library are given in average in order to include all the experimentally measured values obtained by different experimentalist (**19**) and I extrapolated the measured values in order to compare with theoretically calculated values. All reactions have the same residues, which differ by their half-life, mode of decay, energy of emitted gamma rays, etc. The residue of all reactions of alpha particle nucleus with the nucleus of ^{191}Ir and ^{193}Ir are given in the following table 4.1 (**20**).

Residue of rxns.		Produced by	Mode of decay	Half-life	E_γ (MeV)
^{194}Au		^{191}Ir (α, n) ^{191}Ir (α, n)	EC, β	39.5h	0.327, 0.291, 0.64
^{193}Au	^{193}Au	^{191}Ir (α, n)	EC	16h	0.112, 0.173, 0.186
	^{193m}Au	^{191}Ir (α, n)	IT	3.8s	0.257, 0.032
^{192}Au		^{191}Ir (α, n) ^{191}Ir (α, n)	EC, β	4.7h	0.317, 0.296
^{191}Au		^{191}Ir (α, n)	EC	3.0h	0.3, 0.14, 0.60
^{190}Au		^{191}Ir (α, n)	EC, β	42min	4.0

Table 4.1 Sources, mode of decay, half-life and energies of emitted gamma rays.

The reaction products or the residue of nuclear reactions ^{191}Ir (α, n), ^{191}Ir (α, $2n$), ^{91}Ir (α,$3n$),^{191}Ir (α,$4n$), ^{191}Ir (α,$5n$),^{193}Ir (α, $3n$), ^{193}Ir (α, $4n$), and ^{193}Ir α, $5n$), are shown in table 4.1 above. In the reaction ^{191}Ir (α,n) and ^{193}Ir $(\alpha,3n)$, ^{191}Ir $(\alpha,2n)$ and ^{193}Ir $(\alpha,4n)$, ^{191}Ir $(\alpha,3n)$ and ^{193}Ir $(\alpha,5n)$, the product nuclei is the same, so all the decay parameters are the same and differ in half-life, mode of decay, energies of emitted particle, etc. As a result, the observed activity in the irradiated sample is the composite activity due to the reactions in the same set, for example, below the threshold of ^{193}Ir $(\alpha,5n)$,the observed activity is due to the ^{191}Ir $(\alpha,3n)$ reaction only, but beyond it, the observed activity will be the total of the activities produced due to these two reactions. In this over lapping region the cross-section are divided in the ratio of the theoretical cross-section of these two reactions. In the reactions ^{191}Ir (α,n) and ^{193}Ir $(\alpha,3n)$, ^{191}Ir $(\alpha,2n)$ and ^{193}Ir $(\alpha,4n)$, ^{191}Ir $(\alpha,3n)$ and ^{193}Ir $(\alpha,5n)$, the product nuclei have one or more isomeric states other than the ground state. In all cases the half-lives of the isomeric states are very short (sec/msec), so the contribution of these to the excitation function could not be measured distinguishably due to a long cooling time because the high activity was there. But, these isomeric states decay to the ground state, so the total excitation functions were measured.

Chapter Five

Calculations for various (α, *x*n) reactions on Iridium

The excitation function calculations were done for the compound nucleus reaction and Pre-equilibrium nuclear reaction. Weisskopf-Ewing option is used for the compound nucleus reaction, and the GDH model was used for analyzing the pre-equilibrium nuclear reaction. For performing these calculations ALICE -91-computer code is used. The statistical model part of alice-91 can account a large variety of reaction types, clusters of alpha particles can be considered according to Weisskopf-Ewing option.

The theoretical calculation is done taking at the first the initial exciton number n_0 = 4 with configuration (2n+2p+0h), pld-the level density parameter, $A = \frac{acn}{pld}$) = 10.0 Later the values of the parameters are changed to see the effect on calculated values of excitation functions.

The calculated excitation functions for the reactions ^{191}Ir (α, n), ^{191}Ir (α, 2n), ^{191}Ir (α, 3n), ^{191}Ir (α, 4n), ^{191}Ir (α, 5n), ^{193}Ir (α, 3n), ^{193}Ir (α, 4n) and ^{193}Ir (α, 5n) are shown in Figs. 5.1-5.8 below.

5.1 comparisons of calculated results with experimental values

Almost all the experimentally measured values and the theoretically calculated values of excitation functions of pre-compound nuclear reaction on iridium are comparable or exactly fits to each other. But the theoretically calculated compound nucleus reaction excitation functions are far apart from the experimentally measured values and instead of forming a long tail they falls rapidly in almost all reactions. The comparisons of the three excitation functions is done using nearly comparable energy range of the projectile, from 17Mev to 55Mev, assigning for the energy size of the theoretically calculated values in such a way that it crossponds to the experimentally used energy ranges to make the comparison process simple. All excitation functions are given on the same co-ordinate in fig. 5.1-5.8 below.

1. **^{191}Ir (α, n)**

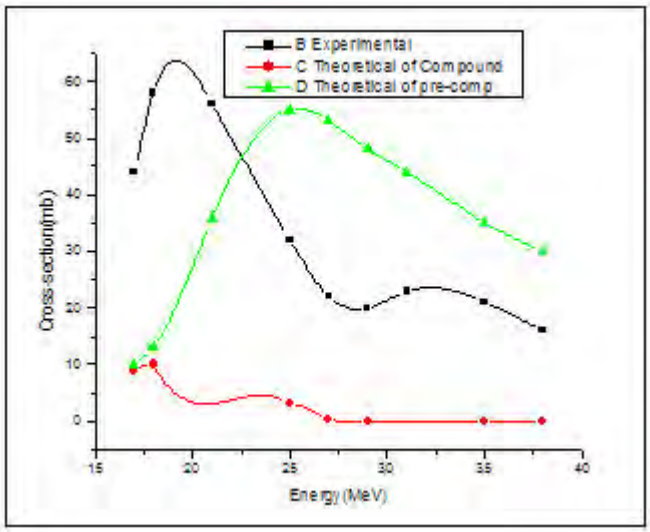


Fig.5.1 Graph showing excitation function of ^{191}Ir (α, n)

B. Experimental

C. Theoretical of compound nuclear reaction

D. Theoretical of pre-compound nuclear reaction

The calculated pre-compound reaction cross-section values starts from the bottom of the assigned value of energy of the projectile at about 17MeV with 10mb and reaches its maximum peak at about 25MeV with 55mb and starts to fall down for increasing value of energy of projectile. Experimental result shows the excitation function starts at about minimum energy of projectile and reaches its maximum peak and then falls with the increasing energy of projectile making a long tail. The calculated value of pre-compound excitation function fit with the experimentally measured values. But the calculated excitation function of compound nuclear reaction excitation function are low and falls rapidly with out making a long tail and hence it doesn't with fit the experimental result.

2. **^{191}Ir (α, 2n)**

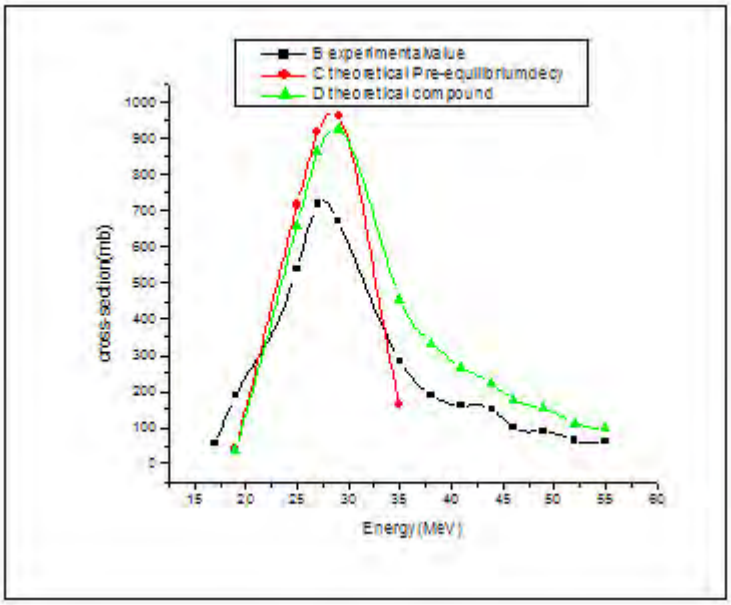


Fig.5.2 Graph showing excitation function of ^{191}Ir (α,2n)

B. Experimental

C. Theoretical of compound nuclear reaction

D. Theoretical of pre-compound nuclear reaction

From the theoretical calculations done by alice-91 computer code, the reaction cross-section of pre-compound nuclear reaction values starts at energy of the projectile about 19MeV with 40mb and reaches its maximum peak at energy about 29MeV with 925mb and then falls down by making a long tail for increasing value of energy of projectile. From the experimental result we observe the reaction cross-section values starts at about minimum energy of projectile and reaching its maximum peak it falls down by making a long tail for the higher energy of projectile. When we compare the experimental and pre-compound nuclear reaction excitation functions, they resemble and the two functions fit exactly, but the compound nucleus reaction excitation function differs and it doesn't fit the experimental result.

3. **^{191}Ir (α, 3n)**

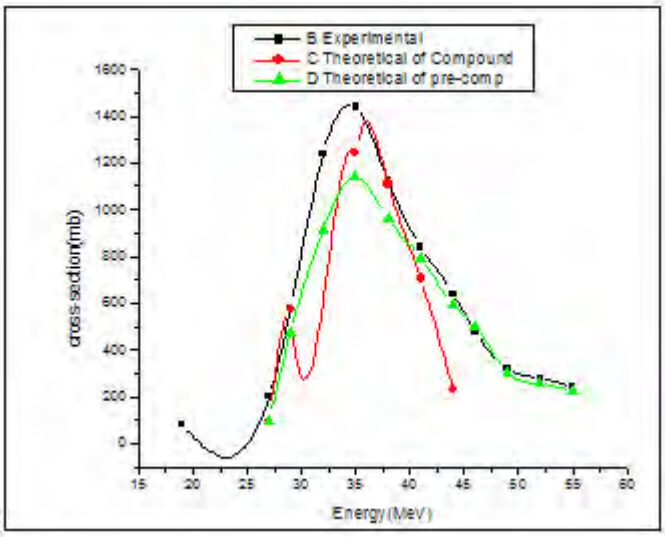


Fig.5.3 Graph showing excitation function of ^{191}Ir (α,3n)

B. Experimental

C. Theoretical of compound nuclear reaction

D. Theoretical of pre-compound nuclear reaction

The calculations of pre-compound nuclear reaction excitation function shows that, it starts at about energy of 32MeV with 689mb and reaches its maximum peak at energy about 38MeV with 1100mb and then falls down for increasing value of energy forming a long tail. The pre-compound excitation function have similar feature with the experimental result, but the calculated excitation function of compound nucleus reaction differs from the experimental excitation function in pre-equilibrium region and hence it doesn't fit with the experimental results..

4. **^{191}Ir (α, 4n)**

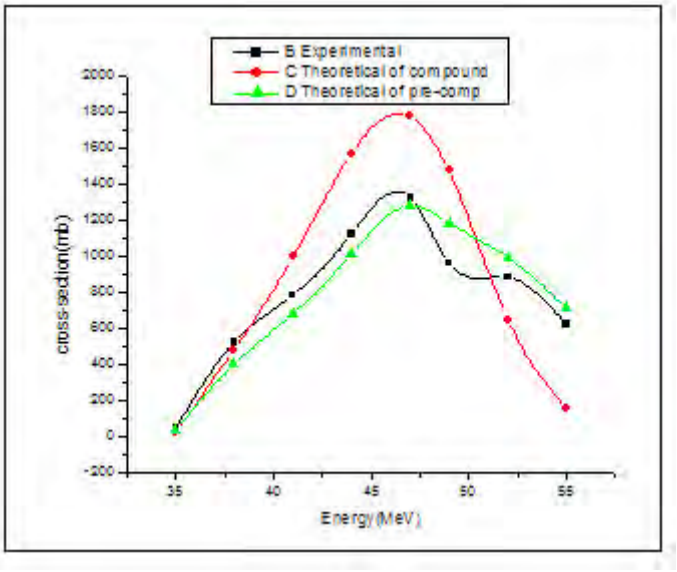


Fig.5.4 Graph showing excitation function of ^{191}Ir (α,4n)

B. Experimental

C. Theoretical of compound nuclear reaction

D. Theoretical of pre-compound nuclear reaction

The pre-compound nuclear reaction excitation function calculations, it starts at energy about 38MeV with 123mb and reaches the maximum peak at energy about 49MeV with 1270mb and the falls for some values of projectile's energy. Experimentally the excitation function of this reaction reaches its maximum from minimum value then falls with the increasing energy of projectile forming a long tail. The calculated value and experimentally measured value of excitation functions fits exactly for different values of projectiles energy. But the calculated excitation function of compound nucleus reaction falls for their maximum peak with out making a long tail and hence it doesn't fit the experimental result

5. **^{191}Ir (α, 5n)**

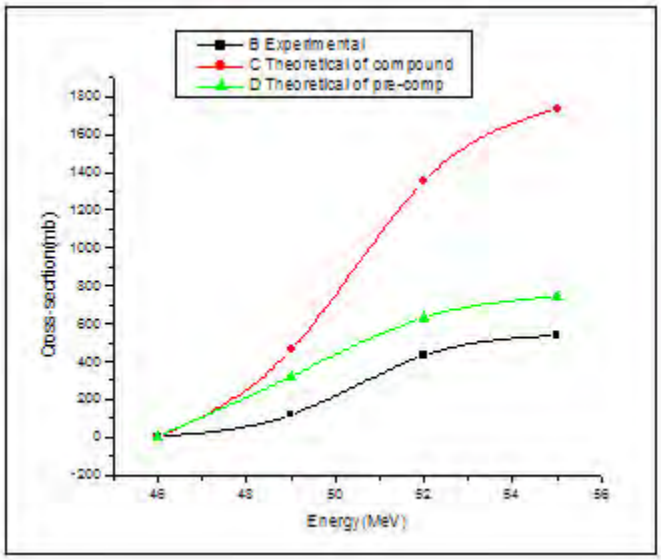


Fig.5.5 Graph showing excitation function of ^{191}Ir (α,5n)

B. Experimental

C. Theoretical of compound nuclear reaction

D. Theoretical of pre-compound nuclear reaction

The theoretical calculation of pre-compound nuclear reaction, the excitation function values starts at energy of projectile enegy about 49Mev with 61mb and reaches its maximum peak and the falls down with increasing energy of projectile. The pre-compound nuclear reaction excitation function fits with the experimental excitation function for which calculated excitation function of compound nuclear reaction doesn't fit with the experimental result.

6. **^{193}Ir (α, 3n)**

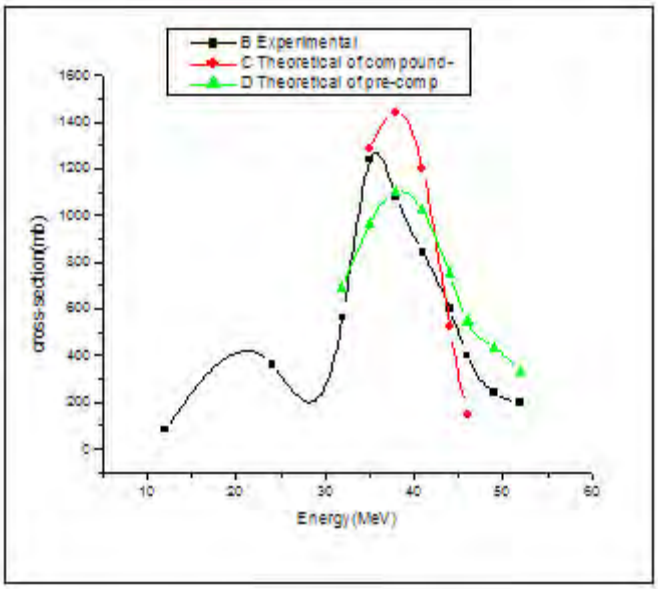


Fig.5.6 Graph showing excitation function of ^{193}Ir (α,3n)

B. Experimental

C. Theoretical of compound nuclear reaction

D. Theoretical of pre-compound nuclear reaction

The excitation function of pre-compound nuclear reaction starts at energy about 27Mev with 99mb and reaches its maximum peak value at energy about 35MeV with 1140mb and the falls down for some increasing energy of projectile forming a long tail. The pre-compound nuclear reaction excitation function fits exactly with the experimental excitation function. But the calculated excitation function of compound reaction falls rapidly with out making a long tail indicating that it differs from the experimental results.

7. **^{193}Ir (α, 4n)**

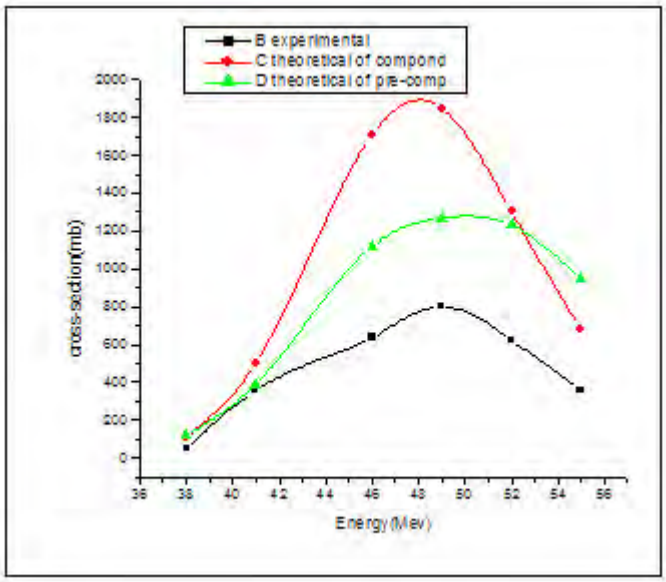


Fig.5.7 Graph showing excitation function of ^{193}Ir (α,4n)

B. Experimental

C. Theoretical of compound nuclear reaction

D. Theoretical of pre-compound nuclear reaction

The theoretically calculated value of pre-compound nuclear reaction excitation function of this nuclear reaction starts at energy about 35MeV with 31mb and reaches its maximum value of reaction cross-section at energy about 47MeV with 1280mb and then falls for the other higher energies of projectile. The excitation function of pre-compound nuclear reaction resemble with the experimental function. The theoretical excitation function of compound nuclear reaction differs and it doesn't fit the experimental results.

8. **^{193}Ir (α, 5n)**

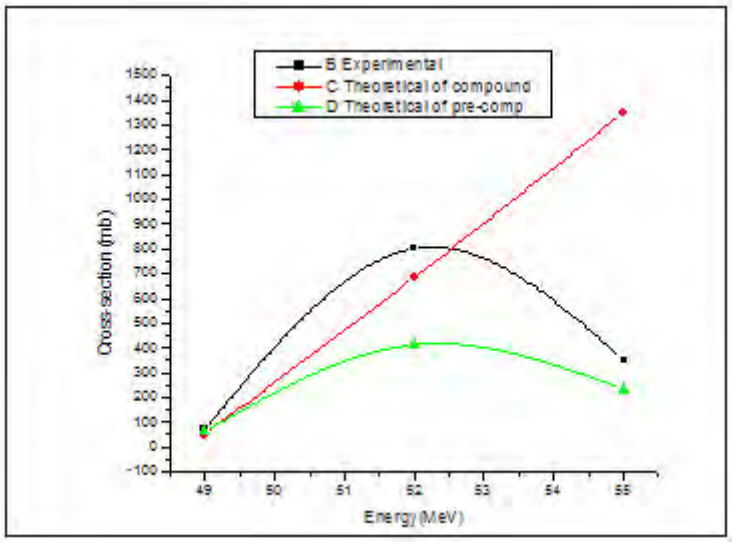


Fig.5.8 Graph showing excitation function of ^{193}Ir (α,5n)

B. Experimental

C. Theoretical of compound nuclear reaction

D. Theoretical of pre-compound nuclear reaction

The theoretically calculated excitation function of pre-compound nuclear reaction and experimental excitation function are of the same form for which the compound nucleus reaction cross-section differs from them. Hence the compound nucleus excitation function is un able to explain the long tail of pre-compound reactions seen experimentally and it doesn't fit with the experimentally seen results.

The changing of PLD-the level density parameter in calculating excitation functions of nuclear reaction have no appreciable effect , but the change of exciton number (n_0) has a considerable change on excitation function of nuclear reactions. The variation in excitation function with PLD and n0 is given in figs. 5.9- 5.12 below.

The relation of excitation function and the level density parameter (pld) is shown in figs.5.9- 5.10, considering the nuclear reaction of ^{191}Ir (α, 2n), below.

a) **For pld =** $\frac{A}{9}$

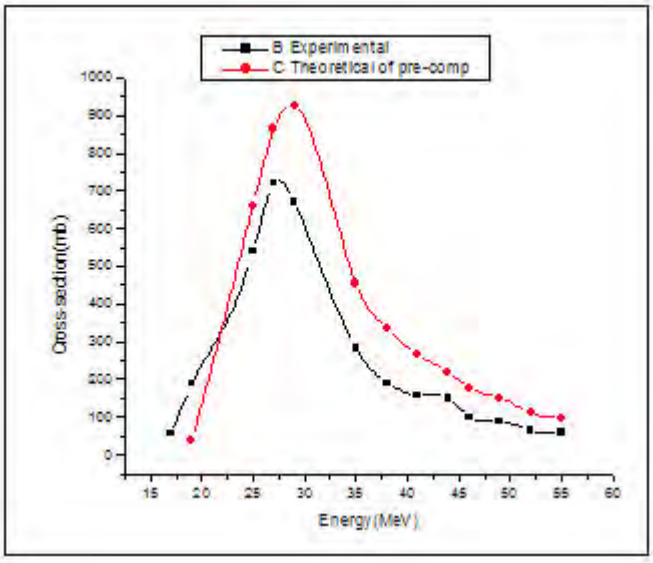


Fig 5.9.Experimental and theoretical excitation functions

B. Extrapolated experimental values of ^{191}Ir (α, 2n)

C. Theoretically calculated value for pld = $\frac{A}{9}$

b) For **pld** = $\frac{A}{10}$

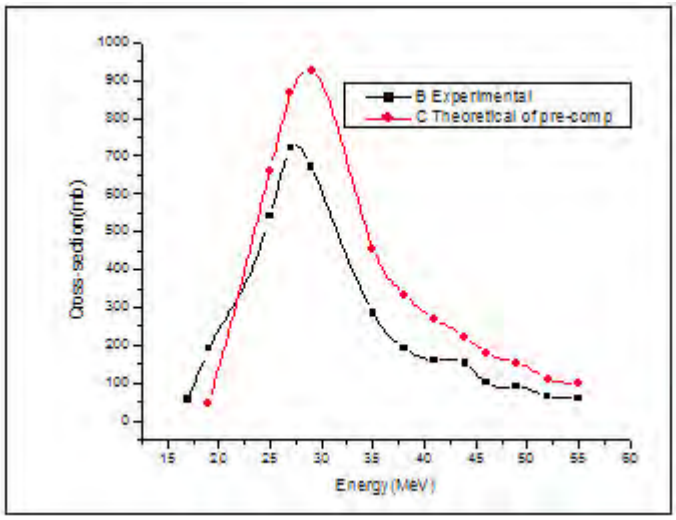


Fig 5.10 Experimental and theoretical excitation functions

B. Extrapolated experimental values of ^{191}Ir (α, 2n)

C. Theoretically calculated value for pld = $\frac{A}{10}$

The relation of excitation function and exciton number is shown again using the ^{191}Ir (α, 2n) as follows in figure 5.11-5.12.

a) **For n_0 = 4 (2p+2n+0h)**

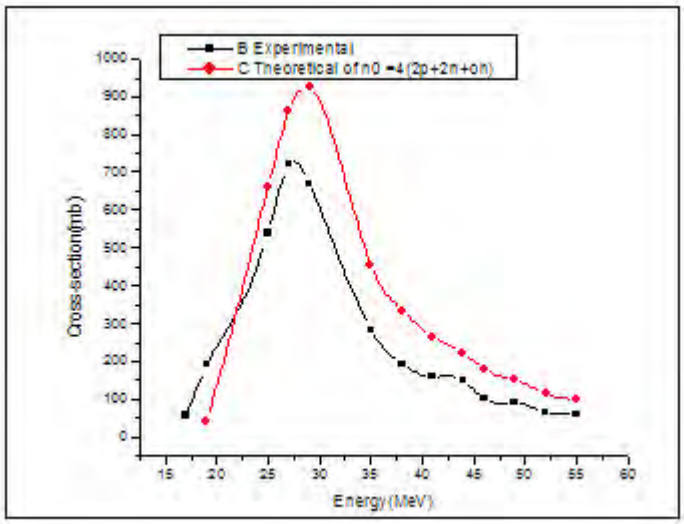


Fig 5.11 Experimental and theoretical excitation functions for exciton number = 4

B. Extrapolated experimental values of ^{191}Ir (α, 2n)

C. Theoretically calculated value for n_o= 4

b) **For n_0 = 6 (3p+2n+1h)**

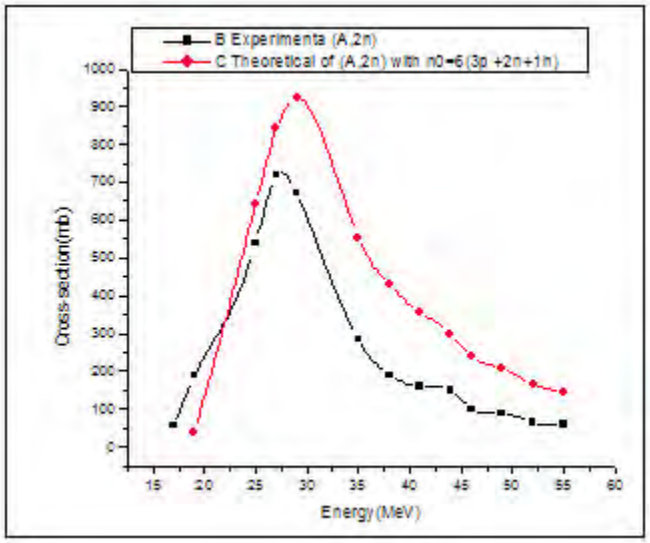


Fig 5.12 Experimental and theoretical excitation functions for exciton number = 6

B. Extrapolated experimental values of ^{191}Ir (α, 2n)

C. Theoretically calculated value for n_o= 6

5.2. **Conclusion**

The excitation functions of the eight alpha induced reactions on ^{191}Ir and ^{193}Ir were calculated. The calculated values from the geometry dependent hybrid model of pre-compound nuclear reaction agrees with the experimentally measured excitation functions of alpha induced reaction on iridium . The theoretical and experimental results have no appreciable change with the variation of 'pld' values, especially in pre-equilibrium region. But the theoretical excitation function values changes considerably with the change of exciton number, showing that the excitation function dependence on the exciton number. In my calculation of excitation function of alpha induced reactions on iridium, the choice of a four-exciton state (2n+2p+0h) for the initial configuration of the pre-compound system gives satisfactory result that really matches with the experimental results. In the long tail portion of the excitation functions, the Weisskopf-Ewing model calculations are not in the agreement and this is due to the existence of the pre-compound nuclear reaction in the decay process. Hence the long tail of excitation function of nuclear reaction shows the pre-compound nuclear reaction.

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