Study of Some $\alpha+ {}^{59}Co$ Systems Using Compound and Pre-compound Nucleus Theory

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By
WUBISHET GEZAHEGN WOLDEGIORGIS

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ADDIS ABABA UNIVERSITY
DEPARTMENT OF
PHYSICS

The undersigned hereby certify that they have read and recommend to the School of Graduate Studies for acceptance a thesis entitled "**Study of Some $\alpha+$ ^{59}Co Systems Using Compound and Pre-compound Nucleus Theory** " by **Wubishet Gezahegn W0ldegiorgis** in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN PHYSICS**.

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Advisor: Prof.A.K.Chaubey _____

Examiner: Dr.Tilahun Tesfaye _____

Examiner: Prof.B.S.Reddy _____

Chairman: Dr.Gizaw _____

ADDIS ABABA UNIVERSITY

Date: **JUNE 2011**

Author: **Wubishet Gezahegn Woldegiorgis**

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Addis Ababa University Wubishet Gezahegn Woldegiorgis

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Abstract

In this work alpha induced reaction on cobalt(^{59}Co) in the energy range of 10 to 80 Mev have been demonstrated. Excitation function for three reactions of the type $^{59}Co(\alpha, n)^{62}Cu$, $^{59}Co(\alpha, 2n)^{61}Cu$, $^{59}Co(\alpha, 3n)^{60}Cu$ were studied. For theoretical excitation function computer code COMPLET have been used. High energy parts of the excitation functions are dominated by pre-equilibrium reaction mechanism where as the low energy parts are dominated by compound nucleus reaction mechanism with its characteristic peak.

Introduction

The study of nuclear reactions induced by alpha particle has again attracted the attention of nuclear physicists. One of the main reasons for this is the requirement of precise nuclear data needed for the development of recently proposed Accelerator Driven Sub-critical (ADS) reactors [1]. Further, the data also have verity of applications including the field of medical sciences, environmental sciences, transmutation of nuclear waste etc. One of the important aim of the study of such reactions is to enhance the basic understanding of the reaction mechanism. The evaluation of the cross section is one of the main tasks in the field of low energy nuclear reactions. These reactions are described by different models which depends on the energy of the projectiles. The most investigated range of energies is [0,200] Mev. In this range one can distinguish three classes of reactions up on the time required for production. The fastest are called direct reactions and the slowest are the reactions giving rise to a compound nucleus. Between these extreme processes there are the pre-equilibrium reactions. To calculate the cross sections in the model of compound nucleus and in pre-equilibrium models,one of the most important ingredients is the level density. There are indications that compound and pre-compound reaction processes play an important role at moderate excitation energies. The nuclear data for the accelerator driven technologies are required for a large number of the target elements covering almost entire periodic table over a wide range of energies. As such, more detailed and accurate measurements are needed to fulfill this requirement of data. The nuclear data required for these applications are obtained mainly from the nuclear scattering and from the reaction model calculations, which depend on the optical models,

whose parameters are determined by elastic scattering and the total cross-section data. Efforts have been made to obtain the estimates of basic nuclear reaction cross-sections both experimentally as well as theoretically. Though, considerable data is available in cross-section data taken by high resolution detectors of better efficiency. It may not be out of place to mention that theoretically it may be possible to explain the measured excitation function (EFs) for a given reaction channel individually using a certain theoretical code. However, a consistent analysis requires reproduction of excitation function for all open channels simultaneous using the same code. Fitting of excitation function for an individual channel may improve the description of the data for the partial channel at the cost of other open channels however, it is unacceptable from the point of view of physics. Several phenomenological as well as quantum-mechanical models have been launched to explain the pre-equilibrium (PE) reaction mechanism. All these models describe the method by in which projectile energy gradually gets redistributed among the constituent nucleons of the composite system through a series of residual two-body interactions. It is interesting to obtain in the analysis, simultaneously, a best description of all existing experimental data for all open channels, as this approach is considered to be internally consistent, detailed and complete. Several models like ALICE-91 , CASCADE , PACE4 , ACT , COMPLET[2] etc., are available and are generally used for theoretical calculations of EFs for light and heavy-ion induced reactions. In all the codes except ACT , the configuration of the codes is such that they predict the total cross-section only for the population of t"he residual nuclei. In the present work, the code COMPLET based on same philosophy as the former code INDEX has been used in the present work using consistently the same set of parameters. At moderate excitation energies, reactions induced by nucleons and light-heavy ions are found to proceed through CN as well as PE emission . As such, precise measurement of EFs for such cases and their analysis may be used to find out the relative contribution of equilibrium and PE processes. With a view to provide a large set of cross-section data and to study the mechanism of PE emission, a pro

gramme of precise measurement and analysis of cross-sections for proton, alpha-particles and heavy-ion induced reactions has been undertaken. These measurements may provide a broad database for testing the capability of theoretical model codes with respect to calculating ratio-isotope production. The formulation and computer codes are given in section 3, while the details of result and discussion of alpha induced reaction on cobalt i.e ${}^{59}_{27}Co(\alpha,n)^{62}_{29}Cu$, ${}^{59}_{27}Co(\alpha,2n)^{61}_{29}Cu$, ${}^{59}_{27}Co(\alpha,3n)^{60}_{29}Cu$ are given in section 4 of the paper.

Chapter 1

1.1 FUNDAMENTALS OF NUCLEAR REACTION

One important field of research to understand nuclear physics is study of nuclear reactions. Nuclear reaction is a process that occurs when a nuclear particle (nucleon or nucleus) gets in to close contact with another. Most of the known nuclear reactions are produced by exposing different materials to a beam of accelerated nuclear particles. Usually a strong energy and momentum exchange takes place and the final products of the reaction are one, two or more nuclear particles leaving the point of close contact in various directions[3]. The products are mostly of a species different from the particles in the original pair. Typically, a nuclear reaction occurs between an energetic reaction partner, called the projectile or bombarding particle,and one that is at rest, called the target, some particles are emitted. Nuclear reactions can be written down in a manner similar to chemical reaction equations. If a target nucleus X is bombarded by particle a and results in a nucleus Y with emitted particle b, this is commonly written in one of two ways[4].

$$a + X \rightarrow Y + b \qquad\qquad or X(a,b)Y \tag{1.1.1}$$

The first study of nuclear reaction was performed by Rutherford in 1919. He used alpha particle emitted in the decay of ^{214}Po to transform ^{14}N to ^{17}O by the reaction

$$^{14}_{7}N +^{4}_{2} He \longrightarrow^{17}_{8} O +^{1}_{1} H \tag{1.1.2}$$

In more compact notation, this reaction rewritten as

$$^{14}_{7}N(\alpha,p)^{17}_{8}O \tag{1.1.3}$$

And 1939, when fission was discovered (Hahn and strassman, Meitner and Frisch), nearly all known nuclear processes which could be initiated with bombarding energies up to approximetly 10 Mev were found. Since then, bombarding energies have been extended to roughly 10 Mev, and many new types of reaction have been produced, particularly those involving mesons and other unstable particles. Although it is now clear that meson play a fundamental role in nuclear forces, the present discussion is limited to nuclear reactions below the threshold for meson production($\approx$150 Mev).

Detailed theories of nuclear reaction were patterned after the two,apparently contradictory, model of nuclear structure. The liquid-drop model and the shell model. In one theory, it was assumed(Bohr,1936) that a nuclear projectile incident on the nucleus would interact strongly with all the nucleons in the nucleus and quickly share its energy with them.In the reaction theory based on the shell model(Bethe,1940; Fernbach, Serber, and Taylor, 1949; Feshbach, Porter, and Wesskopf, 1954), it was proposed that an incident nucleon would interact with the nucleus via the shell model potential and that the probability of absorption into the compound nucleus would be relatively small. These different aspects of nuclear reaction can be unified in to a single theory (Weisskopf, 1957; Feshbach, 1958).

1.2 Conservation Laws in Nuclear Reaction

In analyzing nuclear reactions we apply the same conservation laws we applied in studying radioactive decays. Conservation of total energy and linear momentum can be used to relate the unknown but perhaps measurable energies of the products to the known and controllable energy of the projectile. We can thus use the measured energy of b deduce the excitation energy of states of Y or the mass difference between X and Y. Conservation of proton and neutron number is a result of the low energy of the process in which no meson formation or quark rearrangement takes place. At higher energies we still conserve

total nucleon(baryon) number, but at low energy we conserve separately proton number and neutron number. Conservation of angular momentum enables us to relate the spin assignments of the reacting particles and the orbital angular momentum carried by the outgoing particle, which can be deduced by measuring its angular distribution. We can thus deduce the spin assignments of nuclear states. Conservation of parity also applies: the net parity before the reaction must equal the net parity after the reaction.

1.3 Energetics of nuclear reactions

Conservation of total relativistic energy in our basic reaction gives [4]

$$M_X C^2 + T_X + M_a C^2 + T_a = M_Y C^2 + T_Y + M_b c^2 + T_b \tag{1.3.1}$$

where the T's are kinetic energies(for which we can use the non-relativistic approximation $\frac{1}{2}MV^2$ at low energy) and the M's are rest masses. We define the reaction Q values(the energy released or absorbed in a nuclear reaction), in analogy with radioactive decay Q-values, as the initial mass energy minus the final mass energy:

$$\begin{aligned} Q &= (M_{initial} - M_{final})C^2 \\ &= [M_X + M_a - M_Y - M_b]C^2 \end{aligned} \tag{1.3.2}$$

which is the same as the excess kinetic energy of the final products:$Q = T_{Final} - T_{Initial}$ The Q-value may be positive, negative or zero. If $Q>0$ ($M_{initial}>M_{final}$ or $T_{Final}>T_{Initial}$) the reaction is said to be exoergic or exothermic, in this case nuclear mass or binding energy is released as kinetic energy of the final products. When $Q<0$ ($M_{initial}<M_{final}$ or $T_{Final}<T_{Initial}$) the reaction is endoergic or endothermic, and initial kinetic energy is conserved in to nuclear mass or binding energy. The changes in mass and energy must of course be related by the familiar expression from special relativity, $\Delta E = \Delta MC^2$ - any change in the kinetic energy of the system of reacting particles must be balanced by an

equal change in its rest energy.

1.4 A Picture of Nuclear Reactions

The experiments discussed so far illustrate that a nuclear involves a rearrangement of nuclear constituents, in the same way as a chemical reaction involves a rearrangements of atoms[5]. It has been pointed out earlier in various studies that the energies involved in nuclear transmutations are very much larger than those in chemical reactions. Neutrons, protons, deuteron, alpha particles and photons are common bombarding particles used in the study of nuclear reactions; heavier ions are now being used increasingly in such studies. The neutron and photon have one distinct advantage as bombarding "particles ". They carry no charge and therefore do not have to overcome an electrostatic repulsion in order to interact with an atomic nucleus. Any charged particles have to overcome this coulomb repulsion before they can penetrate the nucleus and interact with its constituents[3]. In 1936, Bohr proposed a theory which pictured a nuclear reaction as taking place in two completely independent steps. First, the incident or bombarding particle is absorbed by the initial, or target nucleus to form compound nucleus. Second, the compound nucleus disintegrates by ejecting one or more particles(proton, neutron, deuteron or α-particle) or a photon, leaving the final, or product nucleus. Bohr's assumed that the mode of disintegration of the compound nucleus was independent of the way it was formed, and that the disintegration process depends only on the properties of the compound nucleus. The two steps of the reaction can thus be considered as a separate processes:

Incident particle + target nucleus $\longrightarrow$ compound nucleus

compound nucleus $\longrightarrow$ product nucleus + out going particle

1.5 Nomenclature Of Nuclear Reaction

Alpha Induced Reaction

Bombardment of by one type of incident particle may produce a number of nuclear reactions leading to a number of final nuclei and out going particles. However if, in addition to the target, both the incident and out going particles are specified, the nuclear reaction is completely defined from consideration of the conservation of atomic numbers[5]. Thus it is possible to adopt an "in-out "specification of nuclear reactions. This is expressed in a short hand notation,in which the target nucleus is written before a bracket and the final nucleus after it. Inside the bracket the incident and out going particles are written together. The first nuclear reaction produced in the laboratory,Rutherfords's pioneer reaction ${}^{14}_{7}N(\alpha,p){}^{17}_{8}O$,is a typical α -induced reaction. Reactions of this class usually have negative Q values because of an unfavorable mass-energy balance.That is, energy must be supplied in the form of kinetic energy of the bombarding principle in order to make the reaction takes place. Further, since the α - particle carries a charge of two fundamental units, the coulomb repulsion effect will be twice as great as protons or deuteron's.For alpha particles, the coulomb barrier is still higher, reaching 25 Mev for heavy nuclei. At this energy the incident alpha particles, the excitation energy of the nucleus is about 20 Mev, which is sufficient not only to compensate for the binding energy of the emitted nucleon but also to overcome the coulomb barrier by the emitted proton. As a consequence, the (α,n) and (α,p) reactions are equally probable. Up on an increase in the energy of alpha particles, the $(\alpha,2n)$ and (α,pn) reactions become most probable. A resonance structure of the energy dependence of the cross sections of these nuclear reactions is observed only in the case of light nuclei and at relatively low energies of α - particles. The products of the (α,n) and (α,p) reaction are stable nuclei[19].

Example.

$$ {}^{14}_{7}N(\alpha,p){}^{17}_{8}O \tag{1.5.1} $$

Neutron-Induced Reactions

Soon after the discovery of neutron, its importance in the study of nuclear disintegration was realized. The neutron, being an uncharged particle, can penetrate relatively easily in to the nucleus since it experiences no coulomb repulsive force due to the nuclear charge[5]. For this reason, it is possible for neutrons of all energies, even to the lowest possible, to initiate nuclear reactions. The probability of occurrence of a particular type of neutron-induced reaction usually depends markedly on the energy of the incident neutron. For this reason, it is often useful to classify neutrons as being either "slow "or "fast ", the devision between these categories being at an energy of the order of 1 Kev. When a neutron comes close to a nucleus, it may be attracted by the strong, but short range nuclear forces, and be captured. The compound nucleus so formed has a surplus of energy and may divest itself of this excess energy in a number of ways. For slow incident neutrons, the most common way is by the emission of electromagnetic radiation. This is a radiative capture reaction[5]. For example, the neutron capture reaction.

$$^{113}_{48}Cd +^{1}_{0} n \longrightarrow^{114}_{48} Cd + \gamma \tag{1.5.2}$$

Occurs with very high probability for slow neutrons.

When the kinetic energy of the incident neutron is increased, the radiative capture reaction becomes progressively less probable. By contrast, the probability of scattering increases, and for sufficiently high neutron energies the emission of charged particles from the compound nucleus becomes possible.

Projectile Particle

Projectile particles are of two types

(1) charged nuclei, including $^{1}_{1}H$, $^{2}_{1}H$, $^{4}_{2}He(\alpha - particle)$, and heavier ions such as $^{12}_{6}C$, and

(2) γ rays and uncharged particles, including neutrons.

A number of devices for accelerating charged particles have been designed. Among the

earliest of these is the cyclotron other accelerators includes synchrotron, the linear accelerator and various heavy ion accelerator.

ALPHA PARTICLE

The identification of alpha -rays was not such an easy matter as the pin pointing of beta-rays by there $\frac{e}{m}$ value. Deflection of alpha particles by magnetic and electric fields yielded a ratio of positive charge to mass which was about one-half of that of the hydrogen ion[5]. Rutherford and Geiger(1908 a,b) found the charge to be +2e, strongly suggesting that the alpha-particle is a doubly ionized helium atom of mass four times that of the hydrogen ion. Their experiment to determine the charge on the alpha particle was the first in which the Geiger counter was used, and deserves more attention[5]. Particles from a given source usually have a well defined range R; some sources have several groups each with a characteristic range. The small variation in the range of particles arises from the "straggling"associated with the statistical fluctuations in the loss of energy during the individual ionization processes. Careful measurement of alpha-particle ranges and velocities led Geiger to the approximate relation

$T_\alpha = 2.12R^{\frac{2}{3}}$

where T_α is the initial energy of alpha-particle in Mev and

R is range in centimeters of air at standard temperature and pressure.

Rutherford suggested in 1907 that there might be a relation between the range R of an alpha -particle and the radioactive constant λ of the corresponding alpha emission. In 1911 Geiger and Nuttall proposed the rule,or relation,

$\ln \lambda = A \ln R + B$

Where A and B are constant; using Geiger's range relation this can be rewritten

$\ln \lambda = A_1 \ln T_\alpha + B_1$

In this thesis the target nucleus Cobalt has been used. Cobalt is an element of the periodic table of elements. It was first discovered by George Brandt, around 1735 to 1739 in Sweden. The origin of the name cobalt comes from the German word Kobald, meaning

evil spirit or goblin. It also developed from the Greece word Cobalos, meaning mine. Cobalt is a transition metal.

$^{59}_{27}Co$

It contains eight isotopes with an atomic mass of $58.9332\ \frac{g}{mol^{-1}}$. Cobalt is a hard, shiny, and fragile element. Naturally occurring Cobalt(Co) is composed of one stable isotope, ^{59}Co. 22 radioisotopes have been characterized with the most stable being ^{60}Co with half life of 5.2714 years, ^{57}Co with half life of 271.79 days, ^{56}Co with half life of 70.86 days. All of the remaining radioactive isotopes have half-lives that are less than 18 hours and the majority of these have half- lives that are less than 1 second. This element also has four meta states, all of which have half-lives less than 15 minutes.

1.6 Wave Mechanical Theory for Single Entrance and Exit Channels

The most important quantity of interest for a specific set of kinematic variables is the reaction cross section. The probability of a given nuclear reaction occurring is expressed as the cross section for that reaction[4]. A large probability that there is a large probability that the specific nuclear reaction also depends on the energy of a projectile particle; hence in order to obtain the maximum yield of a given product nucleus, an appropriate projectile particle must be chosen, and its energy must be controlled. This quantity, σ which has a dimension of area, is measured by the experimental ratio

$$\sigma = \frac{Number\ \ of\ \ events\ \ per\ \ sec\ \ per\ \ nuclei}{Number\ \ of\ \ incident\ \ particles\ \ per\ \ second\ \ per\ \ unit\ \ area} \tag{1.6.1}$$

Nuclear reaction cross sections may be explained using wave mechanical theory under general assumption. Let us consider a particle approaching a nucleus parallel to the Z-axis with a velocity v. This particle can be represented by a plane wave assuming

negligible diffraction effects[4]

$$\psi_{inc} = e^{ikz} \tag{1.6.2}$$

Here the wave amplitude is unity so that there is only one particle per unit volume and in the incident beam there are V particles per unit area per second, where V is the velocity of the incident particle. Since the particles position with respect to x, y axes can not be precisely specified, the angular momentum value of the particle, $l\hbar$ may take any value. To solve this problem the plane wave must be transformed in to a superposition of spherical waves each of which represents a particle of defined angular momentum. Let us find an expression for equation(1.6.2) in terms of expansion of partial waves. It can be seen that e^{ikz} is a solution with axial symmetry of the wave equation

$$\nabla^2\psi + k^2\psi = 0 \tag{1.6.3}$$

This equation can be solved in spherical polar coordinates and the solutions with axial symmetry are of the form

$$\psi_l = g_l(r)P_l(cos\theta) \tag{1.6.4}$$

Where l is an integer $P_l(cos\theta)$ is Legendre polynomial and $g_l(r)$ is the solution of the equation

$$\frac{1}{r^2}\frac{d}{dr}r^2(\frac{dg}{dr}) + (k^2 - \frac{l(l+1)}{r^2})g = 0 \tag{1.6.5}$$

which is bounded at the origin.The most general solution of equation(1.6.3) is given by

$$\psi = \sum_{l=0}^{\infty} A_l g_l(r)P_l(cos\theta) \tag{1.6.6}$$

Where A_l are arbitrary constants. The terms in the infinite series are the partial waves.Hence,

$$e^{ikz} = e^{ikrcos\theta} = \sum_{l=0}^{\infty} A_m g_m(r)P_l(cos\theta) \tag{1.6.7}$$

multiplying both sides by $P_l(cos\theta)sin\theta$ and integrating with the limit from 0 to infinity of equation(1.6.7) and letting $cos\theta = x$ we get

$$\int_{-1}^{1} e^{ikrx} P_l(x)dx = \frac{2}{2l+1} A_l g_l(r)$$
$$\frac{2}{2l+1} A_l g_l(r) = \frac{1}{ikr}((e^{ikr} - (-1)^l e^{-ikr}) - \frac{1}{ikr}\int_{-1}^{1} e^{ikrx} P^{'}(x)dx \qquad (1.6.8)$$

The second term of equation (1.6.8) is of the order of $\frac{1}{r^2}$ which may be seen after integration by parts once more. For large value of r,

we get

$$\frac{2}{2l+1} A_l g_l(r) \sim \frac{1}{ikr}(e^{ikr} - e^{-il\pi} e^{-ikr})$$
$$= \frac{1}{ikr}(e^{\frac{il\pi}{2}}[e^{i(kr-\frac{il\pi}{2})} - e^{-i(kr-\frac{il\pi}{2})}])$$
$$= \frac{2i^l}{kr} sin(kr - \frac{l\pi}{2}) \qquad (1.6.9)$$

Now

$g_l(r)$ can be defined completely by requiring that,

$A_l = (2l+1)i^l$ Hence,

$g_l(r) = \frac{1}{kr} sin(kr - \frac{il\pi}{2})$

The required expression is given by

$e^{ikz} = e^{ikrcos\theta} = \sum_{l=0}^{\infty}(2l+1)i^l) g_l(r) P_l(cos\theta)$

It can be seen that $g_l(r)$ is a spherical Bessel function with an asymptotic expression. That is,

$$g_l(r) = \sqrt{\frac{\pi}{2kr}} J_{l+1/2}(kr) \qquad (1.6.10)$$

Where the asymptotic form of the spherical Bessel function is expressed as,

$$J_{l+1/2}(kr) = \frac{1}{(2l+1)!!}\sqrt{\frac{2}{\pi}}(kr)^{l+1/2}, r \ll 1$$
$$J_{l+1/2}(kr) = \sqrt{\frac{2}{\pi}}(kr - \frac{l\pi}{2}, r \gg 1 \qquad (1.6.11)$$

The incident wave function is then expressed using equation(1.6.10) and equation(1.6.11) as

$$\psi_{inc} = \frac{1}{kr}\sum_{l=0}^{\infty}(2l+1)i^l)P_l(cos\theta)sin(kr-\frac{il\pi}{2})$$
$$= \frac{1}{kr}\sum_{l=0}^{\infty}(2l+1)i^l)P_l(cos\theta)[\frac{e^{i(kr-\frac{il\pi}{2})}-e^{-i(kr-\frac{il\pi}{2})}}{2i}] \quad (1.6.12)$$

from equation (1.6.12), it can be seen that $\frac{1}{r}e^{-i(kr-\frac{l\pi}{2})}$ represents a spherical wave converging (going on to) the nucleus and $\frac{1}{r}e^{+i(kr-\frac{l\pi}{2})}$ represents a spherical wave diverging or going out from the nucleus. If the out going waves are affected in amplitude as well as in phase, we have an inelastic process which can be represented by the wave equation,

$$\psi_l(r) = \frac{1}{2ikr}\sum_{l=0}^{\infty}(2l+1)i^l P_l(cos\theta)(\eta_l e^{i(kr-\frac{l\pi}{2})}) - (e^{-i(kr-\frac{l\pi}{2})}) \quad (1.6.13)$$

where η_l is a complex constant which contains the effects of the scattering center. Its real part gives the change in amplitude and its imaginary part gives the change in phase.η_l can be represented by

$$\eta_l = |\eta_l|e^{2i\delta_l} \quad (1.6.14)$$

The scattered wave is it self the superpositions of partial waves and may be written as

$$\psi_{sc} = \frac{f(\theta)}{r}e^{ikr} \quad (1.6.15)$$

where $f(\theta)$ is the scattering amplitude. Thus the number of particles crossing unit area per second in the scattered beam is given by

$$\upsilon|\psi|^2 = \upsilon|f(\theta)|^2 d\Omega \quad (1.6.16)$$

where $d\Omega$ is an element of solid angle. The value for the scattering amplitude $f(\theta)$ is obtained using equation (1.6.13) and (1.6.15)

$$f(\theta) = \frac{1}{2ikr}\sum_{l=0}^{\infty}(2l+1)(\eta_l - 1)P_l(cos\theta) \quad (1.6.17)$$

The two types of reactions, elastic and inelastic, may be inferred from the discussion above. For elastic scattering where there is no loss of incident particles $|\eta_l|^2 = 1$. It means there is no change in amplitude between the incident and the scattered wave, which implies no change in the real part of η_l. η_l is now written as $e^{2i\delta_l}$.

$f(\theta) = \frac{1}{2ikr}\sum_{l=0}^{\infty}(2l+1)(e^{2i\delta_l}-1)P_l(cos\theta)$

δ_l is the phase shift in the asymptotic form of partial wave 1. For the inelastic reaction $|\eta_l|^2 \ll 1$, that is there is a change in amplitude and δ_l is complex. The cross section for the scattered particle may be obtained by applying the probability current density of the scattered wave function ψ_{sc}.

The number of scattered particles N_{sc} through a solid angle $d\Omega$ is defined as

$$N_{sc} = \frac{\hbar}{2im}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(\frac{\partial\psi_{sc}}{\partial r}\psi_{sc}^{*} - \frac{\partial\psi_{sc}^{*}}{\partial r}\psi_{sc})r_o^2 d\Omega$$

$$N_{sc} = \upsilon\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|f(\theta)|^2 d\Omega \tag{1.6.18}$$

where m is the mass of the scattered particles and r_0^2 is the radius of a sphere with solid angle $d\Omega$. The scattered cross section is given by

$$\begin{aligned}\sigma_{sc} = \quad & \frac{N_{sc}}{Flux} \\ & = \frac{\upsilon\int\int|f(\theta)|^2 d\Omega}{\upsilon} \\ & = \int\int|f(\theta)|^2 d\Omega \\ & = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)|1-\eta_l|^2\end{aligned} \tag{1.6.19}$$

The reaction cross section may be obtained in the same way but using a negative sign before the probability current to indicate the direction of current on to the nucleus.

$$\sigma_r = \frac{N_r}{\upsilon} = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)(1-|\eta_l|^2) \tag{1.6.20}$$

from equation (1.6.20) it is clear that if $|\eta_l| = 0$, that is no change in amplitude of the wave, there is no reaction (σ_r) but scattering may be there. On the other hand if $\eta_l = 1$,

both reaction and scattering are not possible. If $\eta_l = -1$, there is no reaction but but there is maximum scattering.

If $\eta_l = 0$, then there is maximum reaction and also some scattering. The total cross section is obtained by adding equation (1.6.19) and (1.6.20)

$$\sum_0^\infty \sigma_{l,t} = \sum_0^\infty \frac{2\pi}{k^2}(2l+1)(1 - Re\eta_l)$$

$$\sigma_t = \frac{4\pi}{k^2}\sum_0^\infty (2l+1)sin^2\delta_l \tag{1.6.21}$$

Chapter 2

REACTION MECHANISM

Various reaction models have been extremely successful in describing certain classes or types of nuclear reaction process. In general, all reactions can be classified according to the time scale on which they occur, and the degree to which the kinetic energy of the incident particle is converted into internal excitation of the final products. A large fraction of the reactions observed has properties consistent with those predicted by two reaction mechanisms which represent the extremes in this general classification.

These are

(1)The mechanism of compound nucleus formation and

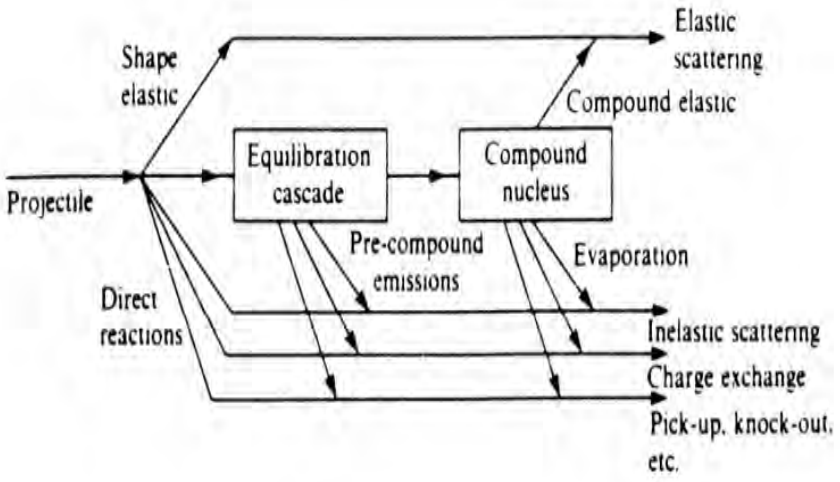
(2)Direct reaction

Nuclear model calculations and data fitting procedure.

Nuclear reaction models

The interaction of a projectile with a nucleus may exhibit several effects. An overview of all possible nuclear reaction mechanisms is given in Fig. 2.1. The simplest form is the formation of the "compound nucleus "which can be described by statistical mechanics as being in a state of statistical equilibrium. The energy distribution of the components of the system is Maxwellian. A component of this system may get a large amount of energy as a result of the statistical fluctuation. This amount of energy may be enough to cause the decay of the compound nucleus. Being a statistical process, the evaporation of particles favors the escape of nucleons having the minimum possible energy. In case of

charged particles, this minimum energy is the Coulomb barrier of the compound nucleus. When the compound nucleus has reached statistical equilibrium, it is said to have been thermalized. If the nuclear reactions proceed directly from the entrance channel to the exit channel without the formation of an intermediate state, they are said to be direct reactions. If the internal states of the two colliding systems do not change, we have elastic scattering and if one or both systems are excited in the exit channel, it is inelastic scattering.



rxn.png

Figure 2.1: An overview of all possible nuclear reaction mechanisms.

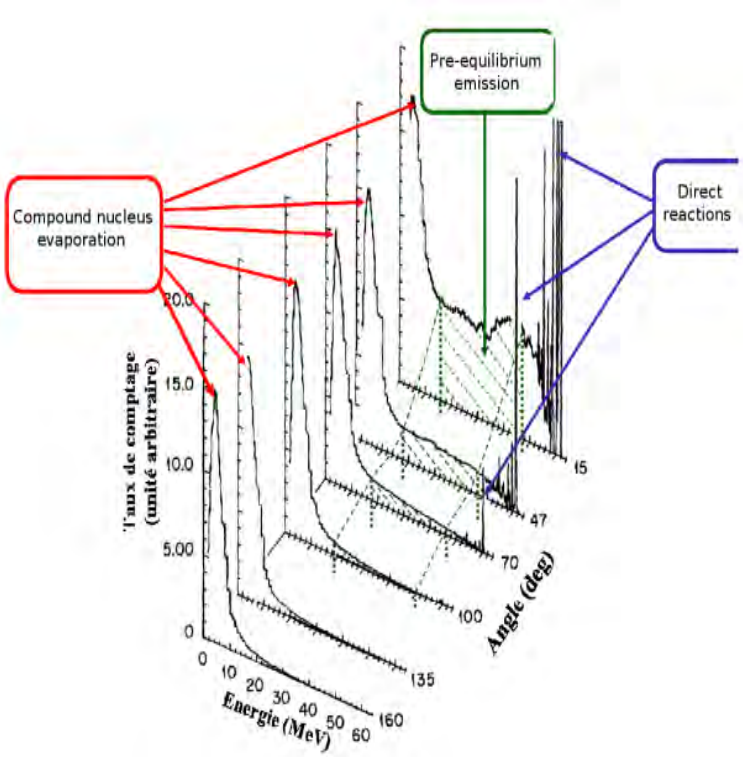


Figure 2.2: graph showing reaction mechanism

In compound nuclear reactions, the excitation energy is shared uniformly among the constituent nucleons. The compound nuclear reaction models are the Weiskoff-Ewing and HauserFeshbach models[8]. The mechanism of compound nucleus formation and decay can be described by the liquid drop model. The second most important mechanism is the direct interaction. This reaction occurs without the formation of an intermediate state and proceeds directly from the entrance to an exit channel. The direct reaction can be elastic scattering, inelastic scattering, knock-out, transfer or pick-up reaction and quasi-elastic scattering. If the internal states of both systems are conserved, it will be elastic scattering while inelastic scattering occurs when one or both systems are excited in the exit channel. If during the nuclear reaction, transfer of one or more nucleons happen from one nucleus to the other, it is known as a transfer or pick-up reaction. When a nucleon or light mass nucleus is ejected from the target but the projectile remains free, it constitutes quasi-elastic scattering.

In pre-equilibrium reactions, the emission of particles from the excited target nucleus is neither by statistical decay of the compound nucleus nor by the prompt emission after collision. The commonly used pre-equilibrium models are the exciton model and the hybrid model. Both these are semi-classical models and originate from the paper by Griffin [6] and later development. It is assumed that all possible ways of distribution of the excitation energy between all different particle-hole configurations with the same exciton number have equal probability to occur. The exciton number changes during the nuclear reaction as a result of intra-nuclear two-body collisions. At each stage of the reaction there may be a non-zero probability that a particle is emitted. If this happens at an early stage, we speak of pre-equilibrium (PE) emission. If the emission does not occur at an early stage, the system eventually reaches the equilibrium or evaporation stage. This stage is described by the Weisskopf-Ewing formalism (which does not treat angular momentum and parity explicitly) or more clearly by the Hauser-Feshbach formalism which explicitly treats vector coupling of spins and parities between compound and residual nuclei and projectiles . The time scale for direct interaction is $\simeq 10^{-21}$ s, for pre- compound emission $\backsimeq 10^{-18}$ s and for compound nucleus evaporation $\simeq 10^{-15}$ s. In general, in the low energy region up to about 10 MeV mostly statistical processes dominate. The pre-equilibrium effects start manifesting themselves at energies around 20 MeV, and at excitation energies above 50 MeV their contribution starts becoming significant. Pre-equilibrium models have been widely used in modeling nuclear cross sections below 200 MeV , i.e. till the spallation process becomes dominant. The pre-equilibrium models have provided an adequate description of the high energy tails (i.e. the region between the evaporation peak and the discrete states) of the outgoing particle spectra. Below we describe briefly the nuclear models, and the most important parameters involving nuclear theory, which were directly used in theoretical calculations of the excitation functions of reactions under consideration over a wide range of energy extending up to about 100 MeV.

2.1 The Compound Nucleus

The Bohr assumption

The actual nuclear process in a nuclear reaction does not start before the two initial particles a and X have come near enough to one another, with in the range of nuclear forces. The nuclear process has ceased when the two products have separated by more than the range. During the time of interaction, a compound system is formed whose properties are decisive for the course of the nuclear reaction. It was N.Bohr who first pointed out that it is useful to divide the nuclear reaction in to two states[8]

(a) the formation of the compound system C and

(b) the disintegration of the compound system in to the products of the reaction

In the first step the incident particle is captured by or(fuses with) the target nucleus, forming an intermediate or compound nucleus which lives a long time ($10^{-16}s$) compared to the approximately 10^{-22}s, it takes the incident particle to travel past the target. During this time the kinetic energy of the incident particle is shared among all the nucleons, and target is lost. The compound nucleus is always formed in a highly excited unstable state, is assumed to approach thermodynamic equilibrium involving all or most of the available degrees of freedom, and will decay, as the second step, into different reaction products, or through so called exit channels. The essential future of the compound nucleus formation or fusion reaction is that the probability for a specific reaction depends on two independent probabilities: the probability for forming compound nucleus, and the probability for decaying in to that specific exit channel.

The following assumption has been proved valid, or at least approximately valid, in many cases. The two stages (a) and (b) can be treated as independent process, in the sense that the mode of disintegration of the compound system depends only on its energy, angular momentum, and parity, but not on the specific way in which it has been produced. Thus the two steps of the reaction can be considered separate processes following one another.

we shall refer to this as the Bohr assumption. It is based on the picture of a nucleus as a system of particles with very strong interactions and short-range forces. If the incident particle comes with in the range of forces, its energy is quickly shared among all constituents well before any re-emission can occur. The state of the compound system is then no longer dependent on the way it was formed[8].

The validity of the Bohr assumption and its limitations can be understood in the following way. Because of the strong interaction between the nucleons, the energy carried by a into X is shared with all other nucleons shortly after contact. This is due to the fact that the "Mean free path " Λ of an entering nucleon in nuclear matter is very much smaller than the nuclear radius if the incident energy ϵ is not too high ($\epsilon < 50$ Mev). Λ can be estimated to be roughly $\Lambda \sim 0.4 \times 10^{-13}$cm if the entering nucleon has a kinetic energy up to about $\epsilon \cong 20$Mev.

For higher energies, Λ increases and is given approximately by Λ(in centimeter) $\sim 1.8 \times 10^{-15} \times E$(in Mev)

The estimate of Λ is made in the following way:

$$\Lambda = (\delta\rho)^{-1} \tag{2.1.1}$$

Where δ is the collision cross section with other nucleons, and

ρ is the nucleon density inside the nucleus. ρ can be calculated for the nuclear radii

$$\rho = \frac{3}{4\pi r_0^3} \tag{2.1.2}$$

Once the energy carried in by a is shared with the other nucleons, it takes a great number of energy exchanges, and thus a long time, before enough energy is concentrated on one particle so that it can be re-emitted by the compound system. This can be seen as follows: The total excitation energy E of the compound system is:

$$E = \epsilon + S_a \tag{2.1.3}$$

Where S_a is the separation energy of a from the compound nucleus.

Because of the small values of Λ, these energy is quickly shared among the A constituents

of C, so that each of them possesses on the average the amount $\frac{E}{A}$. As long as $\frac{E}{A}$ is small compared to the average separation energy S of a nucleon from C ($\frac{E}{A} \ll S$), it takes many exchanges before enough is concentrated on one particle so that it can be re-emitted.

The large number of exchanges is the main reason for the validity of the Bohr assumption. A thorough "mixing"of the energy of the incident particle is expected, so that the state of C before re-emission of another particle shows no traces depending on the special way the excitation energy was delivered.

The condition for the validity of the Bohr assumption are then (note that $\frac{E}{A} \ll S$ can be written as ($\frac{E}{A} \ll S + \frac{S_a}{A} \ll S$, and that $S_a \sim S$):

$$\Lambda \ll R \qquad\qquad \epsilon \ll (A-1)S \tag{2.1.4}$$

Both conditions are fulfilled for nuclei with $A < 10$ as long as $\epsilon \ll 50$Mev, since S is of the order of 8 Mev. It should be noted that the above conditions are necessary but not sufficient. There may be other mechanism with in the compound system preventing thorough "mixing"of the energy of the incident nucleon among all constituents.One of many possible reasons for the breakdown of the Bohr assumption may be found in the Pauli exclusion principle.

The compound nucleus model works best for low incident energies,(10-20 Mev), where the incident projectile has a small chance of escaping from the nucleus with its identity and most of its energy interact. It also works best for medium weight and heavy nuclei, where the nuclear interior is large enough to absorb the incident energy.

Another characteristic of compound nucleus reactions is the angular distribution of the products. Because of the random interactions among the nucleons, we expect the outgoing particle to be emitted with a nearly isotropic angular distribution (that is, the same in all directions). If heavy ion is the incident particle, large amounts of angular momentum can be transferred to the compound nucleus, and to extract that angular momentum the emitted particles tend to be emitted at right angles to the angular momentum, and thus preferentially at 0 and 180 degree. With light projectiles, this effect is negligible. The

evaporation analogy mentioned previously is really quite appropriate. In fact, the more energy we give to the compound nucleus, the more particles are likely to evaporate. For each final states, the cross section has the Gaussian like shape,

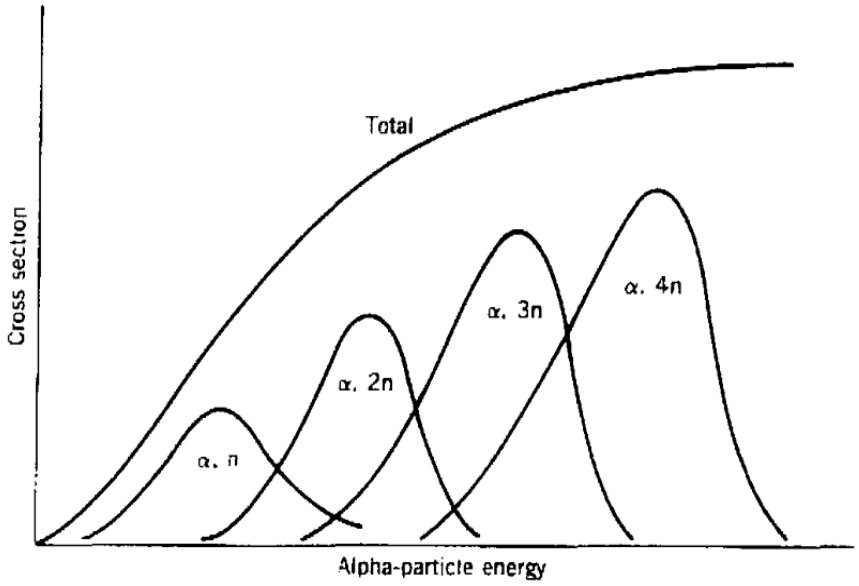


Figure 2.3: At higher incident energies, it is more likely that additional neutrons will evaporate from the compound nucleus[4].

Fig above shows the cross section for (α, xn) reactions.Where x=1,2,3....For each reaction, the cross section increases to a maximum and then decreases as the higher energy makes it more likely for an additional neutron to be emitted.

2.1.1 Nuclear Reactions, Cross Section, and Emission Rates

According to the Bohr assumption, we can write the probability of formation of compound nucleus $\sigma_c(a)$ and the probability of a decay of compound nucleus Y and emitted particle b of a nuclear reaction $X(a,b)Y$ in the form

$$\sigma(a,b) = \sigma_c(a)G_c(b) \tag{2.1.5}$$

Where,$\sigma_c(a)$ is the cross section for the formation of a compound system by particle a incident up on the target nucleus X.

$G_c(b)$ is the probability that the compound system C, once formed, decay by emission of a particle b, leaving a residual nucleus Y. $G_c(b)$ is a pure number; the compound system C must decay eventually in some way; $G_c(b)$ is the probability of this special way of decay. It can also be referred to as the "branching ratio"of the reaction in to the emission of b. Evidently

$$\sum_b G_c(b) = 1 \tag{2.1.6}$$

, if the sum is extended over all particles b which C can emit.

It is useful to specify the reaction X(a,b)Y in greater detail, by considering the cross section $\sigma(\alpha, \beta)$ corresponding to a specific entrance channel α and specific exit channel β. In other words, we specify the quantum states of all reaction partners before and after the reaction[8].

We therefore write

$$\sigma(\alpha, \beta) = \sigma_c(\alpha)G_c(\beta) \tag{2.1.7}$$

Where $\sigma_c(\alpha)$ is the cross section for the formation of C channel α,and $G_c(\beta)$ is the probability that C decays through channel β

According to the Bohr assumption, the disintegration of the compound system in to the different channels β, γ, etc., depends only on the energy E_c, the angular momentum J_c, and the parity of the compound system.

In order to simplify our present considerations, the dependence of the properties of the compound system on the angular momentum J and the parity Π will be ignored in this section.

We now introduce a few magnitudes which describe the disintegration of the compound system C. We begin with the mean life time $\tau(E_c)$ of C before disintegration and define the magnitude.

$$\Gamma(E_c) = \frac{\hbar}{\tau(E_c)} \tag{2.1.8}$$

Which is $\hbar$ times the rate of disintegration per unit time.

Γ is an energy and, later on, will play the role of a level width. We therefore call it the "total width"of the state of C with an excitation energy E_c. C can decay in to several channels, and its total decay rate Γ can therefore be subdivided in to decay rates referring to specific channels.

$$\Gamma(E_c) = \sum_{\beta} \Gamma_{\beta}(E_c) \tag{2.1.9}$$

Where the sum is extended over all channels in to which C can decay, i.e., Over all "open "channels. The specific decay rate $\Gamma(E_c)$ is also a function of E_c and is called the partial width for the decay in to channel β.

The magnitude Γ_{β} can also be defined as follow:

If an assembly of N equal samples of the compound system C is arranged in such away that, on the average, N system constant in time (i.e, as many compound systems decay as are produced), then the number of decays in to the channel β per unit time is given by

$$\frac{N\Gamma_{\beta}}{\hbar} \tag{2.1.10}$$

We can now express the branching probability in terms of the decay rates by the relation

$$G_c(\beta) = \frac{\Gamma_{\beta}}{\Gamma} \tag{2.1.11}$$

2.1.2 The Reciprocity Theorem for Nuclear Reaction

So far, we have considered the wave function only in the incident channel α: the reactions leading to different channels were lumped together in to the reaction cross section $\sigma_r(\alpha)$. We now give a some what more detailed description of the possible reactions[8]. Let us consider the reaction in which channel α is the entrance channel, and which leads in to channel β. The cross section $\sigma(\alpha,\beta)$ for this reaction is defined according to

$$\sigma(\alpha,\beta) = \frac{Number\ of\ emission\ in\ to\ channel\ \beta\ per\ unit\ time\ per\ scattering\ center}{Number\ of\ incident\ particles\ in\ channel\ \alpha\ per\ unit\ area\ per\ unit\ time} \tag{2.1.12}$$

The reaction cross section $\sigma_r(\alpha)$ in channel α is given by

$$\sigma_r(\alpha) = \sum_{\beta\neq\alpha} \sigma(\alpha,\beta) + \sigma_{cap}(\alpha) \tag{2.1.13}$$

$\sigma_{cap}(\alpha)$ is the capture cross section.

Now let as establish an important relation between the cross section of two opposite reaction: $\sigma(\alpha,\beta)$ and $\sigma(\beta,\alpha)$. The two cross sections belong to the inverse reactions

$$\begin{aligned} a_{\alpha''} + X_{\alpha'} &= Y_{\beta'} + b_{\beta''} \quad and \\ b_{\beta''} + Y_{\beta'} &= X_{\alpha'} + a_{\alpha''} \end{aligned} \tag{2.1.14}$$

The relation is quite universal and depends only on the channel wave lengths λ_α and λ_β. It is expressed by

$$\frac{\sigma(\alpha,\beta)}{\lambda_\alpha^2} = \frac{\sigma(\beta,\alpha)}{\lambda_\beta^2} \tag{2.1.15}$$

The channel wave number $K_\alpha = |K_\alpha|$ and the channel wave length λ_α are related as $K_\alpha = \frac{1}{\lambda_\alpha}$

$$\begin{aligned} K_\alpha^2\sigma(\alpha,\beta) &= K_\beta^2\sigma(\beta,\alpha) \\ K_\alpha^2\sigma_c(\alpha)G_c(\beta) &= K_\beta^2\sigma_c(\beta)G_c(\alpha) \\ K_\alpha^2\sigma_c(\alpha)\frac{\Gamma_\beta}{\Gamma} &= K_\beta^2\sigma_c(\beta)\frac{\Gamma_\alpha}{\Gamma} \\ \frac{\sigma_c(\alpha)}{\Gamma_\alpha\lambda_\alpha^2} &= \frac{\sigma_c(\beta)}{\Gamma_\beta\lambda_\beta^2} = U(E_c) \end{aligned} \tag{2.1.16}$$

Since α and β can be any pair of channels which lead to the compound system C, the function $U(E_c)$ must be independent of the channel and we obtain (2.1.17). The probability $G_c(\beta)$ of the disintegration through a specific channel β can be written in the form $(K = \lambda^{-1})$

$$G_c(\beta) = \frac{K_\beta^2 \sigma_c(\beta)}{\sum_\gamma K_\gamma^2 \sigma_c(\gamma)} \tag{2.1.17}$$

Where the sum is extended over all channels γ in to which C can decay. Hence the cross sections (2.1.8) for the reaction $\sigma \longrightarrow \beta$ can be computed if the cross section $\sigma_c(\gamma)$ for the formation of the compound system by all possible channels are known, and if the Bohr assumption is valid.

A few qualitative conclusions can be drawn with out any detailed determination of the cross sections (Bethe,Konopinski). It is expected that $\sigma_c(\alpha)$ is, in general, much larger for neutrons than for protons or other charged particles, since the latter must penetrate the coulomb potential barrier. Thus, according to (2.1.17), the neutron widths(i.e., the partial widths corresponding to channels with neutron emission) are larger than the proton or alpha-particle width,except in the case in which the charged particle has much more kinetic energy at its disposal than the neutron. If a reaction with neutron emission is energetically possible, it is generally more likely to occur than any other reaction.

Exceptions are found only just at the threshold of a reaction with neutron emission, when the neutron has very small energy. Thus, in reactions which are initiated by a particle a, the cross section $\sigma_c(\alpha)$ can be put approximately equal to the cross section $\sigma(a, n)$ of the (a,n) reaction.

This last equation tells that, if the compound nucleus formation cross section through all possible channels is known then it is possible to obtain the decay probability through a given channel.

combining equation(2.1.8) and (2.1.18) the cross section becomes

$$\sigma(\alpha, \beta) = \frac{\sigma(\gamma) K_\beta^2 \sigma(\beta)}{\sum_\gamma K_\gamma^2 \sigma(\gamma)} \tag{2.1.18}$$

ejectiles with energy range ϵ_β to $\epsilon_\beta + d\epsilon_\beta$ leave the residual nucleus with energy in the range U_β to $U_\beta + dU_\beta$, where $U_\beta = E_{CN} - B_\beta - \epsilon_\beta$, E_{CN} and B_β are respectively the compound nucleus energy and the binding energy of the projectile. Introducing the density of the levels $\rho(U_\beta)$ of the residual nucleus and statistical weights g_β and g_α through the two channels, the angle integrated cross section becomes

$$\sigma(\alpha,\beta) = \frac{\sigma(\gamma) g_\beta K_\beta^2 \sigma(\beta) \rho(u_\beta) du_\beta}{\sum_\gamma \int_0^{\epsilon_{max}} g_\gamma k_\gamma^2 \sigma(\gamma) \rho(u_\gamma) du_\gamma} \tag{2.1.19}$$

since $K^2 = 2mE$, m is the reduced mass of the projectile, the above equation is reduced to

$$\sigma(\alpha,\beta) d\epsilon_\beta = \frac{\sigma(\gamma)(2I_\beta + 1) m_\beta \epsilon_\beta \sigma(\beta) \omega(u_\beta) du_\beta}{\sum_\gamma \int_0^{\epsilon_{max}} (2I_\gamma + 1) m_\gamma \epsilon_\gamma \sigma(\gamma) \omega(u_\gamma) du_\gamma} \tag{2.1.20}$$

This last equation is known as the Weiss Kopf-Ewing formula for the angle integrated cross section. To a good approximation, the level density $\rho(u)$ can be shown to be proportional to $exp(\frac{u}{T})$, so that the ejectile spectrum given by the Weiss Kopf-Ewing theory is Maxwellian.

Statistical emission

As mentioned above, the equilibrated compound nucleus deexcites by the so-called evaporation process. This stage is described simply by the Weisskopf-Ewing evaporation theory or more accurately by the Hauser-Feshbach formalism which explicitly treats angular momentum and parity. Suppose the formation of compound nucleus through a reaction channel α and its decay by a channel β, then the Hauser-Feshbach formula for calculating the cross section of the compound nucleus reaction can be written as,

$$\sigma_{\alpha\beta} = \frac{\pi \lambda_\alpha^2 (2J+1) T_\alpha T_\beta}{\sum_i T_i} \tag{2.1.21}$$

where J is angular momentum and T_α, T_β are transmission coefficients of formation and decay channels. The expression given above does not include spin of the interacting particles. The transmission coefficients can be calculated by suitable optical model potentials. For each reaction product all the low-lying levels extending up to an excitation energy

beyond which the level density could be treated statistically are considered. The energy levels in the continuum are obtained using a level density formula. The calculation leads to both total and partial cross sections, so that the formation of isomeric states can be well estimated.

2.1.3 Level densities

The statistical properties of excited nuclear levels have been a matter of concern and study for more than fifty years. One of the basic statistical properties of levels is their density. For the description of the level densities the Fermi-gas and constant temperature models are used frequently with parameters obtained from fitting of some experimental data. But the physical assumptions upon which both these models are based are not sophisticated enough to allow them to account properly for variations of level densities over wide energy interval from the ground state to energies much higher than the neutron separation energy. This is not surprising, as the models discussed were initiated more than fifty years ago, when nuclear physics was not so developed and computer based. Some of the most important concepts, upon which current understanding of the structure of low-lying nuclear levels is based, include shell effects, pairing correlations and collective phenomena . All these concepts have been incorporated into the Generalized Superfiuid Model (GSM) developed by many authors over the last 20 years. The phenomenological versions of the model convenient for an analysis of experimental data were developed intensively during the last years. Now a days microscopic models for the level density are emerging but at the present stage their applications are limited. For practical applications of the statistical model it is very important to obtain parameters of the level density description from reliable experimental data. The cumulative numbers of low-lying levels and the average distances between neutrons resonances are usually used for such data.
In the preequilibrium emission calculations, the initial exciton configurations and level

density parameter are very essential quantity. The nuclear level density influences the shape and the height of the calculated excitation function. The level density of the nuclide involved in the evaporation chain may be calculated from the fermi density distribution [17].

$$\rho(E) = \frac{\Pi^{1/2} e^{2\sqrt{aE}}}{12 a^{1/4} E^{5/4}} \tag{2.1.22}$$

where E is excitation energy and "a"the level density parameter. The level density parameter obtained by experiment shows a linear dependent with the mass number of the compound nucleus. In general it is given by an expression

$$a = \frac{A_{CN}}{K} \tag{2.1.23}$$

where A_{CN} is the mass of the compound nucleus and the free constant has value which ranges from 7.5-8[17]. In this thesis the level density parameter 9 and 10 are taken for all reaction and compared with experimental result.

The symmetry energy term may be calculated using the Fermi gas model. The partition of a given nucleons of A into levels is governed by Pauli principle. The symmetric distribution,Z=A-z=a/2, proves to be energetically more favored. Any other partition, $N = (A/2) + \upsilon$ or $N = (A/2) - \upsilon$ will involve lifting particles from occupied into unoccupied levels. The proton and neutron energy due to symmetry effect using the fermi gas model is given by

$$E_P = \frac{3}{2} Z E_F \tag{2.1.24}$$

$$E_n = \frac{3}{2}(A - Z) E_F \tag{2.1.25}$$

The pairing energy is to be zero for even-even nucleon, $-\sigma$ for odd-even nucleon and -2σ for odd-odd nucleon, with $\sigma = \frac{11}{\sqrt{A}}$ [16].

2.1.4 Resonance in a Compound Nucleus Reaction

The compound nucleus model of nuclear reactions treats the unbound nuclear states as if they formed a structureless continuum. That is, there may be discrete nuclear states,

but there are so many of them and they are so close together that they form a continuous spectrum[8]. Each of these supposed discrete states is unstable against decay and therefore has a certain width; when the states are so numerous that their spacing is much less than the widths of the individual states, the compound nucleus continuum results.

When the bombarding energy E in the entrance channel is close to the energy E_r for exciting a state in the compound nucleus, the cross section for the reaction $A+a \rightarrow C \rightarrow B+b$ takes the form of Lorentz distribution and is given by the Breit-Wigner equation

$$\sigma_{\alpha\beta} = g_\alpha(J)\frac{\pi\Gamma_\alpha\Gamma_\beta}{k_\alpha^2(E-E_r)^2+(\frac{\Gamma}{2})^2} \tag{2.1.26}$$

where α and β indicate the entrance $(A+a)$ and exit $(B+b)$ channels, and k_α is the wave number in the entrance channel. The quantity $g_\alpha(J)$ is a statistical spin factor that takes in to account the effect of angular momentum and spin. This factor takes the following form

$$g_\alpha(J) = \frac{2J+1}{(2i_a+1)(2i_A+1)} \tag{2.1.27}$$

where i_A, i_a and J are the spin quantum numbers of nuclei A, a and the compound nucleus, respectively. In general J is given by the vector sum of the orbital angular momentum and spins of a and A. If i_A and i_a are both zero,J is equal to l the quantum number of the orbital angular momentum brought in by the fusion of a and A, and $g_\alpha(J) = 2l+1$. The energy width of resonance Γ is the total decay width, which is related to the life time of the compound nucleus according to equation ($\Gamma = \sum_i \Gamma_i = \lambda\hbar = \frac{\hbar}{\tau}$)

The energy width is equal to $\sum \Gamma_\beta$, where the sum is over all final(β) channels. The individual $\Gamma_\alpha, \Gamma_\beta, ...$ depend on the structure of the particular nuclear states. Both Γ_α and Γ_β need to be large for $\sigma_{\alpha\beta}$ to be large. We can determine upper limit for elastic scattering and absorption by evaluating their cross sections at the peak of the resonance. Elastic scattering (for which $\alpha = \beta$) is maximum when there is no absorption, i.e when $\Gamma_\alpha = \Gamma$. This gives an upper limit for the integrated elastic scattering cross section of

$$\sigma_{\alpha\alpha}(max) = \sigma_l^{el} = (2l+1)\frac{4\pi}{4k_\alpha^2} \tag{2.1.28}$$

for the l^{th} partial wave and where we have taken both projectile and target spins to be zero. The total absorption cross section is proportional to $\Gamma_\alpha \sum_{\beta \neq \alpha} \Gamma_\beta = \Gamma_\alpha(\Gamma - \Gamma_\alpha)$, which has its maximum when $\Gamma_\alpha = \frac{\Gamma}{2}$. Thus, for spin less particles, the upper limit to the l th partial wave absorption cross section (when $E = E_r$) is

$$\sigma_l^{abs}(max) = (2l+1)\frac{\pi}{k_\alpha^2} \tag{2.1.29}$$

2.2 Pre-equilibrium emission

The experimental results of early 1950s showed that the nuclear reaction mechanism has also an intermediated character between one step direct reactions in which few degrees of freedom are involved and the compound nucleus reactions in which all the energy of the projectile is distributed among all nucleons of the compound nucleus in a completely statistical manner. All the intermediate processes are called pre-compound or pre-equilibrium reactions[18].

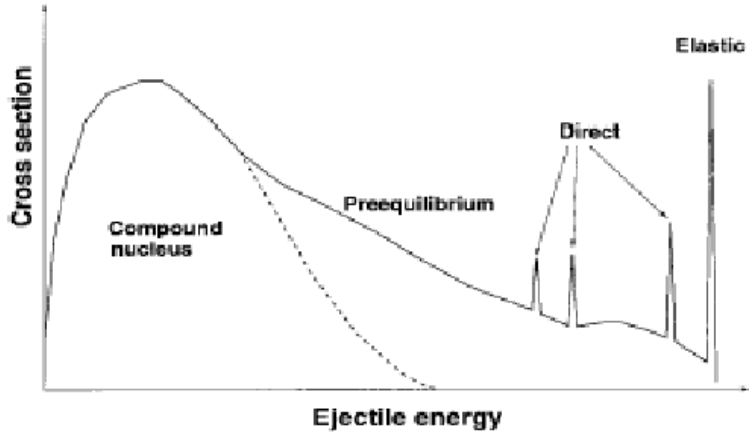


Figure 2.4: 130 ev neutron resonance in scattering from ^{59}Co.

A typical example of neutron emission spectrum showing contributions of different reaction mechanisms in a nuclear reaction are shown in Fig. 2.4. We observe that the two most important reaction mechanisms are compound and the direct. The pre-equilibrium mechanism fills the gap between them.

The existence of pre-equilibrium reactions was revealed by a study of the excitation functions of nuclear reactions showing long tails beyond the maximum . If we consider a heavy target nucleus which is non-fissionable, the significant contribution to the compound nucleus decay is neutron evaporation . The observation leads to the fact that as soon as the evaporation of x-neutrons becomes energetically possible there is an extremely rapid increase of cross section of (p,xn) reaction, p being the projectile. At an energy that exceeds the threshold by an amount equal to the next neutron binding energy, this cross section should reach a value almost equal to that of reaction cross section. A further increase in excitation energy should lead to an exponential decrease of the cross section, the dominant contribution becoming that of the (p, $(x + 1)$ n) reaction. But it does not happen so in reality. Contrary to the expectations, the excitation functions for (p,xn) reactions have high energy tails which slowly decrease with increasing energy. This experimental fact can also be observed in case of light nuclei. This observation gives the evidence of pre-equilibrium reactions.

Pre-equilibrium theory is widely used for analyzing the spectra of particles emitted after the initial interaction of a nucleus with an incoming particle of energy E from 5 to 100Mev. Use of phenomenological pre-equilibrium models, made rather popular the priequilibrium exciton model or its younger brother, the hybrid model. They both are essentially based on the notion of an exciton, i.e particle above or hole below the Fermi level. The initial stage of the reaction is the one which is responsible for the essential part of emission at the high energy end of the spectrum.Here,the initial number of degrees of freedom-or,in the language of the exciton or hybrid models,the initial exciton number-plays a crucial role. The initial exciton number n0,which is specific for each projectile-target combination and

energy,plays the key role.Once we know reliably the initial exciton number,all the rest governed by the master equation with the emission and decay rates which should not depend on the conditions of how the composite system has been created. If one ignores the structure effects,a good overall rule says that for reactions induced by nucleons and alpha particles, the initial exciton number is equal or close to the mass number of the projectile[13,14] and that all these initial excitons of particle type. The exciton model proposed by Griffin[6] is very useful for this purpose.

It is generally recognized that the existence of a diffuse nuclear surface influences the emission spectra of particles at energies where pre-equilibrium(PEQ) reaction mechanism is dominant.The diffuse nuclear surface affects the PEQ emission in three ways:

(a) The two- body interaction will be decreased in the surface region.

(b) The hole energy will be limited by the shallower potential well at the surface and

(c) The effective neutron skin will be formed in the neutron-rich targets.

Semi-classical and quantum mechanical models can treat the emission of particle during the equilibration (i.e. precompound) phase. The exciton model has been mentioned above; below we discuss it in more detail.

2.2.1 Exciton model

This model was proposed by Griffin[6] for the formation and decay of the average compound nuclear state. The nuclear state is characterized by the excitation energy of the composite nucleus and the exciton number, which is the total number of particles (p) above and holes (h) below the Fermi surface.

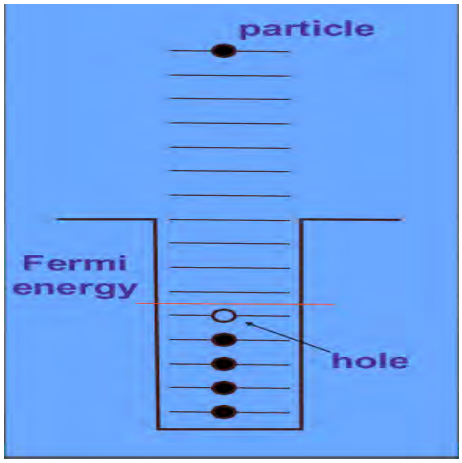


Figure 2.5: exciton (particle and hole) and Fermi energy

According to this model the interaction of a projectile with a target nucleus, gives rise to a simple initial configuration characterized by small number of exciton's (excited particles and holes). Successive two body interactions increase the number of exciton's and lead to a fully equilibrated residual nucleus. Griffin [6] introduced two basic hypotheses to describe each stage of composite nucleus:

1- All the states having the same particle-hole configuration and the same total energy and parity have equal probability.

2- All the decay modes are equiprobable.

The first hypothesis gives the energy distribution of the exciton . The second hypothesis simplifies the evaluation of transition rates obtained as suitable average over all the possible energies of the exciton's in each configuration. In exciton model, any exciton creates a new particle-hole pair, exciton structure of the system is changed and it shifts to the next reaction stage. It takes into account the single preequilibrium emission in its standard formulation . Griffins model has widely been used and amplified by many authors. All the efforts put in the development and elaboration of this model made it a recognized and well established calculational mode for nuclear interactions. It is very useful to analyze the spectra of emitted particles and excitation functions of reactions up to hundreds of MeV energy.

Basis of the model

The pre-equilibrium exciton model is governed by the set of master equation which describes both competing processes, the equilibration of the nucleus and the emission. In the most simple case, when we consider just one possible excitation energy and only the composite system prior to and including the first emission, this set reads

$$\frac{dP(n,E,t)}{dt} = P(n-2,E,t)\lambda^{+}(n-2,E)+P(n+2,E,t)\lambda^{-}(n+2,E)-P(n,E,t)[\lambda^{+}(n,E)+L(n,E)] \tag{2.2.1}$$

where $P(n,E,t)$ is the occupation probability of finding the nucleus with the excitation energy E in an n-exciton state at time t, $\lambda^{\pm}(n,E)$'s are the decay rate from an n-exciton to the $(n \pm 2)$ exciton state and L(n,E) is the emission (integrated over out going energies and summed over all possible ejectiles).

2.2.2 Geometry Dependent Hybrid Model

This model was propossed by Blann[7]. The semi-classical preequilibrium models exciton model and hybrid model both have similar mathematical form but the physical backgrounds are different. In hybrid model, exciton has two probabilities :

(i) To be emitted

(ii) To create a particle-hole pair, independent of rest of exciton's

Each exciton is treated separately so the next exciton stage has 3 times more exciton than the original one. The hybrid model allows multi-particle emission in equilibration phase. 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.

The hybrid model for precompound decay is given by Blann and Vonach[7] as

$$\frac{d\sigma_{\nu}(\varepsilon)}{d\varepsilon} = \sigma_R P_{\nu}(\varepsilon) \tag{2.2.2}$$

And

$$P_\nu(\varepsilon)d\varepsilon = \Sigma_{n=n_0}^{\bar{n}}[\frac{{}^nX_\nu N_n(\varepsilon,U)}{N_n(E)}]gd\varepsilon[\frac{\lambda_c(\varepsilon)}{\lambda_c(\varepsilon)+\lambda_+(\varepsilon)}]D_n \tag{2.2.3}$$

where σ_R is the reaction cross-section,${}_nX_\nu$ is the number of particle type ν (neutron or proton) emitted into the unbound continuum with channel energy between ε and $\varepsilon + d\varepsilon$. The quantity in the first set of square brackets of equation above represents the number of particles to be found (per Mev) at a given energy ε for all scattering processes leading to an n exciton configuration. $\lambda_c(\varepsilon)$ is emission rate of particle into the continuum with channel energy ε and $\lambda_+(\varepsilon)$ is the intranucclear transition rate of a particle. The second set of square brackets in above equation represents the fraction of the ν type particles at a energy which should undergo emission into the continuum, rather than making an intranuclear transition. The D_n represents the average fraction of the initial population surviving to the exciton number being treated.

Early comparisons among experimental results, pre-compound exciton model calculation, and intranuclear cascade calculations indicated that the exciton model gave too few pre-compound particles and that these were too soft in spectral distribution for the expected initial exciton configurations. The intranuclear cascade calculations results indicated that the exciton model deficiency resulted from a failure to properly reproduce enhanced emission from the nuclear surface.

In order to provide a first order correction for this deficiency the hybrid model was reformulated by Blann and Vonach. In this way the diffuse surface properties sampled by the higher impact parameters were crudely incorporated into the pre-compound decay formalism, in the geometry dependent hybrid model(GDH). The differential emission spectrum is given in the GDH as

$$\frac{d\sigma_\nu(\varepsilon)}{d\varepsilon} = \pi\lambda^2\Sigma_{l=0}^{\infty}(2l+1)T_l P_\nu(l,\varepsilon) \tag{2.2.4}$$

where λ is the reduced de Broglie wavelength of the projectile and T_l represents transmission coefficient for l^{th} partial wave. Using the total pre-compound neutron emission

spectrum $\frac{d\sigma_n(\varepsilon)}{d\varepsilon}$, the cross-section which could be involved in the emission of neutrons is calculated as

$$\sigma_n = \int_{U=0}^{E-B_n} \frac{d\sigma_n(\varepsilon)}{d\varepsilon} d\varepsilon \tag{2.2.5}$$

where B_n represents the neutron binding energies.The geometry dependent influences are manifested in two distinct manners in the formulation of the GDH model. The more obvious is the longer mean free path predicted for nucleons in the diffuse surface region. The second effect is less physically secure, yet seems to be important in reproducing experimental spectral shapes. The nuclear density distribution used in the GDH model is a Fermi density distribution function, $\rho(R_l) = \rho_s[\frac{exp(R_l - C)}{0.55fm+1}]^{-1}$, where ρ_s is the density at the center of nucleus, and $C = 1.07A^{1/3}$ fm taken from electron scattering results. The radius for the l^{th} entrance channel partial was defined by $R_l = \lambda(l + 1/2)$. In the GDH model , the fermi energies and nuclear densities are defined to impact parameter R_l.

Many other semi-classical preequilibrium models have been proposed, most of them underestimate the experimental data. To overcome this deficiency, quantum mechanical models are formulated. These models are based on the theory of nuclear scattering. Two important reactions mechanisms are multi-step compound (MSC) and multi-step direct (MSD). One excited particle must be above the binding energy (in continuum of levels) in MSD while all the particles are bound in potential well in case of MSC mechanism. The angular distributions are forward peaked in MSD and the particles emitted from MSC chains are symmetric around 90^0. The MSD reaction models use the DWBA approach to the continuum of levels and to the multiple scattering. Different formulations of MSD and MSC have been proposed. The most important point in using these models is that both MSC and MSD should be applied simultaneously in calculations as one is the necessity of the other.

Equilibrium emission is calculated according to Weisskopf-Ewing(WE) model [8] by neglecting angular momentum. In the evaporation, the basic parameters are binding energies, inverse cross-section, the pairing and the level-density parameters. The reaction

cross-section for the incident channel a and exit channel b can be written as

$$\sigma_{ab}^{WE} = \sigma_{ab}(E_{inc}) \frac{\Gamma_b}{\Sigma_{b'} \Gamma_{b'}} \tag{2.2.6}$$

where E_{inc} is the incident energy. In equation above, Γ_b can be also expressed as

$$\Gamma_b = \frac{2s_b + 1}{\pi^2 \hbar^2} \mu_b \int d\varepsilon \sigma_b^{inv}(\varepsilon) \varepsilon \frac{\omega_1(U)}{\omega_1(E)} \tag{2.2.7}$$

where U, μ_b, s_b, σ_b^{inv} are the excitation energy of the residual nucleus, the reduced mass, the spin, and the inverse reaction cross section , respectively. The total single-particle level density it taken as,

$$\omega_1(E) = \frac{1}{\sqrt{48}} \frac{exp[2\sqrt{\alpha(E-D)}]}{E-D} \tag{2.2.8}$$

where E, D, and g are the excitation energy of compound nucleus, the pairing energy, and the single particle level density, respectively.

2.3 Direct Reaction

At the opposite extreme from compound nucleus reactions are direct reactions, in which the incident particle interacts primarily at the surface of the target nucleus: such reactions are also called peripheral processes[4]. It is assumed in the theory of DNRs that such reactions occur at the periphery of the nucleus, where the nucleon density is low. Consequently, a nucleon that has acquired sufficient energy through interaction with an external agent has a considerable probability of leaving the nucleus with out any collisions. The first quantitative theory of DNRs was proposed by S.Butler of Australia in the 1950's.

As the energy of incident particle is increased, its de Broglie wave length decreases, until it becomes more likely to interact with a nucleon-sized object than with a nucleus sized object. Direct nuclear reactions(DNR) can be caused by all possible incident particles,

from gamma quanta to multiply charged ions, over a wide range of energies (from a few million to several billion electron volts). They are characterized by marked anisotropy and a comparatively weak dependence of the probability of the process-, that is, the effective cross section for the process on the particle's energies. The nucleus formed as a result of a direct nuclear reaction is generally in either a weakly excited state or the ground state[9]. Direct reactions were discovered in the early 1950's. The first to be detected were deuteron stripping(d,p) and pick up (p,d) reactions involving light nuclei. The protons and deutrons emitted in these reactions emerge primarily in the direction of the beam of incident particles. A DNR of the type (x,xy) is called quasi-elastic scattering(QES). The QES reactions produced by alpha particles, protons, and π-mesons in light nuclei are the best studied. Other reactions that have been observed include the knocking out of weakly bound particles-deutrons-from the nucleus,that is, reactions such as (p,pd). The characteristics of DNRs can be explained by assuming that the particles emitted from the nucleus acquire energy and momentum in the process of direct interaction with the incident particle, while the remainder of the target nucleus is involved in the reaction only as an "onlooker "or "spectator ". A 1-Mev incident nucleon has a de Broglie wave length of about 4fm, and thus does not "see "individual nucleon; it is more likely to interact through a compound nucleus reaction. A 20Mev nucleon has a de Broglie wave length of about 1fm and therefore may be able to participate in direct processes.

0f course, it may be possible to have a direct and a compound nucleus processes both contribute to a given reaction. How can we distinguish their contributions or decide which may be more important? There are two principal differences that can observed experimentally:

(1) Direct processes occur very rapidly, in a time of the order of 10^{-22}s, while compound nuclear processes typically take much longer, perhaps 10^{-16} to 10^{-18}s. This additional time is necessary for the distribution and re-concentration of the incident energy. There are ingenious experimental techniques for distinguishing between these two incredibly

short interval of time.

(2) The angular distributions of the outgoing particles in direct reactions tend to be more sharply peaked than in the case of compound nuclear reactions.

Inelastic scattering could proceed either through a direct process or a compound nucleus, largely depending on the energy of the incident particle. The (α, n) reaction is less likely to be a direct process, for it would involve a single transfer of three nucleons into valence states of the target, a highly improbable process.

2.3.1 Angular momentum in Direct reactions

In general, the transition between the initial and final states in a direct reaction requires the transfer of angular momentum between the projectile and target. This angular momentum comes from momentum transfer at the point of contact and it affects the angular distribution of the outgoing particle[4]. We can see how this might come about by using a simple, classical picture of a direct reaction, illustrated schematically in figure below. This shows an incident particle with momentum P_i interacting in the surface of a target nucleus, at a radius R, and an outgoing particle leaving with momentum P_0 at an angle θ relative to P_i. The momentum transfer to the target is given by $P_t = P_i - P_0$ and we use the cosine rule to write

$$P_t^2 = P_i^2 - P_0^2 - 2P_iP_0\cos\theta = (P_i - P_0)^2 + 4P_iP_0\sin^2\frac{\theta}{2} \tag{2.3.1}$$

The magnitude of the transferred angular momentum is given by $L = \sqrt{l(l+1)\hbar} \leq P_tR$. The direction θ of the outgoing particle depends on P_t and, therefore, θ will also depend on L.

As a simple, illustrative example, we consider inelastic scattering where the projectile energy is large compared with the energy transfer. In this case, we can simplify equation (2.3.1) by noting that $P_i \approx P_0 = P$,say. It then follows that

$$\sin\frac{\theta}{2} = \frac{P_t}{2P} \geq \frac{\sqrt{l(l+1)\hbar c}}{2PcR} \tag{2.3.2}$$

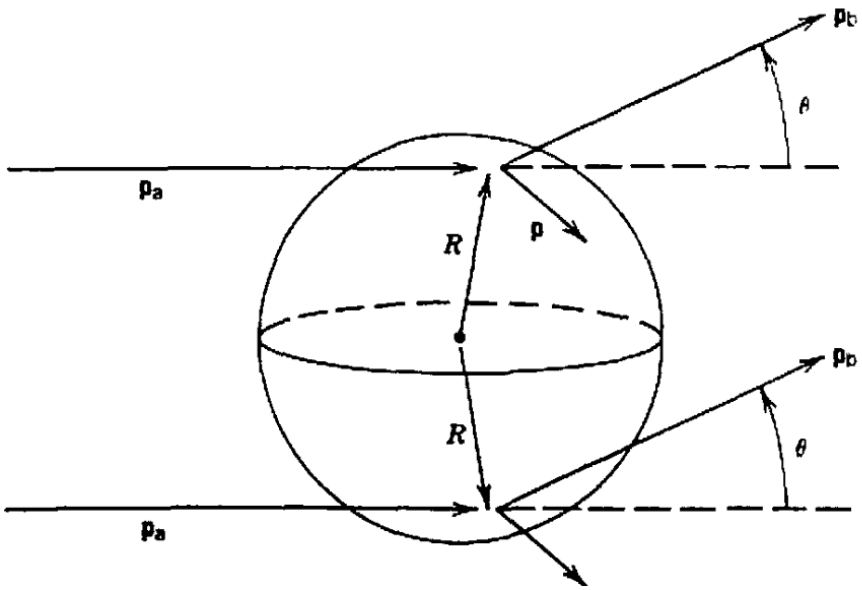


Figure 2.6: Geometry for Direct reaction occurring primarily on the nuclear surface[4]

Chapter 3

3.1 Computer Codes and Formulation

3.1.1 Nuclear data evaluation

Nuclear data evaluation is generally carried out on the basis of experimental data and theoretical model calculations. It is both practically and economically impossible to measure necessary cross section for all the isotopes in the periodic table for a wide range of energies. Nuclear reaction models are frequently needed to provide estimates of the particle-induced reaction cross sections, especially if the experimental data are not available or unable to measure the cross sections due to the experimental difficulty. Therefore, nuclear reaction model calculations play an important role in the nuclear data evaluation.

3.1.2 COMPLET

The code COMPLET is a nuclear reactions code which was designed for versatility and ease of use in the bombarding energy range of a few Mev to several hundred Mev. It predicts the yield of residual nuclei in nuclear reaction with excitation energy up to 225 Mev taking in to account two mechanisms, Pre-equilibrium emission is accompanied in the frames of the model of independently interacting excitons.An approximation concerning pre-equilibrium angular momentum removal is included. The equilibrium part formerly based on Weisskopf-Ewing evaporation formula is also modified to include full angular momentum decoupling regarding emission of light particles with $A \leq 4$. In COMPLET

code a pre-equilibrium process in two stage is assumed. The particles in the initial configuration ($n_0 = EX1 + EX2 + EX3$) can be neutron, proton or alpha particle, represented by the exciton numbers EX1, EX2 and EX3 respectively. It is customary to use the initial exciton number no separated in to proton and neutron above and holes below the Fermi level as a fit parameter theoretical predictions with experimental excitation function. The requirement of detailed input parameters was sacrificed to achieve this goals. The code COMPLET provides yields and spectra for all reactions populated by all combinations of n, p, d, alpha and can provide all input parameters internally. The running time of the code is very short. This code includes damping of fission widths above a critical temperature R_O. The used code is a further simplification of the formula due to Paul and Thoennessen in Ann.Rev.Nucl and particle science 44(1994).

This version needs about 2 Megabyte memory. Therefore the option of calculations of particle-residual nucleus correlations as well as the option for calculating inclusive P-and N-spectra. The code COMPLET includes pre-equilibrium neutrons, protons and alpha emission up to two particle, as well as evaporation of neutron protons, alphas, deutrons, tritons and hellions. With separate PE-angular momentum decoupling for each partial wave and full (up to delta(L)=12) compound nucleus(CN)-angular momentum decoupling. Maximum 100 incoming partial waves (L=0 till 99) are possible. Calculation of inclusive DI-, PE- and CN-Gamma spectra. Also yields for forming the primary CN can be calculated. Order of calculation changed from isotopes to isotones saving M-space. For incoming pions(π^-, π^0, π^+) 100 mb reaction cross section is distributed evenly among incoming partial waves up to L=JANG, If RCSS=0 otherwise, JANG is the maximum angular momentum in the interance channel.

3.2 Description of parameters selected as input

The code COMPLET is based on same philosophy as the former code INDEX[10]. It applies the statistical model of compound nucleus decay developed by Weisskopf-Ewing[8] and the hybrid and geometric-dependent hybrid model of Blann[7] and the further simplification and improvement by J.Ernst[2]
Originally, this code has been developed out of the code OVERLAID ALICE by M.Blann.While some standard routines remained practically unchanged (like FISROT,LYMASS,PUNCH,PLT, PARAP, OVER1, OVER2 and TLJ) others have been substantially modified (like MAIN, SHAFT, NUCMFP, etc) or are completely new (like, INDEX, PARDEN, TRAPRO, ANGULAR,etc). The underlying PE-MODEL is described in Z.Phys.A328(1989). It is contained in subroutine INDEX.

The INPUT is described below. The notion "card "from the old FORTRAN input is still kept but now corresponds to lines. Free formats, the input values should be separated by ", "or "CR ".

CARD 1

General input data: Definition of scattering system and calculation method.

Symbol Description

AP - Projectile mass number

AT - Target mass number

ZP - Projectile charge

ZT Target charge

QVAL - Reaction Q value = AP + AT - ACN.

=0:calculated from M and S mass formula.

=1:Calculated from mass excesses of 1990 nuclear wallet cards

CLD - Ratio of single particle level densities af/an=0: af/an=1.

If parameter ISOT is nonzero, CLD is isotopic abundance input Default value = 1.0

If = 0, use rotating finite range fission barriers due to A.J. Sierk

BARFAC - multiplies the rotating drop fission barrier by this value.

BARFAC=0:BARFAC=1

ROFFAC - Multiplies the rotational energy by this value.=0:ROTFAC=1.

RO - Critical temprature above onset of retarded fission

GI - Nuclear friction parameter from equilibrium deformation to saddle

GO - Nuclear friction parameter from saddle to scission point

NA - The number of nuclide's of each z to be included in the calculation. Up to 21 neutrons may be emitted(maximum NA=22)

NZ - The number of Z-values to be calculated in the emission process. Up to 8 protons may be emitted (maximum NZ=9). For correct PE calculations Binding energies are calculated for all nuclei with $IZ, IA \leqq 5$ (17.7.91)

MC - Shell correction option for masses subroutine.

MC = 0, masses incl. shell correction.

MC = 1, masses without shell correction term

MC = 2, BE values will be supplied as input.

$MC > 2$, BE values are calculated from 1990 nuclear wallet cards.

MP - pairing correction to masses.

MP = 0: No pairing term in masses.

MP = 1: Pairing term in masses, ldgs calculated from msl formula and applied back-shifted

MP = 2: masses are from nuclear wallet cards;

MP = 3: pairing correction in masses, NOTE: changes are not corrections in only level densities

IPA - Pairing corrections in level densities

IP = -1, no corrections

IP = 0, standard correction i.e multiplier = 12

IPA > 0 multiplier is IPA

M3 - Number and type of particles to be emitted from each nuclide

If = 1: N only;=2:N and P;= 3 or = 0 :N, P and Alpha;= 4:N, P, Alpha and Deuteron,

If = 5: N, P, Alpha, Deuteron and Triton; = 6:N,P, Alpha, Deuteron, Triton and Helion(3HE)

If = 7: as before incl. Gammas. Calculations until gamma emission is finished, important for isomeric ratio calculations.

INVER - Inverse cross section parameters.

If = 0 User supplied;

If= 1: Results by O.M.subroutines as in ALICE/85/300,

If= 2: O.M.for N, P as in old ALICE

If = 3: Sharp cutoff values for inverse cross sections.

Option inver = 2 greatly reduces total cpu time

IKE - if = 1, no particle spectra will be printed;

if = 2, equilibrium spectra for each nuclide will be printed;

if = 3, pre-compound spectra will be printed

if= 5, PE and summed equilibrium spectra will be (separately) printed;

if IKE=-2 to -5: Reduced output with spectra as IKE=ABS(IKE)(yields are printed after negative energy input)

if IKE$\leqq$ 0 or IKE $\geqq$ 6 Most reduced output

emitting nuclide's and all partial waves) of pre-compound plus equilibrium spectra. To print gamma spectra, increase the IKE value selected by 5.

if IPCH = 1 or = 2, fission barriers are to be read in after this first record IPCH - =1: Inverse cross sections will be readout for possible future use in separate output file.

= 0: or NE from 1, no printout

KPLT - Number of decades to be plotted as excitation function on line printer. If KPLT = 0:No plotting

CARD 2

Title - 80 columns

If MC = 2 on CARD 1, read user supplied n, p, alpha , deuteron triton and helion binding energies here, Format for IA=1 to NA, IZ=1 to NZ.

If INVER = 0 on CARD 1, read the n, p, alpha , deuteron triton, helion and gamma inverse cross sections here.

In ascending channel energy, first value=0.1Mev, incremented by 1Mev, 48 values per particle type in sequence N, P, A, D, T, 3HE, and Gamma depending on value of M3.

CARD 3

ENERGY and COMPOUND NUCLEUS and PRE-EQUILIBRIUM OPTION

Symbol Description

IKEN - Projectile kinetic energy in the laboratory system.

if = 0; A new problem will begin at CARD1.

if < 0; Previously calculated excitation functions will be printed (if KPLT=0, EKIN values were run in ascending order they are plotted).

if EKIN=0. on two successive cards, a normal exit will occur for negative target mass on card 1.

RCSS = 0: reaction cross section is calculated from subroutine (for pi-induced reactions: if RCSS(input)=0, RCSS=100 mb)>: number of T(l) values to be read from the next card

JCAL

= 1, Weisskopf-Ewing evaporation calculation

= 2, S-wave approximation, liquid drop moment of inertia

= 3, S-wave approximation, rigid body moment of inertia (only if entrance channel cross sections calculated by parabolic approximation, i.e. ZP > 1 and RCSS = 0.)

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

JFRAC - Direct-semi-direct capture gamma ray estimate: <0: no emission

> 0: approach of kalka

JANG - JANG +1 = Maximum number of contributing incoming partial waves.

- usually use the maximum: JANG =99. Otherwise, JANG can be used for cutoff on L-values provided by subroutines OVER1 and 2

All other parameters on this card are for the pre-compound calculation options. put TD-values to zero, if no pre-compound calculation is wanted.

TD - Initial exciton number = p + h

EX1 - Initial excited neutron number

EX2 - Initial excited proton number

EX3 - initial alpha particle exciton number

POT - Fermi energy in Mev

if = 0: POT is calculate from nucl.matter value = 37.8 Mev;

AV - if AV=0: =1, OPTICAL MODEL mean free paths are used in routine MFP. Not to be used above 55 Mev.

If AV = 1: Nucleon-Nucleon mean free paths are used in NUCMFP.

ALF - probability that newly created exiton particle from first stage exiton gets an alpha particle in the second stage.

(1-ALF) : Complementary probability

If ALF>1 Calculation for two initial exiton numbers

A) ATD=TD-3 (min.1.5) AEX1=AEX2=0, AEX3=2.; ATD=TD-6 for TD>9 with weight ULF=INT(ALF)100

B) Weight = (1-ULF), with initial Exciton numbers.

CMFP - mean free paths are multiplied by CMFP. If CMFP = 0: multiplier is 1

GDO - Critical angular momentum. GDO >0: partial waves with L> GDO are not taken in to account in line of isotone cross sections while cross sections for partial waves with L> GDO are accounted for in the line below

N.B For GDO $\leq +0.5$ No cut-0ff.

It is customary to use the initial exciton number no separated in to proton and neutron above and holes below the Fermi level as a fit parameter to match theoretical predictions with experimental excitation function. A good guess would be the number of nucleons in the projectile. On this basis, the theoretical calculations in this thesis is done using no=4(2p+2n+0h) and no=5(2p+3n+0h). These exciton's interact independently with the particles below the Fermi level, creating new particle-hole configuration in the second stage or getting emitted into the continuum. In these interactions the original exciton type is assumed to be conserved. The newly created exciton may be α-particle, α-hole state formed with probability (1-ALF). The value of ALF=0.2 is found to be the best choice.

The Q-value for the formation of the compound nucleus and the emitted nucleons binding energies in the evaporation chain have been calculated using Myres and Swiatecki mass formula[2]. The mean free path multiplier for intra nuclear transition rates are calculated from optical potential parameters.

Chapter 4

4.1 Result and Discussion

The present thesis describes new calculations on the excitation functions of $^{59}Co(\alpha, n)^{62}Cu$, $^{59}Co(\alpha, 2n)^{61}Cu$, $^{59}Co(\alpha, 3n)^{60}Cu$ reactions carried out in the 10-80 Mev alpha incident energy range. In the calculation, the codes COMPLET have been used.

The experimental cross sections are obtained from EXFOR data source, IAEA[10]. The theoretical and experimental cross sections are plotted against the projectile energy and are shown in fig 4.1-4.6. The excitation function for the theoretical calculations are shown by black and red solid line while the experimental results are shown by green line and triangle point on it. The cross sections are measured in mili barn(mb) and the projectile energy in Mev. The experimental data for the reaction $Co(\alpha, n)$ is taken from the Author F.Szelecsenyi, K.Suzuki,Z.Kovacs, M.Takei[12] and data for $Co(\alpha, 2n)$ and $Co(\alpha, 3n)$is taken from Author E,Gadioli, E.Gadioli Erba, J.Asher, D.J.Parker [11]. Also energy range selected from the data is same with theoretical. This makes easy for comparison.

Pre-equilibrium and equilibrium gamma emission may also be handled by the code. The Q-values are calculated from Myers-Swiatecki mass formula[18], which is the liquid drop mass with pairing correction.

For the pre-equilibrium emission, the particles in the initial configuration n_0 can be neutron, proton or α-particle. These exciton interact independently with particles below the Fermi level creating either new particle-hole configurations in the second stage or getting emitted into the continuum. In this thesis $n_0 = 4$, which is equivalent to a break up

of the incoming α-particle in the nuclear potential field above a completely field fermi level; gives best fit with the experimental result. As the initial exciton number has an effect in the excitation function of the pre-equilibrium stages of the nuclear reaction, exciton number $n_0 = 4$ and $n_0 = 5$ are taken for the comparison in all reaction channel $^{59}Co(\alpha, xn)$ where x=1, 2 and 3. The theoretical and experimental excitation functions for these exciton numbers are shown from figure 4.1 to 4.6 . It can be seen from the figure that the exciton number $n_0 = 4$ and $n_0 = 5$ both fits with the experimental curve but $n_0 = 4$ is best choice because the excitation function for $n_0 = 4$ is closer to experimental excitation function. Another comparison is done to see the effect of the level density on the excitation function. The level density value $a = \frac{A}{9}$ and $a = \frac{A}{10}$ are taken for all calculation of cross section in all reaction. The theoretical cross section for the two level density values and experimental cross section are shown. The figure shows that the value for the level density $a = \frac{A}{10}$ better fits the experimental curve for all the three reaction.

Table below shows production of copper isotope by reaction of alpha particle with target nucleus cobalt. When a target is bombarded by a beam of particles, it is common for nuclear reactions to take place leading to radioactive residual nucleus, and, if the cross section σ is known, the number of these radioactive nuclei can be determined as a function of time during the bombardment. Target nuclei are lost during the bombardment and so, eventually, the number of target nuclei becomes depleted. However, in most practical situations, the fraction of nuclei converted is very small, in which case we can consider the number of target nuclei and, hence, the rate of production(P) to be independent of time. The net rate of increase of radioactive nuclei(decay constant λ) is the difference between the rate of production and the rate of decay $\frac{dN}{dt} = P - \lambda N$.

These copper isotopes i.e ^{62}Cu, ^{61}Cu and ^{60}Cu have same mode of decay(β^+) and different half-life also energies of emitted gamma rays.

The residue ^{62}Cu decays via 9.74 min half-life by emitting γ -ray of 1173 Kev, while the residue ^{61}Cu and ^{60}Cu decay with 3.4h and 23min half-lives by emitting gamma-rays of

Residual nucleus	Reaction	Mode of decay	Half-life	$E_\gamma(Kev)$
^{62}Cu	$^{59}Co(\alpha,n)$	β^+	9.74min	1173
^{61}Cu	$^{59}Co(\alpha,2n)$	β^+	3.4h	283; 656; 67; 1186
^{60}Cu	$^{59}Co(\alpha,3n)$	β^+	23min	1332; 1792; 826

Table 4.1: shows the compound nucleus,mode of decay, half-life energy of emitted gamma rays[15].

energy 283, 656, 67, 1186 Kev and 1332, 1792, 826 Kev, respectively.

4.1.1 PRODUCTION OF ^{62}Cu

^{62}Cu is produced when a projectile($\alpha - particle$) strike target element Cobalt(^{59}Co) and emits a single neutron(n). The calculated excitation functions of $^{59}Co(\alpha,n)^{62}Cu$ reaction is compared with the experimental result[12].

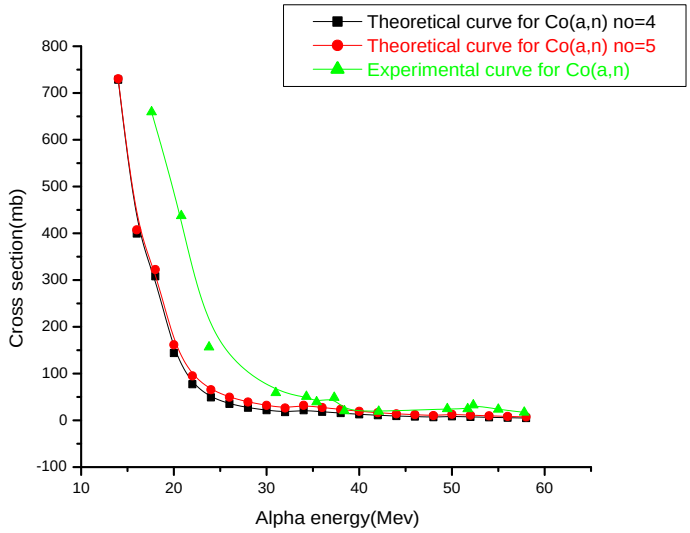


Figure 4.1: Excitation function for $^{59}Co(\alpha,n)$ reaction with level density parameter $\frac{A}{9}$

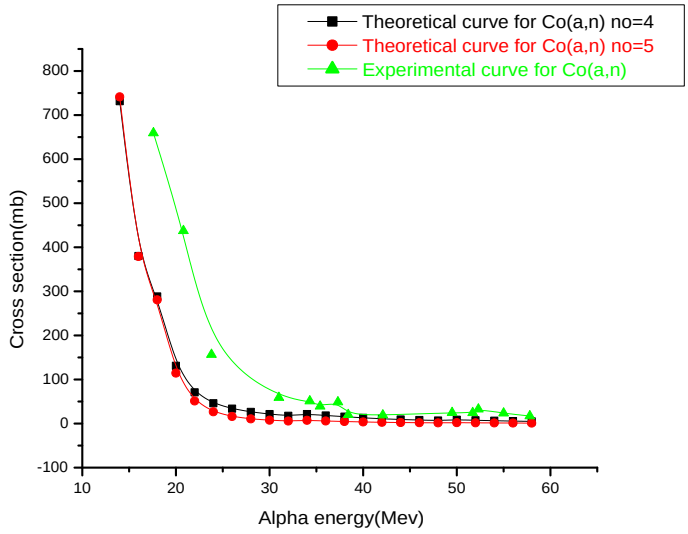


Figure 4.2: Excitation function for $^{59}Co(\alpha, n)$ reaction with level density parameter $\frac{A}{10}$

As can be seen from figure above, experimentally measured and theoretically calculated excitation function for the reaction $^{59}Co(\alpha, n)^{62}Cu$, calculations have been done by using consistent set of parameters. Low energy and high energy tail of theoretical fit with the experimental result.

Compound nucleus reaction gives best result up to 25Mev. After this energy pre-equilibrium nuclear reaction dominates and it is shown by long tail. It is clear that the result obtained from a computer program COMPLET (theoretical result) agree with the experimental result obtained from [11]. Basically, theoretical result have been calculated in two ways, by using different values of exciton numbers($n_0 = EX1 + EX2 + EX3$) i.e $n_0 = 4$ and $n_0 = 5$, relatively $n_0 = 4$(black curve) best fits with experimental result(green curve). Also level density parameter plays a key role. Figure 4.1 and 4.2 is the same type but they are obtained by different values of level density parameter(a) $\frac{A}{9}$ and $\frac{A}{10}$ comparing these curves, $a = \frac{A}{10}$ gives best result.

Above projectile energy of 80Mev resonance (several peaks) formed and this range is dominated by direct nuclear reaction.

4.1.2 PRODUCTION OF ^{61}Cu

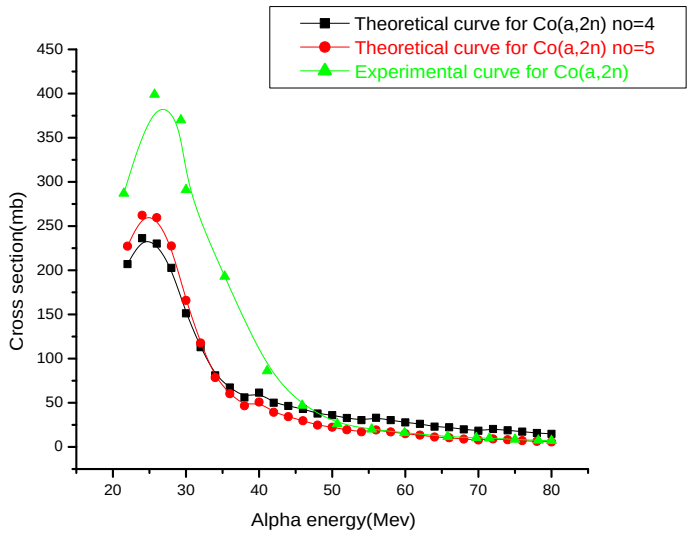


Figure 4.3: Excitation function for $^{59}Co(\alpha, 2n)$ reaction with level density parameter $\frac{A}{9}$

Comparing figure 4.3 and 4.4 one can say that the level density parameter $a \approx \frac{A}{10}Mev^{-1}$ gives a better agreement with experimental result[13], possibly because the diffuseness of the nuclear surface was not taken into account in estimating the theoretical value and possibly because the angular momentum dependence of the level density was not completely taken into account in determining the experimental value. In the low energy region from 22 Mev to 40 Mev mostly statistical process dominates. The pre-equilibrium effects start manifesting them selves at energies around 40 Mev their contribution starts becoming significant. Also other comparison is taken, that is exciton number $n_0 = 4$ and $n_0 = 5$. From figure 4.3 and 4.4, it is evident that the theoretical excitation function for these value fit with experimental excitation function. But $n_0 = 4$ is the best choice because the curve for this value observed to be closer to the experimental curve.

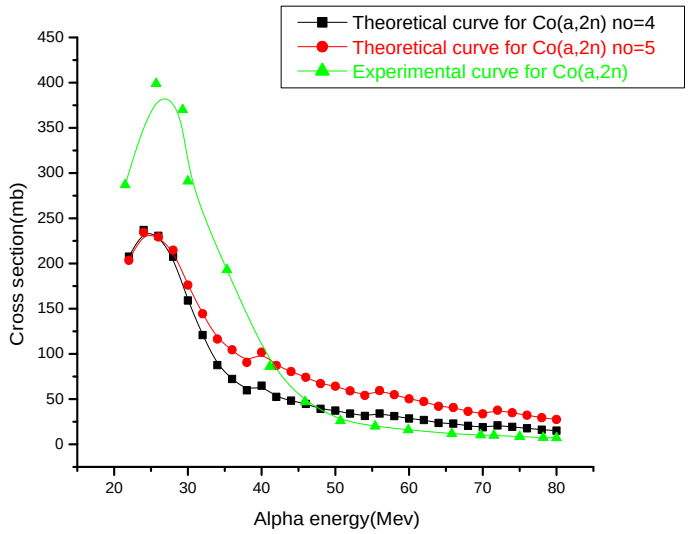


Figure 4.4: Excitation function for $^{59}Co(\alpha, 2n)$ reaction with level density parameter $\frac{A}{10}$

4.1.3 PRODUCTION OF ^{60}Cu

^{60}Cu isotope is arised from reaction of target nucleus cobalt(^{59}Co) with alpha particle (one helium atom) by emitting three neutrons.

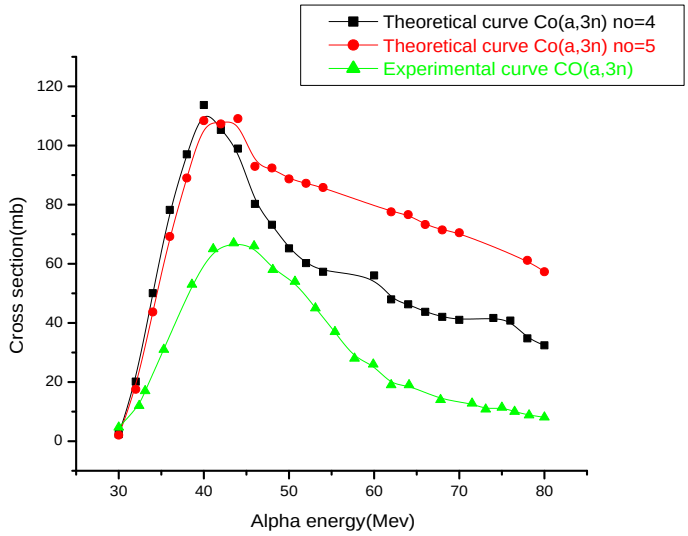


Figure 4.5: Excitation function for $^{59}Co(\alpha, 3n)$ reaction with level density parameter $\frac{A}{9}$

In fact, the more energy we give to the compound nucleus, the more particles are likely to evaporate. For each states, the cross section has the Gaussian like shape. At higher incident energies, it is more likely that additional neutrons will evaporate from the compound nucleus. All figures above shows that the cross section for (α, xn) reactions. Where x=1, 2 and 3. For each reaction, the cross section increase to a maximum and then decreases as the higher energy makes it more likely for an additional neutron to be emitted. As observed from figure (4.5) and (4.6) above, the reaction $(\alpha, 3n)$ started from around 27 Mev, this indicates that energy needed to emit three neutron is greater than energy needed to emit one neutron and two neutron. Also as observed from (α, n) and $(\alpha, 2n)$ reaction the level density a=A/10 and exciton number no=4 (shown by black curve) best agree with the experimental result[11,12] which is shown by green curve. Again from energy range 27 Mev to 50 Mev projectile energy compound nucleus reaction takes place. After alpha energy of 50 Mev pre-equilibrium nuclear reaction dominates the region and is shown by long tail.

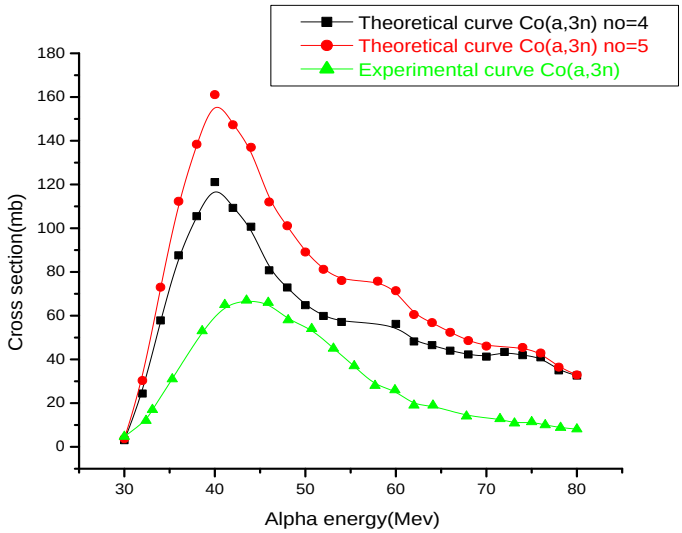


Figure 4.6: Excitation function for $^{59}Co(\alpha, 3n)$ reaction with level density parameter $\frac{A}{10}$

Chapter 5

CONCLUSION

In the present thesis, using equilibrium and pre-equilibrium reactions mechanism, the (α, xn) where x=1, 2, and 3, cross-section values for ^{59}Co target nuclei have been calculated for 10-80 Mev incident energy ranges. The calculation results on the excitation functions and the optimum energy ranges for reaction process are given in figure 4.1-4.6. Broadly, nuclear reaction is understood in terms of three kinds of reaction mechanisms namely, equilibrium, pre-equilibrium and direct reaction. Compound nucleus is formed when incoming projectile energy is shared between all the nucleons in the target nucleus and equilibrium emissions occur due to statistical fluctuation in energy. Direct reaction is a single step process that occurs due to large momentum transfer from projectile to the target nucleons. This results in high energy ejectile emission leaving residual at lower excited states. Between this two extremities, pre-equilibrium reaction process plays a significant role having features of both cross section of the product nuclei corresponding to a particular reaction is the resultant of all the reaction mechanism involved. In this study, contribution from direct reaction process is not expected. Generally the new model calculations used for all reactions are in good agreement with the measurement data. The nuclear level density has a negligible influence on the shape and the height of the calculated excitation function. Also as can be seen in figures 4.1-4.6, the high energy part of the experimental excitation functions can not account for by the equilibrium decay mechanism and the pre-equilibrium emission must be considered along with compound nucleus

decay. Besides, the pre-equilibrium effects increase as the incident energy increases. The results of this study are in good agreement with the earlier investigations.

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Declaration

This thesis is my original work, has not been presented for a degree in any other University and that all the sources of material used for the thesis have been dully acknowledged.

Name: Wubishet Gezahegn Woldegiorgis

Signature: .....

Place and time of submission: Addis Ababa University, June 2011

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This thesis has been submitted for examination with my approval as University advisor.

Name: Prof. A.K. CHAUBEY

Signature: .....