COMPOUND NUCLEUS DECAY OF SOME α+RUBIDIUM SYSTEMS AT VARIOUS ENERGIES

By

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Abstract

In this study, the more emphasis is given to compound nucleus decay. To test this, calculations of the theoretical reaction cross sections of $^{85}Rb(\alpha, n)^{88}Y$, $^{85}Rb(\alpha, 2n)^{87}Y$, $^{85}Rb(\alpha, 3n)^{86}Y$ and composition reaction of $^{85}Rb(\alpha, n)$ and $^{87}Rb(\alpha, 3n)$ reactions are carried out in the incident alpha energy from 15 MeV to 60 MeV. Theoretical calculations of reaction cross sections are done using Alice-91 computer code, which is based on Weisskopf-Ewing model for compound nucleus decay and Geometry Dependent Hybrid (GDH) model for pre-compound nuclear reactions. The calculated results are compared with experimental one and various parameters were changed to see their effects on the reaction cross sections.

Acknowledgements

First I would like to extend my deepest and sincere gratitude to my advisor Prof.A.K.Chaubey for his enthusiastic guidance, encouragement and unlimited support during my work and write up phase. His optimistic attitude has been my constant inspiration.
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Chapter 1

Introduction

The collision of two nuclei can give place to a nuclear reaction and the final products can be different from the initial ones. This process happens when a target is bombarded by particle coming from an accelerator or from a radioactive substance. It was in the latter way that Rutherford observed, in 1919, the first nuclear reaction produced in laboratory

$$\alpha + {}^{14}_{7}N \longrightarrow {}^{17}_{8}O + p \tag{1.0.1}$$

using α-particles from a ^{214}Bi sample.

As in eq. 1.0.1, other reactions were induced using α-particles, the only projectile available initially. With the development of accelerators around 1930, the possibilities multiplied by changing the energy and mass of projectile.

A nuclear reaction is a process that takes place when the nucleon in the incident particles interact with the nucleons in the target: it is a process in which the structure and energy content of an atomic nucleus is changed by interaction with another nucleus or particles.

In order for nuclear reactions to occur, the energy must be high enough to overcome the natural electromagnetic repulsion between the protons. This energy barrier is called the coulomb barrier. If the energy is below the barrier, the nuclei will bounce off each other without occurrence of nuclear reaction. To have a nuclear reaction, projectile from

accelerating machine must be used because projectile from them have sufficient energy to overcome the natural electromagnetic repulsion between protons. But, projectiles from natural radioactive substance do not have sufficient energy to overcome coulomb barrier.

The alpha particle is a doubly ionized helium (${}^{4}_{2}He^{++}$), that can be obtained when nuclei like uranium or radium decay spontaneously or from accelerator machines. Energy of alpha particles obtained from natural radioactive nuclei is much smaller than coulomb barrier so that they are not suitable for study of nuclear reaction. But the alpha particles from the accelerator machines have continuous and high energy to overcome coulomb barrier and they are frequently used for study of nuclear reaction mechanisms of different isotopes. Hence, the alpha particle beam from accelerator machines is used to study the nuclear reactions produced on natural rubidium isotopes.

Rubidium is a chemical element with the symbol Rb and atomic number 37. Rubidium is soft, silverwhite metallic element of alkali metal group. The atomic weight is 85.4676. Elemental rubidium is very soft and highly reactive, with properties similar to other element in group one, such as very rapid oxidation in air.

There are 26 isotopes of rubidium, known. Natural occurring rubidium is composed of just two isotopes: stable ${}^{85}Rb$ (72.2%) and the radioactive ${}^{87}Rb$(27.8%).

There are two most important extreme mechanisms for describing the interaction of two nuclear systems. Which are,

*Compound nucleus reactions and *Direct reactions

Bohr proposed the compound nucleus hypothesis [**1**], according to his hypothesis compound nuclear reaction occurs in two stages

(i) compound nucleus formation

and

(ii) compound nucleus decay.

The simplest form of nuclear reaction is the mechanism of the formation of the compound

nucleus. During compound nucleus formation, the excitation energy and angular momentum are shared uniformly among the constituent nucleons before any particle is emitted from the nucleus but sometimes particles are ejected before equilibrium is reached, that is, before the formation of a compound nucleus which is called the mechanism of pre-compound nucleus decay. The compound nucleus is unstable and rapidly decays into the final products of the nuclear reactions. The formed excited nucleus can live a relatively long time.

In case of direct reaction the energy of incoming particle directly transferred to one nucleon or a small group of nucleons in the nucleus. It proceeds without formation of compound nucleus. The time during which the incident and target nucleus interact is very much shorter than that of a corresponding compound nucleus. This is the time it takes for the particle to pass through the region of space occupied by the nucleus. Because of this, the reaction products exhibit certain characteristics which are entirely different from those seen if the reaction has proceeded through a compound nucleus reaction.

The term, direct reaction, is used for nuclear process including inelastic nuclear collisions, stripping, and its inverse, the pick-up reaction.

At low energies of the incident particles, the major mechanisms of nuclear reaction is, as a rule, is the formation of the compound nucleus. Direct reactions are predominate at high energies.

One of the important quantities of interest for a specific set of kinematic variables for nuclear reaction is the reaction cross section. It is a measure of the probability for a particular reaction to occur. It has dimension of area and its unit is cm^2 or barn (1b=$10^{-24}cm^2$)

The distribution of the reaction cross section as a function of the beam energy is called the excitation function. The graph of this function tells us the mechanism of nuclear reaction in which it takes place. It also enables us to validate nuclear reaction mechanisms by comparing its measured and calculated values for many reactions.

For the alpha particles, the coulomb barrier is still higher, reaching 25 MeV for heavy nuclei. At this energy of 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. Upon an increase in the energy of alpha particles, the (α,2n) and (α,pn) reactions become most probable.

In this thesis work theoretical calculations of excitation functions or cross-sections for compound nucleus decay is made using the Alice-91 computer code which is based on Weisskopt-Ewing model [**2**] . The calculated values are compared with the experimental results and conclude about the absence of compound nucleus decay of some α+rubidium systems at higher energies of alpha particles.

Chapter 2

Nuclear Reaction Theories

Nuclear reaction is a process that occurs as a result of interactions between atomic nuclei when the interacting particles approach each other to within distance of the order of nuclear dimensions. In the usual experimental situation, nuclear reactions are initiated by bombarding one of the interacting particles, the stationary target nucleus, with nuclear projectiles of some type, and the reaction products.

A nuclear reaction is denoted as X(x,yz)Y, where X is the target nucleus, x is the bombarding particle, y, and z are the emitted particles, Y is residual nucleus (together reaction products are recorded within parentheses, and the heavier ones outside). A nuclear reaction can produced in several ways, for example,

$^{63}Cu(p,n)^{63}Zn$, $^{63}Cu(p,2n)^{62}Zn$, $^{63}Cu(p,pn)^{62}Cu$, $^{63}Cu(p,p)^{63}Cu$, $^{63}Cu(p,p)^{63}Cu$

The composition of the incident particles is called the entrance channel of the nuclear reaction, and the composition of the particles formed as a result of the nuclear reaction is called the exit channel.

Nuclear reactions can occur with the liberation and absorption of energy Q that is about 10^6 times greater than the energy absorbed in chemical reactions. Therefore, a change in mass of the interacting nuclei can be denoted in nuclear reactions. The energy Q released or absorbed in nuclear reactions is equal to the difference between the sums of the particle masses (in energy units) before and after the reaction (Q = $[(M_a + M_X)$-$(M_b + M_Y)]c^2)$)

2.1 Mechanisms of Nuclear Reactions

Various reaction models have been extremely successful in describing certain classes or types of nuclear reaction processes. Depending on the mechanisms through which nuclear reaction takes place the time scale on which it occurs is different, the degree to which kinetic energy of the incident particle is converted into internal excitation of the final product is different and the nature of the dependence of the cross section of a nuclear reactions on the energy of the incident particles is also different.

A large fraction of the nuclear reactions observed has properties consistent with those predicted by two reaction mechanisms which represent the extremes in this general classification. These are the mechanisms of compound nucleus reactions and direct reactions. As an example, if we consider the variation of reaction cross section for inelastic proton scattering by ^{54}Fe(p,p') at target nucleus with the energy of out going proton, the reaction mechanism of the whole process can be given on cross- section verses particle energy graph as follows;

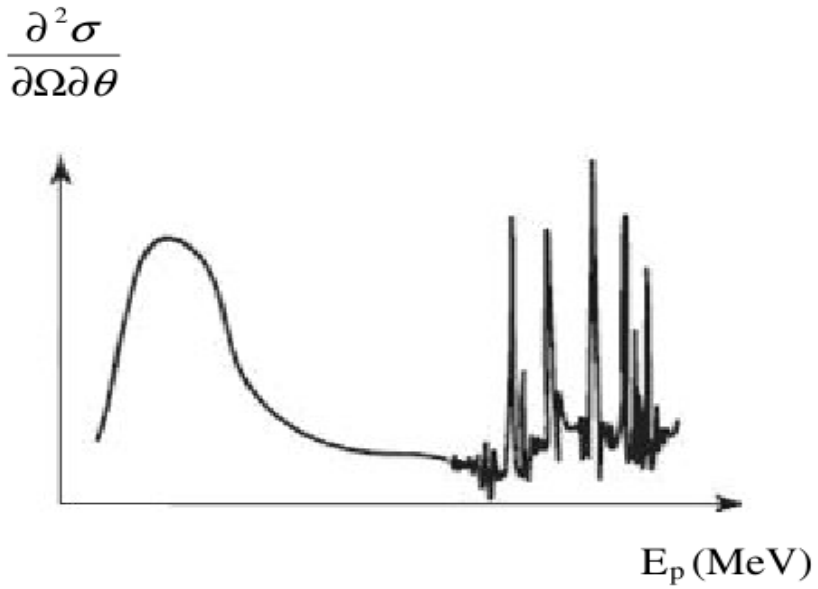

Figure 2.1: A sketch of total reaction cross-section for varying energy of emitted particle from a nuclear reaction [**3**].

From the above graph the broad peak at low energies shows compound formation, the sharp peaks at high energies correspond to direct reactions and the region between the two is the pre-equilibrium region.

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2.1.1 Direct reaction mechanism

Direct reactions (or peripheral reactions), are reactions which proceed directly from the entrance channel to the exit channel without the formation of an intermediate state. These direct reactions are assumed to involve only a very small number of the available degrees of freedom. Most direct reactions are of the transfer type, where one or more nucleons are transferred to or from the incident particles as it passes the target, leaving the two final partners either in their ground states or in one of their many excited states. Such transfer reactions are generally referred to as stripping or pick up reactions, depending on whether the incident particle has lost or acquired nucleons in the reactions.

Elastic and inelastic scattering are direct reactions. If the internal states of the colliding systems do not change, we have elastic scattering. We also define inelastic scattering as the situation where the final particles are the same chemical species, but one or more in an excited state.

In direct reaction, the target nucleus and the incident projectile system have a lifetime of the order of 10^{-23} sec. They are more likely when the incident particle has an energy corresponding to a de Broglie wave length closer to the size of nucleon rather than that of the nucleus. The collisions are largely peripheral, with only a relatively small fraction of the available energy transferred to the target.

2.1.2 Compound Nucleus reaction mechanism

Compound nucleus theory [**4**] is generally given in short as,

$$a + X \rightarrow C^* \rightarrow Y^* + b \tag{2.1.1}$$

where,

a-is projectile, **X**-is target ,

C*-is excited compound nucleus,

Y*-is residual nucleus, and **b** is emitted particle

The projectile **a** is captured by the target **X** to form a highly excited state **C*** in which excitation energy is shared uniformly among the constituent nucleons: then by the process of chance sufficient energy may imparted to the particle **b** which then emitted leaving the residual nucleus **Y***. If **Y*** has enough energy, more emissions can occur, otherwise it will de-excite by β- or -γ-decay.

The compound nucleus system involves much longer scales, as the energy of the captured projectile has to be distributed over all nucleons in the target. The reaction duration clearly depends very much on the incident energy, since higher incoming energy transfers

more energy into the system and makes it easer to give one nucleon enough energy to escape, therefore giving compound system created at higher energy a shorter lifetime. Typical time scales for the decay of a compound nucleus can vary between $10^{-16} - 10^{-15}$ s (at low projectile energies) and 10^{-21}-10^{-20} s (at high projectile energies). Since the energy is redistributed many times among the nucleons in the compound nucleus the decay of the system has no memory of its creation, thus giving a rather uniform angular emission of particles. The idea that the compound nucleus has no memory is of course not completely true since conservation of e.g. angular momentum must be fulfilled, but compared to direct reactions the angular distribution from compound reactions are much more isotropic.

Bohr proposed the compound nucleus theory of nuclear reaction, according to his concept the compound nuclear reaction takes place in two steps:

(i) Mode of formation of compound nucleus,

and

(ii) Independent decay of compound nucleus

In mode of formation of compound nucleus the incident particle together with the target nucleus forms the compound nucleus with its own excitation energy and life-time. The compound nucleus then decays to the final products, since the lifetime of the compound nucleus is much greater than the time taken by incident particle to traverse the nucleus (10^{-22}sec). As a result it forgets history of its formation. It does not know from where it is formed. It is assumed that the mode of decay of compound nucleus is independent of its mode of formation, except for requirement of the various conservation laws; such as conservation of angular momentum and parity. The decay does not depend upon the nature of incoming particle, but it depends only on the quantum mechanical parameters of compound nucleus such as energy of excitation, angular momentum and parity of states. Therefore, to calculate the cross section of nuclear reaction, it is necessary to determine the cross section of two processes that is the formation of compound nucleus and its decay.

The decay process can be treated statistically on the assumption that the probability of decay by the emission of different kinds of particles such as alpha, protons, neutrons and etc is the same.

The total cross section of compound nucleus reaction is given as,

$$\sigma(a,b) = \sigma_c(a)G_c(b) \tag{2.1.2}$$

Where,

σ(a,b) -is cross section for complete reaction X(a,b)Y

σ_c(a) -is the cross section for the formation of compound nucleus

G_c(b) -is probability that compound nucleus decays with the emission of b leaving final nucleus Y*, it is assumed that G_c(b) is independent of the mode of formation of the compound nucleus.

Consider the case that the compound nucleus C^* decays with the emission of a different particle d giving the final nucleus Z, so that

$$a + X \longrightarrow C^* \longrightarrow d + Z \tag{2.1.3}$$

and

$\sigma(a,d) = \sigma_c(a)G_c(d)$

For the same energy, angular momentum, and parity we assume the same $\sigma_c(a)$.

Let the mean life of C^* be τ. The full width at half maximum satisfies the relation $\Gamma\tau{=}\hbar$.

If Γ_b, Γ_d are partial widths of the modes of decay b, d,..., we can express the decay rate through the channel b by the relationship

$$G_c(b) = \frac{\Gamma_b}{\Gamma} \tag{2.1.4}$$

Since the formation and decay of the compound nucleus are two independent processes according to Bohr's assumption, it is possible to find a relationship between Γ_b and $\sigma_c(b)$

From reciprocity theorem we can say that,

$$k_a^2\sigma(a,b) = k_b^2\sigma(b,a) \tag{2.1.5}$$

Where, k_a^2 and k_b^2 are wave numbers in a and b channels respectively

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

$$\sigma(a,b) = \sigma_c(a)\frac{\Gamma_b}{\Gamma} \tag{2.1.6}$$

Let

$$U = \frac{k_a^2\sigma_c(a)}{\Gamma_a} = \frac{k_b^2\sigma_c(b)}{\Gamma_b} \tag{2.1.7}$$

U is a function only of state, that is, angular momentum, energy, and parity of the compound nucleus, but independent of the channel. Using these relations, the decay cross-section will be,

$$G_c(b) = \frac{k_b^2\sigma_c(b)}{\sum k_a^2\sigma_c(a)} \tag{2.1.8}$$

using equations (2.3.7) and (2.3.9) the complete cross-section for compound nucleus reaction is,

$$\sigma(a,b) = \sigma_c(a).\frac{k_b^2\sigma_c(b)}{\sum k_a^2\sigma_c(a)} \tag{2.1.9}$$

The validity of Bohr's hypothesis of the compound nucleus has been elegantly demonstrated by several experiments. In the following we discuss the experiment of Ghoshal **[11]** in which he produced the same compound nucleus Zn^{64*} with the bombardment of ${}_{28}Ni^{60}$ by alpha particles and ${}_{29}Cu^{63}$ by protons. To produce the same excitation in Zn^{64*}, an additional 7MeV was added to the kinetic energy of protons.

The reactions observed were

1.$_{28}Ni^{60}(\alpha, n)_{30}Zn^{63}$

2.$_{28}Ni(\alpha, pn)_{29}Cu^{62}$

3.$_{29}Cu^{63}(p, n)_{30}Zn^{63}$

4.$_{29}Cu^{63}(p, pn)_{29}Cu^{62}$

Since the excitation produced through the two processes are the same, $G_c(b)$ is the same, for it depends only upon the excitation produced in the compound nucleus and not upon the mode of formation. Consequently, according to Bohr's hypothesis one should expect

$\sigma(p, n) : \sigma(p, pn) = \sigma(\alpha, n) : \sigma(\alpha, pn)$

The mechanism of compound nucleus formation and decay can be visualized in the liquid drop model. In which the two colliding droplets combine to form a single drop (the compound nucleus). since the compound nucleus is excited, it has a high temperature. Its decay is thought of as the cooling of this drop, which takes place by evaporation of one or more of the constituent particles.

During the formation of this compound nucleus energy-momentum transfer taking place and there is concentration of energy on any one particular nucleon. When this nucleon acquires the sufficient energy, more than the separation energy it is emitted. Therefore to have compound nucleus formation, total excitation energy of compound nucleus ($E_c = \epsilon$ + B.E) must be much less than the total separation energy (SA) of the nucleons.

$$S \gg \frac{\epsilon + B.E}{A} \tag{2.1.10}$$

(excitation energy per nucleon is very much smaller than separation energy)

Where, S is separation energy of each nucleon, ϵ is the kinetic energy of projectile, B.E is binding energy of nucleon, and A is number of nucleons.

The separation energy is nearly the same as binding energy of projectile of nucleons (S $\approx$ B.E). Therefore the relation of the kinetic energy of projectile, separation energy and total number of nucleons is given by

$$\epsilon \ll (A-1)S \tag{2.1.11}$$

Hence, for the formation compound nucleus the kinetic energy of projectile should be much smaller than $(A-1)S$.

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

Generally in compound nucleus reaction ;

•when any particle enters the target nucleus formation of compound nucleus takes place that is energy or temperature of nucleons increases.

•the basic assumption of the compound-nucleus model is that the compound nucleus has been formed in such a complex manner that it has "forgotten" how it has been formed.

•the angular distribution of the emitted particle is symmetric about 90^o.

•the average lifetime of a compound nucleus is considerably longer (10^{-15} to 10^{-16} sec)

•maximum values of reaction cross section are observed at low energies of incident particle.

•the compound nucleus excitation energy is usually higher than the kinetic energy of the particle emitted.

•the decay of the compound nucleus is similar to the evaporation phenomena.

Apart from two extreme reactions direct and compound nucleus reactions there are some reactions that do not qualify neither as direct nor compound nucleus reactions. These reactions are called pre-compound nuclear reactions [**3**] which are intermediate processes between compound nucleus and direct reactions. The pre-compound nuclear reactions occur when projectile shares its energy among a small number of nucleons which may further interact with other nucleons. For these reactions a particle may emitted long before attainment of compound nucleus formation.

Generally, Overview of reaction mechanisms is as shown below,

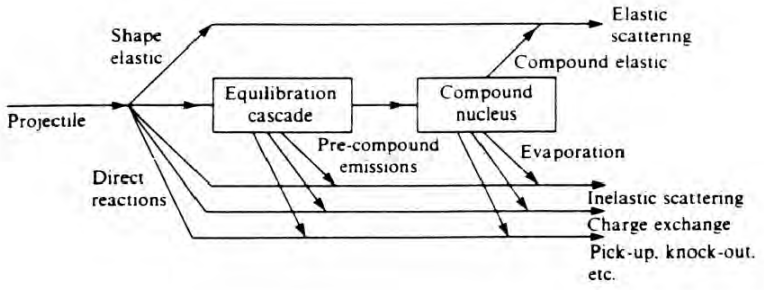

Figure 2.2: Shows overview of reaction mechanisms

Chapter 3

Computer codes

On the basis of statistical models, we can do theoretical calculations using different computer codes such as ALICE-91, COMPLET, PACE-4 and etc. In addition to theoretical calculation these codes enable us to identify reaction mechanisms.
I used Alice-91 for theoretical calculations of excitation functions.

3.1 Alice-91

Alice-91 is developed out of the code Alice. It is based on Weisskopf-Ewing model [**2**] for compound nucleus decay and hybrid/geometry dependent hybrid (GDH) model [**5**] for the pre-equilibrium decay process. This code is capable to predict the excitation functions for pure equilibrium decay as well as with pre-equilibrium decay. In compound nucleus decay calculations, the evaporation of protons, neutrons, deuterons and alphas particles are allowed. The code alice-91 also allow pre-equilibrium neutron, proton and alpha emission up to two particles. The Q-value for the formation of compound nucleus and the neutron, proton, deuteron binding energies for all nuclides of interest in the evaporation chain, have been calculated using Myres-Swiatecki/Lysekil mass formula [**6**] . The pairing energy is calculated from back-shifted model. The inverse reaction cross-section is calculated from the optical model and some times from classical sharp cut off model. The level densities of nuclide involved in the evaporation chain can be calculated from the Fermi gas model

[6] as

$$\rho(u) = (U-\delta)^{\frac{-5}{4}} exp\left(2\sqrt{a(u-\delta)}\right) \tag{3.1.1}$$

Where,U is excitation energy of the nucleus

δ-is pairing term.

a-is level density parameter = $\frac{A}{K}$.

Where A is the mass number of the compound nucleus and K is a constant for which values spread over a wide region.

The level density option due to Kataria/Ramamurthy[**7**] or due to Ignalyuk [**8**] may be selected. The Kataria/Ramamurthy option takes in to account the shell correction. Level density option due to Ignalyuk some work needs to be done on fine-tuning input; it has also shell correction in its operation. The systematic expressions for pre-compound angular distribution of C.kalbach are considered: these options are much faster than the option based on nucleon-nucleon scattering kinematics, and give better agreement with experimental results.

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

Card.1 General Input data.

ap- projectile mass number

at- target mass number

zp- projectile charge

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

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

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

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

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

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

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

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

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

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

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

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

mp = 0, no pairing term in masses

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

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

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

ldopt if zero, Fermi gas level density;

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

if ldopt = 2, Ignalyuk level density.

if ldopt = 3, Gilbert-Cameron level density.

inver is inverse cross section parameter.

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

= 1, user supplies;

= 2, sharp cutoff values each z.

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

ike - is energy bin mesh size in Mev

If = 0, no particle spectra will be printed;

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

If = 2, only pre- compound spectra printed;

If = 3, as 1+2;

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

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

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

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

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

a, kplt- if kplt is 1 and the last energy input line is followed by -1. in column 1-5, excitation functions will be plotted on standard output. Note that kplt and m3 are not in five-column format. m3 is number and type of particles to be emitted from each nuclide.

If m3 = 1 for neutrons only

= 2 for neutrons and protons

= 3 for neutrons, protons, and alphas

= 4 for neutrons, protons, alphas, and deuterons

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

Card 2 title card-80 columns

1. If mc=2 or 12 on card 1, read user supplied n, p, alpha, deuteron binding energies and/or ldgs here, one line per nuclide, order ((ia=1,na+2),iz=1,nz+2)when ever non zero n binding energy is detected, alice will use user provided binding energies for this nuclide, same convention for ldgs.

2. If inver =1 on card 1, read n, p, alpha, deuteron inverse cross sections here, in ascending channel energy,1st value for 0.1 MeV channel energy, then up in 1 MeV steps, 48 values for each particle type, sequence n, p, alpha, deuteron.

Card. 3 energy/options card.

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

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

eq1. Projectile kinetic energy in the laboratory system.

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

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

rcss- is reaction cross section. If left blank, the reactions cross section will be internally generated by the optical model subroutine for incident n or p, and by the parabolic model routine for all other projectiles. If rcss is read in, this value entered for rcss will be used. If a geometry dependent hybrid model and/or fission

calculation is selected, and if one wishes to enter transmission coefficient for entrance channel, then the negative of the number of t(l) to be read must be entered for rcss; the t(l) will then be read on card(s)4

iadst If = 0, no angular distribution,

If = 1, yes-for neutrons;

= 2, yes for protons;

= 3, for neutrons using Kalbach systematics;

= 4, for protons using Kalbach systematics

irfr- choice for refraction with angular distributions

If irfr = 0, no refraction

If irfr = 1/2, entrance channel refraction

If irfr =3, Heisenberg entrance and exit refraction

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

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

jcal- is i2 14 type of calculation option.

jcal = 1, weisskopf-ewing evaporation calculation

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

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

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

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

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

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

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

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

1. If jang is greater than 100 (less than 200) loop over angular momenta will be for increments of jang-100 and ' option on removal of angular

no' momentum holds. if jang is greater than 200, delta l ' option holds, and yes' loop is incremented by jang-200, use jang.gt.100 with jcal = 0 and td = 0 only

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

If td is positive and ex1 and ex2 are blank, default parameters will be selected.

1. The gdo option may still be selected. for default pre compound hybrid model, use td =1, remaining variables zero for gdh calculation, enter td=1,tmx=1,and leave all other variables after td blank.

td-initial exciton number = p+h.

ex1-initial excited neutron number.

ex2-initial excited proton number.

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

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

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

gav-No longer used

3. Cost is mean free paths are multiplied by cost+1. 4. gdo - If =1, gdh calculation (if any) restricted to initial exciton number, hybrid calc. for higher exciton numbers. 5. ij- If ij=1, isospin pre compound option is selected. if so, the next card ' will be containing (p,n)q values qpn (1),qpn (2),and qpnc, 3a' qpnc is (p,n) q value for making compound nucleus by a (p,n) reaction; qpn(i) is for nucleus populated by emission of particle i,1= n,2 = p.

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

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

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

Card 4 entrance Channel .

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

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

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

Chapter 4

Experimental techniques for measurement of excitation function

The stacked foil activation technique [**9**] can be used to measure the excitation function of alpha induced reactions. This technique consisting of target foils interspersed with aluminum degrader foils that are irradiated with diffused alpha particle beam obtained from accelerators at various energies. After irradiation the gamma activities induced in each target foils are analyzed using a gamma ray detectors such as GELI (Germanium-Lithium detector), HPGE (Hyperpure Germanium detector) and GE-IN (Germanium intrinsic detector). Consequently, the excitation functions for a specific reaction are calculated from the intensities of the characteristic gamma rays of particular residual isotope. For this, only those gamma rays, which have appreciable statistics, are considered. The principle of this technique is to analyze the activity of residual nuclei produced by particular reaction. This technique is OFF-BEAM technique. Similarly one can use IN-BEAM technique in which experiment is performed during irradiation of the sample.

4.1 Formulation

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

$$R_p = \sigma \phi N_o \tag{4.1.1}$$

Where,

σ- is activation cross-section,

N_o- is the number of target nuclei of isotope under investigation present in the sample, in my case, Rb

The expression for N_o can be given as,

$$N_o = \frac{mNf}{A_o} \tag{4.1.2}$$

Where,

m-is the mass of the sample,

N- is Avogadro's number, and

f-is the abundance of the isotope in the target. Let t_1- be the time of irradiation of the target by a constant flux incident beam to produce a radioactive reaction product R. The equation that governs the growth of activity during production can be written as,

$$\frac{dR}{dt} = \sigma \phi N_o - R\lambda \tag{4.1.3}$$

Where,

λ-is decay constant

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

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

$$W = R\lambda \tag{4.1.4}$$

$$W = \sigma\phi N_o[1 - exp(-\lambda t_1)] \tag{4.1.5}$$

The term [1-exp(-λt_1)] is called the saturation factor of the reaction.

If the activity of radioactive nucleus R is measured after a time "t" from the time stopping irradiation, then it will be given by:

$$\frac{dR}{dt} = Wexp(-\lambda t) \tag{4.1.6}$$

$$dR = \sigma\phi N_o[1 - exp(-\lambda t_1)]exp(-\lambda t)dt, \tag{4.1.7}$$

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

$$DA = \int_{t_2}^{t_2+t_3} dR \tag{4.1.8}$$

$$DA = \frac{\sigma\phi N_o[1 - exp(-\lambda t_1)][(1 - exp(-\lambda t_3))]}{\lambda exp(-\lambda t_2)} \tag{4.1.9}$$

If A is the number of counts observed by the detector during the time interval $'t_3'$. $'G\varepsilon'$ is geometry dependent detector efficiency of the detector. θ is the absolute intensity of the particular gamma ray and k is the self absorption correction factor of the gamma ray in disk shaped target, which is given as the

$$k = \frac{[1 - exp(-\mu d)]}{\mu d} \tag{4.1.10}$$

where

$\mu-$is gamma ray absorption coefficient

d-is thickness of target under investigation for my case, Rb

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

$$DA = \frac{A}{G\varepsilon.\theta.k} \tag{4.1.11}$$

Relating equations (4.1.9) and (4.1.11), the activation cross-section of a nuclear reaction will be

$$\sigma = \frac{A\lambda exp(-\lambda t_2)}{\phi N_o[1 - exp(-\lambda t_1)][(1 - exp(-\lambda t_3))]G\varepsilon.\theta.k} \tag{4.1.12}$$

This expression has been widely used to calculate the activation cross-section for the alpha induced reactions on different isotopes [**9**].

4.2 Experimental results

The experimental values were taken from EXFOR IAEA vianna [**10**] which are given in average in order to include all the experimentally measured values obtained by different experimentalist [10] and I extrapolated the measured values in order to compare with theoretically calculated values.

Chapter 5

Calculations of excitation functions for some (α,xn) nuclear rections on rubidium

The reaction cross sections calculations are done for the compound nucleus decay and pre-compound nuclear reactions. The code Alice-91 based on Weisskopf-Ewing model and geometry dependent hybrid model are used for these calculations respectively.

The theoretical calculation is done taking at first the initial exciton number n_o =4 with the configuration (2n+2p+0h), pld-level density parameter, A= $\frac{acn}{pld}$=9. Later the value of parameters are changed to see the effect on calculated values of reaction cross sections.

5.1 Comparisons of calculated results with experimental values

The theoretical calculations are done using energy range of projectile which is nearly comparable to experimentally used energy ranges to make the comparison process simple. The theoretical and experimental reaction cross sections for the reactions $^{85}Rb(\alpha,n)^{88}Y$, $^{85}Rb(\alpha,2n)^{87}Y$, $^{85}Rb(\alpha,3n)^{86}Y$ and composition reaction are given below.

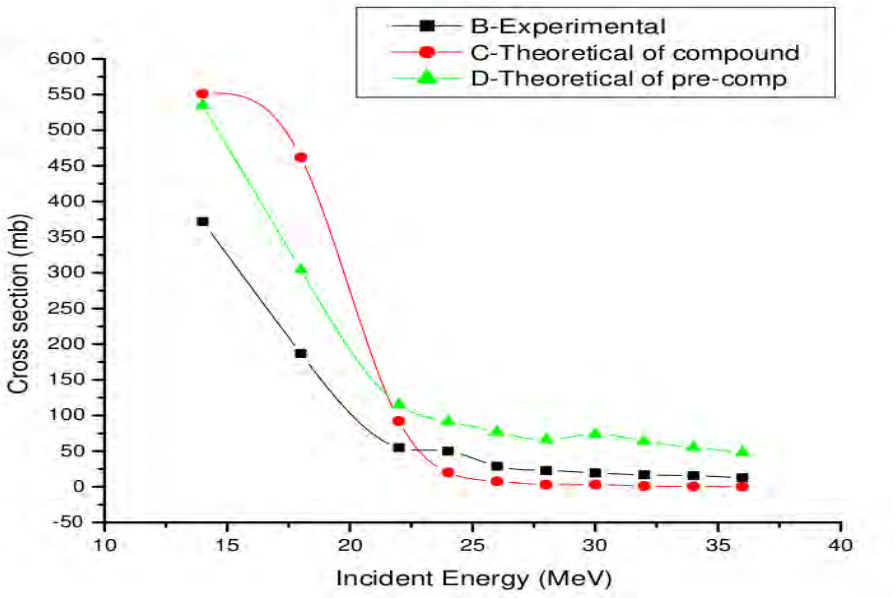

Figure 5.1: Graph of excitation function for $^{85}Rb(\alpha, n)$

B. Experimental

C. Theoretical of compound nucleus decay

D. Theoretical of pre-compound nuclear reaction

The theoretical reaction cross section of compound nucleus decay starts falling down from its maximum point at 15MeV energy of projectile and then goes to zero for increasing energy of projectile. The experimental reaction cross section decreases for increasing energy of projectile from its maximum value. The theoretical reaction cross section of compound nucleus decay is closer and closer to experimental starting from at about 23MeV energy of projectile with 125mb. Therefore, it is more comparable with experimental in increasing energy of projectile.

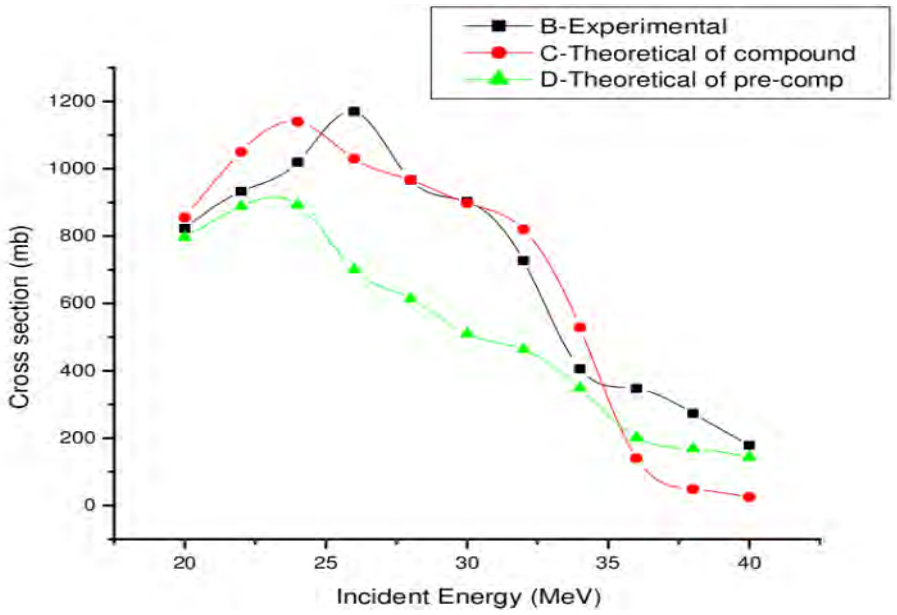

Figure 5.2: Graph of excitation function for $^{85}Rb(\alpha, 2n)$

B. Experimental

C. Theoretical of compound nucleus decay

D. Theoretical of pre-compound nuclear reaction

The calculated reaction cross section for compound nucleus decay is in better agreement with the experimental in lower energies of projectile up to at about 35.5MeV energy of projectile. Then, it goes to zero for increasing energies of projectile but in this region experimentally measured reaction cross section makes a long tail. This long tail is due to pre-compound nuclear reaction.

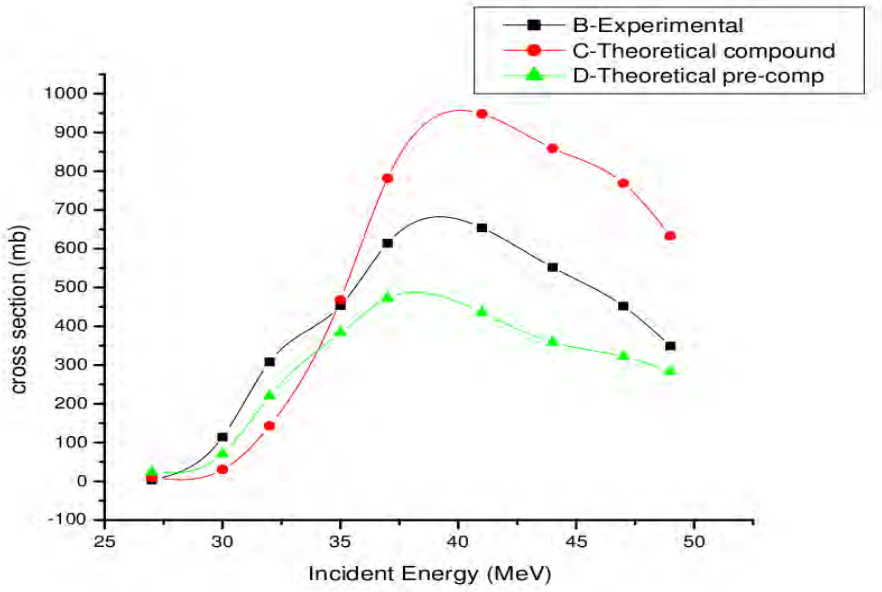

Figure 5.3: Graph of excitation function for $^{85}Rb(\alpha, 3n)$

B. Experimental

C. Theoretical of compound nucleus decay

D. Theoretical of pre-compound nuclear reaction

The theoretical reaction cross section of compound nucleus is not more comparable to experimental than theoretical prediction of pre-compound nucleus reaction. Therefore, there is no compound nucleus decay in the present energy range.

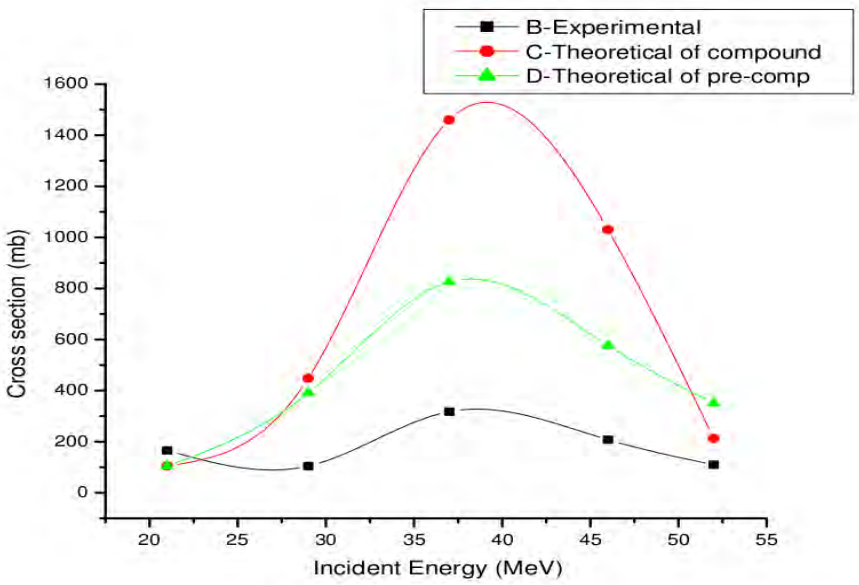

Figure 5.4: Graph of excitation function for composition of $^{85}Rb(\alpha, n)$ and $^{87}Rb(\alpha, 3n)$

B. Experimental

C. Theoretical of compound nucleus decay

D. Theoretical of pre-compound nuclear reaction

There is no compound nucleus decay for this composition reaction in the given energy range bacause its theoretical calculation excitation function is not comparable with experimental one. Therefore, we have only pre-compound nuclear reaction in the given energy range.

$^{85}Rb(\alpha, 2n)$ reaction is used to check the effect of PLD-level density and exciton number (n_o) parameters on theoretical calculated reaction cross sections.

b) For pld=$\frac{A}{8}$

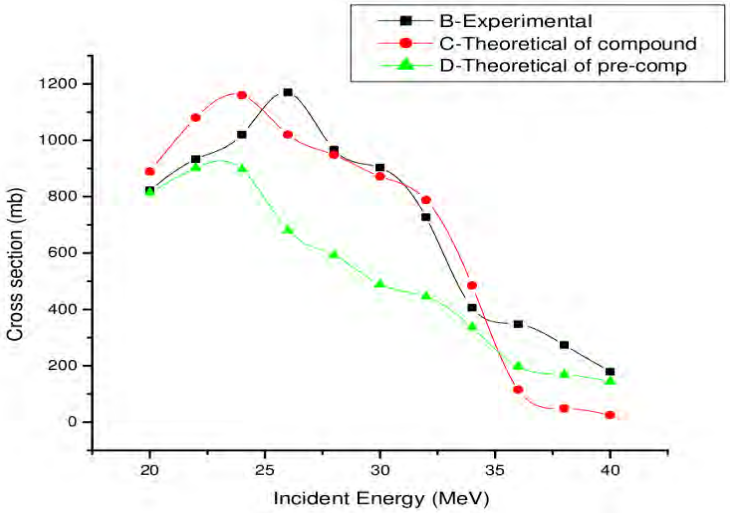

Figure 5.5: Graph of excitation function for $^{85}Rb(\alpha, 2n)$ at pld=$\frac{A}{8}$

For n_o=6(2p+2n+0n)

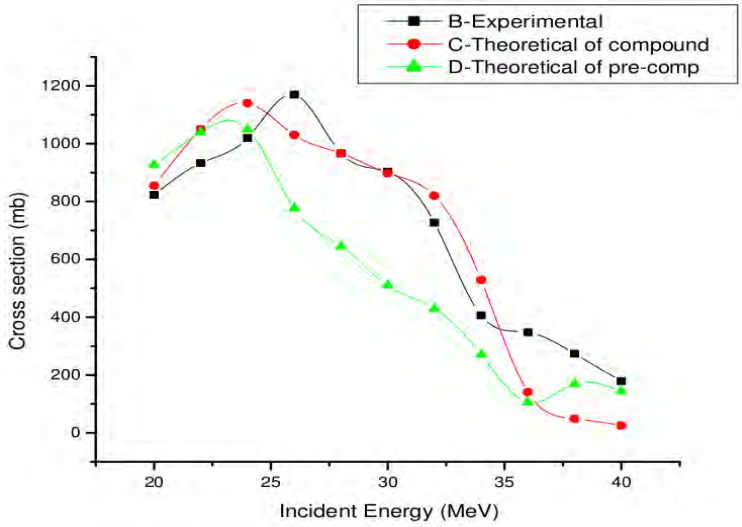

Figure 5.6: Graph of excitation function for $^{85}Rb(\alpha, 2n)$ at n_o=6

5.2 Conclusion

As we can see from the above analysis there is no compound nucleus decay for increasing energies of alpha particles. Also compound nucleus decay does not make a long tail. Therefore, the long tail portion of excitation function of nuclear reaction is due to pre-compound nuclear reaction.

When we compare theoretical excitation functions of figure 5.2 and figure 5.5 which are calculated for different pld(level density) parameters without changing exciton number and also when we compare theoretical excitation functions of figure 5.2 and figure 5.6 which are calculated for different exciton number (exciton number is changed only for pre-compound nucleus) reaction without changing pld we conclude from these comparisons that even though changing of PLD-Level density parameter in calculating excitation functions of nuclear reaction has no appreciable effect special in excitation function of pre-compound nuclear reaction, there is slight change in case of compound nucleus decay. Change of exciton number (n_o) has a considerable change on excitation function of pre-compound nuclear reaction.

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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 project have been dully acknowledged.

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

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