STUDY OF NUCLEAR REACTIONS INDUCED BY PROTON AND ALPHA PARTICLES AT LOW AND MEDIUM ENERGIES

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Study of nuclear reaction mechanism is a fundamental tool to study the properties of nucleus as well as the behavior nuclear force between the nucleus inside the nucleus and hence to understand the nuclear structure. The nuclear physics study is considered to be started with the discovery of radioactivity by Henry Becquerel in 1896 [1]. The nuclear reaction studies got a boost by the invention of particle accelerators like electrostatic generator by Van de Graff [2], accelerators by Cockcroft and Walton [3] and cyclotron by Lawrence [4] which opened an altogether new branch of artificial transmutation. A nuclear reaction is one in which an atomic nucleus interacts with some nuclear projectile resulting in the emission of nuclear particles, heavy ions and/or radiations leaving behind the residual nucleus. Most of the known nuclear reactions are produced by exposing different materials to a beam of accelerated nuclear particles. Macroscopically, in a nuclear reaction, one may have the information of the reaction process before and after the reaction has taken place. However, what exactly happens during the reaction itself is not well known. In order to understand the interaction mechanism between the projectile and target nuclei, the behavior of the emitted particles and the residual nucleus nuclear reaction models have been proposed.

It was Niels Bohr [5] first to propose a satisfactory model to explain the reaction mechanism. According to him, as the incident particle comes in close contact with the target nucleus it is absorbed in it forming a compound system, the energy and the angular momentum of the projectile are shared by all the nucleons in the compound system and a thermodynamic equilibrium is established. It then decays independent of its mode of formation. This is called the compound nucleus mechanism or independent hypothesis. Since, the decay of the compound nucleus is considered independent of its mode of formation and it is treated by the laws of statistics. This results in symmetrical distribution of evaporated particles about 90\(^0\) in the center of mass frame. In 1950, S. N. Ghoshal [6] carried out experiments using accelerated particle beams and established the validity of Bohr’s independent hypothesis. Based on this hypothesis Weisskoff and Ewing [7] developed a detailed theory to explain the particle emission at low excitation energies. Hauser - Feshbach [8] developed a more elaborate description of the reaction mechanisms by including the conservation of spin and parity in each level of de-
The compound nucleus reaction mechanism is likely to be valid at lower excitation energies. On the other hand, at considerably higher excitation energies the reaction is generally described by direct reaction mechanism. The excitation of particular isolated levels of the residual nucleus and the diffraction structure of angular distributions, usually forward peaked, are important features of direct reactions. With the advancement in nuclear electronics and the development of new more efficient detectors with better resolving power, more detailed experiments on nuclear reaction studies have been done. It is expected that emission of particles may also take place during the equilibration of compound system. The particles which are emitted during the equilibration of the compound nucleus are called pre-equilibrium particles, or pre-compound particles and the reaction mechanism is termed as pre-equilibrium (PE) emission [9-11]. Recently it is observed that PE mechanism may cause particle emission, emission of nuclear cluster or even fission at moderate excitation energies [12].

In order to explain PE emission a number of semiclassical and quantum mechanical models have been proposed based on the following assumptions. A series of two-body collisions inside the nucleus is assumed to follow the initial interaction, with a finite probability of particle emission after each collision. The participants sharing the excitation energy of the intermediate system, are small in number. As a result, only a few degree of freedom are involved on one hand and the selectivity of direct reaction is lost on the other. The PE is featured by slowly descending tails of excitation functions, forward peaked angular distribution of emitted particles and relatively large number of higher energy particles than predicted by the compound nucleus mechanism. Some of the important models are, Intranuclear Cascade Model (ICM) [13], Harp Miller and Berne model (HMB) [14], Exciton model [15], Hybrid model [16] and Geometry Dependent Hybrid model (GDH) [17], Feshbach Kerman Koonin model (FKK) [18] and Hydelberg model [19]. Brief description of these models are discussed in Chapter - 2 of the thesis. A theoretical model may be evaluated on the basis of its power to predict the experimental data. In order to test these PE models, it is desirable to have extensive data on excitation functions, energy and angular distributions etc., of emitted particles in nuclear reactions at moderate excitation energies. The nuclear reaction is typically car-
ried out by projecting a target nucleus to a beam of accelerated particles. The reaction product is analyzed by identifying the reaction products in online or offline. In online analysis the outgoing particles are detected by a particle telescope placed at a certain angle from the beam path to collect the particles scattered at that angle covering a small solid angle subtended by the projected area of the detector. Similarly the residual nucleus produced in the reaction is detected using suitable detectors and particles of each species are identified corresponding to definite reaction channel. Since the online analysis is done during the irradiation the processes it is more involved. Alternatively, in offline measurements, the residual nucleus are collected in catcher foils kept behind the target and are identified by detecting the characteristic gamma rays of the nuclei or by chemical separation of the reaction products. The former one is called activation technique [20]. Due to its selectivity, sensitivity and simplicity, activation analysis is one of the most commonly used technique in pure and applied nuclear physics research [20 - 24]. Since in the present analysis the isomeric cross section ratio for a large number of isomeric pairs have been studied, the activation technique is most significant in the present discussion. Further, most of the data used in the present analysis are obtained through activation analysis. The unique decay mode of each radioactive isotope provides a specific way for its identification and measurement. The activities in the samples are induced by their bombardment with elementary particles, radiations or nuclei. In general, several activities due to various reaction products are produced in samples after irradiation. Further, in activation method different samples can be irradiated simultaneously with beam of desired energy by arranging the samples in a stack and samples are separated by suitable energy degraders. Brief description of experimental techniques and measurements are discussed in Chapter - 3 of the thesis.

In order to analyze the experimental data, theoretical calculations are generally done using computer codes. Theoretical analysis of the data has been performed using the nuclear reaction code EMPIRE-II [25]. This code makes use of the Hauser- Feshbach model [26] for the compound nuclear calculations and the NVWY model [19] based on MSD-MSC (Multi Step Direct - Multi Step Compound) approach [27] and the exciton model [28] for the PE emission part. The Hauser- Feshbach model explicitly takes into
account the conservation of spin and parity of each partial wave in each stage of de-excitation. For input parameters standard library [29] is used; which include the nuclear masses, ground state deformations, discrete levels and level schemes, moment of inertia and gamma ray strength functions. The particle transmission coefficients for both the exciton and Hauser- Feshbach formalism were generated via the spherical optical model. Optical model parameters due to A. J. Koning [30] has been used in the present calculation for both protons and neutrons. In the case of $\alpha$, optical parameters due to McFadden and Satchler [31] has been used. The transition matrix element for the intranuclear transition is taken from Serber [32] and the Level density parameters are taken from Ignatyuk [33]. The initial configuration of the compound system defined by initial exciton number $n_0 = np + nh$ is an important parameter of PE emission formalism. In proton induced reactions, the value of $n_0$ is consistently taken as 3. This may be interpreted as the projectile on interaction with the target nucleus excites one particle above the Fermi level leaving a hole in the Fermi level and hence the total of three excitons ($2p + 1h$). Similarly in the case of $\alpha$ induced reactions the value of $n_0$ is taken as 6 which may be interpreted as follows. The $\alpha$ particle is being broken up into four nucleons in the target field while exciting a particle from the target nucleus above the Fermi level and creating a hole in the Fermi level. The parameterization in the code reproduce satisfactorily well over the measured energy range. Chapter - 4 deals with the details of EMPIRE-II computer code used for the theoretical calculations.

With an objective of studying nuclear reactions at low and medium excitation energies and study the nature and progress of nuclear reaction mechanism systematic analysis of excitation functions for a large number of nuclear reactions has been carried out. In the present study the excitation functions for a number of nuclear reactions induced by proton and alpha particles on a large number of target nuclei covering a wide range of masses in the periodic table have been analyzed. The selection of the target is based on the availability of experimental data with the associated group. The calculations are extended for similar cases of reactions for stable isotopes. The experimental data available in the literature are extensively used for this analysis. For the sake of completeness the work is further extended to other isotopes and reac-
tions of interest in the vicinity of the above nuclei. In this way the excitation functions for the $^{58}$Ni(p,n)$^{58}$Cu, $^{58}$Ni(p,2n)$^{57}$Cu, $^{58}$Ni(p,3n)$^{57}$Cu, $^{59}$Ni(p,n)$^{58}$Ni, $^{59}$Ni(p,α)$^{55}$Co, $^{59}$Ni(p,n)$^{59}$Cu, $^{59}$Ni(p,2n)$^{58}$Cu, $^{59}$Ni(p,3n)$^{59}$Ni, $^{60}$Ni(p,n)$^{60}$Cu, $^{60}$Ni(p,γ)$^{61}$Cu, $^{60}$Ni(p,2n)$^{59}$Cu, $^{60}$Ni(p,3n)$^{58}$Cu, $^{60}$Ni(p,p)$^{60}$Ni, $^{61}$Ni(p,n)$^{61}$Cu, $^{61}$Ni(p,2n)$^{60}$Cu, $^{61}$Ni(p,3n)$^{59}$Cu, $^{61}$Ni(p,p)$^{61}$Ni, $^{62}$Ni(p,n)$^{62}$Cu, $^{62}$Ni(p,2n)$^{61}$Cu, $^{62}$Ni(p,3n)$^{60}$Cu, $^{63}$Ni(p,n)$^{63}$Cu, $^{63}$Ni(p,2n)$^{62}$Cu, $^{63}$Ni(p,3n)$^{61}$Cu, $^{63}$Ni(p,p)$^{63}$Ni, $^{64}$Ni(p,n)$^{64}$Cu, $^{64}$Ni(p,2n)$^{63}$Cu, $^{64}$Ni(p,3n)$^{62}$Cu, $^{64}$Ni(p,p)$^{64}$Ni, $^{58}$Ni(α, n)$^{61}$Zn, $^{58}$Ni(α, 2n)$^{60}$Zn, $^{58}$Ni(α, p)$^{61}$Cu, $^{58}$Ni(α, pn)$^{60}$Cu, $^{58}$Ni(α, αn)$^{57}$Ni, $^{59}$Ni(α, n)$^{62}$Zn, $^{59}$Ni(α, 2n)$^{61}$Zn, $^{59}$Ni(α, p)$^{62}$Cu, $^{59}$Ni(α, 3n)$^{63}$Zn, $^{59}$Ni(α, 2n)$^{62}$Zn, $^{60}$Ni(α, p)$^{63}$Cu, $^{60}$Ni(α, 2n)$^{61}$Cu, $^{61}$Ni(α, n)$^{64}$Zn, $^{61}$Ni(α, 2n)$^{63}$Zn, $^{61}$Ni(α, 3n)$^{62}$Zn, $^{62}$Ni(α, n)$^{65}$Zn, $^{62}$Ni(α, 2n)$^{64}$Zn, $^{62}$Ni(α, 3n)$^{63}$Zn, $^{63}$Ni(α, p)$^{66}$Cu, $^{63}$Ni(α, n)$^{67}$Zn, $^{64}$Ni(α, n)$^{66}$Zn, $^{64}$Ni(α, p)$^{67}$Cu, $^{64}$Y(α, n)$^{69}$Zr, $^{69}$Y(p,α)$^{69}$Zr, $^{89}$Y(p,2n)$^{89}$Zr, $^{89}$Y(p,3n)$^{89}$Zr, $^{89}$Y(p,4n)$^{89}$Zr, $^{89}$Y(p,p)$^{89}$Y, $^{89}$Y(p,α)$^{85}$Sr, $^{89}$Y(α, n)$^{92}$Nb, $^{89}$Y(α, 2n)$^{91}$Nb, $^{89}$Y(α, 3n)$^{90}$Nb, $^{89}$Y(α, p)$^{92}$Zr, $^{89}$Y(α, pn)$^{91}$Zr, $^{89}$Y(α, α)$^{89}$Y, $^{93}$Nb(p,n)$^{93}$Mo, $^{93}$Nb(p,2n)$^{92}$Mo, $^{93}$Nb(p,3n)$^{91}$Mo, $^{93}$Nb(p,p)$^{93}$Nb, $^{93}$Nb(α,n)$^{96}$Tc, $^{93}$Nb(α,2n)$^{95}$Tc, $^{93}$Nb(α,3n)$^{94}$Tc, $^{93}$Nb(α,4n)$^{93}$Tc, $^{113}$In(p,n)$^{113}$Sn, $^{113}$In(p,2n)$^{112}$Sn, $^{113}$In(p,3n)$^{111}$Sn, $^{113}$In(p,p)$^{113}$In, $^{113}$In(α,n)$^{116}$Sb, $^{113}$In(α,2n)$^{115}$Sn, $^{113}$In(α,3n)$^{114}$Sb, $^{113}$In(α, 3n)$^{114}$Sb, $^{113}$In(α,p)$^{116}$Sn, $^{113}$In(α,α)$^{115}$In, $^{115}$In(α, n)$^{115}$Sn, $^{115}$In(p,n)$^{115}$Sn, $^{115}$In(p,2n)$^{114}$Sn, $^{115}$In(p,3n)$^{113}$Sn, $^{115}$In(p,p)$^{115}$In, $^{115}$In(α,n)$^{118}$Sb, $^{115}$In(α,2n)$^{117}$Sb, $^{115}$In(α,3n)$^{116}$Sb, $^{115}$In(α,p)$^{118}$Sn, $^{115}$In(α,α)$^{117}$Sn, $^{115}$In(α,α)$^{117}$Sn, $^{115}$In(α,115)In, $^{121}$In(p,n)$^{121}$Te, $^{121}$In(p,2n)$^{120}$Te, $^{121}$In(p,3n)$^{119}$Te, $^{121}$In(p,p)$^{121}$Sb, $^{121}$In(p,Kn)$^{126}$Sb, $^{121}$In(α,n)$^{124}$I, $^{121}$In(α,2n)$^{123}$I, $^{121}$In(α,3n)$^{122}$I, $^{121}$In(α,p)$^{124}$Te, $^{121}$In(α,α)$^{123}$Te, $^{121}$In(p,n)$^{123}$Te, $^{121}$In(p,2n)$^{122}$Te, $^{121}$In(p,3n)$^{121}$Te, $^{123}$In(p,n)$^{123}$Sb, $^{123}$In(α,2n)$^{126}$I, $^{123}$In(α,3n)$^{124}$I, $^{123}$In(α,p)$^{126}$Te, $^{123}$Sb(α,α)$^{125}$Te, $^{197}$Au(p,n)$^{197}$Hg, $^{197}$Au(p,2n)$^{196}$Hg, $^{197}$Au(p,3n)$^{195}$Hg, $^{197}$Au(p,4n)$^{194}$Hg, $^{197}$Au(p,5n)$^{193}$Hg, $^{197}$Au(p,6n)$^{192}$Hg, $^{197}$Au(p,n)$^{194}$Te, $^{197}$Au(p,2n)$^{193}$Te, $^{197}$Au(p,3n)$^{192}$Te, $^{197}$Au(p,4n)$^{191}$Te, and $^{197}$Au(α,4n)$^{197}$Te reactions have been analyzed over the energy ranges from the reaction threshold up to 40 MeV for proton induced reactions and 60 MeV for alpha induced reactions. The result of the present analysis are discussed in Chapter - 5.

In order to make a consistent analysis of the experimental data, an attempt is made to fix the adjustable parameters of the reaction models. In order to see the relative contribution of PE emission at each incident energy, the cross sections for the particular reaction at various incident energies are calculated with including and excluding PE emission. The contribution of PE emission at given energy for the reaction is taken as
the difference between the cross sections calculated with including and excluding PE emission. The relative strength of PE reactions is expressed as the PE fraction defined as the fraction of PE component to the total reaction cross section. This will provide important information on the progress of nuclear reactions. The PE fraction is found to depend critically on the incident energy, mass as well as the spin of the target nucleus, state of the compound nucleus and the nature of the incident particle. The effects of above factors are well discussed in this chapter. In the present case a number of isotopes having isomeric states of measurable half lives of the order of few minutes to few days are studied. In order to observe the relative population of ground state and isomeric state at various incident energies and the effect of various factors like relative spins, level difference, incident energy, incident particle, type of emitted particle, nature of decay of compound nucleus as well as the isomeric state, nature of reaction mechanism etc., the isomeric cross section ratio for the production of various isomeric pairs produced in the reactions under study are calculated. The relative production probability is expressed as isomeric cross section ratio defined as the ratio of the formation cross section of the isomer of high isomeric state to the total production cross section \( \sigma_m/(\sigma_m + \sigma_g) \).

The isomeric cross section ratio thus calculated for the production of \(^{85}\text{Sr}\), \(^{89}\text{Y}\), \(^{89}\text{Zr}\), \(^{90}\text{Zr}\), \(^{90}\text{Nb}\), \(^{93}\text{Mo}\), \(^{93}\text{Tc}\), \(^{94}\text{Tc}\), \(^{95}\text{Tc}\), \(^{96}\text{Tc}\), \(^{113}\text{Sn}\), \(^{116}\text{Sb}\), \(^{118}\text{Sb}\), \(^{121}\text{Te}\), \(^{139}\text{Nd}\), \(^{141}\text{Nd}\), \(^{193}\text{Hg}\), \(^{195}\text{Hg}\), \(^{197}\text{Hg}\) nuclei, produced in the reactions mentioned above, are analyzed at various incident energies.

The analysis indicate that the isomeric cross section ratio has reflection on the relative level difference between the isomeric state and ground state as well as the spin of the states. At relatively larger energies the system is seems to prefer higher spin states rather than the excitation energy available for the system as is indicated by relative population of the above nuclei. It is found that isomeric cross section ratio critically depends on the spins of ground state and isomeric state as well as the incident energy. Qaim et al [34] observed that the isomeric cross-section ratio is primarily governed by the spins of the two levels involved, rather than their separation energies. In the case of nuclei with isomeric spin is greater than the ground state spin the isomeric cross section ratio increases steadily up to certain energy and thereafter it get saturated. In the case
of nuclei with isomeric spin lesser than that of ground state the isomeric cross section ratio shows a initial increase with incident energy and thereafter it decreases upto certain energy and it remains almost constant on further increases of incident energy. This general behavior may be explained as follows. In the first case as the energy of the incident particle increases the state with lower spin get populated initially and thereafter the population of higher spin state getting more and more populated and finally reaches an equilibration between the states. In the second case at very low energy the ground state start populating irrespective of the spin state and after that sufficient energy is available for the population of the isomeric state the system prefer lower spin state first and then started populating the higher spin state accordingly and later get equilibrated as the previous case. Close analysis of the data reveals that the isomeric cross section ratio is affected by many other parameters like presence of intermediate states and decay mode of the isomeric state significantly and the energy difference between the levels and emission of PE particles to a lesser extent [35 - 40]. The presence of intermediate level, ground state and isomeric state is also found to affect the progress of isomeric population with incident energy. Detailed analysis of individual cases are also discussed in chapter 5 of the thesis along with conclusion of the present study and the future plans.
Bibliography


