THE MAHARAJA SAYAJIRAO UNIVERSITY OF BARODA

SYNOPSIS

STUDY OF NEUTRON AND CHARGED PARTICLE EMISSION MECHANISM IN HEAVY ION REACTIONS

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1 Introduction

The importance of an accurate prediction of all what happens when a nuclear interaction takes place can be estimated from the point of view of both basic and applied knowledge and the possible use of nuclear physics in interdisciplinary fields and applications useful to mankind such as medical diagnostics and therapy, dosimetry, environmental control, space physics, and industrial research. Much work is in progress or has recently been published concerning the problem of fusion in heavy ion reactions and properties of the decaying compound nuclei. It can be shown that the compound and pre-compound or pre-equilibrium mechanisms may provide an important mode of de-excitation during the fusion process and that some experimental results which are difficult to understand may be explained by this process [1, 2].

There is an increasing need for information on inclusive nuclear reactions induced both by light particles and heavy ions due to their relevance in interdisciplinary fields and applications. Reactions induced by light particles are better known, both from an experimental and a theoretical point of view [3–5]. The knowledge in the case of heavy-ion reactions is much less systematic and often essential experimental information is lacking. In recent years quantum mechanical theories have been developed to describe the pre-equilibrium nuclear reaction mechanism and the advent of fast computers has enabled numerical computations of these cross sections.

Recently, many experimental techniques have been developed to obtain and detect neutrons and charged particles of different energies and to measure the cross-sections of different particle-induced reactions [6]. 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 experimental difficulties. Therefore, nuclear reaction model calculations play an important role in nuclear data evaluation. Besides, these measurements are necessary to improve theoretical models in order to understand nuclear reaction mechanisms and the properties of the excited states in different energy ranges.

Pre-equilibrium emission takes place after the first stage of the reaction but long before statistical equilibrium of the compound nucleus is attained. It is imagined that the incident particle step-by-step creates more complex states of the compound system and gradually the memory of the initial energy and direction is lost. Pre-equilibrium processes provide a sizeable part of the reaction cross section for incident energies between 10-200 MeV and higher.

Study of equilibrium and pre-equilibrium particle emissions during the decay process of a compound nucleus are very important for a better understanding of the nuclear reaction mechanism induced by medium energy particles. The highly excited nuclear system produced by charged particles first decays by emitting fast nucleons at the pre-equilibrium (PE) stage and later on by the emission of low-energy nucleons at the equilibrium (EQ) stage. The excitation functions for pre-equilibrium calculations can be calculated using hybrid Monte-Carlo (HMS) code which is based on hybrid model. The hybrid model for pre-compound decay was formulated by Blann and Vonach [7] as

$$\frac{d\sigma_v(\varepsilon)}{d\varepsilon} = \sigma_R P_v(\varepsilon),$$

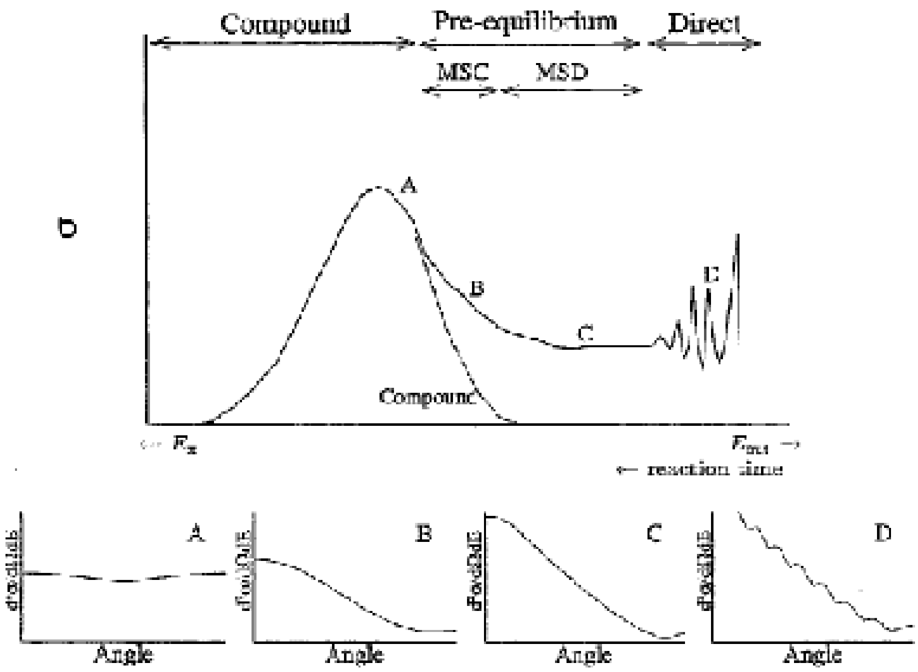

Figure 1: Typical energy spectrum for a A(a,b)B nuclear reaction and associated angular distributions are shown.

where

$$P_v(\varepsilon)d\varepsilon = \sum_{n=n_0}^{\bar{n}} [\chi_v^n N_n(\varepsilon, U)/N_n(E)]gd\varepsilon \times [\lambda_c(\varepsilon)/(\lambda_c(\varepsilon) + \lambda_+(\varepsilon))]D_n,$$

σ_R is the reaction cross-section, χ_v^n is the number of particle type v (proton or neutron) in n exciton hierarchy, $P_v(\varepsilon)d\varepsilon$ represents the number of particles of type v 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 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 the emission rate of a particle into the continuum with channel energy ε and $\lambda_+(\varepsilon)$ is the intranuclear transition rate of a particle.It has been demonstrated that the nucleon-nucleon scattering energy partition function $N_n(E)$ is identical to the exciton state density $\rho_n(E)$, and may be derived by certain conditions on $N - N$ (nucleon-nucleon) scattering cross-sections. The second set of square brackets in equation represents the fraction of the v type particles at an energy which should undergo emission into the continuum, rather than making an intranuclear transition. D_n represents the average fraction of the initial population surviving to the exciton number being treated. The code can be applied for the calculation of excitation functions, energy and angular distribution of secondary particles in nuclear reactions induced by nucleons and nuclei up to an energy range of 300 MeV.

The hybrid model [8,10] of pre-equilibrium decay was the first formulation to consider the importance of multiple pre-equilibrium decay [9]. This was accomplished by use of statistically based, but arbitrary algorithms. Additionally, "multiple" pre-equilibrium decay was restricted to the emission of two or fewer pre-equilibrium nucleons from each nuclide. As pre-equilibrium models have been extended to higher energies, this constraint has become an ever more serious limitation.

To overcome these problems, the new HMS model (2014) is introduced which uses only the kinematically justified two and three exciton densities [11] and which allows unlimited pre-equilibrium emission from each nuclei in a method which follows naturally from the physics. The formulation otherwise follows the philosophy of the hybrid model of pre-equilibrium decay [12]. The new approach is a hybrid Monte Carlo simulation (HMS) model.

2 Motivation and Objective

Considerable efforts are actually being made to create databases of experimental data and theoretical predictions which could be used for interdisciplinary purposes. Examples of such work and of calculations performed for nucleon induced reactions are available in the literature [13–15]. However, for heavy ion reactions comparable information is still lacking, in spite of its increasing importance for applications in interdisciplinary fields. The work planned here as a part of the thesis is aimed at acquiring data which could produce the required comprehensive information and thereby aid in developing phenomenological theories which are able to provide a quantitative account of all measured observables in reactions induced by lighter heavy ions, such as ^{14}N and ^{19}F.
Keeping this in mind our focused objective for the experiment are as follows:

1. To study the emission of charged particles (deuteron, alpha, helion) in the reaction of ^{14}N on heavy targets like Rh, Co, Nb and Au at incident energies going from Coulomb barrier to several tens of MeV/nucleon.
2. To study the emission of neutrons in the reaction of ^{19}F with targets like Ta, Y and V at incident energies of several tens of MeV/nucleon.
3. We also wish to study the excitation functions of the residues emitted in these reactions.

Targets are selected from various regions of periodic table in order to understand effect of mass number on the reaction mechanism and on mode of decay.

3 Experimental Details

- The experiments were performed at IUAC, New Delhi and at TIFR, Mumbai. At both of these facilities desired ion beams of required energies, target making facilities and radiation counting facilities were available.

- Some of the required targets were prepared in target lab at TIFR and IUAC. And remaining targets were procured from Goodfellow Ltd. (Cambridge, UK). Among these are self-supporting stack foils of Rh of 99.99% purity. The stack consisted of a single 5-μm-thick Ti monitor foil, followed by several Rh foils with nominal thicknesses of 32.02 mg/cm^2. Other targets include ^{51}V, ^{89}Y and ^{181}Ta which were rolled from spectroscopic grade material to thicknesses in the range of 1.5-1.8 mg/cm^2. ^{59}Co and ^{93}Nb targets thicknesses were 1.00 mg/cm^2 and 1.72 mg/cm^2 respectively.

- Study of emission of charged particles (alpha, helion, deuteron, etc.) was done for the system $^{14}N +^{59} Co,^{93} Nb,^{197} Au$ at energies around 30 MeV/nucleon. The experiment was done using general purpose scattering chamber (GPSC). Beam was bombarded on self-supporting targets and charged particles were identified using silicon $\Delta E - E$ telescopes having thickness $30\mu m/500\mu m$, mounted inside GPSC. The angular distribution measurements of the emitted charged particles was carried out in the angular range of 20° to 170° in the angular interval of 2° to 5°. A typical alpha spectra at few angles for all three systems is shown in Fig 2.

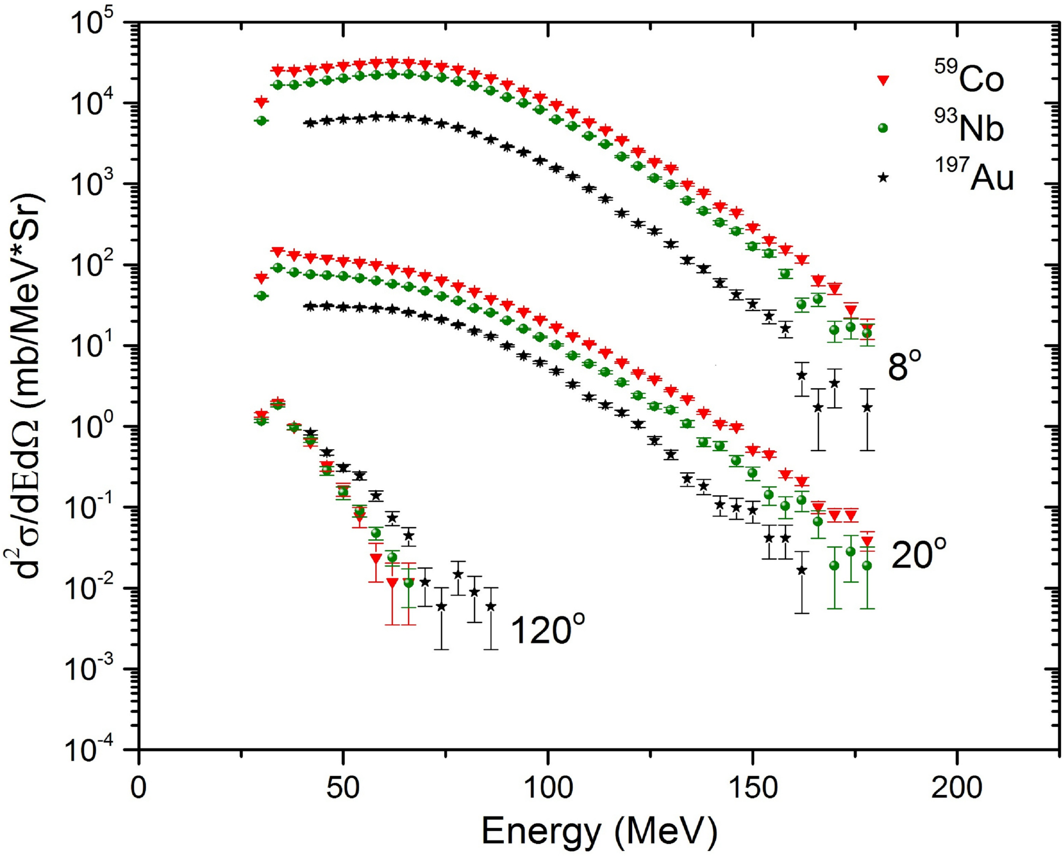

Figure 2: Alpha emission double-differential cross sections for ^{14}N incident on $^{59}Co,^{93} Nb,^{197} Au$ target at 250 MeV. The solid symbols are the experimental results of this work. The estimated errors are smaller than the experimental scatter point size.

- Neutron emission from the reaction in the systems ^{19}F+^{181}Ta, ^{89}Y, ^{51}V was studied in the energy region of 100 to 150 MeV. The detection and energy measurements of the emitted neutron was done at Bhabha Atomic Research Centre–Tata Institute of Fundamental Research (BARC-TIFR) Pelletron-LINAC facility, Mumbai using time of flight technique. This facility has about fifteen liquid scintillator neutron detectors (NE213) arranged at three different azimuthal angle at a distance of 65 to 82 cm from the target at the center. Neutrons were identified using PSD and TAC modules and neutron spectra were obtained using the same with help of LAMPS-VME software. Efficiency measurements of the neutron detectors were done using ^{252}Cf source. Fig 3 shows a typical neutron spectra obtained in such type of reaction.

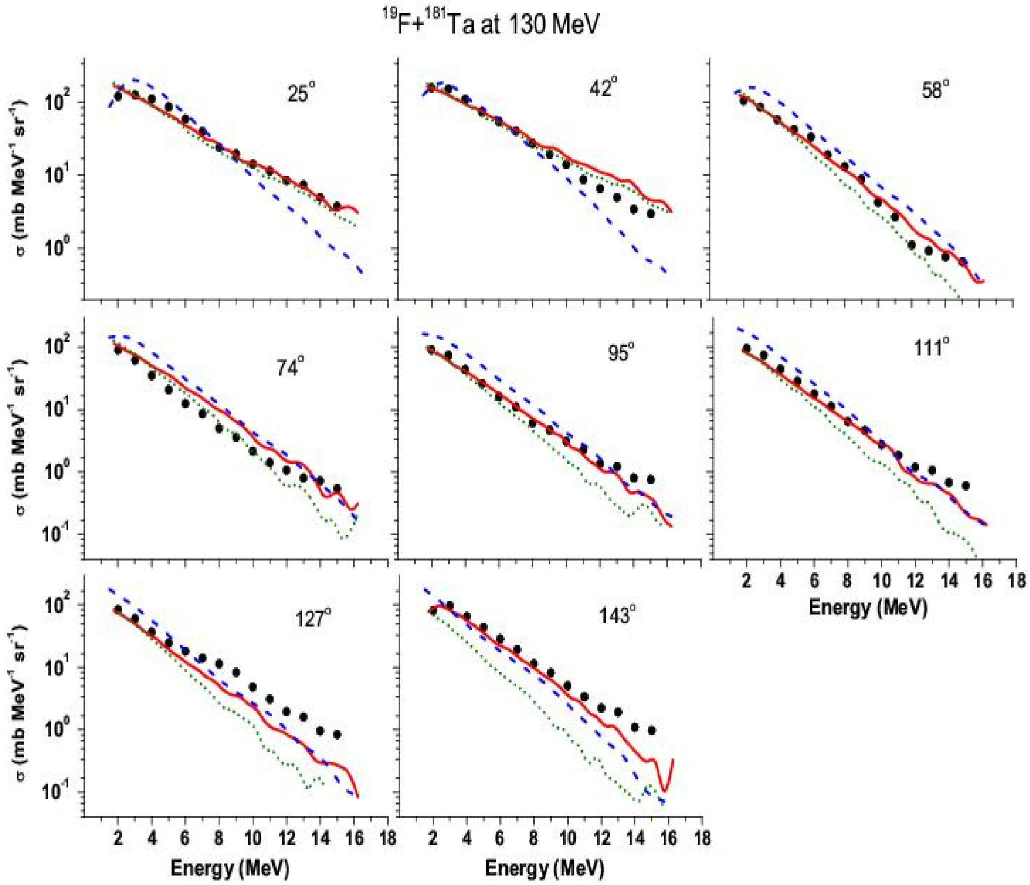

Figure 3: Neutron emission differential cross sections for 130 MeV ^{19}F on ^{181}Ta target. The solid symbols are the experimental results of this work. The calculated cross sections are shown as a solid red curve (OB level density) and dash-dotted green curve (KRK level density) as obtained with the nuclear reaction code ALICE2014 and dashed blue curve as obtained from PACE4. The estimated errors are smaller than the experimental scatter point size.

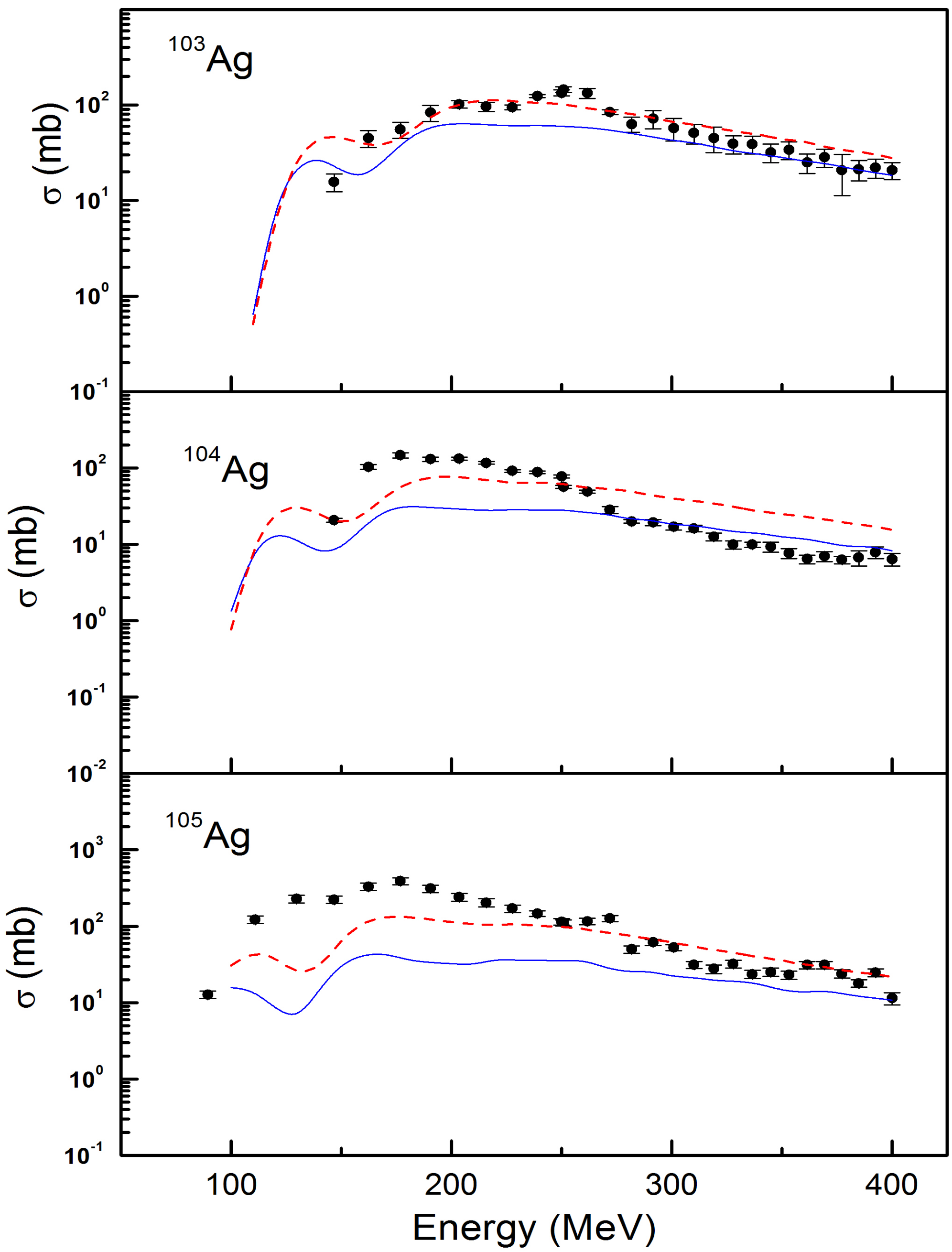

Figure 4: Excitation functions of Ag residues formed in the interaction of ^{14}N with ^{103}Rh as indicated. The solid symbols are the experimental results of this paper. The calculated excitation functions are shown as the red solid curves (OB level density), the blue dashed curves (FG level density), and the black dashed-dotted curves (KR level density) as obtained with the nuclear reaction code ALICE2014.

- Excitation functions for the residues emitted in the reactions ^{14}N+^{103}Rh were measured using the activation technique in conjunction with off-line γ-ray spectroscopy. Several targets of thickness around 500 $\mu g/cm^2$ were used for the purpose of irradiation. Irradiation time was decided according to the half-life of the emitted residues. The induced activity in the target and a catcher in close contact with it were subsequently measured for several weeks. Depending upon how easily beam energy could be changed, irradiation were done at energy intervals of 5 to 10 MeV. Activities were measured using calibrated HPGe detectors. The residues were identified using their characteristic gamma lines and using their half-life by measuring decrease in activity. Details of the identified residues are given in Table-1 for the above mentioned reaction. A typical spectra of excitation function for Ag residue is shown in Fig 4.

4 Outline of the thesis

The thesis is divided into seven chapters. A summarized detail of each chapter is as follows;

Chapter 1- It will give the introduction to the topic heavy ion reactions and the complex series of processes that occur due to the relatively large number of nucleons involved. These processes include the formation of an excited intermediate nucleus in a state far from statistical equilibrium, its equilibration by means of intranuclear interactions, pre-equilibrium emission of nucleons and light clusters, and finally the formation of an intermediate equilibrated nucleus, which further evaporates particles and emits γ rays and/or fission. The chapter will also discuss about the possible importance of pre-equilibrium decay in heavy-ion reactions and how the yields, energy spectra, and angular distributions from such reactions are valuable information for applications and interdisciplinary fields. The chapter will further discuss the subsequent development of phenomenological theories that can explain such kind of reaction data.Lastly the research problem which has been investigated during the course of Ph.D., followed by historical development of the problems will be discussed along with a thorough literature survey. It will also include a detailed discussion about the theory of the heavy ion reaction mechanism and the appropriate models for the explanations of those reaction mechanism. Theoretical calculations were performed using computer code ALICE2014 [12, 16–18] in which pre-equilibrium emission of both nucleons and light clusters is based on the HMS model [11]. Another code that was used is the statistical model code Projection Angular-Momentum Coupled Evaporation (PACE4) which uses a Monte Carlo procedure to determine the decay sequence of an excited nucleus using the Hauser-Feshbach formalism. The chapter will describe details of these model codes related to the current work, that was used for the present theoretical analysis.

Chapter 2- This chapter will give the complete description of the experimental work carried out for study of excitation functions of various residues produced in the reaction of ^{14}N with ^{103}Rh at projectile energies ranging from threshold up to

Table I: List of the identified residues in the reaction of ^{14}N incident on ^{103}Rh along with their half-lives, spin, energies and abundances of the characteristic γ - line.

Isotope	$T_{1/2}$ (h)	J^{π}	E_{γ} (keV)	Abundance $I_{\gamma}(\%)$
^{104}Cd	0.962	0+	709.6	19.5
$^{105}Ag^{g}$	990.96	1/2−	344.5	41.0
			280.4	30.2
			443.4	10.5
			664.6	11.1
$^{104}Ag^{g}$	1.153	5+	555.8	92.6
			767.7	65.7
$^{103}Ag^{g}$	1.095	7/2+	118.7	31.2
			148.1	28.3
			266.9	13.3
^{101}Pd	8.47	5/2+	296.3	19.0
			590.4	12.06
^{100}Pd	87.12	0+	126.1	7.8
^{99}Pd	0.357	5/2+	136.0	73.0
$^{102}Rh^{m}$	25404	6+	475.1	95.0
			631.3	56.0
$^{102}Rh^{g}$	4968	1/2−	475.1	38.4
			628.0	3.8
$^{101}Rh^{m}$	104.2	9/2+	306.9	81.0
			545.0	4.27
$^{100}Rh^{g}$	20.8	1−	539.5	80.6
			822.7	21.1
$^{99}Rh^{g}$	386.4	1/2−	528.2	38.0
			353.1	34.6
^{97}Ru	69.6	5/2+	215.7	86.0
			324.5	10.8
^{95}Ru	1.64	5/2+	336.4	70.2
^{94}Ru	0.86	0+	366.9	75.0
$^{96}Tc^{g}$	102.7	7+	778.2	100.0
			849.9	98.0
			812.6	82.0
			1127	15.2
$^{95}Tc^{g}$	20	9/2+	765.8	93.8
$^{94}Tc^{g}$	4.88	7+	871.1	100.0
			702.6	99.6
			849.7	95.7

$h \rightarrow hours$

400 MeV by means of activation method in conjunction with γ-ray spectroscopy. The chapter will present in detail the procedure, data analysis and calculations of experimental cross-sections as well as theoretical calculations followed by uncertainty analysis and results obtained.

Chapter 3- This chapter will contain complete description and experimental findings about neutron emission in reactions of ^{19}F with ^{181}Ta, ^{89}Y, ^{51}V at beam energies ranging from 130 to 150 MeV. The chapter will contain details of the time-of-flight technique and pulse-shape discrimination method that was used to measure the neutron spectra. This will be followed by details of ALICE and PACE calculations and their comparison with experimental data, and finally the discussion of the results obtained.

Chapter 4- This chapter will give the details about the experiment performed for the measurement of non-equilibrium emission of alpha particles in the interaction of ^{14}N with ^{59}Co and ^{93}Nb at incident energies of 250 and 400 MeV. The data were collected in wide angular range using silicon surface barrier detectors. The chapter will give details of the experiment and theoretical calculations performed using modified PACE code, followed by results and discussion.

Chapter 5- This will be the final chapter which will contain the summary and conclusions obtained through all the three experiments. There are still some unexplored territories in this field which needs some investigation. The chapter will also describe, in brief, the need and scope for such kind of work for other systems to fully understand the heavy ion reaction dynamics.

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List of Publications

A. Publications in Peer-Reviewed Journals

1. **Excitation functions of heavy residues produced in the $^{14}N+^{103}Rh$ reaction up to 400 MeV: Analysis of the pre-equilibrium mechanism with the hybrid Monte Carlo simulation model**

   J. Acharya, S. Mukherjee, G.F. Steyn, N.L. Singh and A. Chatterjee ***Phys. Rev. C 93, 024608 (2016).***

2. **Neutron emission in ^{19}F-induced reactions**

   J. Acharya, S. Mukherjee, A. Chatterjee, N.L. Singh, K. Ramchandran, P.C. Rout, K. Mahata, Vishal Desai, E.T. Mirgule, S.V. Suryanarayana, B.K. Nayak, A. Saxena and G.F. Steyn ***Phys. Rev. C 97, 034607 (2018).***

3. **Non-equilibrium emission of alpha particles in the interaction of ^{14}N with ^{59}Co and ^{93}Nb at incident energy of 250 MeV**

   J. Acharya, S. Mukherjee, G.F. Steyn, S.V. Förtsch, F.D. Smit, R.T. Newman, J.J. Lawrie, O.V. Fotina and A. Chatterjee ***Nucl. Phys. A. 996 (2020) 121695.***

B. Publications in Proceedings of the National Conferences

1. **Neutron emission in $^{19}F+^{181}Ta$ reaction at 150 MeV**

   J. Acharya, S. Mukherjee, A. Chatterjee, N.L. Singh, K. Ramchandran, P.C. Rout, K. Mahata, Vishal Desai, E.T. Mirgule, S.V. Suryanarayana, B.K. Nayak, A. Saxena and G.F. Steyn ***Proceedings of the DAE Symp. Nucl. Phys. 60 (2015) 456.***

2. **Pre-equilibrium neutron emission in $^{19}F+^{89}Y$ reaction at 150 MeV**

   J. Acharya, S. Mukherjee, A. Chatterjee, N.L. Singh, K. Ramchandran, P.C. Rout, K. Mahata, Vishal Desai, E.T. Mirgule, S.V. Suryanarayana, B.K. Nayak, A. Saxena and G.F. Steyn ***Proceedings of the DAE Symp. Nucl. Phys. 61 (2016) 358.***

3. **Alpha-Particle Emission in the Interaction of ^{14}N with ^{59}Co at incident energies of 250 and 400 MeV**

   J. Acharya, S. Mukherjee, G.F. Steyn, S.V. Förtsch, F.D. Smit and O.V. Fotina ***Proceedings of the DAE Symp. Nucl. Phys. 63 (2018) 468.***

4. **Entrance Channel Dependence of fusion-fission Dynamics in mass ∼200 region**

Golda K. S., H Singh, C. Yadav, Mohit Kumar, Saneesh N., A. Jhingan, Kavita Chouhan, R. Kumar, R.R. Dubey, Abhishek Yadav, Neeraj Kumar, A. Banerjee, Anjali Rani, Kavita Rani, **J.R. Acharya**, Ratan Singh, S. Noor, S.K. Duggi, Sugathan P. ***Proceedings of the DAE Symp. Nucl. Phys. 63 (2018) 680.***

5. **Study of fission fragment mass distribution in ^{12}C+^{178}Hf reaction**

   Kavita Chauhan, K.S. Golda, A. Jhingan, P. Sugathan, A. Chatterjee, Rakesh Kumar, N. Saneesh, Mohit Kumar, Abhishek Yadav, C. Yadav, Rakesh Dubey, Neeraj Kumar, Akashrup Banerjee, Anjali Rani, S.K. Duggi, Kavita Rani, Shoaib Noor, **Jaimin Acharya**, Hardev Singh ***Proceedings of the DAE Symp. Nucl. Phys. 63 (2018) 696.***