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Effect of nuclear structure in fusion enhancement of $^{19}O+^{12}C$ reaction at sub-barrier energies

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Introduction

In the recent times, due to availability of radioactive ion beam facilities the use of neutron rich projectiles to probe the fusion dynamics is a topic of immense interest [1]. The investigation of fusion excitation function for isotope series of neutron rich nuclei provides unique prospect. Because, using neutron rich projectiles the Coulomb potential changes a little due to unchanged charge distribution. Therefore, comparative analysis of fusion excitation function for an isotopic chain facilitate to explore the role of attractive nuclear potential with increasing neutron content. Moreover, an enhancement in fusion cross-section is observed using neutron rich nuclei compared to β-stable projectile [2]. It is best studied at near and sub-barrier energies since at low energies the low ℓ-waves are significant, which underpin the role of attractive nuclear potential, are enhanced.

The fusion enhancement has been observed in mass asymmetric reaction $^{15}C+^{232}Th$ [3]. However, in the light mass region, the study of fusion by employing the exotic projectiles is relevant for astrophysical interest. Because these neutron rich nuclei are estimated as the possible cause of heating of neutron star crust [4]. The experimental study of fusion of $^{18,19}O$ projectiles with ^{12}C target shows fusion enhancement compared to use of stable ^{16}O projectile [5, 6]. Recently, we have investigated the dynamics of compound nuclei (CN) $^{28,30}Si^*$ at same $E_{c.m.}$ = 7.0 MeV. The evaluated fusion cross-sections σ_{fusion}, within DCM, at same $E_{c.m.}$ = 7.0 MeV for CN $^{28}Si^*$ and $^{30}Si^*$, show that LPs are having major contribution in σ_{fusion}. For compound nucleus $^{30}Si^*$, 1n has highest part in σ_{fusion}, which tends to be responsible for observed fusion enhancement in agreement with experimental data [7]. Further, the use of radioactive ^{19}O beam facilitate to study fusion enhancement with exotic projectile. In the present work, dynamics of $^{16,18,19}O+^{12}C$ reactions leading to formation of (CN) $^{28,30,31}Si^*$, have been analyzed, comparatively, at sub-barrier energy within dynamical cluster decay model (DCM) [7, 8] approach, to explore the effects of neutron richness of projectile on the reaction mechanism and to look for the underlying cause of fusion enhancement.

Methodology

The DCM is based on quantum mechanical fragmentation theory and is worked out in terms of collective coordinates of mass asymmetry η = (A$_T$-A$_P$)/(A$_T$+A$_P$) and relative separation (R) with effects of temperature, deformation and orientation duly incorporated in it. In terms of these collective coordinates, using the ℓ- partial waves, the decay cross-section is defined as

$$\sigma = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_c}(2\ell+1)P_0P;\ k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \quad (1)$$

where ℓ_c, the critical angular momentum, penetrability P refers to R motion and is calculated using WKB approximation, preformation probability P_0 refers to η motion and is given by sol. of stationary Schrodinger

$$\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V_R(\eta,T)\}\psi^{\nu}(\eta)$$

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Dynamical aspects of fusion enhancement for neutron rich compound systems

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Introduction

Understanding the mechanism of fusion of neutron rich systems has importance not only in the nuclear reactors and production of heavy elements but also in the astrophysical scenarios. Various experimental measurements have suggested an enhancement of fusion probability as compared to standard statistical model at near barrier energies for such systems [1]. Various authors have also indicated the presence of strong isotopic dependence of the fusion cross sections near the barrier. These studies have established the importance of interplay between nuclear structural and reaction dynamical aspects present in these many-body systems. The enhancement of fusion cross sections observed through these isotopic chains of nuclear reactions is being considered as one of the best methods to understand the character of neutron rich matter. The existence of these experimental studies motivates to investigates the dynamical aspects associated with the fusion reactions of the neutron rich nuclei. The present work investigate the fusion dynamics involved in the isotopic chain of reactions ($^{39,40,41,47}K +^{28} Si$) to explore the effect of neutron number on fusion enhancement at near barrier energies.

Methodology

The Dynamical cluster decay model (DCM) [2] of Gupta and collaborators is worked out in terms of collective co-ordinates of mass (and charge) asymmetries. In terms of above said co-ordinates, for ℓ-partial waves, the com-

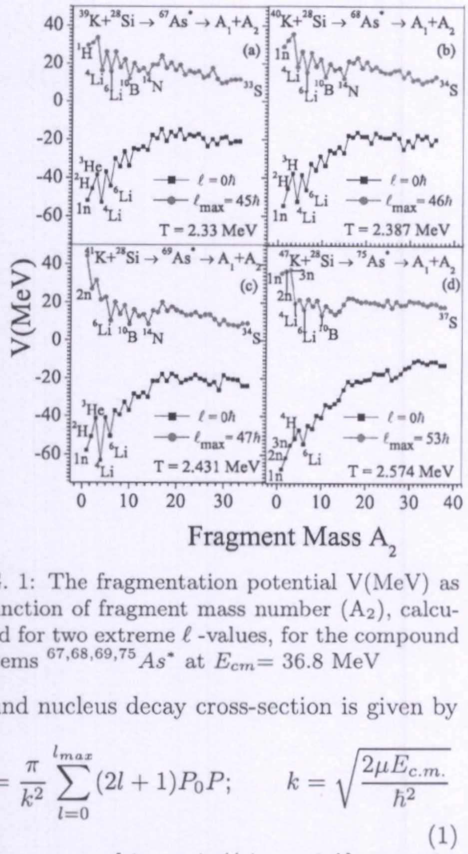

FIG. 1: The fragmentation potential V(MeV) as a function of fragment mass number (A_2), calculated for two extreme ℓ -values, for the compound systems $^{67,68,69,75}As^*$ at E_{cm}= 36.8 MeV

pound nucleus decay cross-section is given by

$$\sigma = \frac{\pi}{k^2}\sum_{l=0}^{l_{max}}(2l+1)P_0P; \qquad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \tag{1}$$

Where, $\mu = [A_1 - A_2/(A_1 + A_2)]m$, is the reduced mass, with m as the nucleon mass and ℓ_{max} is the maximum angular momentum. Where P is the barrier penetration probability and P_0 is the preformation probability at a fixed R on the decay path. The P_0 are evaluated by solving stationary Schrödinger wave equation and P calculated as the WKB tunneling probability.The structure information in

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Dynamical hindrance effect in fusion for the decay of the compound nucleus ^{64}Zn

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Introduction

Light charged particle evaporation spectra from the compound nucleus, populated at moderate excitation energy (~ 100 MeV), allows us to test the application of statistical model for the decay of the compound nucleus. The basic parameters of nuclear properties such as yrast line, level density, emission barriers and angular momentum distribution parameters, are modified by the deformation of highly excited and rapidly rotating nuclei. This leads to dynamical hindrance to fusion. [1, 2]

We present here of analysis for decay of the compound nucleus ^{64}Zn. It was populated at same excitation energy $E^* \sim 70$ MeV, through an asymmetric channel $^{16}O + {}^{48}Ti$ (E_{lab} = 76 MeV) and symmetric channel $^{37}Cl + {}^{27}Al$ (E_{lab} = 125 MeV). The inclusive alpha spectra and neutrons are compared with the predictions of conventional statistical model calculations (CASCADE). The limitations of this description for the case of symmetric reaction are also explained.

Experimental details

The experiment was performed with 15UD Pelletron at IUAC, New Delhi, India using the General Purpose Scattering Chamber (GPSC). A ^{48}Ti foil and an ^{27}Al foil each of about 1.0 mg/cm^2 thickness were used as targets. Light charged particle spectra were recorded using two ΔE-E telescopes. These spectra were taken at 30°, 36°, 42°, 48° and 54° for both the systems. While the neutrons were detected using the liquid scintillator cells of BC501 at laboratory angles θ = 30°, 60°, 90° and 120° with respect to the beam direction. The neutron detectors were placed at a distance of 1 m from the target.

Analysis and Discussions

The experimental analysis was carried out using CANDLE software, and the theoretical results were obtained using the statistical model code CASCADE. In the CASCADE code, the spin dependent energy is parameterized as

Dynamical effects of Si-isotopes induced reactions at similar centre of mass energies $E_{c.m.}$

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Introduction

The study of the complex phenomena observed in sub-barrier energies through fusion of isotopic chain of reactions is topic of interest in nuclear physics. A number of authors have theoretically investigated the sub-barrier fusion phenomena using different models to explain fusion enhancement and fusion hindrance phenomenon [1]. Since dynamics of fusing nuclei play a key role in the fusion mechanism, it will be interesting to study the fusion enhancement/hindrance for lower-mass nuclei using the dynamical cluster decay model (DCM) [2] to get a better insight of the fusion process.

With this motivation, fusion of ^{28,30}Si+^{12}C populating $^{40,42}Ca^*$ [3] with Z=20 shell closure and neutron number gradually moving away from N = 20 neutron shell closure has been investigated within DCM at energies above and below Coulomb barrier. The cross-sections for ^{30}Si+^{12}C are reproduced using neck length parameter (ΔR) at the different energies. The empirically fitted values of ΔR are used to predict the fusion cross-sections at similar centre of mass energies $E_{c.m.}$ for ^{28}Si+^{12}C. The predicted fusion cross-section values are in good agreement with the experimental measurements. Also, the fusion cross-sections has been predicted for energies far below the barrier. The hindrance phenomenon observed at sub barrier energies ^{30}Si+^{12}C has been addressed through barrier lowering parameter which is the in-built property of the model.

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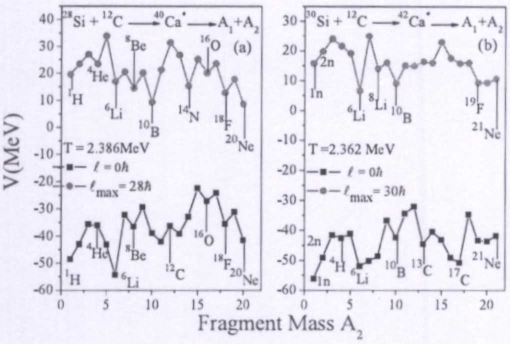

FIG. 1: The fragmentation potential $V(MeV)$ as a function of fragment mass number A_2, calculated for two extreme ℓ-values, for the CN $^{40}Ca^*$ and $^{42}Ca^*$ at $E_{c.m.}$ = 9.5 MeV and ΔR = -0.7 fm, for deformed fragmentation paths.

Methodology

The DCM [2] of Gupta and collaborators is worked out in terms of collective co-ordinates of mass (and charge) asymmetries. In terms of above said co-ordinates, for ℓ-partial waves, the compound nucleus decay cross-section is given by

$$\sigma = \frac{\pi}{k^2}\sum_{l=0}^{l_{max}}(2l+1)P_0P; \qquad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \tag{1}$$

Where, $\mu = [A_1 - A_2/(A_1 + A_2)]m$, is the reduced mass, with m as the nucleon mass and ℓ_{max} is the maximum angular momentum. Where P is the barrier penetration probability and P_0 is the preformation probability at a fixed R on the decay path. The P_0 are evaluated by solving stationary Schrödinger wave

Investigation of Role of Entrance Channel Mass Asymmetry on Fusion Fission Dynamics

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Abstract. The fusion-fission dynamic process has been stimulating the interests of nuclear physicists from several years and still understanding the dynamics of fusion-fission process is an active field of research. A number of attempts have been made in the past few decades to estimate the strength of nuclear dissipation in fusion-fission dynamics. Various probes are used to carry out these measurements such as neutron multiplicity, charged particles multiplicity, evaporation residue cross-section etc. In the present work the effect of entrance channel has been studied in reactions ^{12}C + ^{204}Pb and ^{19}F + ^{197}Au populating same compound nucleus ^{216}Ra using statistical model (SM) VECSTAT by simultaneously explaining both neutron multiplicities and fission\evaporation residue cross-sections by separately taking in account the reduced dissipation coefficient sensitive from equilibrium to saddle (β_{gs}) and saddle to scission (β_{ss}) regime. The work shows that smaller β_{gs} values are required to explain fission\evaporation residue (ER) cross-sections and larger β_{ss} values are required to explain neutron multiplicities and for consistent SM analysis fission\evaporation residue cross-sections are more appropriate tools to investigate entrance channel effects rather than neutron multiplicities.

INTRODUCTION

The presence of dissipation phenomenon as predicted by Kramers [1] is now very well established at both experimental and theoretical fronts. It has been established that there exists certain temperature above which dissipation effects come in to picture. In the recent years various experimental and theoretical work have shown the need of dissipation strength in fusion-fission reactions at high excitation energies. From theoretical point of view different models have been developed based on multidimensional Langevin equations etc. [2] which have invoked dissipation to study fission. Recently, Banerjee *et. al.* [3] have shown that dissipative fission hindrance is required to explain the experimental values of both pre-scission neutron multiplicities and evaporation residue cross-sections within statistical model results. Experimentally, the quest of the nuclear dissipation and effect of temperature, shell closure, entrance channel mass asymmetry on it has been observed by estimating the dissipation strength/fission time delays using various probes. One of the important effects that effect the fusion-fission dynamics is entrance channel mass asymmetry. Several pre-scission neutron multiplicity M_{pre} measurements have been reported in the literature [4, 5] populating the same CN depending on the entrance channel mass asymmetry (α) relative to the Businaro-Gallone (BG) critical mass asymmetry (α_{BG}) [6]. These studies have shown sensitivity of pre-scission neutron multiplicity to entrance channel dynamics involving quasi-fission contribution. The difference observed in the M_{pre} values is attributed to the spin distribution and large delay associated during the formation of the CN.

In the present work the effect of entrance channel has been studied in reactions ^{12}C + ^{204}Pb and ^{19}F + ^{197}Au [5, 7] populating same compound nucleus ^{216}Ra using statistical model VECSTAT by simultaneously explaining both

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Fusion of neutron-rich oxygen nuclei

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Abstract. Measurement of the fusion excitation function for ^{18}O + ^{12}C and ^{19}O + ^{12}C is described. The fusion cross-section is extracted through the direct measurement of evaporation residues resulting from the fusion process. At near barrier energies, the single additional neutron present in ^{19}O results in an enhancement in the fusion cross-section by a factor of over three as compared to ^{18}O.

1 Introduction

Measuring the fusion excitation function for an isotopic chain of projectile nuclei presents an unique opportunity to examine the character of neutron-rich matter. For a given element, with increasing neutron number the neutron density distribution usually extends further out while the proton distribution remains largely unaffected. Hence, the repulsive Coulomb potential is largely unchanged while the attractive nuclear potential changes. As fusion at near barrier energies is sensitive to the interplay between the repulsive Coulomb and attractive nuclear potentials, the comparison of the fusion excitation function for isotopically related projectiles provides a sensitive probe of the change in the attractive nuclear potential. This change in the attractive potential can be related to changes in both the structure and dynamics of the neutron density distribution as the number of neutrons increases.

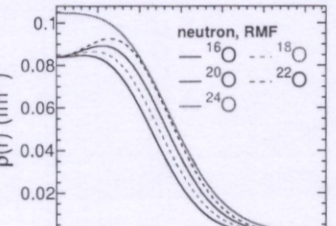

Figure 1. Neutron-density distribution of oxygen isotopes calculated within a relativistic mean field theory (RMF).

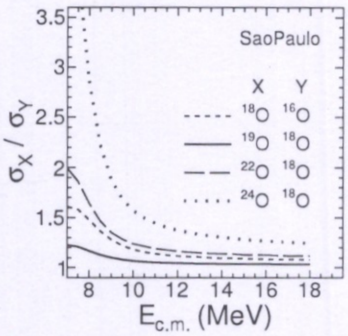

Figure 2. Relative cross-section for Oxygen isotopes using a simple barrier penetration model with the RMF density distributions.

Presented in Fig. 1 are the neutron density distributions for oxygen isotopes calculated within the context of a relativistic mean field theory [1, 2]. As expected, with increasing neutron number the tail of the density distribution extends further out. It is perhaps surprising however that the tail of the neutron density distribution for ^{22}O is so close to that of the drip-line nucleus ^{24}O. This observation is particularly noteworthy as beams of ^{20,21}O are presently available at GANIL and a beam of ^{22}O is anticipated in the near future. In this paper, we describe the first step towards the systematic measurement of the fusion excitation functions of the oxygen isotopes namely fusion in ^{18}O+^{12}C and ^{19}O+^{12}C.

An extended neutron distribution could impact fusion both through its static spatial extent as well as through its dynamics (e.g. polarization effects). The influence of the static contribution can be estimated by using a one-dimensional barrier penetration model such as the Sao-

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Paulo model [3]. For the density distributions presented in Fig. 1, we have calculated the relative fusion cross-sections for several oxygen isotopes and present the results in Fig. 2. Evident in the figure is the fact that at all energies as the neutron-richness increases the fusion cross-section increases. At energies well above the barrier ($E_{c.m.} \sim 8$ MeV) this enhancement is relatively constant and can be considered geometric. Near and below the barrier however, the enhancement increases rapidly with decreasing incident energy. In this energy domain the enhancement reflects the increased importance of the nuclear potential due to the neutron-skin. It should be emphasized that as this is a purely static calculation, the inclusion of fusion dynamics could result in an enhancement larger than that depicted in Fig. 2.

In order to measure the fusion excitation function for $^{18}O + ^{12}C$ and $^{19}O + ^{12}C$ two separate experiments were performed at the John D. Fox accelerator laboratory at Florida State University. In the initial experiment we measured the fusion excitation function for $^{18}O + ^{12}C$, extending the measured cross-section down to the sub 1 mb level, a factor of 30 lower than previously measured. Having established the technique, we subsequently measured the fusion excitation function for $^{19}O + ^{12}C$. The experimental details of both measurements are summarized below.

2 The $^{18}O + ^{12}C$ experiment

2.1 Experimental setup

The experimental setup for this experiment consisted of two ExB microchannel plate detectors and two annular silicon detectors as depicted in Fig. 3. The beam first passes through a ExB microchannel plate detector, designated MCP_{US}, situated approximately 1.3m upstream of the target position. For each ion traversing this detector a fast timing signal is generated. The beam subsequently encounters a second ExB microchannel plate detector, designated MCP_{TGT}. The 100 $\mu g/cm^2$ thick carbon foil of MCP_{TGT} is dual function. Not only does it serve as a secondary emission for the detector, but it also serves as the target for the experiment. The coincidence of these two ExB MCP detectors with the appropriate time-of-flight provided the incident beam count. The typical intensity of the ^{18}O beam incident on the target was $\sim 2 \times 10^5$ ions/s.

2.2 Measuring the fusion products

Fusion of a ^{18}O nucleus in the beam together with a ^{12}C nucleus in the target foil results in the production of an excited ^{30}Si nucleus. For collisions near the Coulomb barrier the excitation of the fusion product is relatively modest, $E^* \approx 35$ MeV. De-excitation of this fusion product by evaporation of a few neutrons, protons, and α particles results in an evaporation residue (ER). Statistical model calculations [4] indicate that for a ^{30}Si compound nucleus, the nuclei ^{29}Si, ^{28}Si, ^{28}Al, ^{27}Al, and ^{25}Mg account for the bulk of the ERs. Emission of the light particles deflects the ER from the beam direction allowing their detection and identification in two annular silicon detectors, designated T2 and T3, that are situated downstream of the MCP_{TGT}. These detectors subtend the angular range 3.5° $< \theta_{lab} <$ 25° allowing detection of the majority of the ERs produced [5]. By measuring the time-of-flight of particles between the MCP_{TGT} detector and the silicon detectors [6] together with the energy deposit in the Si detector, evaporation residues are distinguished from scattered beam, as well as emitted light particles. By utilizing the measured energy deposit and time-of-flight, the mass of the ion can be calculated providing clear separation of ERs from the incident beam [7].

2.3 Fusion excitation function for $^{18}O + ^{12}C$

The fusion cross-section is extracted by summing the total number of evaporation residues observed. Comparison of this yield with the number of incident ^{18}O ions while accounting for the target thickness and the geometric efficiency of the experimental setup yields the absolute fusion cross-section [7]. The measured excitation function is displayed in Fig. 4a together with previously published results [9–11]. Vertical error bars on the new data reflect both the statistical uncertainties as well as a 2% systematic error associated with the analysis. Horizontal error bars represent the uncertainty in whether the fusion occurs at the front or back of the target foil. While prior measurements using the direct measurement of evaporation residues only measured the fusion cross-section down to the 25 mb level [9], in this work the fusion cross-section is measured down to the 820 μb level, a factor of approximately 30 lower in cross-section. In the energy region where the present data overlaps with published data, overall agreement of the cross-sections is good, close to the statistical uncertainties. This overall agreement indicates both that our approach in extracting the fusion cross-section is sound and that there are no significant uncertainties in the values of the target thickness or detector efficiency. Closer comparison of the present dataset with the data of Ref. [9] indicates that the presently measured cross-sections are approximately 3-5% lower for $E_{c.m.} \geq$ 10 MeV. This is within the statistical uncertainties of the data reported by Eyal et al. In addition, the present data are higher in their statistical quality.

We have compared the experimental fusion excitation function with the predictions of a microscopic model. Over the past several years, the density constrained TDHF (DC-TDHF) method for calculating heavy-ion potentials [12] has been employed to calculate heavy-ion fusion cross-sections with remarkable success [13, 14]. While most applications have been for systems involving heavy nuclei, recently the theory was used to study above and below barrier fusion cross-sections for lighter systems, specifically for reactions involving various isotopes of O+O and O+C [15, 16]. One general characteristic of TDHF and DC-TDHF calculations for light systems is that the fusion cross-section at energies well above the barrier are usually overestimated [17, 18], whereas an excellent agreement is found for sub-barrier cross-sections [15].

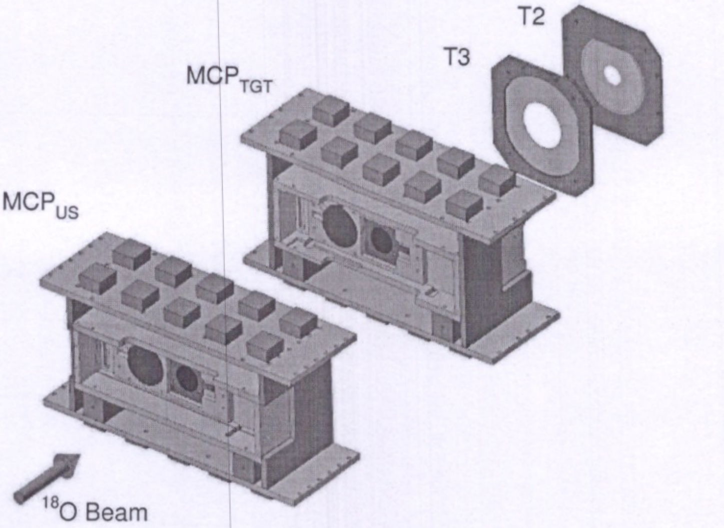

Figure 3. Experimental setup utilized to directly measure the evaporation residues and extract the fusion cross-section

Comparison of the experimental fusion excitation function with the DC-TDHF microscopic model is presented in Fig. 4a. Overall comparison of the experimental cross-sections with the DC-TDHF calculations indicate that for energies $\gtrsim$7 MeV the experimental cross-sections (symbols) are lower than the theoretical predictions (solid line). In order to facilitate a quantitative comparison of the experimental excitation function with the theoretical predictions, we have fit the experimental cross-sections with a functional form [19] that describes the penetration of an inverted parabolic barrier. The values of the fit parameters are presented in Table 1.

$$\sigma = \frac{R_C^2}{2E}\hbar\omega \cdot ln\left\{1 + exp\left[\frac{2\pi}{\hbar\omega}(E - V_C)\right]\right\} \qquad (1)$$

where E is the incident energy, V_C is the barrier height, R_C is the radius of interaction, and $\hbar\omega$ is the barrier curvature.

Shown in Fig. 4b is the ratio of the fit of the experimentally measured cross-sections to the DC-TDHF calculations. For energies 7.5 MeV < $E_{c.m.}$ < 14 MeV, the ratio $\sigma_{Experiment}/\sigma_{DC-TDHF}$ is $\approx$ 0.75 and is relatively constant with respect to energy. As the incident energy decreases below 7.5 MeV, the ratio increases reaching a value of over 10 at the lowest energy measured, $E_{c.m.} \approx 5$ MeV. The fact that the ratio is only $\approx$ 0.75 at energies above the barrier can be understood as due to the presence of breakup reactions in this energy range. With decreasing incident energy, the role of breakup reactions diminshes hence the ability of the DC-TDHF model to describe fusion is expected to improve. We therefore focus our attention on the comparison of the model and experiment in the sub-barrier region. The key feature in the ratio is therefore its change with decreasing incident energy in the sub-barrier domain, specifically its increase from a value smaller than unity to a value larger than unity. This trend emphasizes that the experimental and theoretical excitation functions

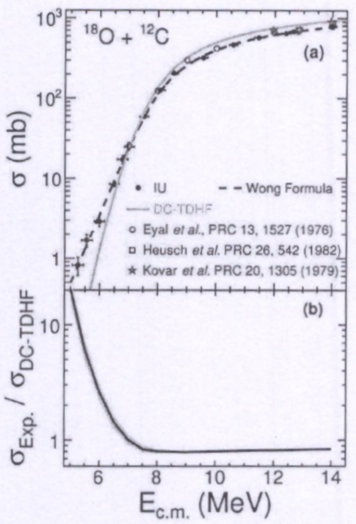

Figure 4. Comparison of the measured cross-section for $^{18}O+^{12}C$ with the predictions of the DC-TDHF model.

have different shapes with the experimental cross-section falling more slowly with decreasing incident energy than is theoretically predicted by the DC-TDHF model. This enhancement of the experimental fusion cross-sections relative to the DC-TDHF predictions is a factor of $\approx$10 as the incident energy decreases from $E_{c.m.}$ = 7 MeV to $E_{c.m.}$ = 5 MeV. We have assessed the impact of the experimental uncertainties on the ratio presented and display the result as a shaded band in Fig. 4b. The trends exhibited by the ratio are significantly larger than the magnitude of the uncertainties.

The fact that the experimental fusion cross-sections decrease more slowly with decreasing energy than the calculated cross-sections can be interpreted as a larger tun-

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neling probability for the experimental data as compared to the theoretical calculations. This enhanced tunneling probability can be associated with a narrower, lower barrier. The underlying reason that the barrier determined from the experimental data is weaker than in the model is presently unclear.

3 The ^{19}O + ^{12}C experiment

3.1 Producing and Chararacterizing a ^{19}O beam

A beam of ^{18}O ions at an energy of 80.7 MeV was used to bombard a deuterium gas cell at a pressure of 350 torr to produce the ^{19}O beam. To increase the gas density, the gas cell was cooled to a temperature of 77 K. Ions of ^{19}O produced via a (d,p) reaction were separated from the incident beam by the electromagnetic spectrometer RESOLUT [20]. Despite the rejection of most of the unreacted beam by RESOLUT, the beam exiting the spectrometer consisted of both ^{19}O and ^{18}O ions. It was therefore necessary to identify each ion incident on the target. By accomplishing this it was possible to simultaneously measure the fusion excitation function for ^{18}O + ^{12}C and ^{19}O + ^{12}C which provided an important consistency check. Comparison of the ^{18}O + ^{12}C with the prior high statistics measurement of ^{18}O + ^{12}C demonstrated that there were no systematic differences between the two measurements. This dual measurement thus provided confidence that any observed fusion enhancement was a robust signal.

3.2 Experimental setup

Although the experimental setup for the ^{19}O beam was largely the same as in the prior experiment, a few changes were made to handle the radioactive beam. In order to identify beam particles, the energy deposit (ΔE) and time-of-flight (TOF) of each particle was measured prior to the target. After exiting RESOLUT particles traversed a thin foil (0.5 μm thick aluminized mylar) which served as the electron emission foil for an MCP detector. Approximately 3.5 m downstream of this thin foil the oxygen ions passed through a compact ionization detector (CID) depositing an energy, ΔE. CID served two roles: to help identify the ion as well as to reduce its energy. While the production of ^{19}O is favored at higher energies, the measurement of the fusion cross-section at near barrier energies requires reducing the energy of the radioactive ion after its production. To perform the excitation function measurement, the energy of the incident beam was decreased by adjusting the gas pressure in CID. Upon exiting CID the ions were incident on a 105 $\mu g/cm^2$ carbon foil. This carbon foil, as in the prior experiment, served both as a secondary electron emission foil for the target microchannel plate detector (MCP_{TGT}) and as the target for the fusion experiment [8]. To measure the energy distribution of ^{19}O and ^{18}O ions incident on the target, a surface barrier, silicon detector was periodically inserted into the beam path just prior to the target.

The timing signals from both microchannel plate detectors together with the energy deposit in the ionization chamber allowed identification of ions in the beam through measurement of the ΔE-TOF. Ions of $^{19}O^{7+}$, $^{18}O^{7+}$, and $^{18}O^{6+}$ are clearly identified with ^{19}O ions corresponding to approximately 31 % of the beam intensity. The two charge states of ^{18}O contributed to approximately 50 % of the beam intensity on target. The intensity of the ^{19}O beam incident on the target was 1.5 - 4 x 10^3 ions/s.

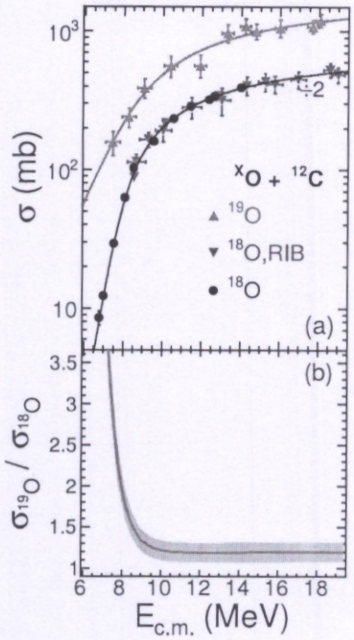

Figure 5. Comparison of the measured cross-section for ^{18}O + ^{12}C and ^{19}O + ^{12}C. The cross-sections for the ^{18}O reaction have been scaled by a factor of two for clarity.

3.3 Fusion excitation function for ^{19}O + ^{12}C

The same general trend is observed for both of the excitation functions depicted in Fig. 5a. With decreasing incident energy the cross-section decreases as expected for a barrier controlled process. At essentially all energies measured the ^{19}O data exhibits a larger fusion cross-section as compared to the ^{18}O data.

Table 1. Fit parameters for the ^xO + ^{12}C fusion excitation functions. See text for details.

	V_C (MeV)	R_C (fm)	$\hbar\omega$ (MeV)
^{18}O + ^{12}C	7.66 ± 0.10	7.39 ± 0.11	2.90 ± 0.18
^{19}O + ^{12}C	7.73 ± 0.72	8.10 ± 0.47	6.38 ± 1.00

To quantitatively examine the differences in the two excitation functions we have fit the excitation functions with the Wong formalism of penetration of an inverted parabolic barrier [19]. The fit of the high resolution ^{18}O data is indicated as the solid black line in Fig. 5a. The solid red curve in Fig. 5a depicts the fit of the ^{19}O data. A reasonable fit of the measured fusion cross-sections is achieved in both cases. The extracted parameters for the

^{18}O and ^{19}O reactions are summarized in Table 1. Since the charge density distribution is essentially unchanged, it is unsurprising that the barrier height, V_C, remains essentially the same for both of the reactions examined. Moreover, as expected with increasing neutron number an increase in R_C is observed. This increase in the radius can be viewed by calculating the quantity $R_C/\mathrm{A}^{1/3}$ where A is the mass number of the compound nucleus. This quantity has a value of 2.38 for the ^{18}O induced reaction, while it is 2.58 for the ^{19}O induced reaction. The most significant change in the fit parameters is a substantial increase in the magnitude of $\hbar\omega$ for the ^{19}O case corresponding to a narrower barrier, reflecting an increase in the attractive nuclear potential.

Depicted in Fig. 5b as the solid (red) line is the dependence of the measured ratio of $\sigma(^{19}\mathrm{O})/\sigma(^{18}\mathrm{O})$ on $\mathrm{E_{c.m.}}$. At energies well above the barrier $\sigma(^{19}\mathrm{O})/\sigma(^{18}\mathrm{O})$ is essentially flat at a value of ≈ 1.2. As one approaches the barrier it rapidly increases to a value of approximately 3.5. Hence, the addition of a single additional neutron in ^{19}O as compared to ^{18}O results in a dramatic enhancement in the fusion cross-section at sub-barrier energies.

4 Summary

We have measured the fusion excitation functions for ^{18}O + ^{12}C and ^{19}O + ^{12}C using low intensity beams. Comparison of these excitation functions indicates a significant enhancement at near barrier energies for the neutron-rich projectile. The addition of a single neutron increases the fusion cross-section by more than a factor of three at the lowest energy measured. This enhancement may reflect the increased role of neutron transfer or coupling to collective degrees of freedom. These measurements represent the first step in the measurement of the fusion excitation function for an isotopic chain of oxygen nuclei. Acquiring a systematic, high quality dataset of this type, coupled with microscopic calculations of the fusion process has considerable promise in elucidating the nature of neutron-rich nuclear matter.

5 Acknowledgements

The support of the staff at Florida State University's John D. Fox accelerator in providing the ^{18}O and ^{19}O beams made this experiment feasible. We gratefully acknowledge their efforts. Development of the Sao Paulo model code by Dr. Helber Dussan is gratefully acknowledged. This work was supported by the U.S. Department of Energy under Grant Nos. DE-FG02-88ER-40404 (Indiana University), DE-FG02-87ER40365 (Indiana University Nuclear Theory), DE-SC0008808 (NUCLEI SciDAC Collaboration), DE-FG02-02ER-41220 (Florida State University), DE-SC0013847 (Vanderbilt University) and the National Science Foundation under Grant No PHY-1491574 (Florida State University). J.V. acknowledges the support of a NSF Graduate Research Fellowship under Grant No. 1342962.

References

[1] P. Ring, Prog. Part. Nucl. Phys. **37**, 193 (1996)
[2] B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. **16**, 1 (1986)
[3] L. R. Gasques et al., Phys. Rev. C **69**, 034603 (2004)
[4] N. G. Nicolis and J. R.Beene, unpublished, 1993
[5] T. K. Steinbach, PhD Thesis, Indiana University (2016)
[6] R. T. deSouza et al., Nucl. Instr. and Meth. **A632**, 133 (2011)
[7] T. K. Steinbach et al., Phys. Rev. C. **90**, 041603(R)(2014)
[8] T. K. Steinbach et al., Nucl. Instr. and Meth. **A743**, 5 (2014)
[9] Y. Eyal and M. Beckerman and R. Checkhik and Z. Fraenkel and H. Stocker, Phys. Rev. C **13** 1527 (1976)
[10] D. Kovar, D.F. Geesaman, T.H. Braid, Y. Eisen, W. Henning, T.R. Ophel, M. Paul, K.E. Rehm, S.J. Sanders, P. Sperr, J.P. Schiffer, S.L. Tabor, S. Vigdor, B. Zeidman and F.W. Prosser Jr., Phys. Rev. C **20**, 1305 (1979)
[11] B. Heusch, C. Beck, J.P. Coffin, P. Engelstein, R. M. Freeman, G. Guillaume, F. Haas, P. Wagner, Phys. Rev. C **26**, 542 (1982)
[12] A. S. Umar and V. E.Oberacker, Phys. Rev. C **74** 021601(R) (2006)
[13] R. Keser and A. S. Umar and V. E.Oberacker, Phys. Rev. C **85** 044606 (2012)
[14] Back, B. B., Esbensen, H., Jiang, C. L. and Rehm, K. E., *Recent developments in heavy-ion fusion reactions* Rev. Mod. Phys. **86**, 317 (2014)
[15] A. S. Umar, V. E.Oberacker and C. J. Horowitz, Phys. Rev. C **85** 055801 (2012)
[16] R. T. deSouza, S. Hudan and V. E. Oberacker and A. S. Umar", Phys. Rev. C **88**, 014602 (2013)
[17] C. Simenel, R. Keser, A. S. Umar and V. E. Oberacker, Phys. Rev. C, **88**, 024617 (2013)
[18] A. S. Umar, C. Simenel and V. E. Oberacker, Phys. Rev. C **89**, 034611 (2014)
[19] C. Y. Wong, Phys. Rev. Lett.**31**, 766 (1973)
[20] I. Wiedenhöver et al., *Fifth International Conference on Fission and Properties of Neutron-rich Nuclei*, Eds. J.H. Hamilton and A.V. Ramayya, World Scientific, Sanibel Island, FL 2012

Abstract Submitted
for the APR17 Meeting of
The American Physical Society

Measuring the fusion cross-section of ^{39,47}K + ^{28}Si at near barrier energies[1] JUSTIN VADAS, VARINDERJIT SINGH, BLAKE WIGGINS, JACOB HUSTON, SYLVIE HUDAN, ROMUALDO DESOUZA, Indiana Univ - Bloomington, ABDOU CHBIHI, DIETER ACKERMANN, GANIL, KYLE BROWN, Michigan State University — The outer crust of an accreting neutron star provides an interesting environment for nuclear reactions to occur. In particular, the enhancement of fusion between neutron-rich nuclei relative to their β-stable counterparts has been suggested as a trigger for an X-ray superburst. Recently, nuclei in the mass range of A=20-40 have been proposed as the most likely candidates for this process. To investigate this question, comparing the fusion excitation functions for both neutron-rich and β-stable nuclei at energies near the fusion barrier is necessary. The development of a ^{47}K radioactive beam at NSCLs ReA3 facility makes such a comparison possible for the first time. An approved experiment to measure the fusion excitation functions for ^{39,47}K + ^{28}Si will be described. This experiment utilizes a technique optimized for measuring the total fusion cross-section of reactions involving low-intensity (10^3 - 10^6 ions/s) radioactive beams. In addition, protons and α particles emitted by the compound nucleus as it de-excites are measured. Preliminary results will be presented.

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Measuring the fusion cross-section of ^{39,47}K + ^{28}Si at near barrier energies[1]

JUSTIN VADAS, VARINDERJIT SINGH, BLAKE WIGGINS, JACOB HUSTON, SYLVIE HUDAN, ROMUALDO DESOUZA, Indiana Univ - Bloomington, ABDOU CHBIHI, DIETER ACKERMANN, GANIL, KYLE BROWN, Michigan State University

— The outer crust of an accreting neutron star provides an interesting environment for nuclear reactions to occur. In particular, the enhancement of fusion between neutron-rich nuclei relative to their β-stable counterparts has been suggested as a trigger for an X-ray superburst. Recently, nuclei in the mass range of A=20-40 have been proposed as the most likely candidates for this process. To investigate this question, comparing the fusion excitation functions for both neutron-rich and β-stable nuclei at energies near the fusion barrier is necessary. The development of a ^{47}K radioactive beam at NSCLs ReA3 facility makes such a comparison possible for the first time. An approved experiment to measure the fusion excitation functions for ^{39,47}K + ^{28}Si will be described. This experiment utilizes a technique optimized for measuring the total fusion cross-section of reactions involving low-intensity (10^3 - 10^6 ions/s) radioactive beams. In addition, protons and α particles emitted by the compound nucleus as it de-excites are measured. Preliminary results will be presented.

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The American Physical Society

High-rate axial-field ionization chamber for particle identification of Radioactive beams[1] ROMUALDO DESOUZA, JUSTIN VADAS, VARINDERJIT SINGH, G. VISSER, A. ALEXANDER, S. HUDAN, J. HUSTON, B. WIGGINS, Indiana Univ - Bloomington, A. CHBIHI, GANIL, M. FAMIANO, M. BISCHAK, Western Michigan University — The design, construction and performance characteristics of a simple axial-field ionization chamber suitable for identifying ions in a radioactive beam are presented. The detector is optimized for use with low-energy radioactive beams ($<$) 5 MeV/A. A fast charge sensitive amplifier (CSA) integrated into the detector design is also described. Coupling this fast CSA to the axial field ionization chamber produces an output pulse with a rise-time of 60 to 70 ns and a fall time of 100 ns, making the detector capable of sustaining a relatively high rate while providing a time resolution of 6 to 8 ns. Tests with an α source establish the detector energy resolution as $\approx$8% for an energy deposit of $\approx$3.5 MeV. Beam tests indicate that the detector is an effective tool for the characterization of low-energy radioactive beams at beam intensities up to 3 x 10^5 ions/s.

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Date submitted: 30 Sep 2016

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Probing shell effects in the reaction dynamics of low energy heavy ion collisions populating different isotopes of Rn

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Introduction

Heavy ion fusion reactions around Coulomb barrier are a rich source of information about properties of compound nuclei (CN) and have been a topic of extensive experimental and theoretical research. The CN resulting from these reactions are sensitive towards the entrance channels aspects such as equilibration in energy, mass, angular momentum and nuclear structure, etc. For the shell correction energies, which are the microscopic component of fission barrier, there is a great surmise that shell closure at Z=82 and N=126 favors survival probability of CN against fission [1]. However, recent experimental studies have indicated the absence of extra stability of shell closed nucleus [2]. In the present study, an attempt has been made to understand such aspects using CN $^{210,212,214,216}Rn^*$ formed in the low energy reactions $^{16,18}O+^{194,198}Pt$ around the Coulomb barrier. This study has been made within the quantum mechanical fragmentation theory (QMFT)-based Dynamical cluster-decay model (DCM) [3] in which the CN decays into light particles (LPs), intermediate mass fragments (IMFS), heavy mass fragments, near-symmetric and symmetric fission (nSF, SF). Quite interestingly, all of these decay modes are treated on the same footing as dynamical collective mass motion of preformed fragments through the potential barrier.

It is relevant to mention here that collective mass motion of the fragments is quantified in terms of the preformation probability P_0 which carries the important information about the nuclear structure of the decaying nucleus. Subsequently, penetration probability P of the outgoing fragments across the potential barrier is calculated. These two significant quantities P_0 and P are then used to calculate the cross section for particular decay channel.

In the present work, we intend to see the effects of neutron shell closure in compound nucleus $^{212}Rn^*$ (N = 126) and its neighbouring isotopes $^{210,214,216}Rn^*$, having N = 124, 128, 130, respectively, on their decay. The calculations for the fragmentation potential and P_0 have been made for the decay of CN $^{210,212,214,216}Rn^*$ at E^*=49 MeV. In DCM, the neck length parameter ΔR is the only free parameter of DCM, which is fitted to calculate LPs or evaporation residues (ER) cross section σ_{ER} and fusion-fission (FF) cross section σ_{FF} in decay of CN under study, for which the experimental data is available [1, 4].

Methodology

The DCM [3], worked out in terms of collective co-ordinates of mass (and charge) asymmetries, for ℓ-partial waves, gives the compound nucleus decay cross-section as

$$\sigma = \frac{\pi}{k^2}\sum_{l=0}^{l_{max}}(2l+1)P_0P; \qquad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \tag{1}$$

where, $\mu = [A_1A_2/(A_1+A_2)]m$ is the reduced mass, with m as the nucleon mass and ℓ_{max} is the maximum angular momentum. P is penetrability of interaction barrier (of the preformed clusters with preformation probability P_0), calculated as the WKB tunneling probability, around the Coulomb barrier.

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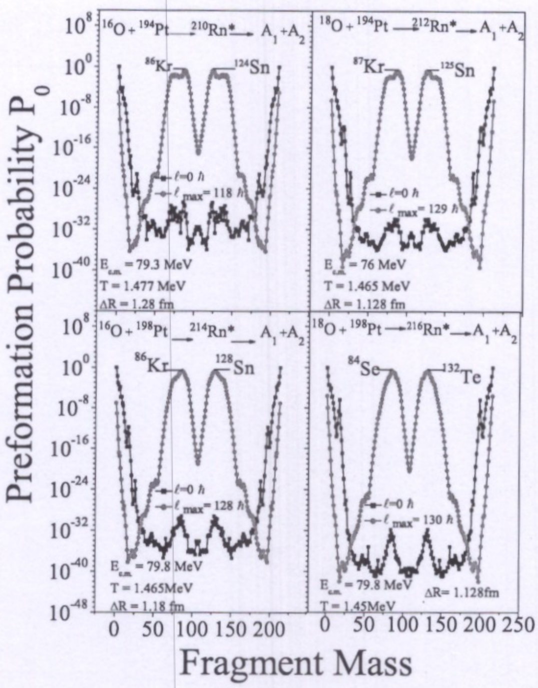

FIG. 1: P_0 profile for the decay of CN $^{210,212,214,216}Rn^*$ at $\ell = 0$ and ℓ_{max} having similar $E^*_{CN} \sim 49$ MeV.

Calculations and Discussions

Fig. 1 (a-d) presents the calculated P_0 of fragments in the decay of CN $^{210,212,214,216}Rn^*$ at E^*_{CN}=49 MeV and, $\ell = 0\ \hbar$ and respective ℓ_{max}-values. Interestingly, these calculations reveal that among the FF fragments, most significant minima exist for the fragment(s) $^{86,87,86}Kr$ and its complimentary fragment(s) $^{124,125,128}Sn$ having proton shell closure Z = 50, respectively, in the decay of CN $^{210,212,214}Rn^*$, having highest P_0 for the FF fragments, particularly at the ℓ_{max}-values. Please note that for ^{86}Kr neutron shell closure is N = 50. It is important to point out here that for these nuclear systems the neutron shell closure for the compound nucleus $^{212}Rn^*$ is N = 126 and, its neighbouring isotopes $^{210,214}Rn^*$ are having N = 124 and 128, respectively, i.e., closer to the N = 126 shell closure. However, in the case of compound nucleus $^{216}Rn^*$ N = 130 which is away from the N = 126 shell closure and results in neighborhood of deformed magic Z = 38, highly preformed fragments ^{84}Se and its complimentary heavy fragment ^{132}Te which is also next to magic number Z = 50.

Moreover, the P_0 value for the LPs (A≤4) for the CN $^{210,212,214,216}Rn^*$ is in competition with the FF fragments at the respective ℓ_{max}-values. These preliminary results are quite motivating to study the complete comparative dynamics of CN $^{210,212,214,216}Rn^*$.

References

[1] P.V. Laveen *et al.*, JPG:NPP **42** 095205 (2015).
[2] V. Singh *et al.*, PRC **89** 02609 (2014).
[3] R.K.Gupta *et al.*, PRC **71** 014601(2005); IJMPE **15** 699 (2006); PRC **77** 054613 (2008).
[4] Rohit Sandal *et al.* PRC **91** 044621 (2015); Proc. DAE NP Symp. **57** 534 (2012); E. Prasad *et al.* PRC **84** 064606(2014); NPA **882** 62 (2012).

Study of ^{48}Ti induced reactions in sub-barrier region forming $^{106}Cd^*$ and $^{106}Sn^*$ compound systems at $E^*_{CN} \sim 48MeV$

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Introduction

The study of the heavy ion reactions give immense information about nuclear structure and the reaction dynamics.The deformation and the orientation effects of the participating nuclei play an important role in the reaction process. Thus, a relevant difference in the nuclear structure may lead to significant change in the sub-barrier fusion excitation functions [1]. It has been observed that fusion cross section, σ_{fus} also depends on the N/Z ratio in the sub-barrier region [1].

Keeping in view such observations we intend to explore dynamics of compound nuclei (CN) $^{106}Cd^*$ and $^{106}Sn^*$ formed via $^{48}Ti^*$ induced reactions in sub barrier region with in the dynamical cluster decay model (DCM) [2]. A work in the same mass region has been carried out previously [3], within DCM, and it is observed that there is negligible contribution from the intermediate mass fragments, IMFs to the σ_{fus} and the light particles, LPs (A≤4) have larger contribution in the same. It is relevant to mention here that the missing structure information in statistical models is included in the DCM through preformation probability (P_0). The available experimental data [1] has been fitted by the only parameter of DCM, i.e. neck length ΔR, for both the spherical as well as oriented considerations. It is important to note here that one of decaying compound nucleus is magic i.e. $^{106}Sn^*$ has proton shell closure, Z = 50. In the present work, we try to investigate effect of shell closure in the reaction dynamics alongwith the N/Z dependence in sub-barrier regime (having studied the decay of CN $^{106}Cd^*$ and $^{106}Sn^*$ with N/Z = 1.2 and 1.1, respectively), within the model calculations.

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Methodology

The DCM [2, 3] of Gupta and collabrators is worked out in terms of collective co-ordinates of mass (and charge) asymmetries. In terms of above said co-ordinates, for ℓ-partial waves, the compound nucleus decay cross-section is given by

$$\sigma = \frac{\pi}{k^2}\sum_{l=0}^{l_{max}}(2l+1)P_0P; \qquad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2.}} \tag{1}$$

Where, $\mu = [A_1 - A_2/(A_1 + A_2)]m$, is the reduced mass, with m as the nucleon mass and ℓ_{max} is the maximum angular momentum. P is the barrier penetration probability and P_0 is the preformation probability at a fixed R on the decay path. The structure information in P_0 enters through the fragmentation potential $V_R(\eta, \beta_{\lambda i}, \theta_i, T)$ for hot and compact orientations, which is calculated as,

$$V_R(\eta,\beta_{\lambda i},\theta_i,T) = \sum_{i=1}^{2}[V_{LDM}(A_i,Z_i,T)] + \sum_{i=1}^{2}[\delta U_i]\exp(\frac{-T^2}{T_0^2}) + V_C(R,Z_i,\beta_{\lambda i},\theta_i,T) + V_P(R,A_i,\beta_{\lambda i},\theta_i,T) + V_\ell(R,A_i,\beta_{\lambda i},\theta_i,T) \tag{2}$$

Here V_{LDM} and δU are, respectively, the liquid drop and shell correction energies, V_c, V_P and V_ℓ are the Coulomb, proximity and angular momentum dependent potentials.

TABLE I: The DCM calculated σ_{fus} of CN $^{106}Cd^*$ and $^{106}Sn^*$, formed in the reactions ^{48}Ti+^{58}Fe and ^{48}Ti+^{58}Ni, and their comparison with the experimental data [1].

Reaction	N/Z	$E_{c.m.}(MeV)$	T(MeV)	$\ell_{max}(\hbar)$ (Sph.)	$\ell_{max}(\hbar)$ (Def.)	ΔR (fm) (Sph)	ΔR (fm) (Def.)	σ_{fus}^{DCM} (mb) Sph.	σ_{fus}^{DCM} (mb) Def.	$\sigma_{fus}^{Expt.}$ (mb)
^{48}Ti+^{58}Fe→$^{106}Cd^*$	1.2	72.0	2.070	72	70	1.314	1.305	34.8	35.0	34.8±6.58
^{48}Ti+^{58}Ni→$^{106}Sn^*$	1.1	80.0	2.075	68	67	1.170	1.366	57.0	57.2	57.2±2.95

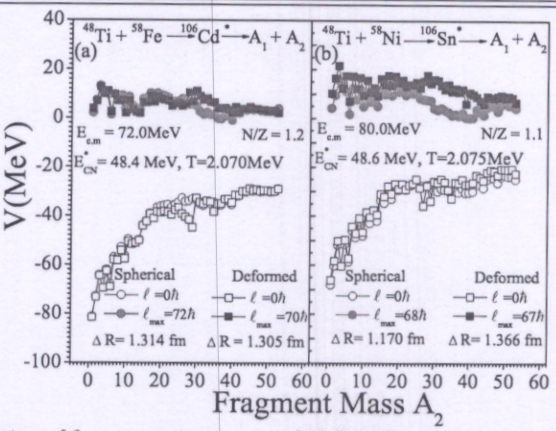

FIG. 1: The variation of fragmentation potential V (MeV) with fragment mass A_2 for the decay of CN $^{106}Cd^*$ and $^{106}Sn^*$ at $E^*_{CN} \sim 48MeV$ for $\ell = 0$ and the respective ℓ_{max}-values.

Calculations and Discussions

Fig.1 shows the variation of fragmentation potential with fragment mass A_2 for the decay of CN (a) $^{106}Cd^*$ and (b) $^{106}Sn^*$ at two extreme ℓ-values. It is noticed that at $\ell = 0$, the light particles (LPs) are more dominant whereas with the increase in ℓ-values the fission fragments starts competing with LPs for spherical as well as deformed configuration for the decay of both the CN under study. The fission fragments in the decay of both the CN show little prominence in comparison to the LPs at ℓ_{max}-value. They are minimized little more in comparison to the LPs (apparently, this behaviour is explicit for more number of fission fragments in case of compound nucleus $^{106}Sn^*$), particularly for the spherical considerations, whereas for the choice of oriented nuclei LPs regains prominence at both the extreme ℓ-values. The potential energy surface (PES) are nearly same for both the considerations for the decay of CN $^{106}Cd^*$ and $^{106}Sn^*$. However, for the magic compound system $^{106}Sn^*$ the change in the PES is quite evident at the ℓ_{max}-value. It is motivating to investigate the preliminary result to further explore the fact that whether this change in PES is attributed to the magicity of the compound system or the N/Z ratio.

Table I presents the preliminary results of the DCM calculated σ_{fus} and their comparison with the experimental data [1]. The calculated σ_{fus} for both the reactions are in good comparison with the experimental data, for both the spherical as well as oriented configurations of the nuclei. Here, we observe that the σ_{fus} is enhanced for the neutron deficient magic compound nucelus i.e. $^{106}Sn^*$ having N/Z = 1.1. Work is in progress.

References

[1] A. M. Stefanini *et al.*, PRC **92**, 064607 (2015); A. M. Vinod Kumar *et al.*, PRC **53**,803(1996)

[2] R. K. Gupta *et al.*, PRC **71**, 014601 (2005);IJMPE **15**, 699 (2006);PRC **85**, 014609 (2012);PRC **92**, 024623 (2015).

[3] Manpreet Kaur *et al.* EPJA **50** ,61 (2014).

Investigating the effect of shell closure on fusion-fission dynamics by estimating the fission delay

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Introduction

Current interest in nuclear physics research is the synthesis of super heavy elements (SHE). Attempts to achieve the theoretical predicted island of stability are in progress. The theoretically predicted stability of SHE is due to the presence of shell closure in these nuclei. Different theoretical models predict different numbers for the next neutron and proton shell closure after 126 and 82, respectively. The understanding about the effect of existing shell closure on fusion dynamics is necessary to achieve the next shell closure which will contribute to the production of SHE and will provide an important insight into the determination of an island of stability

The effect of shell closure on fusion dynamics has been investigated by several authors using different probes. It has been very well established that pre-scission neutron multiplicity can act as a neutron clock to evaluate the time scales of the fusion-fission process. The delay in the fusion-fission process, if any, and its variation with the shell closure can provide information about the importance of shell closure on fusion dynamics. Further, the simultaneous analysis of the experimental Evaporation Residue (ER) cross-sections and neutron multiplicity in the same framework will provide a consistent picture of fusion dynamics. In the present work, we present the simultaneous analysis of neutron multiplicity and ER cross-sections to understand the effect of shell closure on fusion dynamics for $^{19}F+^{198}Pt \rightarrow ^{217}Fr$ (N=130) and $^{19}F+^{194}Pt \rightarrow ^{213}Fr$ (N=126).

Theoretical Calculations

The experimental neutron multiplicity and ER cross-sections have been obtained from the work of Singh *et al.* [1-2]. The theoretical data has been analyzed using the statistical model based code Joanne2 [3]. In this code, the pre-saddle particle decay widths and fission widths are calculated using rotating finite range model (RFRM), the deformation and rotational energies using Liquid drop model (LDM) and particle binding energies and transmission coefficients are obtained using optical model potential.

Results

The experimental ER cross-sections for both the systems were fitted by varying the value of scaling factor for the fission barrier, k_f. It was observed that the ER cross-sections for both the systems were reasonably fitted by using $k_f=1.17$ in the calculations. Figure 1 shows the comparison of experimental cross-sections (solid points) and theoretical cross-sections (lines). The pre-scission neutron multiplicity was fitted by varying the delay time (both transient time (τ_{tr}) and saddle to scission time (τ_{ssc})) and using k_f =1.17. The errors in the delay time is estimated using the errors in the experimental results. It has been observed that theoretical neutron multiplicity depends on the total delay (= τ_{tr} + τ_{ssc}) and is insensitive to the distribution of the delays. Figure 2 shows the variation of the total time delay required to fit the neutron multiplicity as a function of excitation energy for ^{217}Fr (solid line) and ^{213}Fr (dotted line). Evidently the statistical model calculations under-predicted the experimental neutron multiplicities for all excitation energies except the lowest two excitation energies for ^{213}Fr (shell closed compound nucleus (CN)). So, the total delay time was varied to explain the experimental neutron multiplicity. It is observed that the excitation energy dependent delay is required to explain the experimental results for both the CN.

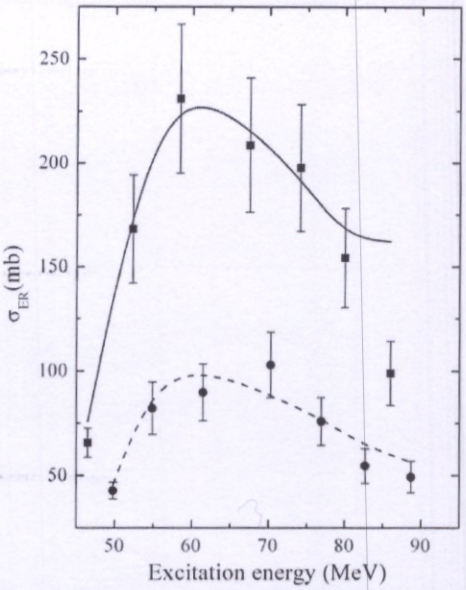

Fig. 1 Comparison of experimental ER cross-sections (^{217}Fr (solid squares) and ^{213}Fr (solid circles)) and theoretical calculations (^{217}Fr (solid line) and ^{213}Fr (dotted line)) at $k_f = 1.17$ for both the systems.

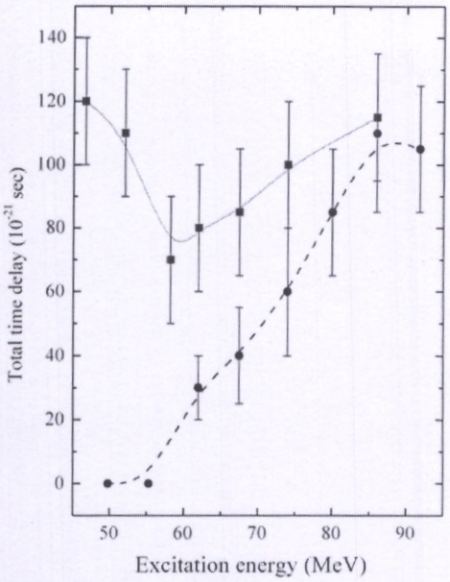

Fig. 2 Comparison of total time delay required to fit the pre-scission neutron multiplicities ^{217}Fr (Solid squares and solid line) and 213Fr (Solid circle and dotted line).

Conclusions

The comparison of the fission delay for both the system under consideration indicates that the delay is less for shell closed CN in comparison to the non-shell closed CN. The difference in the delay time is maximum at lowest excitation energy studied and delay time for both systems approaches each other as one moves from low to high excitation energy. This observation may be attribute to the washing out of the effect of shell closure with increase in the excitation energy. Also, this observation indicates that the shell closure does not provide any extra stability to CN against the fission delay, which was predicted by theoretical models. This present work is also consistent our earlier observation [2].

Acknowledgement

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References

[1] V. Singh *et al.* Phys. Rev. C **86**, 014609 (2012).
[2] V. Singh *et al.* Phys. Rev. C **89**, 024609 (2014).
[3] J. P. Lestone Phys. Rev. Lett. **70**, 2245 (1993).

Study of evaporation residue cross-section for ^{48}Ti + ^{140,142}Ce systems.

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Introduction

For understanding the reaction mechanism of heavy compound nucleus (CN), the study of evaporation residue (ER) cross-section plays a vital role. For heavier systems, the probability of formation of CN is strongly influenced by the properties of the di-nuclear system at contact configuration, where entrance channel plays a major role in reaction dynamics [1]. Nuclear structure of the colliding nuclei also plays a key role, which influence the fusion probability. In some of the recent studies the dependence of the fusion reaction on the nuclear shell structure of projectile and target nuclei was also investigated and the importance of N = 82 in the heavy ion fusion reaction was proposed. It was reported that shell closure of one of the interacting nuclei can lead to the enhanced ER cross-section and helps in the synthesis of heavy nuclei [2]. Keeping these points in mind, a systematic measurement of ER cross-sections for ^{48}Ti + ^{140,142}Ce, ^{124}Sn systems was performed [3]. Here, ^{140}Ce target is neutron shell closed (N_T=82) but ^{142}Ce have 84 neutrons. By comparing the ER cross-sections of these systems, the effect of neutron shell closure on fusion probability can be examined. The ER excitation function for third system (^{48}Ti + ^{124}Sn) was also measured at few energy points to estimate the transmission efficiency of the spectrometer.

Experimental Set-up

The experiment was carried out in HYbrid Recoil mass Analyzer (HYRA) [4] by using 15 UD Pelletron + LINAC accelerator facility at IUAC, New Delhi. ER cross-section measurements were taken using pulsed beam of ^{48}Ti with 4μs separation at laboratory energies ranging from 205 to 257 MeV (including energy loss from 1.1mg/cm^2 Ni window foil, carbon backing and half thickness of target). Thin isotopically enriched targets ^{140,142}Ce of thickness 212μg/cm^2 and 225μg/cm^2, with a thick carbon backing of 24μg/cm^2 and 18.8μg/cm^2 respectively and for calibration purpose, target ^{124}Sn with thickness of 162μg/cm^2 were used in the experiment. Elastically scattered ^{48}Ti ions were detected by two silicon surface barrier detectors placed at ±24° w.r.t. beam direction. For all beam energies, helium gas pressure in HYRA was set to 0.30 Torr. HYRA magnetic field settings were calculated using a simulation program TERS [5]. The ERs were separated from other contaminants using HYRA spectrometer and were detected by a position sensitive multi-wire proportional counter (MWPC) of dimensions 6 inch X 2 inch placed at the focal plane of the spectrometer. A time of flight (TOF) spectrum was generated using anode of MWPC as start and RF of beam as stop. The logical OR signal of two monitor detectors and MWPC anode was the master strobe for data acquisition system.

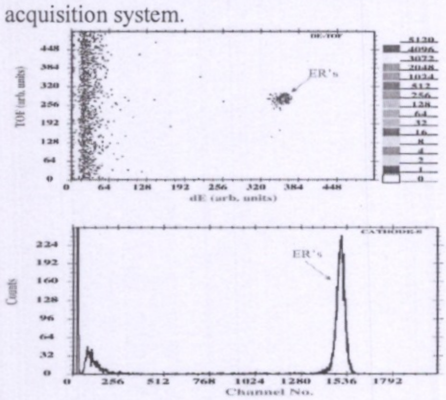

Fig. 1(a) 2D TOF vs. cathode spectrum and (b) 1D cathode spectrum of MWPC at 257 MeV beam energy.

A two dimensional plot was generated by using TOF and energy loss (ΔE) signal of MWPC for ^{48}Ti + ^{142}Ce system at beam energy of 257 MeV, which separates the ERs from beam background is shown in Fig. 1.

Analysis

The formula to calculate ER cross-section is given by

$$\sigma_{ER} = \frac{Yield(Mon)}{Yield(ER)} \cdot \left(\frac{d\sigma}{d\Omega}\right) \cdot \Omega_{Mon} \cdot \frac{1}{\eta HYRA},$$

where, Yield(ER) is the ER yield at the focal plane, Yield(Mon) is the average yield from both monitor detectors (left and right), $(\frac{d\sigma}{d\Omega})$ is the differential Rutherford scattering cross-section, Ω_{Mon} is the solid angle subtended by the monitor detectors and η_{HYRA} is the efficiency of HYRA. The ER yield was obtained from two-dimensional plot of TOF and energy loss, and yield of monitor detectors from the one-dimensional single spectrum using CANDLE software.

Experimentally extracted normalized ER cross-sections (in arbitrary units) w.r.t. laboratory energy, E_{lab} in MeV for the two systems are shown in Fig.2. In this preliminary analysis, the efficiency of gas filled separator is assumed to be same for both the systems.

Results

The preliminary relative ER cross-section measured for both the systems around and below barrier energies are found to be almost same within error bars. At above barrier energies, the cross-sections for ^{48}Ti + ^{140}Ce was few orders of magnitude larger than those for the reaction ^{48}Ti + ^{142}Ce. At the highest energy, the measured cross sections for ^{48}Ti+^{142}Ce is found to be larger as compared to ^{48}Ti+^{140}Ce. This difference in two energies is not very clear from this preliminary analysis. Though ^{140}Ce target is shell close (N_T=82) one may expect a difference in ER cross sections for these two systems. The present result indicates that the fusion of massive nuclei depends on the shell structure of colliding partners. In one of the recent fission mass distributions measurements [1], less Quasi-fission was observed for shell closed nuclei. More such measurements are necessary to disentangle the QF and shell effect. Furthermore, it would be of considerable interest to populate the same CN with different entrance channel mass asymmetries to explore the possible role of entrance channel on fusion probability. Using HYRA spectrometer, we plan to extend such experiments on ER cross-section measurements for ^{48}Ti + ^{136,140,142}Ce and ^{32}S + ^{156}Gd systems. A detail analysis of the results will be presented.

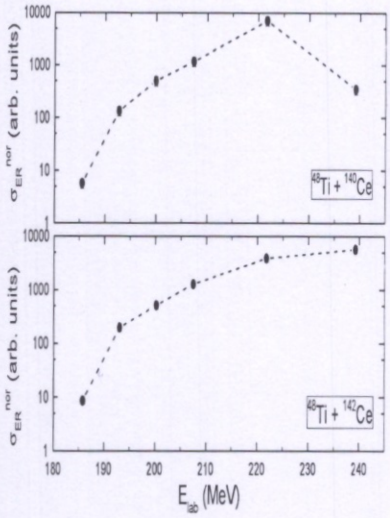

Fig. 2 Preliminary normalized ER cross-sections for (a) ^{48}Ti + ^{140}Ce and (b) ^{48}Ti + ^{142}Ce systems.

References

[1] G.N. Knyazheva etal.,Phys. Rev. C **75** (2007) 064602.

[2] H. Ikezoe et al., Phys. At. Nucl. **66** (2003) 1053.

[3] B. R. Behera et al., IUAC Annu. Rep. 2012-13.

[4] N. Madhavan et al., Pramana-J. Phys. **75** (2010) 317.

[5] S. Nath, Comput. Phys. Commun. **180** (2009) 2392.

Dynamical aspects of fusion enhancement for neutron rich compound systems

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Introduction

Understanding the mechanism of fusion of neutron rich systems has importance not only in the nuclear reactors and production of heavy elements but also in the astrophysical scenarios. Various experimental measurements have suggested an enhancement of fusion probability as compared to standard statistical model at near barrier energies for such systems [1]. Various authors have also indicated the presence of strong isotopic dependence of the fusion cross sections near the barrier. These studies have established the importance of interplay between nuclear structural and reaction dynamical aspects present in these many-body systems. The enhancement of fusion cross sections observed through these isotopic chains of nuclear reactions is being considered as one of the best methods to understand the character of neutron rich matter. The existence of these experimental studies motivates to investigates the dynamical aspects associated with the fusion reactions of the neutron rich nuclei. The present work investigate the fusion dynamics involved in the isotopic chain of reactions ($^{39,40,41,47}K +^{28}Si$) to explore the effect of neutron number on fusion enhancement at near barrier energies.

Methodology

The Dynamical cluster decay model (DCM) [2] of Gupta and collaborators is worked out in terms of collective co-ordinates of mass (and charge) asymmetries. In terms of above said co-ordinates, for ℓ-partial waves, the com-

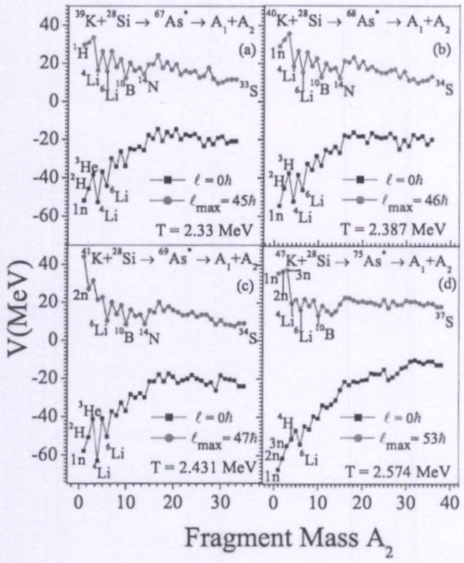

FIG. 1: The fragmentation potential V(MeV) as a function of fragment mass number (A_2), calculated for two extreme ℓ -values, for the compound systems $^{67,68,69,75}As^*$ at E_{cm}= 36.8 MeV

pound nucleus decay cross-section is given by

$$\sigma = \frac{\pi}{k^2}\sum_{l=0}^{l_{max}}(2l+1)P_0P; \qquad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \tag{1}$$

Where, $\mu = [A_1 - A_2/(A_1 + A_2)]m$, is the reduced mass, with m as the nucleon mass and ℓ_{max} is the maximum angular momentum. Where P is the barrier penetration probability and P_0 is the preformation probability at a fixed R on the decay path. The P_0 are evaluated by solving stationary Schrödinger wave equation and P calculated as the WKB tunneling probability.The structure information in

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TABLE I: The experimental and DCM calculated σ_{Fus} of CN $^{67,68,69,75}As^{*}$ at different values of $E_{c.m.}$.

Reaction	$E_{lab}(MeV)$	$E_{c.m.}(MeV)$	$E^{*}_{CN}(MeV)$	T (MeV)	$\ell_{max}(\hbar)$	ΔR (fm)	σ_{Fus} DCM	σ_{Fus} Expt
$^{39}K + ^{28}Si \rightarrow ^{67}As^{*}$	88.05	36.8	38.15	2.33	45	1.075	9.0	7.7±1.27
	89.6	37.4	38.78	2.351	44	1.15	21.35	21.3±3.96
	94.27	39.4	40.68	2.406	43	1.3	131.5	127.0±12.4
	101.69	42.5	43.78	2.493	43	1.375	257.1	265.0±31.6
$^{40}K + ^{28}Si \rightarrow ^{68}As^{*}$	89.37	36.8	40.67	2.387	46	1.075	12.0	-
	95.92	39.5	43.37	2.463	47	1.3	144.0	-
	103.21	42.5	46.37	2.5444	47	1.375	262.0	-
$^{41}K + ^{28}Si \rightarrow ^{69}As^{*}$	90.68	36.8	42.85	2.431	46	1.075	14.2	-
	97.33	39.5	45.56	2.504	47	1.3	146.2	-
	104.73	42.5	48.55	2.58	47	1.375	264.0	-
$^{47}K + ^{28}Si \rightarrow ^{75}As^{*}$	98.57	36.8	52.64	2.574	53	1.075	40.0	34.0±5.63
	100.44	37.5	53.33	2.591	51	1.15	66.22	63.6±12.1
	105.80	39.5	55.33	2.638	50	1.3	213.6	177.0±29.4
	114.10	42.6	58.44	2.708	50	1.375	361.9	327.0±35.6

P_0 enters through the fragmentation potential $V(\eta, R)$ as shown in Fig. 1 [2].

Calculations And Discussions

The calculations have been performed within the DCM for an isotopic chain of reactions $^{39,40,41,47}K +^{28} Si$ with quadruple deformed nuclei having compact configurations. The experimental fusion cross-sections, σ_{Fus} for $^{39,47}K +^{28} Si$ reactions have been reproduced using neck length parameter ΔR, the only free parameter of DCM. The DCM calculated σ_{Fus} for both $^{39,47}K +^{28} Si$ reactions give a good agreement with the experimental cross-sections for same value of ΔR having same center-of-mass energies (Ec.m.), as summarized in the Table I. In view of this, σ_{Fus} for $^{40,41}K +^{28} Si$ reactions, at same Ec.m., have been predicted using these ΔR values.

It is observed that the σ_{Fus} increases for the reactions induced by the more and more neutron-rich isotope of K. The increase in the fusion cross-sections at energies well above barrier may be attributed to the increase in the size of compound nucleus whereas the increase in the cross sections near barrier may be due to the dynamics involved in the fusion. The enhancement in σ_{Fus} is more as one move from ^{39}K to ^{40}K as compared to the movement from ^{40}K to ^{41}K. This can be explained by considering number of neutrons in K isotopes. While going from ^{39}K to ^{40}K one moves from a nucleus with paired neutron to an unpaired neutron nucleus whereas for the case of ^{40}K to ^{41}K the transition is from unpaired to paired neutron nucleus. Hence, one can conclude that the presence of an unpaired neutron results in a larger fusion enhancement as compared to paired neutron. This work motivate planning of experiments to validate these observations.

References

[1] Varinderjit Singh, J. Vadas, T.K. Steinbach, *et al.* PLB **765**, 99 (2017), J. Vadas, Varinderjit Singh, B. B. Wiggins *et al.* PRC **97** 031601(R) (2018).

[2] R. K. Gupta *et al.*, PRC **71**, 014601 (2005); IJMPE **15**, 699 (2006); PRC **77**, 054613 (2008); PRC **92**, 024623 (2015); NPA (2018) *Accepted*.

Dynamical hindrance effect in fusion for the decay of the compound nucleus ^{64}Zn

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Introduction

Light charged particle evaporation spectra from the compound nucleus, populated at moderate excitation energy (~ 100 MeV), allows us to test the application of statistical model for the decay of the compound nucleus. The basic parameters of nuclear properties such as yrast line, level density, emission barriers and angular momentum distribution parameters, are modified by the deformation of highly excited and rapidly rotating nuclei. This leads to dynamical hindrance to fusion. [1, 2]

We present here of analysis for decay of the compound nucleus ^{64}Zn. It was populated at same excitation energy E* ~ 70 MeV, through an asymmetric channel ^{16}O + ^{48}Ti (E_{lab} = 76 MeV) and symmetric channel ^{37}Cl + ^{27}Al (E_{lab} = 125 MeV). The inclusive alpha spectra and neutrons are compared with the predictions of conventional statistical model calculations (CASCADE). The limitations of this description for the case of symmetric reaction are also explained.

Experimental details

The experiment was performed with 15UD Pelletron at IUAC, New Delhi, India using the General Purpose Scattering Chamber (GPSC). A ^{48}Ti foil and an ^{27}Al foil each of about 1.0 mg/cm^2 thickness were used as targets. Light charged particle spectra were recorded using two ΔE-E telescopes. These spectra were taken at 30°, 36°, 42°, 48° and 54° for both the systems. While the neutrons were detected using the liquid scintillator cells of BC501 at laboratory angles θ = 30°, 60°, 90° and 120° with respect to the beam direction. The neutron detectors were placed at a distance of 1 m from the target.

Analysis and Discussions

The experimental analysis was carried out using CANDLE software, and the theoretical results were obtained using the statistical model code CASCADE. In the CASCADE code, the spin dependent energy is parameterized as

$$E_I = \frac{\hbar^2 I(I+1)}{2J_0(1+\delta_1 I^2+\delta_2 I^4)}$$

where δ_1 and δ_2 are deformation parameters, J_0 is rigid body moment of inertia and I is the spin.

The inclusive experimental spectra are well reproduced by CASCADE calculations. A typical comparison of alpha spectrum at 36° is shown in Fig. 1. For fitting the spectra, the spin dependent level density with E_I values generated with the increased values of δ_1 and δ_2 are introduced as it is observed that slope becomes softer as we increase δ_1 and δ_2.

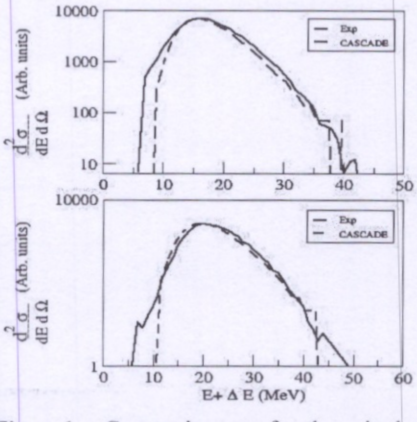

Fig. 1 Comparison of the inclusive experimental α-particle spectrum at 36° with CASCADE for **(a)** the asymmetric system $^{16}O+^{48}Ti$ (upper panel) with $\delta_1=0.41\times10^{-4}$ and $\delta_2=0.43\times10^{-7}$ and **(b)** the symmetric system $^{37}Cl+^{27}Al$ (lower panel) with $\delta_1=0.15\times10^{-3}$ and $\delta_2=0.14\times10^{-6}$ is found to fit.

The inclusive α-particle spectra from the symmetric $^{37}Cl+^{27}Al$ system fit perfectly with the theoretical calculations when we consider $l = l_{max}$ = 32h (calculated using HICOL), as shown in in Fig. 1 (b). $\delta_1=0.15\times10^{-3}$ and $\delta_2=0.14\times10^{-6}$are used here along with HICOL l value. In case of symmetric systems, we need to increase δ_1 and δ_2 to get the fit while in the case of asymmetric system fit is easily obtained with default values only. All this suggests that symmetrical system severely hinders the fusion process. The fusion of lower partial waves is delayed progressively and the fusion of higher partial waves (> 32h) is completely inhibited.

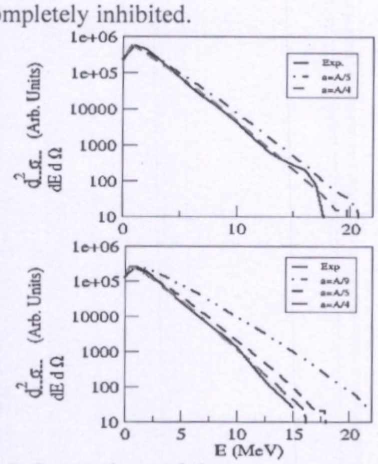

Fig. 2 Comparison of the neutron spectra at 120° for **(a)** the asymmetric system $^{16}O+^{48}Ti$ (upper panel) and **(b)** the symmetric system $^{37}Cl+^{27}Al$ (lower panel); with CASCADE calculations.

The neutron spectra are shown in Fig. 2, for asymmetric (upper panel) as well as symmetric (lower panel) case. In both the cases, it is seen that spectra are softer than the statistical model predictions. Unusually high value of level density parameter has to be used (a = $A/4$) to get the fit. This suggests a very low nuclear temperatures for neutron evaporation (as, $T=\sqrt{E/a}$).

References

[1] J. Kaur *et al.*, Phys. Rev. C. **70** 017601 (2004).

[2] Maninder Kaur *et al.*, Phys. Rev. C. **89** 034621 (2014).

Systematic investigation to estimate the magnitude of nuclear dissipation in fission dynamics

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Introduction

Fusion-fission process is full of surprises since its discovery. A number of attempts have been made to determine the fission barrier, shell effects and magnitude of nuclear dissipation. The understanding of these effects is a key for the production of super heavy elements and achieve the theoretical predicted island of stability. Recently a number of authors have attempted to estimate the magnitude of nuclear dissipation using neutron multiplicity, charge particle multiplicities, GDR multiplicity, fission cross-sections and evaporation residue (ER) cross-sections as a probe. In our previous studies aiming to explore the effect of shell closure on fission dynamics and estimating the magnitude of nuclear dissipation by measuring neutron multiplicities and ER cross-sections for ^{19}F + ^{194,196,198}Pt [1] , it was observed that nuclear dissipations is lower for shell closed system in comparison to the non-shell closed systems. However dissipation is necessary to explain the experimental neutron multiplicities whereas lowering in the fission barrier (i.e no dissipation) is required to reproduce ER cross-sections. Hence a consistent picture about the magnitude of nuclear dissipations is still missing.

The fission cross-sections for ^{19}F + $^{194.198}$Pt at near barrier energies have already been measured by Mahata *et al.* [2]. Our group has measured the fission cross-sections for ^{19}F + $^{194.198}$Pt at higher beam energies and same are measured for ^{19}F + ^{196}Pt at energy range from near to well above the barrier. Also the statistical model has been modified to include the collective enhancement of level density (CELD), orientation effect and shell corrected level density and fission barrier [4]. The present work contains the re-analysis of the experimental data with the latest statistical model to paint a consistent picture about role of nuclear dissipation in fission dynamics.

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Experimental set-up

Experimental fission cross-section has been obtained by measuring the fission angular distribution for energy range from 90.5 to 118.7 MeV. The measurements were carried out using General Purpose Scattering chamber (GPSC) using ^{19}F beam from Pelletron accelerator. The details of the experimental setup and data analysis are discussed in [3].

Statistical model calculations

The experimentally measured fission and ER cross-sections have been used to get the fusion cross-sections. Fusion cross-sections are fitted using coupled channel calculations to obtain the spin distribution which has been used as an ingredient for statistical model calculations. The statistical model has been modified to include the effect of collective en-

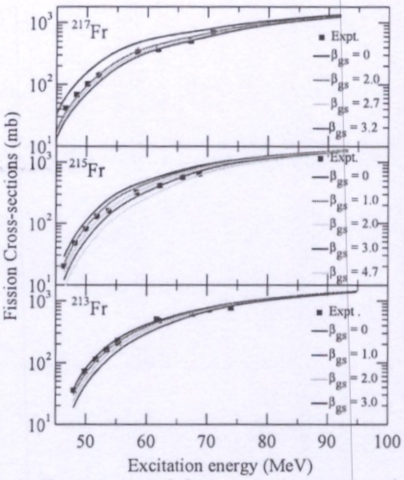

FIG. 1: Experimental fission cross-sections (solid square) along with the statistical model predicted cross-section for different β_{gs} (lines).

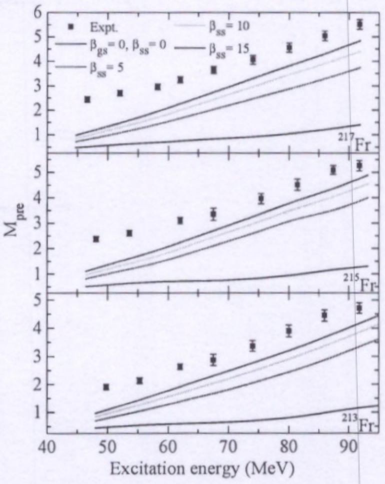

FIG. 2: Experimental neutron multiplicities (solid square) along with the statistical model prediction for different β_{ss} (lines) with β_{gs} as used to reproduce fission cross-sections.

hancement in level density, orientation effects and shell effect in various parameters such as fission barrier, level density, nuclear masses etc [4]. Nuclear dissipation in pre and post saddle regime is considered separately. Experimental fission cross-sections has been reproduce using pre-saddle nuclear dissipations (β_{gs}) as free parameter. Fig. 1 shows the experimental fission cross-sections along with the statistical model prediction for different values of β_{gs}. Experimental neutron multiplicity has been explained using β_{gs} obtained from fission cross-sections along post-saddle nuclear dissipations (β_{ss}) shown in Fig. 2.

Conclusions

It has been observed that a small pre-saddle dissipation is 1×10^{21} sec^{-1} for ^{213}Fr (shell closed compound nucleus (CN)) is necessary to explain the fission/ER cross-sections, whereas the same for ^{217}Fr is 3×10^{21} sec^{-1}. The lowering of dissipation for ^{213}Fr may be correlated to shell effect on dissipation. On the other side post-saddle dissipation as high as 15×10^{21} sec^{-1} is not sufficient to reproduce the neutron multiplicity data. The inability of reproducing the experimental data may be attributed to dynamical effects associated with fusion-fission process. Also the magnitude of pre and post saddle dissipations indicates that nuclear dissipation depend on deformation. The magnitude of dissipation is small when CN is near the equilibrium and it increases as the nucleus become more and more deformed. Also from Fig. 2, it is observed that the deviation of experimental data from statistical model predictions is minimum for ^{213}Fr whereas maximum for ^{217}Fr. These observations may be due to the effect of shell closure on nuclear dissipations which may result in the lowering of dissipation, which is consistent with results obtained from cross-section measurements.

References

[1] Varinderjit Singh *et al.* Phys. Rev. C **86**, 014609 (2012), Phys. Rev. C **89**, 024609 (2014).

[2] K. Mahata *et al.* Phys. Rev. C **65**, 034613 (2002).

[3] Varinderjit Singh *et al.* EPJ Web of Conf. **86**, 00052 (2015).

[4] T. Banerjee *et al.* Phys. Lett. B **776**, 163 (2018).

Effect of nuclear structure in fusion enhancement of $^{19}O+^{12}C$ reaction at sub-barrier energies

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Introduction

In the recent times, due to availability of radioactive ion beam facilities the use of neutron rich projectiles to probe the fusion dynamics is a topic of immense interest [1]. The investigation of fusion excitation function for isotope series of neutron rich nuclei provides unique prospect. Because, using neutron rich projectiles the Coulomb potential changes a little due to unchanged charge distribution. Therefore, comparative analysis of fusion excitation function for an isotopic chain facilitate to explore the role of attractive nuclear potential with increasing neutron content. Moreover, an enhancement in fusion cross-section is observed using neutron rich nuclei compared to β-stable projectile [2]. It is best studied at near and sub-barrier energies since at low energies the low ℓ-waves are significant, which underpin the role of attractive nuclear potential, are enhanced.

The fusion enhancement has been observed in mass asymmetric reaction $^{15}C+^{232}Th$ [3]. However, in the light mass region, the study of fusion by employing the exotic projectiles is relevant for astrophysical interest. Because these neutron rich nuclei are estimated as the possible cause of heating of neutron star crust [4]. The experimental study of fusion of $^{18,19}O$ projectiles with ^{12}C target shows fusion enhancement compared to use of stable ^{16}O projectile [5, 6]. Recently, we have investigated the dynamics of compound nuclei (CN) $^{28,30}Si^*$ at same $E_{c.m.}$ = 7.0 MeV. The evaluated fusion cross-sections σ_{fusion}, within DCM, at same $E_{c.m.}$ = 7.0 MeV for CN $^{28}Si^*$ and $^{30}Si^*$, show that LPs are having major contribution in σ_{fusion}. For compound nucleus $^{30}Si^*$, 1n has highest part in σ_{fusion}, which tends to be responsible for observed fusion enhancement in agreement with experimental data [7]. Further, the use of radioactive ^{19}O beam facilitate to study fusion enhancement with exotic projectile. In the present work, dynamics of $^{16,18,19}O+^{12}C$ reactions leading to formation of (CN) $^{28,30,31}Si^*$, have been analyzed, comparatively, at sub-barrier energy within dynamical cluster decay model (DCM) [7, 8] approach, to explore the effects of neutron richness of projectile on the reaction mechanism and to look for the underlying cause of fusion enhancement.

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Methodology

The DCM is based on quantum mechanical fragmentation theory and is worked out in terms of collective coordinates of mass asymmetry η = $(A_T\text{-}A_P)/(A_T\text{+}A_P)$ and relative separation (R) with effects of temperature, deformation and orientation duly incorporated in it. In terms of these collective coordinates, using the ℓ- partial waves, the decay cross-section is defined as

$$\sigma = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_c}(2\ell+1)P_0P;\; k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \quad (1)$$

where ℓ_c, the critical angular momentum, penetrability P refers to R motion and is calculated using WKB approximation, preformation probability P_0 refers to η motion and is given by sol. of stationary Schrodinger

$$\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}+V_R(\eta,T)\}\psi^{\nu}(\eta)$$

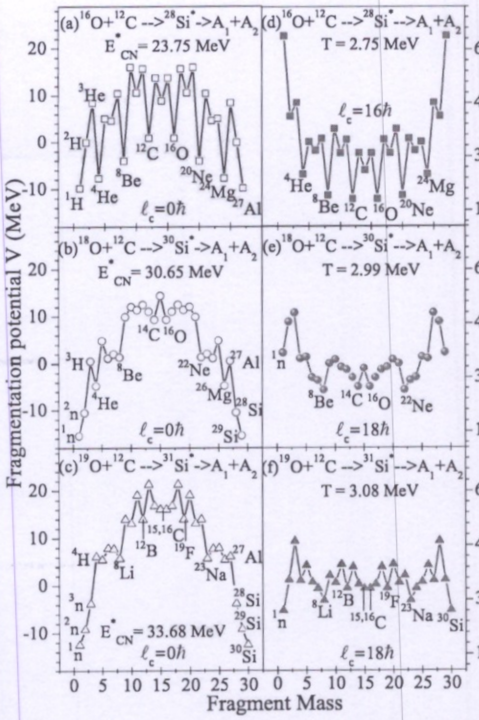

FIG. 1: Fragmentation potential V (MeV) for the decay of (a,d)$^{28}Si^*$ (b,e)$^{30}Si^*$ at $E_{c.m.}$ = 7.0 MeV and (c,f)$^{31}Si^*$ at $E_{c.m.}$ = 7.4 MeV at $\ell = 0\hbar$ (left panel) and their respective ℓ_c values (right panel).

$$= E^{\nu}\psi^{\nu}(\eta) \tag{2}$$

The minimized fragmentation potential ($V_R(\eta, T)$ in eq.2) is the sum of temperature dependent Coulomb, proximity, centrifugal potential along with temperature dependent liquid drop energies and shell effects. For a fixed β_{λ_i}, the potential values for all possible mass (A) combinations corresponding to a given charge (Z) is minimized in mass coordinate (η) and gives the most probable/minimized potential.

Calculations and Discussion

Fig. 1 presents the collective potential energy surface in fragmentation of CN $^{28,30,31}Si^*$ at, $\ell = 0\ \hbar$ (left panel) and the respective critical angular momentum values, ℓ_c (right panel). It is clear from Fig. 1(a,b,c) that light particles (LPs) are minimized at lower ℓ-value. However, at higher ℓ values i.e. at ℓ_c, the characteristic of LPs emission shows drastic change with increasing N/Z ratio of compound nuclei. In the decay of $^{28}Si^*$ compound nucleus, ^8Be, ^{12}C, ^{16}O, ^{20}Ne (nα-clusters) are energetically favorable (Fig. 1(d)), similar to what is encapsulated in Ikeda diagram at threshold decay energy of $E^* = 23.9$ MeV [9]. While for compound nucleus $^{30}Si^*$ in addition to nα-clusters, ^{14}C, ^{22}Ne (xn-xα clusters; x is an integer) are also preferentially minimized (Fig.1(e)). On the other hand, it is interesting to note that in case of compound nucleus $^{31}Si^*$, the LPs are neutron rich which are in strong competition with neighboring xn-xα clusters at ℓ_c value (Fig.1(f)). It will be interesting to look for the role of nuclear structure via preformation probability P_0 of different clusters in these reactions, which plays an imperative role in calculation of fusion cross-sections. Furthermore, the calculations of σ_{fusion} for compound nucleus $^{31}Si^*$ at different excitation energies are in progress, to further investigate the phenomenon of fusion enhancement.

References

[1] A. Lemasson et al., Phys. Rev. Lett. **103** 232701 (2009); J.J. Kolata et al., Phys. Rev. C **85**, 054603 (2012); Z. Kohley et al., Phys. Rev. C **87**, 064612 (2013).
[2] J.F. Liang et al., Phys. Rev. C **75**, 054607 (2007); Phys. Rev. C **78**, 047601 (2008).
[3] M. Alcorta et al., Phys. Rev. Lett. **106**, 172701 (2011); J.J. Kolata et al., Phys. Rev. C **85**, 054603 (2012); P.F.F. Carnelli et al., Phys. Rev. Lett. **112**, 192701 (2014).
[4] C.J. Horowitz et al., Phys. Rev. C **77**, 045807 (2008).
[5] T.K. Steinbach et al., Phys. Rev. C **90**, 041603(R) (2014).
[6] V. Singh et al., PLB **765**, 99 (2017).
[7] M. Kaur et al., AIP Conf. Proc. **1953**, 140113 (2018).
[8] R.K. Gupta et al., J. Phys. G **31**, 631 (2005); Phys. Rev. C **77**, 054613 (2008); Phys. Rev. C **95**, 014611 (2017).
[9] K. Ikeda et al., Prog. Theor. Phys. Suppl. E **68**, 464 (1968).

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Abstract Submitted
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Probing the fusion of neutron-rich nuclei with reaccelerated radioactive beams[1] JUSTIN VADAS, VARINDERJIT SINGH, BLAKE WIGGINS, JACOB HUSTON, SYLVIE HUDAN, ROMUALDO DESOUZA, ZIDU LIN, CHARLES HOROWITZ, Indiana Univ - Bloomington, ABDOU CHBIHI, DIETER ACKERMANN, GANIL, MICHAEL FAMIANO, Western Michigan University, KYLE BROWN, Michigan State University — Fusion in neutron-rich environments is presently a topic of considerable interest. For example, the optical emission spectrum from the neutron star merger GRB170817A clearly establishes this neutron-rich environment as an important nucleosynthetic site. A good approach to understand how fusion proceeds in neutron-rich nuclei is to measure the fusion excitation function for an isotopic chain of nuclei. Reaccelerated radioactive beam facilities provide the opportunity to systematically address this question. Using the ReA3 facility at NSCL, a ^{28}Si target was bombarded with beams of ^{39,47}K at near-barrier energies, $36 < E_{c.m.} < 43$ MeV. The low intensity of the radioactive ^{47}K beam ($2\text{-}4 \times 10^4$ ions/s) necessitated the development of an efficient experimental technique. Incident ions were identified on a particle-by-particle basis by ΔE-TOF just upstream of the target. Fusion products were directly measured and identified by the E-TOF technique with an efficiency of ~70%. The measured fusion excitation functions will be presented, and compared with coupled channels calculations.

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Dynamical effects of Si-isotopes induced reactions at similar centre of mass energies $E_{c.m.}$

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Introduction

The study of the complex phenomena observed in sub-barrier energies through fusion of isotopic chain of reactions is topic of interest in nuclear physics. A number of authors have theoretically investigated the sub-barrier fusion phenomena using different models to explain fusion enhancement and fusion hindrance phenomenon [1]. Since dynamics of fusing nuclei play a key role in the fusion mechanism, it will be interesting to study the fusion enhancement/hindrance for lower-mass nuclei using the dynamical cluster decay model (DCM) [2] to get a better insight of the fusion process.

With this motivation, fusion of ^{28,30}Si+^{12}C populating $^{40,42}Ca^*$ [3] with Z=20 shell closure and neutron number gradually moving away from N = 20 neutron shell closure has been investigated within DCM at energies above and below Coulomb barrier. The cross-sections for ^{30}Si+^{12}C are reproduced using neck length parameter (ΔR) at the different energies. The empirically fitted values of ΔR are used to predict the fusion cross-sections at similar centre of mass energies $E_{c.m.}$ for ^{28}Si+^{12}C. The predicted fusion cross-section values are in good agreement with the experimental measurements. Also, the fusion cross-sections has been predicted for energies far below the barrier. The hindrance phenomenon observed at sub barrier energies ^{30}Si+^{12}C has been addressed through barrier lowering parameter which is the in-built property of the model.

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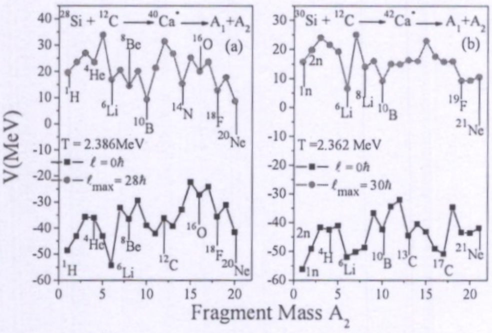

FIG. 1: The fragmentation potential $V(MeV)$ as a function of fragment mass number A$_2$, calculated for two extreme ℓ-values, for the CN $^{40}Ca^*$ and $^{42}Ca^*$ at $E_{c.m.}$ = 9.5 MeV and ΔR = -0.7 fm, for deformed fragmentation paths.

Methodology

The DCM [2] of Gupta and collaborators is worked out in terms of collective co-ordinates of mass (and charge) asymmetries. In terms of above said co-ordinates, for ℓ-partial waves, the compound nucleus decay cross-section is given by

$$\sigma = \frac{\pi}{k^2}\sum_{l=0}^{l_{max}}(2l+1)P_0P; \qquad k = \sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \tag{1}$$

Where, $\mu = [A_1 - A_2/(A_1 + A_2)]m$, is the reduced mass, with m as the nucleon mass and ℓ_{max} is the maximum angular momentum. Where P is the barrier penetration probability and P_0 is the preformation probability at a fixed R on the decay path. The P_0 are evaluated by solving stationary Schrödinger wave equation and P calculated as the WKB tunneling probability. The structure information in P_0 enters through the fragmentation potential $V(\eta, R)$ as given in Fig. 1.

Calculations and Discussions

The analysis of heavy ion induced fusion reactions across coulomb barrier has been performed within the DCM for ^{28,30}Si+^{12}C reactions populating compound nuclei (CN) $^{40,42}Ca^*$, respectively. To understand the possible structure of the decaying CN $^{40,42}Ca^*$ formed in the ^{28,30}Si+^{12}C reaction, fragmentation potential has been calculated for various fragments/clusters formed inside the CN. The calculated fragmentation potentials have been plotted with respect to fragment mass in the decay of $^{40,42}Ca^*$ at similar $E_{c.m.}$, as shown in Fig. 1(a and b) which describes the fragmentation for the extreme values of angular momentum values. At $\ell = 0\hbar$, the contribution of the LPs or ERs(evaporation residues) is more prominent than the intermediate mass fragments and symmetric fission fragments, which otherwise start appearing at higher ℓ values. The tunneling of these energetically favored fragments through the barrier is determined through the scattering potential and penetration probability of these fragments. The barrier modification (ΔV_B) values, which is difference between the top of the barrier V_B and actual potential V_{R_a} used for penetration is plotted as a function of $E_{c.m.}$ is plotted for the dominant decay channel at highest value of angular momenta, shown in Fig. 2(a). It can be noticed that the lowering of barrier increases as $E_{c.m.}$ decreases for both the compound systems, which signifies the lower cross-sections at lower energy values. It also indicates that the lowering of barrier values (ΔV_B) required in case of $^{40}Ca^*$ is lesser than that of $^{42}Ca^*$ at all values of $E_{c.m.}$. Thus, the quantum tunneling of fragments/clusters in case of $^{40}Ca^*$ through the barrier is less hindered as compared to compound nucleus $^{42}Ca^*$. Therefore, less hindrance threshold is observed in $^{40}Ca^*$ in comparison to $^{42}Ca^*$, at lower energy values. Finally, the calculated fusion excitation values

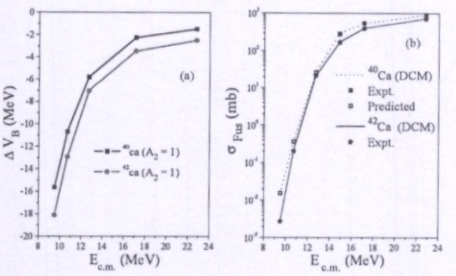

FIG. 2: (a)ΔV_B as a function of $E_{c.m.}$ and (b) The fusion cross section, σ_{Fus} calculated at comparable center of mass energies for $^{40,42}Ca^*$ within DCM and are compared with available experimental data where applicable for deformed fragmentation.

are plotted as function of $E_{c.m.}$ in Fig. 2(b). It can be observed that the calculated fusion excitation values are in agreement with the available experimental data. Also, it can be seen that the cross section values of $^{40}Ca^*$ are larger in comparison to $^{42}Ca^*$. Also, it can be clearly noticed that the cross sections of $^{42}Ca^*$ (solid line) decrease very steeply at the lowest energies in contrast to $^{40}Ca^*$ (dotted line). These observations can be understood through the lower ΔV_B values of fragments/clusters from compound nucleus $^{40}Ca^*$ and possibly its double shell closure in comparison to that of compound nucleus $^{42}Ca^*$ which may lead to enhanced cross section values.

References

[1] T. Ichikawa, *et al.* Phys. Rev. C **75**, 057603 (2007); A. S. Umar, *et al.* Phys. Rev. C **85**, 055801 (2012); S. Misicu, *et al.* Phys. Rev. Lett. **96**, 112701 (2006)

[2] R. K. Gupta, *et al.* Phys. Rev. C **71**, 014601 (2005); IJMPE **15**, 699 (2006), B. B. Singh, *et al.*, Phys. Rev. C **77**, 054613 (2008). R. Kaur, *et al.* Phys. Rev. C **98**, 064612 (2018).

[3] G. Montagnoli, *et al.* Phys. Rev. C. **97**, 024610 (2018), Y. Nagashima, *et al.* Phys. Rev. C. **26**, 2661(1982)

Abstract Submitted
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Effect of neutron-excess on above-barrier fusion cross-sections in ^{1215}C + ^{12}C: Evidence for increasing neutron dynamics[1] ROMUALDO DESOUZA, VARINDERJIT SINGH, SYLVIE HUDAN, Indiana Univ - Bloomington, ZIDU LIN, Arizona State University - Tempe, CHARLES HOROWITZ, Indiana Univ - Bloomington — Examination of the average fusion cross-section at energies above the fusion barrier for ^{12,13,14,15}C + ^{12}C reveals that the fusion cross-section increases more rapidly than can be simply attributed to the increased size. Comparison with static barrier penetration models suggests that dynamics are the origin of this increased cross-section. Calculations with a time-dependent Hartree-Fock model also fail to describe the observed trend suggesting that for neutron-rich nuclei, neutron dynamics may play a larger role than is presently accounted for.

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Assessing the impact of valence sd neutrons and protons on fusion[1] ROHIT KUMAR, VARINDERJIT SINGH, J. VADAS, T.K. STEINBACH, B.B. WIGGINS, S. HUDAN, R.T. DESOUZA, Indiana University Bloomington — Assessing the impact of valence sd neutrons and protons on fusion Experimental near-barrier fusion cross-sections for $^{17}F + ^{12}C$ are compared to the fusion excitation functions for $^{16,18}O$, ^{19}F, and ^{20}Ne ions on a carbon target. Comparison of the reduced fusion cross-section for the different systems accounts for the differing static size of the incident ions and changes in fusion barrier. Remaining trends of the fusion cross-section above the barrier are observed. These trends are interpreted as the interplay of the sd protons and neutrons. The experimental data are also compared to a widely-used analytic model of near-barrier fusion, a time-dependent Hartree-Fock model, and coupled channels calculations.

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Fusion of neutron-rich nuclei around the N=20 and N=28 shell closure.[1] SYLVIE HUDAN, JAMES JOHNSTONE, VARINDERJIT SINGH, REKAM GIRI, ROMUALDO DESOUZA, Indiana University, DIETER ACKERMANN, ABDELOUAHAD CHBIHI, QUENTIN HOURDILLE, GANIL, AUSTIN ABBOTT, CATHERINE BALHOFF, ANDY HANNAMAN, ALAN MCINTOSH, MAXWELL SORENSEN, ZACH TOBIN, ADI WAKHLE, SHERRY YENNELLO, Texas AM University — Fusion in neutron-rich environments is presently a topic of considerable interest. Experiments for an isotopic chain allow systematic exploration of the dependence of fusion on neutron number. To study fusion away from the closed N=20 and N=28 shells and explore the role of the unpaired proton, experiments were conducted at NSCL's ReA3 facility for $^{39,45,47}K+^{16}O$, ^{28}Si and $^{36,44}Ar+^{16}O$, ^{28}Si at near-barrier energies. Details of the E-TOF experimental technique utilized will be discussed. Preliminary results yielding the experimental fusion excitation functions and comparison to theoretical models will also be presented.

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3.4.6 Number of books and chapters in edited volumes published per teacher during the last five years (15)										
3.4.6.1: Total number of books and chapters in edited volumes / books published, and papers in national/international conference-proceedings year wise during the last five year										
Sr. No.	Name of the teacher	Title of the book/chapters published	Title of the paper	Title of the proceedings of the conference	Name of the conference	National / International	Year of publication	ISBN/ISSN number of the proceeding	Affiliating Institute at the time of publication	Name of the publisher
1	**Amit Sarin**	Electromagnetic Field Theory	-	-	-	National	2019	9789327299564	IKG Punjab Technical University	Kalyani
2	**Amit Sarin**	-	Theoretical Modeling of Indoor Radon/Thoron Concentration Based on Exhalation Rates from Different Building Materials	13th DAE-BRNS Nuclear and Radiochemistry	NUCAR 2017	national	2019	8183720803	IKG Punjab Technical University	IAEA https://inis.iaea.org/search/search.aspx?orig_q=RN:48054019
3	**Amit Sarin**	-	Educating Rural Population of Majha Region of Punjab about Energy Security and Renewable Sources of Energy	MMQC-2016	International Conference on Latest Developments in Materials, Manufacturing	International	2016	978-93-5212-858-7	IKG Punjab Technical University	
4	**Maninder Kaur**		Evolution of preformation probability of alpha particles in the decay of trans-lead nuclei 83Z92 with N=126	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2016	National	2016		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
5	**Maninder Kaur**		An attempt to estimate the pre- and post-saddle fission rates in fusion-fission dynamics	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2016	National	2016		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
6	**Maninder Kaur**		Investigation of fusion-fission dynamics using ER gated neutron multiplicity and charged particles multiplicity as probes	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2016	National	2016		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India

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7	**Maninder Kaur**		Investigating the effect of shell closure on fusion-fission dynamics by estimating the fission delay	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2017	National	2017	818372081-1	IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
8	**Maninder Kaur**		Probing shell effects in the reaction dynamics of low energy heavy ion collisions populating different isotopes of Rn	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2017	National	2017	818372081-1	IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
9	**Maninder Kaur**		Study of 48T i induced reactions in sub-barrier region forming 106Cd and 106Sn compound systems at ECN ~ 48MeV	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2021	National	2017	818372081-1	IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
10	**Maninder Kaur**		Effect of nuclear structure in fusion enhancement of $^{19}O + ^{12}C$ reaction reaction at sub-barrier energies	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2018	International	2018		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
11	**Maninder Kaur**		Dynamical aspects of fusion enhancement for neutron rich compound systems	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2018	International	2018		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
12	**Maninder Kaur**		Dynamical hindrance effect in fusion for the decay of the compound nucleus ^{64}Zn	DAE Conference Proceedings	DAE-BRNS Symposium on Nuclear Physics 2018	International	2018		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
13	**Maninder Kaur**		Investigation Rf Role Rf Entrance Channel Mass Asymmetry Rn Fusion Fission Dynamics	Advanced Materials and Radiation Physics (AMRP-	AIP Conf. Proc. 2352, 050010-1–050010-4; https://doi.org/10.1063/5.0052690	National	2020		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
14	**Maninder Kaur**		Dynamical effects of Si-isotopes induced reactions at similar centre of mass energies Ec.m		DAE-BRNS Symposium on Nuclear Physics Lucknow (India) 64, 455.	National	2019		IKG Punjab Technical University	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India

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15	**Varinderjit Singh**, T. K. Steinbach, J. Vadas, B. B. Wiggins, J. Huston, S. Hudan, R. T. deSouza, L. T. Baby, V. Tripathi, S. A. Kuvin, I. Wiedenhover		Experimental evidence for a fusion enhancement in ^{19}O + ^{12}C at near barrier energies	APS April Meeting 2016, Salt Lake City, Utah, USA,	APS April Meeting 2016, Salt Lake City, Utah, USA,	Internation	2016	http://meetings.aps.org/link/BAPS.2016.APR.E9.3	Indiana University, Bloomington, IN, USA	American Physical Society
16	Justin Vadas, Tracy Steinbach, Jon Schmidt, **Varinderjit Singh**, Sylvie Hudan, Romualdo deSouza, Lagy Baby, Sean Kuvin, Ingo Wiedenhover		Does the α Cluster Structure in Light Nuclei Persist Through the Fusion Process?	APS April Meeting 2016, Salt Lake City, Utah, USA,	APS April Meeting 2016, Salt Lake City, Utah, USA,	Internation	2016	http://meetings.aps.org/link/BAPS.2016.APR.E9.1	Indiana University, Bloomington, IN, USA	American Physical Society
17	Tracy Steinbach, Justin Vadas, **Varinderjit Singh**, Sylvie Hudan, Romualdo deSouza, Lagy Baby, Sean Kuvin, Ingo Wiedenhover, Sait Umar, Volker		Measuring the fusion cross-section of ^{18}O + ^{12}C with low intensity beams near and below the coulomb barrier	APS April Meeting 2016, Salt Lake City, Utah, USA,	APS April Meeting 2016, Salt Lake City, Utah, USA,	International	2016	http://meetings.aps.org/link/BAPS.2016.APR.E9.2	Indiana University, Bloomington, IN, USA	American Physical Society
18	Rupinder Kaur, Maninder Kaur, **Varinderjit Singh**, BirBikram Singh, B. S. Sandhu, J. Sadhukhan, Santanu Pal		Investigation of fusion-fission dynamics using ER-gated neutron multiplicity and charged particles multiplicity as probes	DAE Conference Proceedings	DAE-BRNS Symp. on Nucl. Phys. Kolkata (India) **61**, 518 (2016).	National	2016		Indiana University, Bloomington, IN, USA	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
19	Rupinder Kaur, Maninder Kaur, Inderjit Singh, Varinderjit Singh, J. Sadhukhan, S. Pal, B. S. Sandhu		An attempt to estimate the pre- and post-saddle fission rates in fusion-fission dynamics	DAE Conference Proceedings	DAE-BRNS Symp. on Nucl. Phys. Kolkata (India) **61**, 518 (2016).	National	2016		Indiana University, Bloomington, IN, USA	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
19	R. deSouza, J. Vadas, **Varinderjit Singh**, B. B. Wiggins, T. Steinbach, Z. Lin, C. Horowitz, L. Baby, S. Kuvin, V. Tripathi, I. Wiedenhover and S. Umar		Fusion of neutron-rich oxygen nuclei	EPJ Web of Conferences 163, 00013	FUSION 2017	International	2017	2100-014X	IKG Punjab Technical University	Springer
20	**Varinderjit Singh**, T. K. Steinbach, J. Vadas, B. B. Wiggins, J. Huston, S. Hudan, R. T. deSouza, L. T. Baby, S. A. Kuvin,V. Tripathi, I. Wiedenhover,		Enhancement of fusion at near-barrier energies for neutron-rich light nuclei: 19O +12C		A.S. Umar, APS April Meeting 2017, Washington DC, USA, **H12**.00007	International	2017	https://meetings.aps.org/Meeting/APR17/Session/H12.8	IKG Punjab Technical University	American Physical Society
21	Justin Vadas, **Varinderjit Singh**, Blake Wiggins, Jacob Huston, Sylvie Hudan, Romualdo deSouza, Abdou Chbihi, Dieter Ackermann, Kyle Brown		Measuring the fusion cross-section of 39,47K + 28Si at near barrier energies	APS April Meeting 2017, Washington DC, USA,	APS April Meeting 2017, Washington DC, USA,	International	2017	http://meetings.aps.org/link/BAPS.2017.APR.H12.8	IK Gujral Punjab Technical University, Kapurthala	American Physical Society

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22	Romualdo deSouza, Justin Vadas, **Varinderjit Singh, G. Visser, A. Alexander,** Sylvie Hudan, J. Huston, B. Wiggins, A Chbihi, M. Famiano and M. Bisschek		High-rate axial field ionisation chamber for particle identification of Radioactive beams	APS April Meeting 2017, Washington DC, USA,	APS April Meeting 2017, Washington DC, USA,	International	2017	http://meetings.aps.org/link/BAPS.2017.APR.H13.6	IK Gujral Punjab Technical University, Kapurthala	American Physical Society
23	Rupinder Kaur, BirBikram Singh, Mandeep Kaur, Maninder Kaur, **Varinderjit Singh**, B.S. Sandhu, and Raj K. Gupta		Probing shell effects in the reaction dynamics of low energy heavy ion collisions populating different isotopes of Rn	DAE Conference Proceedings	DAE-BRNS Symp. on Nucl. Phys. Patiala (India) **62**, 632(2017).	National	2017		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
24	Rupinder Kaur, BirBikram Singh, Mandeep Kaur, Maninder Kaur, **Varinderjit Singh**, and B.S. Sandhu		Study of ^{48}Ti induced reactions in sub-barrier region forming ^{106}Cd* and ^{106}S compound systems at E^{*}_{CN} ~ 48MeV	DAE Conference Proceedings	DAE-BRNS Symp. on Nucl. Phys. Patiala (India) **62**, 634(2017).	National	2017		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
25	Rupinder Kaur, Maninder Kaur, BirBikram Singh, and **Varinderjit Singh**		Investigating the effect of shell closure on fusion-fission dynamics by estimating the fission delay	DAE Conference Proceedings	DAE-BRNS Symp. on Nucl. Phys. Patiala (India) **62**, 658(2017).	National	2017		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
26	Devinder Pal Kaur, B. R. Behera, M. Kaur, **V. Singh**, D. Siwal, M. Thakur, P. Sharma, I. Mukul, K. Kapoor, N. Madhavan, S.		Study of evaporation residue cross-section for ^{48}Ti + ^{140,142}Ce systems.	DAE Conference Proceedings	DAE-BRNS Symp. on Nucl. Phys. Patiala (India) **62**, 606(2017).	National	2017		IK Gujral Punjab Technical University, Kapurthala	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
27	Rupinder Kaur, **Varinderjit Singh, Maninder Kaur**, Sarbjeet Kaur, BirBikram Singh, B.S. Sandhu		Dynamical aspects of fusion enhancement for neutron rich compound systems		DAE-BRNS Symposium on Nuclear Physics	International	2018		IKG Punjab Technical University	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
28	H. Arora, Gulzar Singh, B.R. Behera, Jagdeep Kaur, Ajay Tyagi, Hardev Singh, Rohit Sandal, **Varinderjit Singh, Maninder Kaur**, Ashok Kumar, K.P. Singh, K.S.		Dynamical hindrance effect in fusion for the decay of the compound nucleus ^{64}Zn		DAE-BRNS Symposium on Nuclear Physics	International	2018		IKG Punjab Technical University	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
29	**Varinderjit Singh**, B.R. Behera, Maninder Kaur, Akhil Jhingan, Rupinder Kaur, P. Sugathan, Davinder Siwal, S. Goyal, K.P. Singh, Santanu Pal, A. Saxena, S. Kailas		Systematic investigation to estimate the magnitude of nuclear dissipation in fission dynamics		DAE-BRNS Symposium on Nuclear Physics	International	2018		IKG Punjab Technical University	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India

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30	Manpreet Kaur, Rupinder Kaur, Sarbjeet Kaur, BirBikram Singh, Maninder Kaur, and **Varinderjit Singh**		Effect of nuclear structure in fusion enhancement of 19O+12C reaction at sub-barrier energies		DAE-BRNS Int. Symp. on Nucl. Phys., Bombay (India) **63**, 550 (2018).	International	2018		IKG Punjab Technical University	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
31	Justin Vadas, **Varinderjit Singh**, Blake Wiggins, Jacob Huston, Sylvie Hudan, Romualdo deSouza, Zidu Lin, Charles Horowitz, Abdou Chbihi, Dieter		Probing the fusion of neutron-rich nuclei with reaccelerator radioactive beams.	APS April Meeting 2018, Columbus Ohio, USA,	APS April Meeting 2018, Columbus Ohio	International	2018	http://meetings.aps.org/link/BAPS.2018.APR.H1 1.8	IK Gujral Punjab Technical University, Kapurthala	American Physical Society
32	Rupinder Kaur, **Varinderjit Singh, Maninder Kaur,** BirBikram Singh, and B. S. Sandhu		Dynamical effects of Si-isotopes induced reactions at similar centre of mass energies Ec.m		DAE-BRNS Symposium on Nuclear Physics Lucknow (India) 64, 455.	National	2019		IKG Punjab Technical University	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
33	H. Arora, B.R. Behera, K. Rani, Shruti, M. Kumar, Amit, C. Sharma, Subodh, D. Arora, A. Kaur, S. Singh, N. Saneesh, **Varinderjit Singh**, A. Jhingan, K.S. Golda, H. Singh, P.		ER Gated light particle spectra at various energies to study the entrance channel effect due to mass asymmetry		DAE-BRNS Symposium on Nuclear Physics Lucknow (India) 64, 497.	National	2019		IKG Punjab Technical University	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
34	Devinder Pal Kaur, B.R. Behera, N. Madhavan, M. Kaur, **V. Singh**, D. Siwal, M.Thakur, P. Sharma, I. Mukul, K. Kapoor, S. Nath, J. Gehlot, A. Jhingan, A.		Evaporation residue cross-sections studies for 188,190Hg CN systems		DAE-BRNS Symp. on Nucl. Phys. Lucknow (India) **64**, 339.	National	2019		IKG Punjab Technical University	Board of Research in Nuclear Sciences, Department of Atomic Energy, Government of India
35	Romualdo Desouza, **Varinderjit Singh**, Sylvie Hudan, Zidu Lin, Charles Horowitz		Effect of neutron-excess on above-barrier fusion cross-sections in 12−15C + 12C: Evidence for increasing neutron dynamics	APS April Meeting 2021, USA, Y11.00001 (2021).	APS April Meeting 2021, USA	International	2021	http://meetings.aps.org/Meeting/APR21/Session/Y11.1	IK Gujral Punjab Technical University, Kapurthala	American Physical Society
36	Rohit Kumar, **Varinderjit Singh**, J. Vadas, T.K. Steinbach, B.B. Wiggins, S. Hudan, R.T. deSouza,		Assessing the impact of valence sd neutrons and protons on fusion	APS April Meeting 2021, USA, Y11.00002 (2021).	APS April Meeting 2021, USA	International	2021	http://meetings.aps.org/Meeting/APR21/Session/Y11.2	IK Gujral Punjab Technical University, Kapurthala	American Physical Society
37	Sylvie Hudan, James Johnstone, **Varinderjit Singh**, Rekam Giri, Romualdo deSouza, Dieter Ackermann, Abdelouahad Chbihi, Quentin Hourdille		Fusion of neutron-rich nuclei around the N=20 and N=28 shell closure	APS April Meeting 2021, USA, Y11.00003 (2021).	APS April Meeting 2021, USA	International	2021	http://meetings.aps.org/Meeting/APR21/Session/Y11.3	IK Gujral Punjab Technical University, Kapurthala	American Physical Society

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38	**Neetika sharma**	-	Form factors and transverse structure of nucleon in light-front holographic		National Conference on Non-Linear Phenomena in Physics - NCNLPP-2019,	National	2019		IKG Punjab Technical University	
39	**Neetika sharma**	-	Parametrization Approach to Momentum Transfer Dependance of Generalized Parton Distributions	-	106th ISCA at Lovely Professional University, Jalandhar (January 2019).	National	2019		IKG Punjab Technical University	
40	Mohammad Ahmady, Ruben Sandapen, and **Neetika Sharma**	-	Predictions for Diffractive phi Meson Production Using an AdS/QCD Light-front Wavefunction	Diffraction 2020	AIP Conf.Proc. 1819, 1, 030011	International	2017	9780740000000	IISER Mohali	AIP
41	Mohammad Ahmady, Ruben Sandapen, and **Neetika Sharma**	-	Diffractive phi electroproduction with a holographic meson wavefunction	Deep inElastic Scatring and related subjects	PoS DIS2016, 173	International	2016	-	IISER Mohali	Proceedings of Science
42	**Neetika Sharma**	-	Generalized Parton Distributions for Nucleon in the Impact Parameter Space	Spin 2016	Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660049	International	2016	2010-1945	IISER Mohali	World Scientific

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