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Probing Incomplete Fusion Dynamics in ^{12}C Induced Reactions at Moderate Excitation Energies

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Abstract— **The excitation functions for various evaporation residues populated in the interaction of ^{12}C with ^{51}V have been measured in the energy range from 3 MeV/A to 7 MeV/A. The experiment was performed using 15 UD Pelletron, a National accelearator facility for university researchers in India. The well-known nuclear activation terchnique followed by offline gamma ray spectroscopy was used for these measurements. The theoretical predictions were obtained using fusion based statistical model code ALICE-91. It is obsereved that for residues populated through pxn channels, the experimentals values are well reproduced by theoretical predictions indicating that these residues are mainly populated by Complete fusion only. However, for the residues those produced via xαyn channels the measured cross-section values are observed to be much higher than those obtained by model calculations. The enhancement in cross-sections values may be attributed to the presence of incomplete fusion with complete fusion dynamics in the production of these residues. It is concluded that the ICF dynamics also plays an important role with CF dynamics in heavy ion induced reactions at energy near to Coulomb barrier.**

Index Terms— **Activation technique, Complete and incomplete fusion reaction, Excitation Functions, Heavy ions, HPGe-gamma ray spectroscopy, Nuclear Reactions, Model calculations.**

1 Introduction

The study of heavy ion (HI) induced reactions has been the interest of many nuclear physicists over the past few years [1],[2],[3],[4]. With the availability of the heavy ion beam of suitable energy range the interest has renewed in the recent past. The fusion reactions are very important to study the nuclei at high excitation and high spin states. A systematic study of energy dependence of fusion cross section is most essential to understand reaction mechanism. Study of fusion reaction at low energies is helpful in the study of resonance like structure. At low energies, complete fusion characterized by full momentum transfer is dominant part of the total reaction cross section. As the projectile energy increases to 5-10 MeV/A and above, it turns out that the fused system does not consist of the sum total of all the nucleons involved. There are particles which can be emitted from either very fast (much faster than those coming from an evaporation process) if they are emitted by the projectile or possibly very slow if they are emitted from the target. The fast particles are forward peaked. They consist of nucleons as well as clusters of nucleons like alpha particles. Such a process where the remaining part of the projectile and of the target fused together after the initial colliding nuclei have emitted light particles has been called incomplete fusion, breakup fusion or massive transfer. Some recent studies near coulomb barrier have indicated that Fusion/Fission also plays an important role in heavy ion induced reactions.

Several models have also been proposed to explain some of the features of ICF reaction dynamics, such as break-up fusion model (BUF) [5], sum rule model [6], promptly emitted particle (PEP) model [7], and hot-spot model [8] etc. The BUF model of Udagawa and Tamura is based on the Distorted Wave Born Approximation (DWBA) and explains ICF in terms of break-up of heavy-ion projectile into α-clusters, as it approaches the nuclear field of the target nucleus. The sum rule model of Wilczynski et al., suggested that ICF reactions occur in the peripheral interactions and are localized in ℓ -windows above the critical angular momentum of the complete fusion of the projectile with the target. Morgenstern *et al.,* [9] and Chakrabarty *et al.,* [10] studied the entrance channel mass-asymmetry dependence of ICF through the measurement of the velocity spectra of heavy residues in different mass-asymmetric systems. Some recent studies illustrated the onset of ICF just above the Coulomb barrier energies [1],[2]. These results motivated researchers to investigate ICF dynamics at relatively lower bombarding energies. The effect of various entrance channel parameters viz., projectile energy, mass-asymmetry of interacting nuclei, α-Q-value, and orbital angular momentum has to be systematically investigated for the onset and strength of ICF dynamics. In HI-induced reactions a large number of reaction channels are expected to open-up at energies near and above the Coulomb barrier. The measurement and analysis of excitation functions may provide significant information about the involved reaction mechanism at these energies.

For a better understanding of complete, incomplete

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/PE emission dynamics, a wide range of experimental data is required. Although excitation functions for ^{51}V were measured by Ismail et.al., [11], their results differ to a large extent; hence precise and accurate measurements are still essential. With this motivation the present work was undertaken to measure the excitation functions for ^{51}V up to ~ 80.0 MeV ^{12}C beam energy using the maximum number of possible γ-rays for a single reaction.

With this motivation, the present experiment for $^{12}C+^{51}V$ interactions was performed at the Inter University Accelerator Centre (IUAC), New Delhi, India.

A theoretical analysis of the data was carried out under the prescription of the statistical model using the computer code ALICE-91 [12],[13],[14]. The details of experimental procedure and measurements have been given in section 2. Section 3 contains the results and theoretical interpretation of the data. Section 4 encapsulates the conclusion of present work.

2 Experimental Procedure and measurements

The experiment was carried out using the 15UD Pelletron facility to measure the excitation functions (EFs) for evaporation residues produced in the $^{12}C + ^{51}V$ system at the energies below 7 MeV/nucleon. Details of the experiment are as follows:

2.1 Target Preperation

Self –supporting ^{51}Nb targets of thickness ~ 1.2 mg/cm^2 were prepared by rolling natural Vanadium of purity better than 99.9%. The rolling technique is the most efficient method to prepare self supporting targets. Mechanical rolling was done by sandwiching the material between the mirror polished stainless steel sheets of 1mm thickness and size 7 cm x 5 cm. The surfaces of the sheets were cleaned with acetone to obtain purity and uniformity in the thickness of the target. The distance between the two rollers was gradually decreased in many steps to obtain the desired area. The target thickness was determined by gravimetry. The minimum thickness that can be achieved by sandwich rolling is up to 500μg/cm^2. Rolling is by far the most conservative process with regard to material loss in preparing thin targets. To prevent target foil sticking on the sheets, paraffin was sometimes used as a lubricant.

2.2 Calibration and Efficiency Measurement of HPGe Detector

In the complex γ-ray spectrum the corresponding peaks of γ-rays of evaporation residues can be readily identified by a detector of good resolution and proper calibration. The good resolution of detector helps to separate very closely spaced gamma ray peaks and nicely detects weak gamma rays of discrete energies. Hence, High Purity Germanium (HPGe) detector of high resolution and standard sources having gamma energies covering the complete range of the γ-rays expected during the experiments are indispensable. In the present measurements, the energy calibration of 100 cc. HPGe detector (resolution 1.86 keV for 1332 keV gamma ray of ^{60}Co) was performed using ^{152}Eu gamma standard source. The detector efficiency is a measure of fraction of the gamma rays detected and is determined by using standard gamma ray source spectrum. If C is the observed disintegration rate of gamma ray source at the time of observation, S_o is the absolute disintegration rate at the time of manufacturing of gamma ray source, t is the time lapsed between the start of counting and the date of fabrications of the source, the detection efficiency '∈' for the gamma ray of absolute intensity 'θ' be defined as

$$\in = \frac{C\, exp(\lambda t)}{S_o \theta G} \quad (1)$$

where λ is the decay constant of the radioactive nuclei and G is the geometry factor ($G = \Omega/4\pi$, here Ω is the solid angle in steradians subtended by the detector surface facing the source).

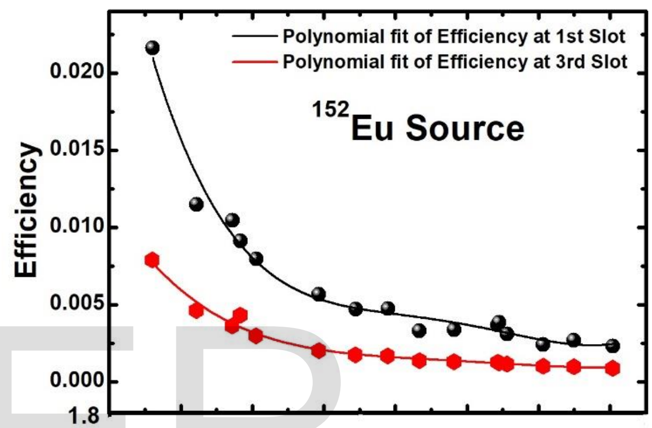

Fig. 1. Typical geometry dependent efficiency curves of HPGe detector for different gamma energies at different source-detector separation

The probable error in the geometry factor can be eliminated by determining the relative detection efficiency as

$$\in . G = \frac{C\, exp(\lambda t)}{S_o \theta} \quad (2)$$

Experimentally, C was determined for each photo-peak by placing the ^{152}Eu source at the desired geometry. The value of S_o was supplied by the manufacturer. θ and λ were taken from elsewhere [15]. The geometry dependent efficiency was estimated at different distances between source and detector. The values of thus obtained were plotted as a function of energy using the program ORIGIN. A typical geometry dependent efficiency curve of the 100cm^3 HPGe detector obtained at 1st and 3rd slot atdistance of 4.5 and 6.5 cm from the detector surface are shown in figure1.

2.3 Target Irradiations

Individual targets of ^{51}V were irradiated by $^{12}C^{6+}$ beam of energy ~ 55.0 – 80.0 MeV in the General-Purpose Scattering Chamber (GPSC) of 1.5 m diameter having In vacuum Transfer Facility (ITF). ITF allows target shifting without disturbing high vacuum and to minimize the time lapse between the stop of irradiation and beginning of the counting. The targets mounted on ladder were fixed inside the scattering chamber. The two-surface barrier (SSB) detectors were also kept at ± 10 ° to the beam direction for monitoring the flux of the incident beam. The experimental setup is shown in figure.2. The incident flux was calculated from the charge collected in Faraday cup as well as from the counts of the two Rutherford monitors. The obtained values agree with each other within 5% error. The stacked targets were exposed about six and half-hours owing to the half-lives of radioactive isotopes of interest. During exposure the beam current was maintained ~25nA to 30 nA. The mean energy of ^{12}C-ion beam incident at half the thickness on each foil in the stack was calculated from the energy range program SRIM-2008. The inherent energy spread is found to be negligible.

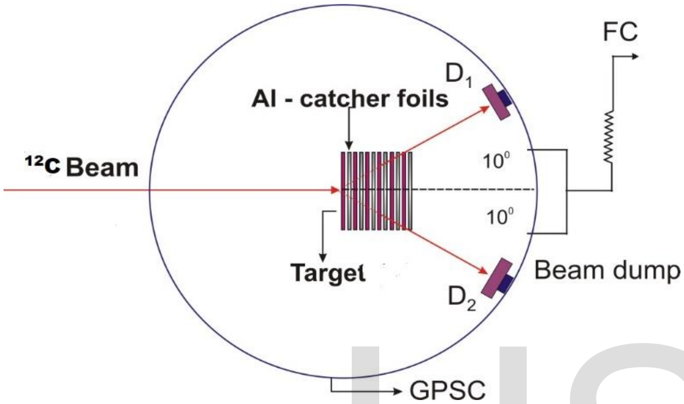

Fig. 2. Exprimental setup used for present study at IUAC, New Delhi

2.4 Post Irradiation Analysis and Identification of Evaporation Residues

The major step in the experiment is the recording of the gamma ray spectra of the induced activities in the target foils. The activities were followed using a high resolution HPGe detector coupled to PC through CAMAC based CANDLE software. Several spectra were taken at suitable intervals to permit the identification of the half-lives of various residual nuclei. Proper account of the dead time (<10%) was included in our calculations. In nuclear reactions, evaporation residues are produced in excited state by emission of charge particles/neutrons. These excited residual nuclei decays to their ground state by emitting characteristic γ-rays. As each isotope has a unique mode of decay and it comes to ground state by emitting characteristic γ-rays so identification of characteristics γ-rays and their intensity provides the measure of particular evaporation residue. The reaction products were identified not only by the energy of the characteristic γ-radiations but also by the measured half- lives of residues. The following expression is used for computing the production cross-sections of evaporation residues [16].

$$\sigma(E) = \frac{A\lambda\, exp(\lambda t_2)}{N_0.\phi(\in.G).\theta K[1-exp(-\lambda t_1)][1-exp(-\lambda t_3)]} \quad (3)$$

where, A is the observed counts under the photo peak of characteristic γ-ray, λ is the decay constant of the product nucleus, N_o is the total number of nuclei present in the target , ϕ is the incident ion beam flux, (∈.G) is the geometry dependent efficiency of the HPGe detector, θ is the absolute intensity of the characteristic γ-rays, k is the self absorption correction factor for the γ-ray in the target, t_1 is the irradiation time of the target stack , t_2 is the time span between stopping the beam and the beginning of counting and t_3 is the data collection time. In the measurements, the experimental cross-section values for a given reaction were taken as the weighted average of these individual cross-sections.

TABLE 1

Nuclear Spectroscopic Data Used For The Evaluation of Cross-sections in ^{51}V

Residue	$T_{1/2}$	J^π	E_γ (keV)	Absolute Intensity (%)
^{58}Co	70.76d	2^+	811.2	100.0
^{57}Co	271.7d	$7/2^-$	121.2	85.5
^{56}Co	78.76d	4^+	846.6	100.0
			1036.9	14.0
			1237.6	67.6
^{54}Mn	312.2d	3^+	834.2	100.0

3 Experimental Results

In the present work the various reactions induced by a particles on ^{51}V were observed by detecting the characteristic γ-rays obtained from the decay of residual nuclei. The possible reaction channels for ^{51}V (residual nucleus unstable) in the energy range considered in the present measurement are listed in Table 1. The other details, viz., residual nucleus, half-life, γ-ray energies, and corresponding absolute intensities, are also given in the table. In the list very weak γ- rays are not included whenever strong γ- rays are available for the same emitting nuclide. γ- rays having higher energies are also not included in the list. We have considered only those γ- rays that gave appreciable activities for the meaningful excitation studies. The activation cross section for a given reaction was determined from the intensities of the various γ- rays identified as arising from the same residual nucleus. The reported value is the weighted average [17] of the various cross-section values so obtained. In this present work the excitation functions for four evaporation residues (ERs) produced by (C, αn), (C, α2n), (C, α3n) and (C, 2αn) reaction channels have been measured in the energy range 55 MeV to 80 MeV. The measured cross-sections are shown in figures 3 - 6. The size of the circles includes the errors of energy values in the experimental data. The errors in the cross-section arise mainly due to uncertainties in the target thickness (±3%), detector efficiency (±5%), the beam current integration (±2%), counting statistics (±4%) and evaluating the γ-ray intensity and the background subtraction (≤ 4%). The statistical error given in the results is the larger one of the internal and external errors [17]. In general, these errors are less than 12% except for few points.:

3.1 Model Calculations, Results and Their Interpretation

The excitation functions have been estimated theoretically using the computer code ALICE-91 [12],[13],[14]. It is based on the WeissKopf-Ewing model [18] for compound nucleus reaction while pre-equilibrium emission is stimulated within the framework of Hybrid/geometry dependent hybrid model [12],[13]. The inverse reaction cross-sections used in the code are calculated using optical model [19] subroutines, although code has an option of classical sharp cut off model also. The transmission coefficients are calculated using the parabolic model of Thomas [20] for heavy ions. Like all semi-classical models, ALICE-91 assumes equipartition of energy among the

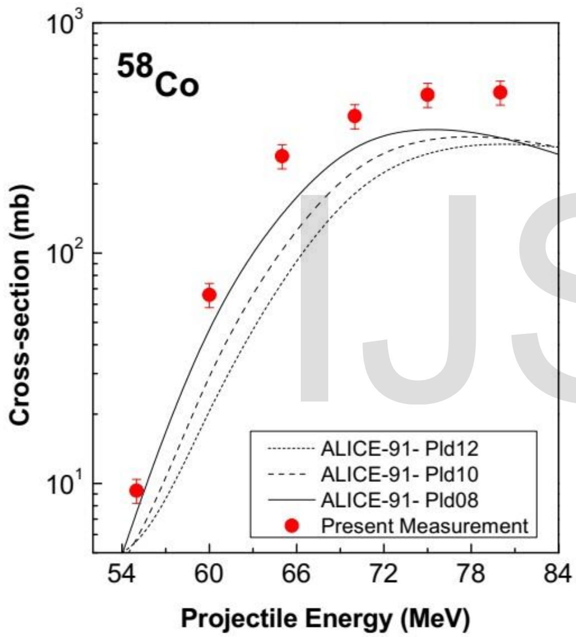

Fig. 3. Experimentally measured EFs (represented by red circles) of evaporation residue ^{58}Co(αn) with ALICE-91 predictions at different level density parameter

initially excited particles and holes. The important input parameters required in this code are the level density parameter 'a', the initial exciton number 'n$_0$' and mean free path (MFP) multiplier 'COST' along with the description of the projectile and target nucleus. The MFP for intranuclear transition rates may be calculated from the optical model of Becchetti and Greenless [19]. The MFP multiplier COST is used to adjust the nuclear mean free path in order to reproduce the experimental data. It accounts for the difference, if any, between the calculated and the actual MFPs for two-body residual interactions.

Level densities of residue may be calculated either from the Fermi Gas model or from the constant temperature form. The

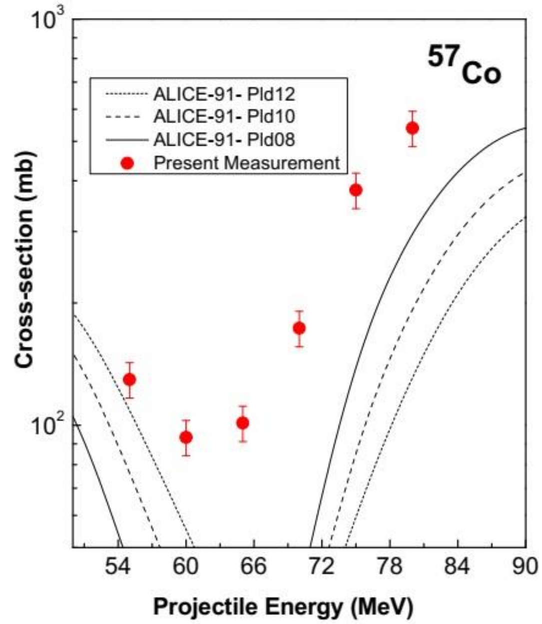

Fig. 4. Experimentally measured EFs (represented by red circles) of evaporation residue ^{57}Co($\alpha 2n$) with ALICE-91 predictions at different level density parameter

Fermi gas model [21] gives

$$\rho(U) = (U-\delta)^{-\frac{5}{4}} \exp(2\sqrt{a(U-\delta)}) \quad (4)$$

where, δ is the pairing term and U is the excitation energy of the nucleus. The level density parameter a is taken as A/K, A being the mass number of the composite nucleus and K is an adjustable parameter. The level density $\rho(U)$ in the constant temperature form [22] is given as

$$\rho(U) \propto \frac{1}{T}\, \varepsilon^{u/T} \quad (5)$$

The differential cross-section for emitting a particle with channel energy ε may be written as (cross-section per unit energy to emit a particle of type ν).

$$\left(\frac{d\sigma}{d\varepsilon}\right)_\nu = \pi\, ƛ^2 \sum_{I=0}^{\infty}(2I+1)\, T_l(2S_\nu+1)\sum_{l=0}^{\infty} T_\nu^l(\varepsilon) \sum_{j=|I-1|}^{I+1} \rho(E,J)/D$$

(6)

where $ƛ$ is the reduced de-Broglie wavelength of the incident ion, T_l is the transmission coefficients for the l^{th} partial wave of the incident ion. $\rho(E,J)$ is spin dependent level density for the residual nucleus, D is the integral of numerator over all particles and emission energies, ε the excitation energy of the compound nucleus. S_ν is the intrinsic spin of particle ν, $T_\nu^l(\varepsilon)$ is the transmission coefficients for the particle ν with K.E. ε and orbital angular momentum l.

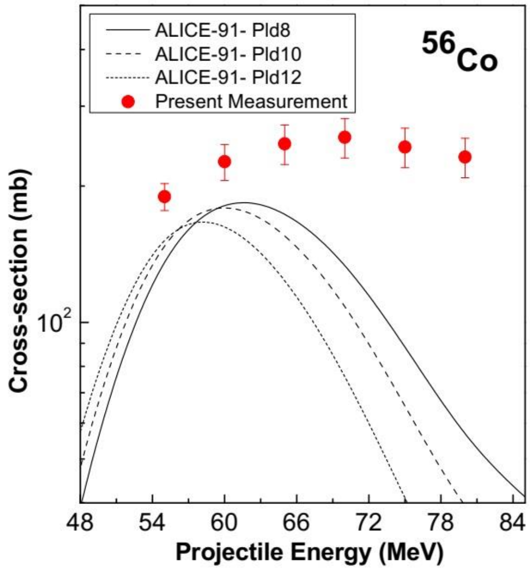

Fig. .5 Experimentally measured EFs (represented by red circles) of evaporation residue ^{56}Co($\alpha 3n$) with ALICE-91 predictions at different level density parameter

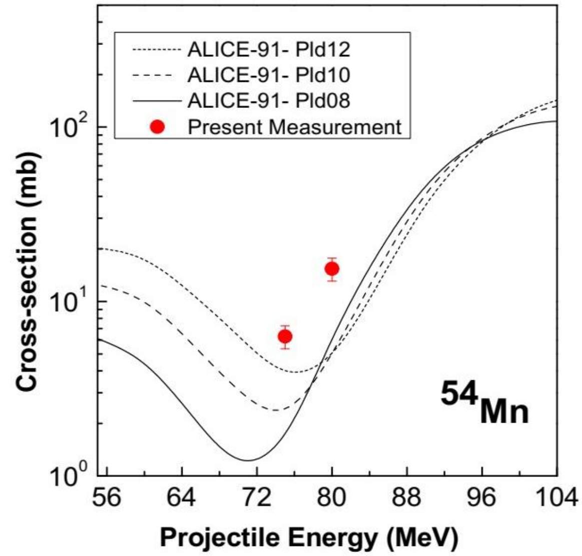

Fig. 6. Experimentally measured EFs (represented by red circles) of evaporation residue ^{54}Mn($2\alpha n$) with ALICE-91 predictions at different level density parameter

The various parameters used for calculations of excitation functions were selected as in our earlier publication [3]. However, the initial exciton number is found to play an important role in the theoretical predictions. Assuming that the incident projectile breaks up in the field of target nucleus and the nucleons occupy excited states above the Fermi energy, the initial exciton number n_0 with configuration (6p + 6n + 0h) has been taken to 12 for ^{12}C projectile. In this code, the level density parameter constant K may be varied to match the experimental data and it greatly affacts the values and shape of excitation functions. In our earlier work [3] for *xn* and *pxn* ($x = 1,2,3\ldots$) channels (Complete fusion Channels) it has been established that K = 8 reproduce well the experimental data. In this code, Incomplete fusion is not taken into consideration, as any such enhancement over the theoretical calculations may be attributed to ICF.

The EFs for the reaction channel (αn) is shown in figure 3. An agreement between theoretical and experimental values exists upto 60 Mev MeV and above this energy significant enhancement of cross-section is found. This simply indicates that ^{58}Co is populated via CF and ICF of ^{8}Be fragment both. Regarding the residues ^{57}Co, populated through (α,2n) channel, it is obvious from figure4. that our measured cross-sections are higher than the theoretical predictions in the complete energy range but in the same trend as the theoretically calculated values. This enhancement can be explained by the ICF of ^{8}Be fragment of the projectile to the target. Figure5. shows the EFs for the residue ^{56}Co populated by the channel (α3n). It can be seen from the figures that measured excitation functions are much higher above 60 MeV energy and also do not follow the trends of theoretically estimated values. Strong influence ICF may attribute to this enhancement of cross-section values. The EFs for ^{54}Mn could be measured at only two energies 75 and 80 MeV. This residue is expected to populated through (2αn) channel. The measured values are higher that those obtained through model calculations but in the same trend as the theoretically calculated values, which can be explained by assuming that these channels are populated not only by CF but also with ICF of ^{4}He fragment of projectile to the target.

4 Conclusion

The excitation functions for (C, αn), (C, α2n), (C, α3n) and (C, 2αn) reactions have been measured for ^{12}C + ^{51}V system in the energy range 55-80 MeV. The comparative study of experimentally measured excitation functions with theoretical predictions shows the considerable enhancement in cross-sections for ^{58}Co, ^{57}Co, ^{56}Co and ^{54}Mn nuclides indicating that the processes other than compound nucleus formation are playing an important role in the production of these isotopes. The large difference in our measured and calculated values gives clear signatures of incomplete fusion for these channels in the considered energy range. Moreover, for a perfect modeling of the ICF process, more detailed experiments consisting of the measurement of forward recoil range distributions and spin distribution of residues populated by CF as well ICF, using particle-gamma coincidence technique both at relatively low and higher bombarding energies are desirable.

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REFERENCES

[1] Avinash Agarwal, Anuj Kumar Jashwal, Munish Kumar, S. Prajapati, Sunil Dutt, Muntazir Gull, and I. A. Rizvi, Kamal Kumar, Sabir Ali, Abhishek Yadav, Rakesh Kumar and A. K. Chaubey "Effect of neutron excess in the entrance channel on the 18O + 93Nb system: An experimental study relevant to incomplete-fusion dynamics "*Phys. Rev. C* vol.103, 034602 (2021)

[2] K. Kumar, T. Ahmad, S. Ali, I. A. Rizvi, A. Agarwal, R. Kumar, K. S. Golda, and A. K. Chaubey "Low-energy incomplete fusion and its sensitivity to projectile structure" *Phys. Rev. C* vol.87, 044608 (2013).

[3] M. Kumar, A. Agarwal, S. Prajapati, K. Kumar, S. Dutt, I. A. Rizvi, R. Kumar, and A. K. Chaubey "Influence of projectile structure and target deformation on incomplete fusion in the $^{16}O+^{51}V$ system" *Phys. Rev. C* vol.100, 034616 (2019).

[4] A. Yadav, V. R. Sharma, P. P. Singh, R. Kumar, D. P. Singh, Unnati, M. K. Sharma, B. P. Singh, and R. Prasad "Effect of α-Q value on incomplete fusion" *Phys. Rev. C* vol.86, 014603 (2012).

[5] T. Udagawa and T. Tamura "Breakup-Fusion Description of Massive Transfer Reactions with Emission of Fast Light Particles" Phys. Rev. Lett. 45, 1311 (1980).

[6] K. Siwek-Wilczyńska, E. H. du Marchie van Voorthuysen, J. van Popta, R. H. Siemssen, and J. Wilczyński "Incomplete Fusion in ^{12}C + ^{160}Gd Collisions Interpreted in Terms of a Generalized Concept of Critical Angular Momentum" Phys. Rev. Lett. 42, 1599 (1979).

[7] J.P. Bondorf, J.N. De, G. Fái, A.O.T. Karvinen, B. Jakobsso, and J. Randrup "Promptly emitted particles in nuclear collision "Nucl. Phys A vol. 333, 285 (1980).

[8] R. Weiner and Westrom "Diffusion of heat in nuclear matter and preequilibrium phenomena" Nucl. Phys. A vol 286, 282 (1977).

[9] H. Morgenstern, W. Bohen, W. Galster, K. Grabisch, and A. Kyanowski "Influence of the Mass Asymmetry on the Onset of Incomplete and the Limit to Complete Fusion" *Phys. Rev. Lett.* Vol 52, 1104 (1984

[10] S. Chakrabarty, B.S. Tomar, A. Goswami, G.K. Gubbi, S.B. Manohar, Anil Sharma, B. Bindukumar, S. Mukherjee "Complete and incomplete fusion reactions in the 12 C + 169 Tm" Nucl. Phys. A vol. 678, 355 (2000)

[11] M Ismail, R P Sharma and M H Rashid "Measurement of excitation functions and mean projected recoil ranges of nuclei in ^{12}C-induced reactions on vanadium" Pramana vol. 49, pages623 (1997)

[12] M. Blann "Hybrid Model for Pre-Equilibrium Decay in Nuclear Reactions" Phys Rev. Lett. Vol.27, 337 (1971).

[13] M. Blann "Importance of the Nuclear Density Distribution on Preequilibrium Decay" Phys Rev. Lett. Vol.28, 757 (1972).

[14] M. Blann, ALICE-91, report, LLNL/IAEA/NEA Data Bank, 1991 (unpublished)

[15] E. Browne and R.B. Firestone, *Table of Radioactive Isotopes* (John Wiley & Sons, New York 1986).

[16] F. K. Amanuel, B. Zelalem, A. K. Chaubey, A. Agarwal, I. A. Rizvi, A. Maheshwari, and T. Ahmad "Investigation of the influence of incomplete fusion on complete fusion of ^{12}C-induced reactions at ≈ 4–7.2 MeV/nucleon" Eur. Phys. J. A vol.47, 156 (2011).

[17] S.F. Mughabghab, M. Divadeenam and N.E. Holden, "*Neutron cross-sections* " vol.1, Part 1, p.89 Academic, New York (1989).

[18] V. F. Weisskopf and D. H. Ewing "On the Yield of Nuclear Reactions with Heavy Elements" Phys. Rev. **57,** vol.472 (1940)

[19] F. D. Becchetti, Jr. and G. W. Greenlees "Nucleon-Nucleus Optical Model Parameters, A>40, E<50 MeV" Phys Rev. 182, vol. 1140 (1969).

[20] T. Darrah Thomas "Angular momentum effects in neutron evaporation" Nucl. Phys. Vo. 53, 577 (1964).

[21] M. Blann and H. Vonach "Global test of modified precompound decay models" Phys. Rev. C vol. 28 , 1475 (1983).

[22] D. Bodansky, "Compound Statistical Features in Nuclear Reactions" Ann. Rev. Nucl. Sci. vol. 12, 79. (1962).