Study of light particles emitted from heavy-ion induced fusion reactions

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A projectile and a target in peripheral contact causes the reaction to proceed *via* various exit channels depending on the incident energy and mass number. One of the exit channels of reactions with E $\leq$ 5 MeV/A is fusion-evaporation, where the compound nucleus formed de-excites to the ground state by emission of light charged particles, neutrons, and γ-rays. The influence of dynamical effects on the decaying compound nucleus is not thoroughly understood and different probes such as, the evaporation spectra of light particles, Giant Dipole Resonance γ-rays, ER cross section, etc. are used to understand it.

The inconsistencies in explanation of the evaporation spectra of light particles have been a major motivation behind this work [1–4]. The measurements carried out earlier were inclusive in nature having contributions from channels other than fusion. This indicated the importance of coincidence measurements in order to single out the behaviour of emitted particles corresponding to the fusion reaction channel. In many of the studies carried out earlier, either charged particles or neutrons were measured. In order to know more about dynamics of the reaction, it is of utmost importance to simultaneously measure the charged particles and neutrons in coincidence with evaporation residue.

Earlier studies have emphasized that, at high excitation energy fusion dynamics for mass symmetric system is different from the dynamics for mass asymmetric system populated at same excitation energy. The mass symmetric systems due to longer formation time undergo extended shape profiles and lead to pre-equilibrium emissions. The charged particle spectra were found to be softer while the neutron spectra were harder in comparison to the standard statistical model calculations [1–4].

Different explanations have been put forth to understand these deviations, due to which a consistent picture of the compound nucleus cannot be interpreted. Modifications in statistical model parameters is needed in order to understand the observed deviations. The charged particle spectra has been explained by rescaling the Yrast line or by considering influence of the dynamical effects. Whereas, the neutron spectra has been explained by considering modified level density parameter, along with inclusion of modified radius parameter in some cases.

In order to explain these prevailing shortcomings, a systematic study of the decay of three compound nucleus, ^{64}Zn, ^{80}Sr, and ^{96}Ru, populated using different entrance channels was carried out [5–7]. These experiments were performed by using 15 UD pelletron facility at IUAC, New Delhi. The evaporation spectra emitted from the reactions were studied at various energies to observed the influence of mass asymmetry on the particle spectra. The compound nucleus ^{64}Zn was populated by reactions ^{16}O + ^{48}Ti and ^{37}Cl + ^{27}Al at 76 MeV and 125 MeV, respectively. The emitted neutron, proton, and α-particle spectra were studied in the framework of statistical model. The inclusive as well exclusive particle spectra were studied for ^{16}O + ^{64}Zn and ^{32}S + ^{48}Ti at near barrier as well as higher energies. The statistical model was modified to explain the experimental spectra. The compound nucleus ^{96}Ru was populated by a completely mass symmetric system (^{48}Ti + ^{48}Ti) at 140 MeV and 150 MeV, where fu-

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TABLE I: Compilation of the systems studied in present work showing various characteristics of nuclei while formation and decay. The partial waves actually contributing to fusion are computed by HICOL model code.

Reaction	Mass asymm. (α)	E_{lab} (MeV)	E* (MeV)	Shape equi. time ($\times 10^{-22}$ sec)	Thermal equi. time ($\times 10^{-22}$ sec)	Formation Time ($\times 10^{-22}$ sec)	Decay Time ($\times 10^{-22}$ sec)	$\ell\hbar$ (CASCADE)	$\ell\hbar$ (HICOL)
^{16}O + ^{48}Ti	0.5	76	67	223.2	7.4	223.2	9.22	34	30
^{37}Cl + ^{27}Al	0.16	125	67	251.2	11.2	251.2	9.22	33	30
		45	36	23.5	17.6	23.5	276	10	11
^{16}O + ^{64}Zn	0.6	59	47	30.0	18.2	30.0	92.7	24	26
		89	71	45.3	8.3	45.3	20.7	41	36
		85	47	25.8	13.9	25.8	78.4	14	11
^{32}S + ^{48}Ti	0.2	94	52	35.8	23.0	35.8	71.6	24	27
		125	71	54.9	9.2	54.9	19.2	44	38
		140	59	41.1	24.8	41.1	72.6	26	25
^{48}Ti + ^{48}Ti	0	150	64	54.9	31.2	54.9	55.9	34	37

sion hindrance effects were found to be absent. Details of the measurements carried out with their formation and decay times are presented in Table I.

The light particles emitted from these reactions were used as a probe to study properties of the highly excited compound nucleus in the present work. Exclusive measurement of the particles emitted from the same compound nucleus were carried out to understand the reaction dynamics. From the observations in the present work, it is concluded that at higher energy and high excitation energy the mass symmetric system need modifications in ingredients of the statistical model in order to explain the experimental spectra. The higher partial waves are strongly hindered at these energies and inclusion of dynamical effects are needed to explain the charged particle spectra. Although this is not the only method which can be used to explain the particle spectra. Modifying the Yrast line by increasing the deformation parameter or the radius constant can also be used to explain the charged particle spectra. In case of neutrons emitted from mass symmetric systems at high excitation energy, the decrease in level density parameter is required to explain the evaporation spectra.

The emission barrier increases due to increase in deformation, which in turn suppresses the charged particle emission, but neutrons being neutral particles are not affected by the same and are emitted during initial stages of the reaction. The influence of dynamical effects of the particle spectra suggests that the longer formation time causes system to undergo pre-equilibrium emissions and preferential emission of neutrons take place suppressing the heavier α-particle emission (emitted when the compound nucleus starts to cool down). In case of completely mass symmetric system, no influence of the dynamical effects was observed at the energies studied. This points out the ambiguity in dependence of the anomalous particle distribution on the excitation energy. Further measurements of mass symmetric systems are needed to understand a clearer picture of the onset of anomaly in light particle spectra by employing advanced detection systems.

References

[1] I. M. Govil *et al.*, Phys Rev C **66** 034601 (2002).
[2] M. Kaur *et al.*, Phys Rev C **89** 034621 (2014).
[3] A. Kumar *et al.*, Phys Rev C **68** 034603 (2003).
[4] J. Kaur *et al.*, Phys Rev C **70** 017601 (2004).
[5] H. Arora *et al.*, DAE-BRNS **65** 253 (2021).
[6] H. Arora *et al.*, DAE-BRNS **64** 497 (2019).
[7] H. Arora *et al.*, DAE-BRNS **63** 672 (2018).