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Systematic study of projectile break-up on fusion cross-sections at energies ≈ 4-7 MeV/nucleon: Recent results

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In the present work, excitation functions of several reaction residues populated via complete fusion (CF) and incomplete fusion (ICF) processes have been measured at energies ≈ 4-7 MeV/nucleon. The analysis has been done within the framework of statistical model calculations which indicates significant ICF contribution in the α-emitting channels. The deduced complete fusion functions *F(x)* obtained from the EFs data are compared with the universal fusion function (UFF), where ≈ 10 - 35 % fusion suppression has been observed, indicating the prompt break-up (incomplete fusion) of the projectiles. The suppression factor for the present work strongly follows an exponential relation with the break-up threshold of the projectile.

KEYWORDS: Heavy-ion, Complete fusion, Incomplete fusion

1. Introduction

In recent years, widespread experimental and theoretical efforts have been employed to understand the dynamics of fusion reactions induced by heavy-ions (HI) at energies ≈ 4-7 MeV/nucleon. These HI fusion reactions also play an important role in the formation of super heavy nuclei that are far away from the valley of stability [1]. Generally, at these energies, the complete fusion (CF) process is considered to be the sole contributor to the total reaction cross-section. However, in the last couple of decades, significant observation of incomplete fusion (ICF) reactions [2,3] at these energies created a resurgent interest. Several theoretical models [4] have been proposed to understand the reaction dynamics of ICF, which are reliable up to some extent at energies ≥ 10.5 MeV/nucleon, but these models are unable to explain the ICF data precisely at energies < 10.5 MeV/nucleon. Further, most of the ICF studies has been done using the beams like

^{12}C, ^{16}O, ^{20}Ne etc., having α-cluster nature. However, the study using the non α-cluster beams ^{13}C, ^{14}N, ^{18}O, and ^{19}F are still limited. Hence, in the present work, it has been proposed to extend the investigation of ICF reaction dynamics using the non α-cluster beam. In the present work, an attempt has been made to understand the relative contribution of CF and/or ICF processes at low energies by measuring the excitation functions (EFs) of several reaction residues populated in ^{19}F + ^{175}Lu system. The analysis of EFs has been done within the framework of statistical model code PACE4 [5]. Further, an attempt has also been made to understand the effect of projectile break-up on fusion cross-section within the framework of universal fusion function (UFF)

2. Experimental details, data analysis and interpretations

The experiments have been performed at the ion beam facility of the Inter University Accelerator Centre (IUAC), New Delhi, India. The ^{19}F beam produced by the 15UD pelletron accelerator focused on ^{175}Lu target stack. The detailed explanation of experiments may be found elsewhere [4]. In the present work, 17 radionuclides viz., ^{190,189,188}Hg(*xn*) where x = 4-6, ^{190,189}Au(*pxn*) where, x = 3-5, ^{189,188,187,186}Pt(*αxn*), where x = 1-4, ^{187,186,185}Ir(*αpxn*), where x = 2-4, ^{183,182}Os(*2αxn*), where x = 3,4, and ^{181}Re(*2α4n*), have been identified respectively. The production cross-section of these radionuclides are analyzed within the framework of statistical model code PACE4. It has been observed that, the EFs of *xn* and *pxn* channels are well reproduced by the PACE4 model, indicating the production of these channels solely via CF process. However, in the case of α-emitting channels, the measured cross-sections show significant enhancement as compared to the PACE4 predictions. Since, PACE4 does not include the ICF calculations, therefore, the observed enhancement in the production cross-section may be attributed to the contribution coming from the ICF reactions over the entire range of energy. Further, an attempt has also been made to understand the role of strongly bound projectiles (^{19}F, ^{16}O, and ^{13}C having higher break-up threshold) break-up on fusion cross-section at energies above the Coulomb barrier. The complete fusion function $F(X)$ (where, $F(X)$ is a dimensionless fusion cross-section [see Ref.3 for more details]), has been deduced from the experimental EFs data and analyzed within the framework of UFF [6]. In the present work, the experimental fusion function has been obtained for six systems [4] viz., ^{19}F + ^{159}Tb, ^{19}F + ^{169}Tm, ^{19}F + ^{175}Lu, ^{16}O + ^{159}Tb, ^{169}Tm, and ^{13}C + ^{169}Tm respectively. The deduced CF fusion functions for strongly bound projectiles (^{19}F, ^{16}O, and ^{13}C) on different targets are plotted against the dimensionless parameter 'X' (reduced collision energy), illustrated in Fig. 1(a). As can be seen from this figure, the experimental fusion function for all the systems are suppressed by ≈ 10-35 % as compared to the UFF (solid line), owing to the prompt break-up of the projectiles; i.e., some part of flux has gone to the incomplete fusion reactions. Moreover, to understand the role of fusion suppression with respect to the break-up threshold energy ($E_{B.U.}$) of the projectile, an attempt has also been made to check the consistency of the above systematics for strongly bound projectile ^{19}F ($E_{B.U.}$ = 4.01 MeV). Fig. 1(b) represents the exponential relation between the suppression factor log(1-$F_{B.U.}$) (where, $F_{B.U.}$ is the suppression factor [7] obtained by fitting the experimental fusion functions with $X > 0$) in terms of $E_{B.U.}$. The suppression factor for the strongly bound projectile ^{19}F are deduced from fitting and by empirical equation given in Ref. [7] and are presented in Fig. 1(b). As can be seen from this figure, the suppression factor for ^{19}F projectile is found to be lower than for the weakly bound projectile ^{9}Be and higher than for the strongly bound projectile ^{10}B, which is related to the fact that the break-up threshold energy of ^{19}F is larger than that of ^{9}Be and smaller than that of ^{10}B. The present results for the ^{19}F projectile on different targets presented in Fig. 1(b) are found to be in good agreement with the systematics developed by Wang *et al*,. [7] and show a well-established exponential relation between the CF suppression factor and the break-up threshold of the projectile.

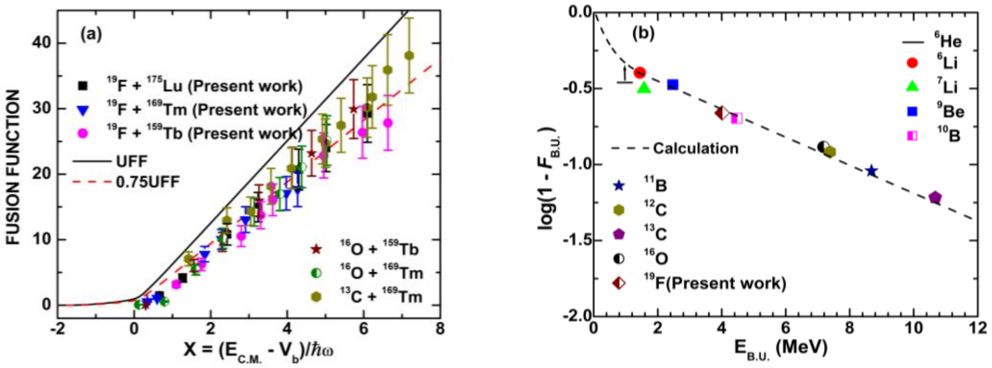

Fig. 1. (a) The complete fusion function for strongly bound projectiles on different target nuclei compared with UFF. The dotted red line is the UFF multiplied by 0.75. (b) The deduced suppression factor for the ^{19}F projectile is plotted as a function of the break-up threshold energy of the projectile.

3. Summary

The experimentally measured EFs of reaction residues populated in ^{19}F + ^{175}Lu system have been measured and analyzed within the framework of statistical model code PACE4. The deduced complete fusion functions from the EFs data for strongly bound projectiles are suppressed by ≈10-35% with respect to UFF. This clearly indicates the prompt break-up of strongly bound projectile. Moreover, the deduced suppression factor for ^{19}F (tightly bound) projectile, strongly depend on the break-up threshold energy of the projectile; i.e., the CF suppression is mainly determined by the break-up threshold of the projectile. Hence from the present analysis, it has been observed that, non α-cluster projectile ^{19}F shows significant fusion incompleteness in addition to strongly bound α-cluster projectiles and magnitude of fusion incompleteness can be understood on the basis on breakup threshold energy ($E_{B.U.}$) of the projectile.

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