Effects of Projectile Break-up on Fusion

Rahbar Ali[1]*, D. Singh[2], Harish Kumar[3], Suhail A. Tali[3], M. Afzal Ansari[3], Rakesh Kumar[4], K. S. Golda[4], S. Muralithar[4], R. P. Singh[4] and R. K. Bhowmik[4]

[1]Department of Physics, G. F. (P. G.) College, Shahjahanpur-242001, India
[2]*Department of Physics, Ranchi University, Jharkhand-202002, India*
[3]*Department of Physics, Aligarh Muslim University, Aligarh-202002, India*
[4]*Inter University Accelerator Centre, New Delhi-202002, India*
* email: rahbara@gmail.com

1. Introduction

In last couple few decades, great efforts have been made in the study of fusion process in heavy ion induced reactions [1-4]. It has been shown that at energies 5 MeV above the Coulomb barrier, the fusion process was playing an important role in reaction cross section [1-4]. The widely used statistical model code PACE-2 [5], describes the fusion cross section. While at higher energies, fusion process gives the way to incomplete fusion (ICF), where projectile fragmentation will takes place and decreasing the reaction cross section corresponding to the fusion. It has been experimentally established that complete fusion (CF) and incomplete fusion (ICF) is the dominating mode of reaction at energies above the coulomb barrier [1-4,6,7]. Fusion occurs when interacting nuclei have sufficient kinetic energy to overcome Coulomb barrier and are subsequently trapped inside the potential pocket to form the composite nucleus. On the other hand, if only part of the projectile, following break-up, fuses with the target nucleus, the process is called incomplete fusion (ICF). It is assumed that un-fused part does not interact with target nucleus and behaves as a spectator. However, first experimental evidence for ICF process was observed by Inamura *et al.,* [8]. Later, Glain *et al.,*[9], Parker *et al.,* [10] and Tserruya *et al.,* [11] also found evidence for ICF process. Studies on ICF using loosely bound projectiles have also been done by Gomes *et al.,* [12]. Ali *et al.,* [3], Singh *et al.,* [6] and others [2,7] have measured the excitation functions (EFs) and/or forward recoil range distributions (FRRDs) of the evaporation residues produced through CF and ICF in projectile-target systems. In view of the literature, very few studies are available with heavier targets (A>150) in lower energy range. With this aim, an attempt has been made to study ICF reaction in ^{16}O + ^{156}Gd reaction at projectile energy ranging~68-98 MeV.

2. Essentials of Experimental Setup

The experiment discussed here for the measurement of EFs was performed at 15UD Pelletron of Inter University Accelerator Centre, New Delhi. Beams of $^{16}O^{+7}$ ions with energy ~100 MeV from Pelletron focused on stack of the ^{156}Gd enriched targets (abundance ~ 94.6%) of thickness lying ~ 1.2-2.5 mg.cm^{-2} which is placed at the centre of the scattering chamber. In the present measurement, EFs for ^{16}O + ^{156}Gd system were measured using recoil catcher activation technique followed by γ-ray spectrometry. In the present experiment, targets for irradiation were taken in the form of the stacks of these target interspersed with thin aluminum foils. Irradiations of ^{156}Gd samples (each containing 4 and 3 samples respectively) were irradiated separately at projectile energy 100 MeV and 95 MeV to encompass the energy range between 68-98 MeV. Keeping in view the half-lives of interest, stack-I was irradiated for about 2 hours and for stack-II was irradiated for about 3 hours. After the irradiation, stacks of the targets along with Al degraders were taken out from the scattering chamber and induced activities produced in various targets along with Al degraders were recorded by pre-calibrated High Purity Germanium (HPGe) detector. The identification of the reaction products populated via CF and/or ICF have been done by the characteristic γ-rays of the reaction products and also by following their half-lives.

3. Results and Discussion

The excitation functions (EFs) of various radio-nuclides have been measured in the interaction of ^{16}O with ^{156}Gd at ~ 68-98 MeV beam energies. The residues are expected to be populated via CF and/or ICF of the projectile ^{16}O with the target nucleus ^{156}Gd. As a representative case, reaction products ^{166}Hf (6n) having half-lives 6.8 min are populated via 6n emission from the composite system $^{172}Hf^{*}$ produced through CF of ^{16}O with ^{156}Gd. Measured EFs are compare with statistical model code PACE-2 with different values of level density parameter (K = 8, 10, 12) to match the experimental values. It has been observed that the value of K =10 reproduces the measured EF data well.

Complete fusion of ^{16}O is as follows

$$^{16}O + {}^{156}Gd \Rightarrow {}^{172}Hf^{*} \Rightarrow {}^{166}Hf + 6n$$

One of another representative case, the reaction products ^{161}Er (2α3n) having half-life 3.24 hrs is produced in 2α-emitting channels. It has been observed that no theoretical predictions from PACE-2 are available. Hence, these residues are solely produced via ICF of ^{16}O (i.e. fusion of fragment ^{8}Be with the target ^{156}Gd), forming composite system $^{164}Er^{*}$, which decays by emission of 3n along with 2α-particles as spectator which moves in forward direction.

(i) Incomplete fusion of ^{16}O (i.e. fusion of fragment ^{12}C is)

$$^{16}O\,({}^{8}Be + 2\alpha) + {}^{156}Gd \Rightarrow {}^{8}Be + {}^{156}Gd$$

$$\Rightarrow {}^{164}Er^{*} \Rightarrow {}^{161}Er + 3n$$

(2α-particle as spectator)

We have observed that all the residues produced in α-particle cluster(s) emission, are due to projectile break-up. In the present measurement, we have studied the dependence of ICF fraction on projectile energy and entrance channel mass-asymmetry for $^{16}O+^{156}Gd$ system along with the previously measured systems: ^{16}O + ^{74}Ge [13], ^{16}O + ^{169}Tm [14], ^{20}Ne + ^{59}Co [15], ^{20}Ne + ^{165}Ho [16].

4. Conclusion

The excitation functions of various ERs have been measured in the energy range 68-98 MeV for $^{16}O+^{156}Gd$ system and have been compared with Statistical model code PACE-2. The measured EFs of the ERs populated via xn and pxn channels through CF process only. While the disagreement between measured EFs and calculated EFs in alpha emission products are most likely to be due to break-up of the projectile in (^{12}C+α) and/or (^{8}Be+2 α) which leads to ICF process. It has been observed that ICF probability increases with projectile energy. It has also been observed that ICF-fraction invariable increases with projectile energy. The present observation thus supports the Morgenstern *et al.,* [17]. In short, it has been observed that break-up probability of the projectile increases with projectile energy and mass-asymmetry of the interacting partners.

Acknowledgements

Authors wish to thank Chairman, Department of Physics AMU-Aligarh, for providing me experimental facility to carry out research experiment. Special thanks are given to the Director, IUAC-New Delhi for its kind hospitality and financial assistance. I am also grateful to the members of the Pelletron group for providing the good quality beam of $^{16}O^{+7}$ and their co-operation during the course of the experiment.

Reference

[1] D. J. Parker *et al.*, Phy. Rev C **30,** 143 (1984).
[2] B.S. Tomar *et al.*, Phy. Rev. C **49,** 941 (1994).
[3] Rahbar Ali *et al.*, NPA **968**, 403 (2017).
[4] H.C. Britt *et al.*, Phys. Rev. **124**, 877 (1961).
[5] A. Gavron, Nucl. Phys. C **21**, 230 (1980).
[6] D. Singh *et al.*, PRC **97**, 64604(2018).
[7] Harish Kumar *et al.*, PRC **99**, 34610 (2019).
[8] T. Inamura *et al.,* Phys. Lett. **68B,** 51 (1977).
[9] J. Glain *et al.*, PRC **9,** 1126 (1974).
[10] Parker *et al.*, Phy. Rev C **30**, 143 (1984).
[11] Tserruya *et al.*, PRL **60**, 14 (1988).
[12] Gomes *et al.*, Phys. Lett. **B601**, 20 (2004).
[13] D. Singh *et al.*, JPSJ **82,** 114201 (2013).
[14] P. P. Singh *et al.,* PLB **67**1, 20 (2009).
[15] D. Singh *et al.*, PRC **83**, 54604 (2011).
[16] D. Singh *et al.*, NPA**879**, 107 (2012).
[17] Morgenstern *et al., Phys. Rev. Lett.* **52** 1104 (1984).