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Complete and incomplete fusion reactions in the interaction of ^{16}O+^{55}Mn system below 7 MeV/A: Measurement and analysis of Excitation Functions

Sunil Dutt[1,2,a], Avinash Agarwal[2], Munish Kumar[2], Kamal Kumar[1], I. A. Rizvi[1], R. Kumar[3], and, A. K. Chaubey[4]

[1] *Department of Physics, Aligarh Muslim University, Aligarh, 202 002, INDIA*
[2] *Department of Physics, Bareilly College, Bareilly, 243 005, INDIA*
[3] *Nuclear Physics Group, Inter University Accelerator Centre, New Delhi, 110 067, INDIA*
[4] *Department of Physics, Addis Ababa University, Addis Ababa, ETHIOPIA*

Abstract. In this paper, we have made an attempt to measure the excitation functions for the evaporation residues identified in the interaction of ^{16}O+^{55}Mn system with a view to study the complete and incomplete fusion reaction dynamics in heavy ion induced reactions. The motivation of this experiment is to study the breakup of ^{16}O in reactions below 7 MeV/A and to compare the excitation functions for ^{12}C, ^{16}O and ^{20}Ne induced reactions with different targets leading to the same composite system (^{71}As in this case). PACE-4 and ALICE-91 have been used for the analysis with the same set of input parameters as those adopted in the case of ^{12}C+^{59}Co and ^{20}Ne+^{51}V systems. The measured excitation functions for a particular decay channel in the three cases (i.e. ^{12}C+^{59}Co, ^{16}O+^{55}Mn and ^{20}Ne+^{51}V) have been compared and found to obey Bohr's assumption in case of complete fusion channels. The effects of Coulomb barrier and other entrance channel parameters are found to be quite significant in determining the decay mode of the composite system. Further the incomplete fusion dynamics is also observed to be of considerable importance in the present energy region.

1 Introduction

Investigation of different reaction mechanisms involved in the Heavy Ion (HI) induced reactions e.g., complete fusion (CF), incomplete fusion (ICF) and direct reactions etc. have been a point of interest even at energies as low as 5 MeV/A. Recent studies report breakup of ^{12}C, ^{16}O and ^{20}Ne into ^{4}He, ^{8}Be and ^{12}C projectile fragments and their incomplete fusion with the target [1–5]. Long back, in 1950, Ghoshal in his famous experiment showed that proton and alpha projectiles forming the same compound nucleus decay similarly and thus corroborate the Bohr compound nucleus assumption [6]. The formation of a quasi stable compound nucleus through the absorption of the incident particle by the target nucleus and the disintegration of the compound nucleus by the emission of either the original incident particle (scattering) or the emission of another particle or a photon are the two successive processes according to this hypothesis to occur a nuclear reaction. For fairly heavy nuclei (Z>30), the intermediate compound state has a mean life which is long compared with the time a nucleon takes to cross the nucleus (10^{-21} to 10^{-22} seconds). As a result of the comparatively long mean life of the compound state, the second process is independent of the first [7]. Some more studies that are extension of Ghoshal's experiment have also been performed to compare proton induced reactions with heavy ion induced reactions leading to the same composite system [8, 9]. With the motivation to study the projectile structure and entrance channel effect on complete and incomplete fusion reactions and to repeat the Ghoshal like experiment with heavy ions, experiments have been performed with ^{12}C, ^{16}O and ^{20}Ne heavy ion projectile beams with low mass target nuclei leading to the formation of same compound nucleus. To the best of our knowledge the excitation functions for ^{16}O+^{55}Mn system have been reported for the first time. The experimentally measured excitation functions are then compared with the values calculated using statistical model codes ALICE-91 and PACE-4 [10–12]. The paper is organised as follows. In section-2 the details of the experimental setup and procedure are discussed. The results obtained and their analysis is presented in section-3, while brief summary and conclusions of the study are discussed in section-4.

2 Experimental Details

The experiments for ^{16}O+^{55}Mn and ^{12}C+^{59}Co systems have been performed at the Inter University Accelerator Centre (IUAC), New Delhi, India using the 15UD accelerator facility. However, the experiment for ^{20}Ne projectile has been carried out at the Variable Energy Cyclotron Centre (VECC), Kolkata, India using the 6+ charge state beam. The irradiations have been carried out in the General Purpose Scattering Chamber (GPSC) having an in-vacuum transfer facility (ITF) using conventional recoil-catcher technique. The ITF has been used to minimise the

[a] e-mail: sunilduttamu@gmail.com

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Table 1. List of identified Evaporation Residues (ERs) and their spectroscopic data used in the present study.

Reaction	Half-Life $T_{1/2}$	Spin-Parity J^{π}	E_{γ} (keV)	(I_{γ}%)
^{69}As(2n)	152 m	4^{+}	232.73	10.9
^{69}Ge(pn)	1.627 h	$5/2^{-}$	574.10	13.3
			1106.77	36.0
^{67}Ge(p3n)	18.9 m	$1/2^{-}$	167.05	84.0
^{66}Ge(p4n)	2.26 h	0^{+}	190.26	5.7
			273.02	10.5
			470.59	7.4
			536.67	6.2
^{68}Ga(2pn)	1.135 h	1^{+}	1077.29	3.0
^{67}Ga(2p2n)	3.261 d	$3/2^{-}$	97.31	37.0
			184.58	20.4
			300.22	16.6
			393.53	4.6
^{66}Ga(αn)	9.49 h	0^{+}	833.58	6.0
			1039.35	37.9
			1333.21	1.2
^{65}Ga(α2n)	15.2 m	$3/2^{-}$	115.15	55.0
			153.07	9.0
			751.89	8.2
^{63}Zn(αp3n)	38.1 m	$3/2^{-}$	669.76	8.4
			596.70	6.6
^{62}Zn(αp4n)	9.26 h	0^{+}	548.38	15.2
			596.70	25.7
^{61}Cu(2α2n)	3.333 h	$3/2^{-}$	282.96	12.5
			656.01	10.7
			1185.24	3.7

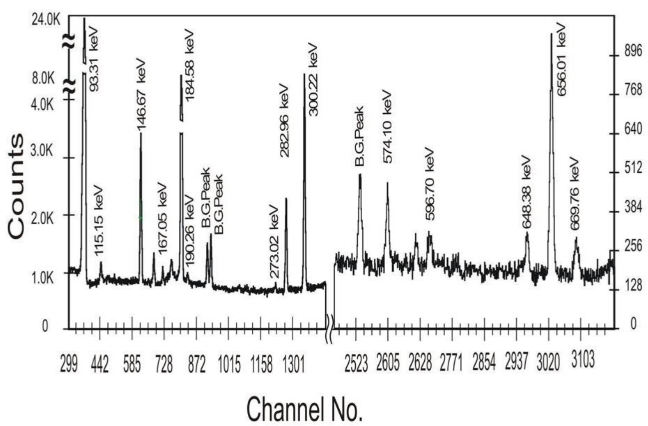

Figure 1. Typical ≈-ray spectrum of ^{16}O+^{55}Mn system obtained from irradiations at ≈81.15 MeV projectile energy. The energies of the identified peaks are given in keV.

lapse time between the stop of irradiations and the beginning of the counting of the activity.

The self-supporting targets of ^{55}Mn of thickness 1 mg/cm^2 have been prepared by using vacuum evaporation technique, while the Aluminium catcher foils of thickness 1.97 mg/cm^2 have been prepared by rolling technique. A stack containing ^{55}Mn targets has been irradiated by a 7+ charge state O-16 beam at 100 MeV energy to cover the desired energy range of ≈50-100 MeV for measuring the excitation functions of radio nuclide produced in the interaction. Thick Al-catchers has been placed behind the each target foil so that the recoiling products may be trapped in the catcher foil thickness during the irradiations of the target. The thickness of the targets and aluminium foils were determined by the 5.487 MeV alpha particles from a ^{241}Am source while passing through the material of the target. The incident beam energy on each target foil in the stack has been estimated using the code SRIM [13]. Considering the half-lives of interest, the irradiation has been carried out for ≈ 6.5 hrs duration. An average beam current of ≈ 49nA has been maintained during the experiment. The two Rutherford monitors (SSB detectors) have been also kept at 10^0 to the beam direction to monitor the flux of the incident projectile beam. The incident flux has been determined from the charge collected in Faraday cup installed behind the target-catcher assembly as well as from the counts of the two Rutherford monitors. After irradiation the activities induced in the target-catcher assemblies has been counted using a pre-calibrated CANBERA's HPGe detector coupled to the IUAC developed data acquisition system FREEDOM [14] based on CAMAC. As a representative case a typical γ-ray spectrum has been shown in Fig. -1. The efficiency and energy calibration of HPGe detector has been done using various standard sources, i.e. ^{152}Eu, ^{60}Co and ^{133}Ba of known strength. The post analysis of the γ-ray spectra has been done using CAMAC based data acquisition system CANDLE [15] in offline mode. The evaporation residues produced in the reaction have been identified by their characteristic γ-rays and confirmed by their half-life measurements. Proper care has been taken to keep the dead time of the detector ≤10% by suitably adjusting the source-detector separations. However, the overall errors have been estimated to ≤17%, excluding the uncertainty in branching ratio, decay constant etc., which have been taken from the Table of Radioactive Isotopes [16]. The production cross-section of the evaporation residues have been computed using the standard formulation as given in Ref [18]. The detailed description of the experimental procedure etc. used for the ^{12}C+^{59}Co and ^{20}Ne+^{51}V systems is given elsewhere [4, 5, 17].

3 Results and Analysis

In the present experiment excitation functions (EFs) for residues produced in the ^{16}O+^{55}Mn system via CF and/or ICF processes were measured at projectile energies up to 100 MeV. To investigate the ICF reaction dynamics, the excitation functions for the reactions ^{55}Mn (O,2n) ^{69}As, ^{55}Mn (O,pn) ^{69}Ge, ^{55}Mn (O,p3n) ^{67}Ge, ^{55}Mn (O,p4n) ^{66}Ge, ^{55}Mn (O,2pn) ^{68}Ga, ^{55}Mn (O,2p2n) ^{67}Ga, ^{55}Mn (O,αn) ^{66}Ga, ^{55}Mn (O, α2n) ^{65}Ga, ^{55}Mn (O, αp3n) ^{63}Zn, ^{55}Mn (O, αp4n) ^{62}Zn and ^{55}Mn (O, 2α2n) ^{61}Cu have been measured. The cross sections from a given reaction channel were determined separately from the observed intensities of all possible identified γ-rays, arising from the same radionuclide. The reported values are the weighted average of the various cross-section values obtained [19].

The theoretical predictions of the excitation functions have been done with the statistical model codes, ALICE-

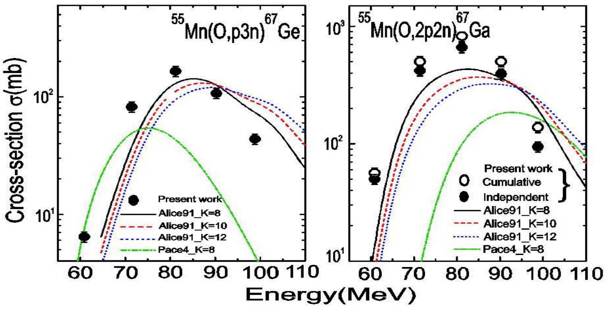

Figure 2. (Color online) Experimental and theoretical excitation functions for the production of complete fusion channels p3n (^{67}Ge) and 2p2n (^{67}Ga) in the ^{16}O+^{55}Mn system. Theoretical predictions of the code ALICE-91 are shown by solid, dash and dot curves for level density parameter constant K=8,10 and 12 and by dash-dot curve for K=8 for PACE-4. The dark circles represent the measured cross-section with associated errors. Open circles represent the cumulative cross-section for the production of ^{67}Ga isotope.

91 [10, 11] and PACE-4 [12]. The PACE-4 code uses a Monte Carlo procedure to determine the decay sequence of an excited nucleus using the Hauser-Feshbach formalism. This formalism takes angular momentum directly into account. The angular momentum projections are calculated at each stage of de-excitation, which enables the determination of the angular distribution of emitted particles. However, the code ALICE-91 is based upon Weisskopf-Ewing model [20] for compound nucleus calculations and Hybrid model [10] for pre-equilibrium calculations. Exciton number N_0, mean free path multiplier COST and level density parameter a (= A/K, where A is the atomic mass of the compound system and K is the level density parameter constant) are some of the important parameters out of many input parameters used in the code. The initial exciton number N_0 and COST chiefly administrate pre-equilibrium contribution, while the parameter 'a' governs mainly the equilibrium component. The higher value of parameter N_0 diminishes the involvement of pre-equilibrium emission and settles on the convolution of the initial configuration, if present. For this system of ^{16}O+^{55}Mn, N_0=16 has been occupied for the theoretical calculations and these predictions are found to be in good agreement with the experimentally measured excitation functions. N_n=8, N_p=8 and N_h=0 along with level density parameter constant K= 8, 10 and 12 has been taken for the present case. As the heavy ion induced reactions involve large angular momenta and Weiskopf-Ewing model calculations do not include angular momentum effects, the excitation functions have been shifted by an amount equal to E_{rot}= (m/M)E_{Lab}, where E_{Lab} is the projectile energy, m is mass of projectile and M is mass of target. Some of the experimentally measured excitation functions along with theoretical predictions have been shown in Figs. 2&3. Theoretical predictions by ALICE-91 have been found to be in good agreement for complete fusion channels and have been shown in the Fig. 2. The PACE-4 predictions could not reproduce the experimental data points, however the trend is found to be same as shown in Fig 2. Hence, ALICE-91 predictions have been adopted for the further

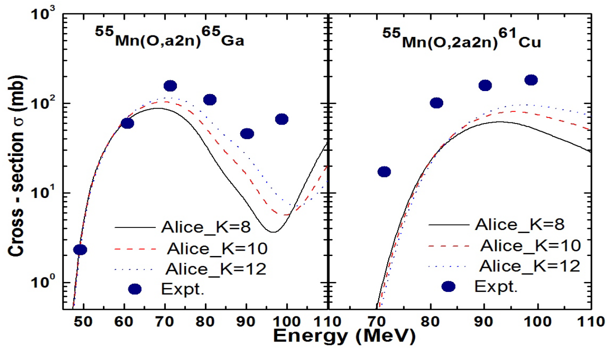

Figure 3. (Color online) Experimental and theoretical excitation functions for the production of incomplete fusion channels α2n (^{65}Ga) and 2α2n (^{61}Cu) in the ^{16}O+^{55}Mn system. The other details are same as in Fig. 2.

analysis of this system. The evaporation residues ^{69}Ge (pn), ^{67}Ga (2p2n) and ^{66}Ga (αn) have been found to have precursor contributions from higher charge isobars ^{69}As (2n), ^{67}Ge (p3n) and ^{66}Ge (p4n) respectively. The independent production cross-section (σ_{ind}) of daughter nuclei may be calculated by using the following expression as given by Cavinato et al. [21]

$$\sigma_{cum} = \sigma_{ind} + F_{pre}\ \sigma_{pre}$$

where σ_{cum} and σ_{pre} are the cumulative yield of the daughter residue and independent contribution of the precursor, and F_{pre} stands for precursor fraction. Since, ALICE-91 does not take ICF into account, therefore the enhancement of experimental cross-sections over ALICE-91 predictions for α-emitting channels have been featured to the contribution coming from incomplete fusion processes as these residues may not only be populated via complete fusion but incomplete fusion is also playing an important role. The value of incomplete fusion cross-section for α- emitting channels has been calculated by subtracting the theoretical cross-section from the experimental values ($\Sigma\sigma_{ICF} = \Sigma\sigma_{exp} - \Sigma\sigma_{ALICE-91}$) and has been plotted in Fig. 5 along with the total complete fusion $\Sigma\sigma_{CF}$ and total reaction cross section, σ_{TF} (= $\Sigma\sigma_{CF} + \Sigma\sigma_{ICF}$).

As given in Ref. [22], the value of $\Sigma\sigma_{CF}$ has been corrected by using the ALICE-91 predictions in order to incorporate the missing complete fusion channels due to the limitations of the technique. The variation of probability of incomplete fusion fraction $\%F_{ICF} = (\Sigma\sigma_{ICF} / (\Sigma\sigma_{CF} + \Sigma\sigma_{ICF})) * 100$, with the projectile energy has been deduced and is shown in Fig. 5. To corroborate the Ghoshal's experiment for heavy ions as the projectile, the measured excitation functions for the same decay channels in the three cases of ^{12}C+^{59}Co, ^{16}O+^{55}Mn and ^{20}Ne+^{51}V forming the same compound nucleus ^{71}As have been studied. In Fig. 4, comparison of the measured excitation functions for complete fusion channel, p3n and incomplete fusion channel, α2n have been presented with respected to the projectile energy for the three systems. In order to bring the peaks of p3n channel into approximate correspondence for the three systems, an energy shift of 9 MeV for ^{12}C+^{59}Co and 8 MeV for ^{20}Ne+^{51}V systems have been made with respect to the ^{16}O+^{55}Mn system. Different values of cross-sections have been observed for the same decay channel for C, O and Ne projectiles. This difference

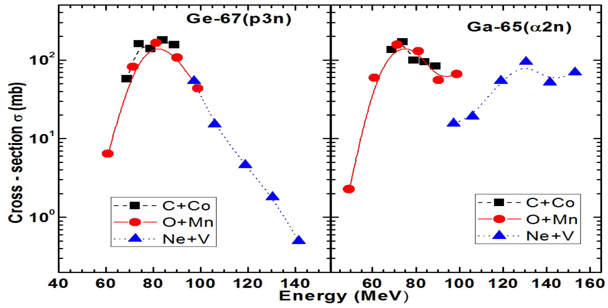

Figure 4. (Color online) Experimental cross-sections for complete fusion channel p3n and incomplete fusion channel α2n for ^{12}C+^{59}Co, ^{16}O+^{55}Mn and ^{20}Ne+^{51}V systems plotted against the respective projectile energies. The lines are drawn to guide the eyes.

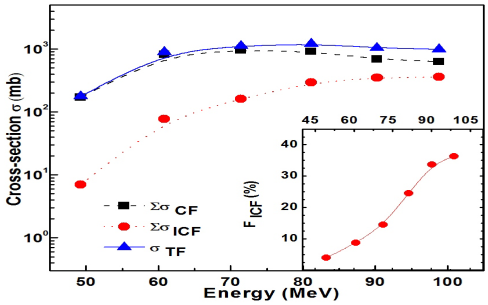

Figure 5. (Color online) Total fusion cross-section (σ_{TF}) along with the sum of complete ($\Sigma\sigma_{CF}$) and incomplete fusion ($\Sigma\sigma_{ICF}$) contributions for ^{16}O+^{55}Mn system at 50-100 MeV. (Inset) Variation of probability of incomplete fusion (%F_{ICF}) has been plotted as a function of incident projectile energy. The lines are drawn to guide the eyes.

may be due to the different values of Coulomb barrier and /or projectile structure.

4 Summary and Conclusions

In the present work, the excitation functions of several evaporation residues populated through complete and incomplete fusion channels have been measured in the energy range of 3-7 MeV/A. The independent cross-section has been deduced from the cumulative and precursor decay contributions for the residues ^{69}Ge, ^{67}Ga and ^{66}Ga. The value of $\Sigma\sigma_{CF}$, $\Sigma\sigma_{ICF}$ and σ_{TF} have been calculated and $\Sigma\sigma_{ICF}$ has been found to increase with the projectile energy. The observed increasing trend of %F_{ICF} with the projectile energy indicates that the breakup probability of incident projectile increases with the increase in projectile energy (i.e. ^{16}O breaks in to ^{12}C+α / ^{8}Be+^{8}Be and/or 4α-clusters). The trend of the decay mode for the three systems has been found to be the same for complete fusion channels, however different shape for α-emitting channels shows breakup of projectile before compound nucleus formation. Hence, supporting the fact that the complete fusion of projectile takes place for xn and/or pxn channels, and incomplete fusion takes place for α-emitting channels.

In this study, we found the validation of Ghoshal's experiment also for heavy ion projectiles viz. ^{12}C, ^{16}O and ^{20}Ne, induced reactions. The difference in the cross-sections of projectiles for a particular channel populated via three different entrance channels as a function of projectile energy is due to the difference in the Coulomb barriers of the systems.

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