Experimental study of cross sections in the $^{12}C + {}^{27}Al$ system at ≈3–7 MeV/nucleon relevant to the incomplete fusion process

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Background: The reaction mechanism in the low mass region particularly at low projectile energies in heavy-ion fusion processes has not been fully understood. More and more experimental data on fusion processes are required for the accurate description of reaction processes involved at low projectile energies. In the literature, cross section data for the fusion process using a ^{12}C beam in the lower mass region and at low projectile energies are scarce.
Purpose: To understand the dynamics of fusion processes and to test various existing theoretical models, the measurements of reaction cross sections in the $^{12}C + {}^{27}Al$ system have been carried out.
Method: The experiments were performed for the measurement of the cross sections for the residues produced in the interaction of the ^{12}C ion with a ^{27}Al target nucleus at 20 different energies covering the energy range from ≈39 to 85 MeV. The off-line γ-ray spectrometry based activation technique has been used to measure the cross sections.
Results: The measured excitation functions were compared to those evaluated with the code PACE4 based on the statistical approach and Monte Carlo procedure. The enhancement of experimental cross sections as compared to the theoretical predictions of code PACE4 has been observed. The SUMRULE model predictions indicate that incomplete fusion processes are associated with smaller values of the angular momenta than that of its critical value required for complete fusion processes.
Conclusions: In the lower mass region, phenomena such as incomplete fusion and direct reaction processes are of importance even at energies as low as ≈3–7 MeV/nucleon, where fusion evaporation channels are expected to be dominant.

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I. INTRODUCTION

Recently, much attention has been paid in the study of low energy heavy ion (HI) nuclear interactions to understand the reaction mechanisms involved. The observed familiar fusion or fusion-like phenomena at the low energy nuclear reaction mechanisms such as complete fusion (CF), incomplete fusion (ICF), and direct reaction (DR) have been extensively studied in the heavy mass target region [1–11]. Fusion between two nuclei may occur when the projectile overcomes barriers resulting from the long-range repulsive Coulomb potential and reach the short-range attractive nuclear potential. This leads to various fusion phenomenon, viz., (i) CF: defined as the capture of all the charge and mass of the projectile by the target nucleus, forming an equilibrated compound nucleus; (ii) ICF: in which the projectile is assumed to break up in the vicinity of the field of the target nucleus into the fragments called projectile-like fragments (PLFs) and only one of the PLFs fuses with the target nucleus, while the remnant continues to move in the forward cone with approximately the same velocity as that of the incident ion; and (iii) DR: in which the interaction of the projectile with a single or a few nucleons of the target nucleus takes place.

The reaction mechanism of CF is well understood from both experimental [1–3] and theoretical physics points of view. In spite of the availability of plenty of experimental data and various ICF models [12–19], a complete and satisfactory description of the CF and ICF simultaneous processes has yet to emerge. Even the Mogenstern *et al.* [20,21] study of the mass-asymmetry dependence of ICF prescription is unable to successfully explain the ICF data at the relatively low energies of ≈3–7 MeV/nucleon.

As such, the study of HI reaction dynamics is still an active area of investigation at low projectile energies. Despite the absence of satisfactory theoretical models, investigated experimental data of reaction cross sections may help in elucidating the important parameters that must be included in the modeling of CF and ICF processes. Most of the experimental studies have been confined to heavier mass target nuclei [1–11]; however, in the lower mass region, the experimental data are much less [22,23]. With this motivation, in the present work the measurement and analysis of the excitation functions (EFs) for reactions produced in the $^{12}C + {}^{27}Al$ system have been carried out in the energy range from ≈39 to 85 MeV, using off-beam

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γ-ray spectrometry. This paper is organized as follows. The experimental details are discussed in Sec. II. The analysis of the data is given in Secs. III and IV. The conclusions of the present study are given in Sec. V.

II. EXPERIMENTAL DETAILS

The experiments were carried out in the general purpose scattering chamber (GPSC), using 15 UD Pelletron accelerator facility at the Inter University Accelerator Centre (IUAC), New Delhi, India. Spectroscopically pure self-supporting foils of ^{27}Al (purity $\approx$99.999%) of thickness $\approx$1.2–2.5 mg/cm^2 were prepared by the rolling technique. In this experiment, six stacks (each consisting of three to four targets) were irradiated by a $^{12}C^{6+}$ beam at energies $\approx$57, 68, 71, 76, 83, and 85 MeV. The irradiation of these stacks covered the desired energy range from $\approx$38 to 85 MeV, maintaining a constant beam current of $\approx$3 pnA. The total charge collected in the Faraday cup was used to calculate the flux of the incident beam. The activities induced in the irradiated samples were recorded individually using a high purity germanium detector (HPGe) (resolution $\approx$2 keV for 1.33 MeV γ ray of ^{60}Co) coupled to a PC based multichannel analyzer setup employing FREEDOM software.

As a typical case, the observed γ-ray spectra indicating the γ rays 146.5 and 1368 keV corresponding to the residues ^{34m}Cl and ^{24}Na, respectively at $\approx$42 MeV, are shown in Figs. 1(a) and 1(b). Further confirmation of these γ rays was performed by measuring the half-lives (decay curves) of these residues. A list of the observed reactions, energy of identified γ rays, branching ratios [24], and their half-lives are given in Table I.

The measured intensities of the observed characteristic γ rays of the residues populated in the reactions ^{27}Al(^{12}C, $\alpha\, n$)^{34}Cl, ^{27}Al(^{12}C, $2\alpha\, 3p$)^{28}Mg, and ^{27}Al(^{12}C, $3\alpha\, 2pn$)^{24}Na were used to determine the cross sections by using standard formulations [23]. The measured values of the cross sections are given in Table II. In the literature, the cross sections for the residues ^{34}Cl and ^{24}Na produced in the ^{12}C + ^{27}Al target nucleus also exist [25,26], measured by using different techniques with large energy uncertainties.

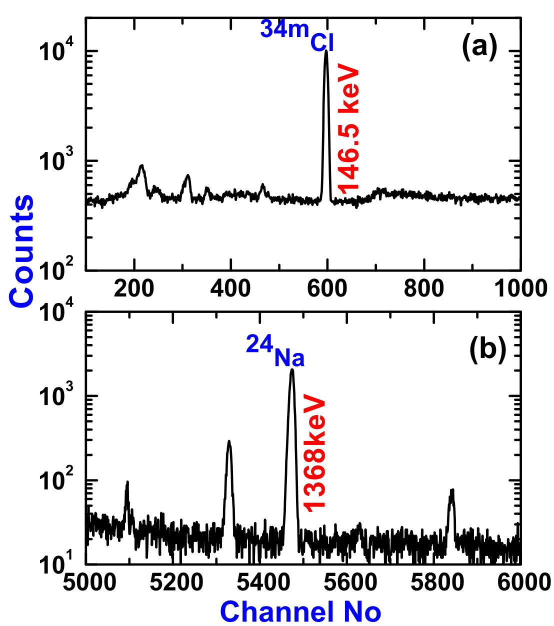

FIG. 1. (Color online) Observed γ-ray spectrum of a ^{27}Al sample irradiated by $^{12}C^{6+}$ beam at $\approx$42 MeV.

TABLE I. Reaction studies, including identified γ rays, their branching ratios, and measured half-lives.

Reaction	Measured half-life	E_γ (keV)	a_γ (%)
^{27}Al(^{12}C, $\alpha\, n$)^{34}Cl	32.0 m	146.5	40.5
^{27}Al(^{12}C, $2\alpha\, 3p$)^{28}Mg	20.9 h	400.5	36.0
		1342.3	54.0
^{27}Al(^{12}C, $3\alpha 2pn$)^{24}Na	14.6 h	1368.0	100.0

III. ANALYSIS OF EF WITH CODE PACE4

Based on a statistical approach and the Monte Carlo procedure, the estimation of reaction cross sections (using the Bass formula [27]) was done with the code PACE4 [28]. In this code, the optical model parameters for neutron, proton, and α emission were taken from Perey and Perey [28]. The γ-ray strength functions for $E1$, $E2$, and $M1$ transitions were taken from the tables of Endt [29]. This code has been modified to take into account the excitation energy dependence of level density parameter using the prescription of Kataria *et al.* [30]. The level density used in this code is calculated from the expression $a = (A/K)$, where A is the mass number of the compound nucleus and K is a free parameter taken as K=10. The analysis of the present system was performed by the same set of parameters of code PACE4 as used in the analysis the other target systems using HI beams [3,7–10,23,31]. In the

TABLE II. Experimentally measured residual cross sections.

E_{lab} (MeV)	σ(^{34}Cl) (mb)	σ(^{28}Mg) (mb)	σ(^{24}Na) (mb)
39.1 ± 1.4	74.43 ± 7.53		0.57 ± 0.07
42.0 ± 1.3	125.06 ± 12.7		0.86 ± 0.09
48.5 ± 1.2	118.69 ±11.4		2.95 ± 0.39
52.5 ± 1.1	56.71 ± 5.77	0.06 ± 0.01	3.28 ± 0.42
56.4 ± 1.1	35.35 ± 3.13	0.08 ± 0.01	3.35 ± 0.35
56.7 ± 1.1	25.78 ± 2.41	0.09 ± 0.02	3.27 ± 0.45
58.8 ± 1.2	15.32 ± 1.53	0.33 ± 0.05	4.22 ± 0.45
59.5 ± 1.1	15.25 ± 1.52	2.24 ± 0.24	2.89 ± 0.26
64.1 ± 1.1	8.95 ± 0.89	4.57 ± 0.52	1.52 ± 0.17
64.8 ± 1.0	9.51 ± 0.96	4.31 ± 0.57	1.87 ± 0.19
67.3 ± 1.1		3.87 ± 0.40	2.16 ± 0.17
69.4 ± 1.1	16.32 ± 1.55	1.25 ± 0.19	2.89 ± 0.29
70.0 ± 1.2		1.20 ± 0.13	2.50 ± 0.23
72.5 ± 1.1	23.45 ± 2.26	1.25 ± 0.2	3.68 ± 0.41
76.2 ± 1.1	37.65 ± 3.48	0.72 ± 0.09	2.65 ± 0.31
77.3 ± 1.2	34.81 ± 3.51	0.57 ± 0.08	2.61 ± 0.15
80.0 ± 1.0	40.29 ± 4.10	0.98 ± 0.10	3.91 ± 0.32
81.1 ± 1.1	21.45 ± 2.14	0.64 ± 0.05	2.63 ± 0.28
82.1 ± 1.1	6.78 ± 0.76	0.68 ± 0.08	2.35 ± 0.23
85.0 ± 1.0	2.58 ± 0.25	1.26 ± 0.11	2.60 ± 0.28

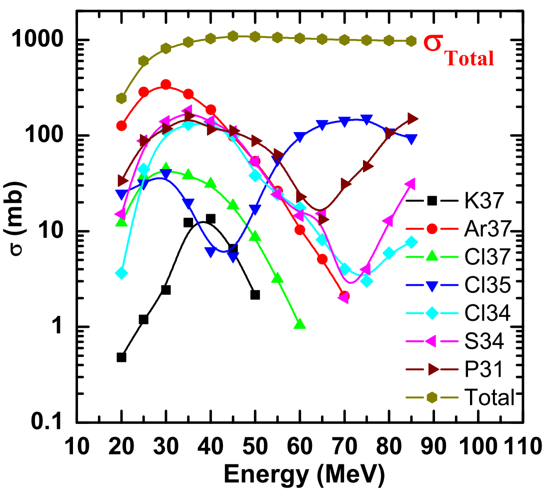

FIG. 2. (Color online) Calculated EFs for dominant reaction channels and total fusion cross sections obtained from PACE4 code in the $^{12}C + ^{27}Al$ system.

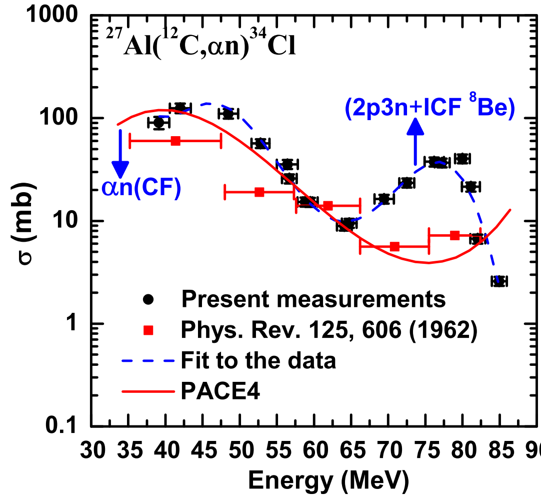

FIG. 3. (Color online) Experimentally measured and theoretically calculated cross sections for the reaction $^{27}Al(^{12}C,\alpha n)^{34}Cl$ along with the measured cross sections by Landenbauer-Bellis *et al.* [25].

present measurements, most of the CF residues produced were either stable or very short lived and could not be detected because of the limitation of the technique used, while PACE4 calculations for CF (xn and pxn) channels gave satisfactory reproduction of the experimental data [3,7–10,23,31]. Thus, the calculated CF yields from the code PACE4 are taken into account for comparison purposes to determine ICF yields for α-emitting channels. The calculated EFs for some dominant reaction channels and total fusion cross sections obtained from PACE4 code are shown in Fig. 2. The solid curves represent the fit to the PACE4 calculations. As can be observed from Fig. 2, the residue ^{34}Cl produced via the $^{27}Al(^{12}C, \alpha\, n)$ reaction channel is the dominant one.

The residue ^{34}Cl has both metastable and ground states. In the present work, only the metastable state of the residue ^{34}Cl was observed. The production cross sections of the metastable residues ^{34m}Cl were converted into the total cross section of the residue ^{34}Cl by using standard radioactive decay method [23] and is shown in Fig. 3 along with PACE4 calculations. The measured values of cross sections by Landenbauer-Bellis *et al.* [25], having large uncertainties in the energy, are also shown in Fig. 3 for comparison. The measured values of cross sections in the lower projectile energy region of Fig. 3 are well reproduced by PACE4 calculations, suggesting the contribution of the $\alpha\, n$ channel from complete fusion, while at higher bombarding energies both the trend and magnitude of measured cross sections are different as predicted by PACE4, indicating the contribution from the $2p3n$ reaction channel; therefore one cannot completely rule out that a change of parameters in PACE4 might explain the data. It also suggests that the α breakup of ^{12}C leads to a behavior by the ^{8}Be ICF process which might be responsible for the observed experimental enhancement over PACE4 predictions at higher energies [3,8,23,31].

The theoretical calculations performed for the production of the residue ^{28}Mg in the reaction $^{27}Al(^{12}C,2\alpha 3p)$ give negligible cross-section values and hence they are not shown in the Fig. 4. Thus, the observed enhancement by a few orders of magnitude over their negligible theoretical predictions for this channel may be attributed to the fact that the residues ^{28}Mg are not likely to be populated by the CF process but may contribute due to ICF processes.

The experimentally measured cross sections for the reaction $^{27}Al(^{12}C,3\alpha 2pn)^{24}Na$ is shown in Fig. 5, where the dashed lines guide to the experimental data. The observed enhancement by several orders of magnitude over their negligible theoretical predictions for this channel and no conclusive trend of EFs may be attributed to the fact that the residues ^{24}Na are not likely to be populated by CF and ICF processes but via the direct reaction mechanism. Landenbauer-Bellis *et al.* [25]

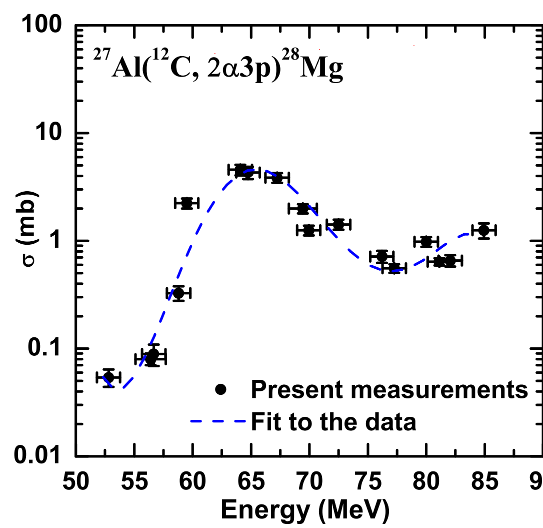

FIG. 4. (Color online) Experimentally measured cross sections for the reaction $^{27}Al(^{12}C,2\alpha 3p)^{28}Mg$.

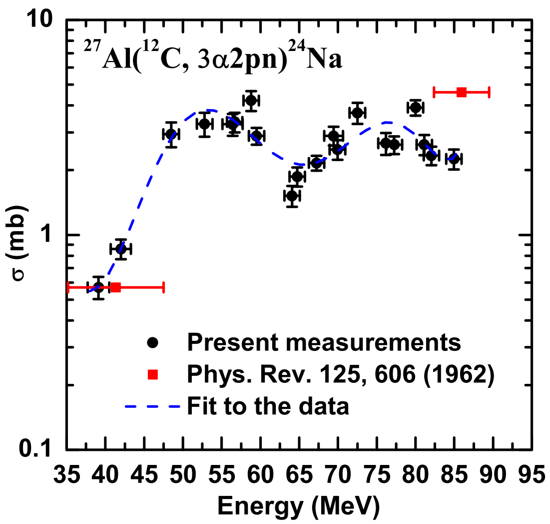

FIG. 5. (Color online) Experimentally measured cross sections for the reaction ^{27}Al(^{12}C,$3\alpha 2pn$)^{24}Na. The measured values of the cross sections for the residue ^{24}Na by Landenbauer-Bellis *et al.* [25] are also shown for comparison.

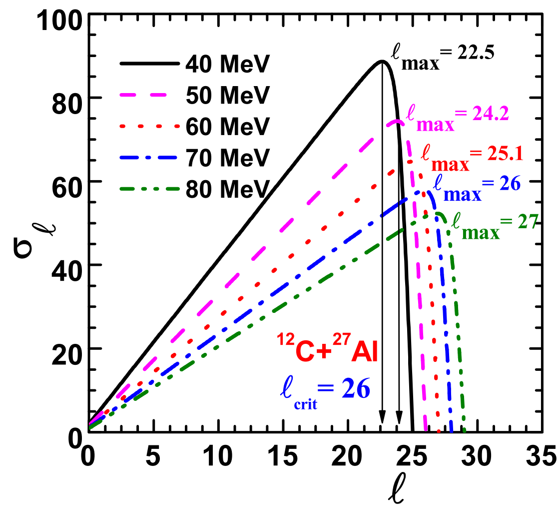

FIG. 6. (Color online) Fusion ℓ distributions calculated by using the code CCFULL for the $^{12}\mathrm{C}+{}^{27}\mathrm{Al}$ system at $E_{\mathrm{lab}} = 40, 50, 60, 70$, and 80 MeV, respectively.

have also indicated the production of the residues ^{24}Na by the direct reaction process.

IV. ANALYSIS WITH SUMRULE MODEL

The SUMRULE model calculations [32,33] have also been performed for the dominant ICF channels populated in the system $^{12}\mathrm{C}+{}^{27}\mathrm{Al}$. The details of SUMRULE model are given in a recent publication [31]. As a typical example, the experimentally measured cross section for the reaction ^{27}Al(^{12}C, $\alpha\, n$)^{34}Cl is 40.29 ± 4.1 mb at $\approx$80 MeV; however, the prediction of the SUMRULE model is $\approx$0.138 mb only. The disagreement between the presently measured and SUMRULE calculations for ICF channels may invalidate the concept of critical angular momentum at these low projectile energies. As such, the present findings indicate a diffused boundary in ℓ space which may penetrate close to the barrier, such that the fusion may take place even for $\ell < \ell_{\mathrm{critical}}$. Figure 6 shows the fusion ℓ distributions for the $^{12}\mathrm{C}+{}^{27}\mathrm{Al}$ system calculated using the code CCFULL [34] at energies 40, 50, 60, 70, and 80 MeV. The values of $\ell_{\max}$ below 70 MeV are found to be are less than the ℓ_{critical} ($26\hbar$) for fusion for the present system. As such, the ICF contributions are expected to be negligible at these energies. However, the present analysis indicates that a significant number of partial waves below ℓ_{critical} may contribute to ICF channels.

V. CONCLUSIONS

The EFs for reactions ^{27}Al(^{12}C,αn)^{34}Cl, ^{27}Al(^{12}C,$2\alpha 3p$)^{28}Mg, and ^{27}Al(^{12}C,$3\alpha 2pn$)^{24}Na in the $^{12}\mathrm{C}+{}^{27}\mathrm{Al}$ system were measured in the energy range $\approx 39-85$ MeV. Theoretical calculations based on code PACE4 with physically accepted parameters were performed. The analysis of the data indicates that in the reaction channel ^{27}Al(^{12}C,αn)^{34}Cl, the residues ^{34}Cl are populated through CF and ICF processes.

The residues ^{28}Mg (half-life = 20.9 h) were identified by the characteristic γ rays of 400.6 keV (35.9%) and 1342.3 keV(54.0%) which have independent modes of decay. However, the residue ^{28}Mg decays to its daughter nuclides ^{28}Al by electron capture through some others γ lines 972.2 keV(0.10%), 1372.8 keV(4.7%), and 1620 keV (0.3%) of low intensities which could not be observed. Since the experimentally measured cross sections are a few orders of magnitude higher than the calculations based on the PACE4 code, the production of the residue ^{28}Mg in the reaction ^{27}Al(^{12}C,$2\alpha 3p$)^{28}Mg is attributed to contributions from the ICF of ^{12}C.

The residue ^{24}Na (half-life = 14.6 h) produced in the reaction ^{27}Al(^{12}C,$3\alpha 2pn$) was identified by the characteristic γ ray of 1368 keV (100%). Since the mass number of residue ^{24}Na is very close to mass of the target ^{27}Al, the production of residues ^{24}Na are due to the direct reaction mechanism by stripping of two protons and one neutron from the target nucleus as pointed out by Landenbauer-Bellis *et al.* [25]. The SUMRULE model predictions for the present system concludes that ICF is associated even at smaller values than that of the critical value of the angular momentum for CF process.

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