Projectile and Target Fragmentation in the Interaction of
$^{12}$C and $^{27}$Al


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Abstract. The emission of intermediate mass fragments (IMFs) produced in the inclusive $^{12}$C+$^{27}$Al and $^{27}$Al+$^{12}$C reactions at incident energies corresponding to a c.m. excitation energy of 107.5 MeV were studied at lab. angles of 12° to 25°. Double differential cross sections of the IMF spectra are compared to model calculations, which include direct breakup of both the projectile and target, nucleon coalescence, as well as partial and complete fusion. This study indicates the importance of the complementary nature of a reaction together with its inverse process in fully understanding the driving reaction mechanisms in the interaction of two light-mass nuclei.

INTRODUCTION

Most of the studies involving the interaction of light nuclei were performed at incident energies well below 10 MeV/amu where mean field processes together with particle evaporation are able to describe the data. Above 10 MeV/amu, however, nucleonic degrees of freedom become increasingly important. The need for a better understanding of the predominant reaction mechanisms regarding the interactions of light nuclei at these energies is further stimulated by the increasing number of applications e.g., in hadron therapy with carbon beams. Previous studies of Intermediate Mass Fragments (IMFs) emitted in the interaction of $^{12}$C and $^{16}$O with medium to heavy-mass nuclei at incident energies of some tens of MeV/amu have convincingly demonstrated that the IMFs can originate from two unrelated mechanisms: binary fragmentation of the projectile and nucleon coalescence. In the case of two light nuclei, this scenario may change. If it is assumed that fragments emitted from this interaction are due in part to projectile and in part to target fragmentation, a significant dependence on the entrance channel of the fragment yield is to be expected. Hence, it is the aim here to place stringent constraints on the data by measuring and analyzing the IMF spectra in both the direct as well as the inverse reaction of two light non-identical nuclei.

EXPERIMENT

Beams of $^{12}$C and $^{27}$Al ions at nominal energies of 156 and 348 MeV, respectively, were supplied by the cyclotron facility of iThemba LABS, South Africa. Inclusive spectra of fragments of $4 \leq Z \leq 14$ produced in both the $^{12}$C + $^{27}$Al and its inverse reaction were measured with a silicon detector telescope at in-plane laboratory-emission angles of 12° to 25°. Both $^{12}$C and $^{27}$Al targets, each of a thickness of 100 $\mu$g cm$^{-2}$, were mounted at the center of a 1.5 m diameter scattering chamber. The detector telescope was mounted on a movable arm inside the scattering chamber and consisted of a 21-$\mu$m-thick ($\Delta E$) followed by a 1000-$\mu$m-thick (E) silicon surface barrier detector. A 50-mm-thick brass collimator with a 3-mm-thick tantalum insert was mounted in front of the detector telescope. This insert with an aperture of 14 mm in diameter defined a solid angle of 1.04 msr. Energy calibrations of the Si detectors were performed using kinematics of elastic scattering of both beams. This $\Delta E$–E detector configuration resulted in the following energy thresholds: The low-energy thresholds varied from 15 MeV in the case of the Be fragments to 70 MeV for the Si fragments. The spectra of fragments of $Z \leq 6$ are also affected by a high energy cut off. These values are 150 MeV for $^9$Be, 200 MeV for B, and 250 MeV for C fragments. The standard $\Delta E$–E technique was used for particle identification.
which allowed for clean charge separation of all the fragments. Isotope separation, however, was only achieved for $^7$Be and $^9$Be. Electronic dead time never exceeded 5% and was generally around 1%. The cross sections are believed to be accurate to within a systematic error of 10%.

**THEORY**

The theoretical model that is applied was developed from extensive experimental results of two-ion interactions of both $^{12}$C and $^{16}$O with heavier nuclei, as well as angular and forward angle recoil range distributions of many of the produced residues. Since details of this model are presented in [1, 2, 3, 4, 5], only extensions to the break-up part of the model are here briefly described.

While in the present study the binary fragmentation (break-up) of $^{12}$C is treated in the same way as in the previous calculations, the fragmentation of the Al ions is regarded to be rather tentative at this stage. We are inclined to believe that the observed spectator fragments are produced by a kind of “ablation” mechanism whereby a part of aluminum (indicated hereafter as participant fragment) overlaps with carbon producing an intermediate excited nucleus while the non-overlapping part is the spectator fragment that is emitted without undergoing any further interactions. Although this production mechanism seems to imply a much stronger interaction compared to the fragmentation of carbon, we still hypothesize that the spectator fragment spectra are given by [2, 3, 4, 5]

$$
\frac{d^2 \sigma}{dE'd\Omega}(E_0, E', \theta) = \sigma_f \times \int_{E_{\text{min}}}^{E_0} P(E_i) S(E, E', \theta) dE_i, \quad (1)
$$

where $\sigma_f$ is the incomplete fusion cross section and $P(E_i)$ is the probability that the fragmenting ion, with initial energy $E_0$, survives while suffering an energy loss of $E_i$. The cross section for producing a fragment with energy $E'$ at the angle $\theta$ when the fragmenting ion has an energy of $E = E_0 - E_i$ is [6, 7, 8]

$$
S(E, E', \theta) = P_3 P_\rho |\varphi(p)|^2, \quad (2)
$$

where $P_3$ and $P_\rho$ are the linear momenta in the c.m. system of the spectator and participant fragments, respectively. $|\varphi(p)|^2$ is the square of the Fourier transform of the relative motion wave function of the nucleons constituting the observed fragment within the projectile. In the case of the heavier aluminum, $|\varphi(p)|^2$ is substituted by the expression derived from the cluster approximation for a harmonic oscillator potential [9]

$$
|\varphi(p)|^2 = p^{2L} \exp(-p^2/2P_L^2), \quad (3)
$$

where $L$ is the relative motion angular momentum. For $L = 0, 1, 2$, this expression satisfactorily reproduces $|\varphi(p)|^2$ of spectator fragments emitted from break-up of $^{12}$C and $^{16}$O, evaluated in a square well approximation [10]. In the case of aluminum fragmentation the values for $P_L$ were obtained from a best fit of the spectator spectra. $P_L$ is related to the average linear momentum of the cluster and is expected to increase with the spectator mass. As shown in Fig. 1, the $P_L$ values seem to follow approximately an $A^{1/2}$ dependence.

**RESULTS AND DISCUSSION**

The double-differential cross sections of the fragments emitted in the two inclusive reactions can be divided into the following three groups:

- **Low Z Fragments (LZFs)** These fragments have charges $Z \leq 6$. The dominant reaction mechanisms for producing these fragments are binary projectile and target fragmentation (or break-up) as well as nucleon coalescence resulting mainly from complete fusion reactions. The probability that LZFs are produced as evaporation residues is small. A subset of the results is presented in Figs. 2 and 3, which show the comparison of experimental and calculated spectra of $^9$Be at the selected angles and the decomposition of the calculated spectra into the contributions of the hypothesized mechanisms: projectile and target break-up as well as nucleon coalescence.

- **Intermediate Z Fragments (IZFs)** These fragments have charges $6 < Z \leq 13$. Since these cannot be produced by carbon fragmentation, they originate from $^{27}$Al fragmentation, nucleon coalescence, and evaporation. While the contribution from nucleon coalescence is expected to decrease with increasing mass of the IZFs, the probability of producing these as evaporation residues, both in complete as well as incomplete fusion reactions, increases. The evaluation of this last contribution is quite complex.

![FIGURE 1. $P_L$ values as a function of the spectator fragment mass $A$. The solid line shows an $A^{1/2}$ dependence. See text for details.](image-url)
FIGURE 2. Spectra of $^9$Be observed in the reaction and at the laboratory emission angles as indicated. The experimental data are given by the points. The error bars reflect the statistical uncertainty. The incoherent sum of the calculated contributions is given by the solid histograms, the contribution from $^{12}$C fragmentation by the dotted histograms, from $^{27}$Al fragmentation by the dashed histograms, and nucleon coalescence by the thin line histograms.

FIGURE 3. See caption of Fig. 2

One of these processes might be, for instance, the fusion of a $^3$He with $^{27}$Al. The corresponding cross section would merely be the $^9$Be production cross section deduced from the complementary $^{12}$C+$^{27}$Al reaction channel. However, an oxygen residue could also be produced by the decay of an intermediate nucleus formed in the incomplete fusion with one of the $^{27}$Al fragments. This production cross section is estimated from the production cross section of the complementary spectator fragment that is observed at forward angles in the inverse $^{27}$Al+$^{12}$C reaction. For example, an oxygen fragment observed in the $^{12}$C+$^{27}$Al reaction might be the evaporation residue of a neon nucleus that is produced in the fusion of carbon with a beryllium fragment originating from $^{27}$Al fragmentation. This cross section is equal to the produc-

FIGURE 4. Spectra of O and Na fragments observed in the reaction and at the laboratory emission angle as indicated. The experimental data are given by the points. The error bars reflect the statistical uncertainty. The incoherent sum of the calculated contributions is given by the solid histograms, the contribution from $^{27}$Al fragmentation by the dotted histograms, from nucleon coalescence by the thin line histograms and from complete and incomplete fusion reactions by the dashed histograms.

FIGURE 5. See caption of Fig. 4.

since it requires identifying all the incomplete fusion processes as well as their cross sections. These processes are described in [2, 3, 4, 5] as break-up followed by fusion. For $^{27}$Al fragmentation, as mentioned above, we assume a partial overlap between the aluminum and carbon nuclei producing an intermediate nucleus that subsequently decays to the observed fragment. In both cases, the incomplete fusion cross section is obtained from the spectra of the spectator assuming that any fragmentation process is accompanied by the incomplete fusion of the companion participant fragment with the partner ion.

To be more specific, an oxygen fragment emitted from the $^{12}$C+$^{27}$Al reaction, may be produced by the incomplete fusion of a $^{12}$C fragment with $^{27}$Al. This intermediate system then further decays into the oxygen residue.
tion cross section of fluorine, i.e., as observed at forward angles in the inverse $^{27}$Al+$^{12}$C reaction. Obviously, oxygen may be the evaporation residue of many incomplete fusion reactions. For a complete description, all of these processes must be included.

As an example of IZF spectra, those of oxygen and sodium are shown in Figs. 4 and 5. These considerations emphasize the importance of studying both the direct and the inverse reaction. Consequently the number of arbitrary assumptions is greatly reduced allowing for a more stringent test of the proposed theoretical description.

Large Z Fragments Fragments emitted with $Z > 13$ are mostly produced as evaporation residues. In the present experiment, only fragments up to silicon were measured. The production, whereby also a proton or deuteron can be transferred from $^{12}$C to $^{27}$Al in a direct reaction, is not included in the present model. The comparison of the experimental and calculated spectra of silicon is shown in Fig. 6.

It has to be noted that even if the evaporation residue energy is low in the c.m. system, it may be quite large in the lab system because of the kinematic boost. This has important consequences, for instance, in hadron therapy where the interaction of a few hundred MeV carbon beam with a heavier nucleus inside the body may produce fragments heavier than carbon with an energy of some tens of MeV. Hence these fragments have a much higher LET, thereby greatly increasing the biological effectiveness of carbon ions in the Bragg peak region.

**FIGURE 6.** Spectra of Si fragments observed in the reactions and at the laboratory emission angle as indicated. The experimental data are given by the points of which the error bars reflect the statistical uncertainty. Note the low-energy detection threshold. The calculated spectra of silicon fragments produced as residues in complete and incomplete fusion reactions are given by the line histograms.

**CONCLUSION**

The calculations shown in Figs. 2 to 6 are still preliminary at this stage. Nevertheless, it is quite apparent and satisfying to note that, by relating this study to previous analyses with the same model, the present calculations not only reproduce the main features of the observed spectra but also provide a reasonable quantitative account of them. These results suggest that, by measuring the spectra of different particles in the direct as well as in the inverse reactions and including this information in the model calculations, an important contribution towards understanding the reaction mechanisms has been achieved.

**REFERENCES**


