Low-energy intermediate mass fragments in the $^{16}O+^{12}C$ reaction at 38 MeV/nucleon

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The $^{16}O+^{12}C$ reaction at an incident energy E/A of 38 MeV has been investigated experimentally. Singles energy spectra and the angular distribution of reaction residues having $3 \le Z \le 9$ were measured. A small low-energy cutoff in the spectra combined with measurements at large angles (up to 70°) allowed a study of the systematics involved in the production of low-energy reaction residues. A target-related origin is proposed for these yields. Cascade model calculations are presented which support this hypothesis.

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I. INTRODUCTION

The mechanisms associated with the production of intermediate mass fragments (IMF) in heavy ion reactions, over a wide range of incident energies, have been investigated both theoretically [1] and experimentally [2]. A common feature of these reactions is the appearance of a projectile-related quasielastic group which dominates the IMF spectra at forward angles [3]. Under certain circumstances, lower kinetic energy IMF (LE-IMF) yields of a less definite origin are also observed [2]. At bombarding energies $E/A<20$ MeV, a variety of mean-field-dominated energy damping mechanisms, such as complete and incomplete fusion or deep-inelastic collisions, are known to contribute to the production of such LE-IMF's [4]. However, at higher incident energies the conditions become less favorable for the occurrence of such phenomena [5]. This is the case of light heavy ion systems ($A_p, A_t<20$) where, at beam energies of ≈ 40 MeV/nucleon, the energy damping mechanisms just mentioned are expected to yield primary reaction residues with sufficient excitation energy as to guarantee their near disintegration. Still, measurements on $^{12}C + ^{12}C$ [5] and $^{14}N + ^{14}C$ [6] indicate that LE-IMF production remains important at incident energies $E/A>30$ MeV. Those observations, however, have been limited to detection angles $\theta<30°$ and using detection systems having somewhat large low-energy cutoffs, thus leaving out the angular and energy region where LE-IMF's dominate over the projectile quasielastic components. In view of this, here we have aimed at establishing more clearly the systematics of LE-IMF production in the system $^{16}O + ^{12}C$ at 38 MeV/nucleon, by performing measurements over a more extended angular region (7.5°–70°) while reducing the low-energy cutoff of our detection system down to ≈ 1.5 MeV/nucleon. Based on the concept of a target-related origin for the observed LE-IMF yields, a simple reaction model is proposed, the predictions of which are shown to reproduce the main features of the data.

II. EXPERIMENT AND RESULTS

The experiment was performed using the 608 MeV ^{16}O beam from the SARA Accelerator System of the ISN, to bombard a (natural) carbon foil, 1 mg/cm^2 thick. Energy spectra of $3 \le Z \le 9$ reaction residues in the angular range $7.5° \le \theta_{lab} \le 70°$ were obtained using a detection system consisting of a four-unit (20 μm + 100 μm + 2000 μm + 5000 μm) solid-state counter telescope with a circular collimator subtending a solid angle of 0.5 msr. With this experimental setup, isotopic resolution was obtained for residues having kinetic energies $E \ge 1.5$ MeV/nucleon. To illustrate the type of angular evolution observed for the energy spectra, those corresponding to ^6Li and ^{12}C reaction products are shown in Fig. 1(a) and 1(b), respectively. As can be seen, there is a smooth evolution from the forward-angle region, dominated by a strong quasielastic group, to the most backward angles where a low-energy group, having its maximum near the experimental low-energy cutoff, is clearly observed. This low-energy group, the LE-IMF's, become relatively more important for the lower mass fragments. The presence of two distinct components can also be appreciated in the energy-integrated angular distributions, as shown in Fig. 2. There, a forward-peaked group, characteristic of the projectile quasielastic components, can be seen, followed by a more isotropic component. The mass distribution of the observed ($6 \le A \le 18$) yields is shown in Fig. 3. To illustrate the angular evolution of the mass distribution, in Figs. 4(a) and 4(b), we show that corresponding to the most forward (7.5°) and most backward (70°) angles observed. Figures 3 and 4 also contain theoretical predictions to be described later.

III. DISCUSSION

An estimate for the importance of LE-IMF's relative to the projectile quasielastic yields in the observed spectra, was made by a two-component decomposition of the energy spectra using the analytic parametrization pro-

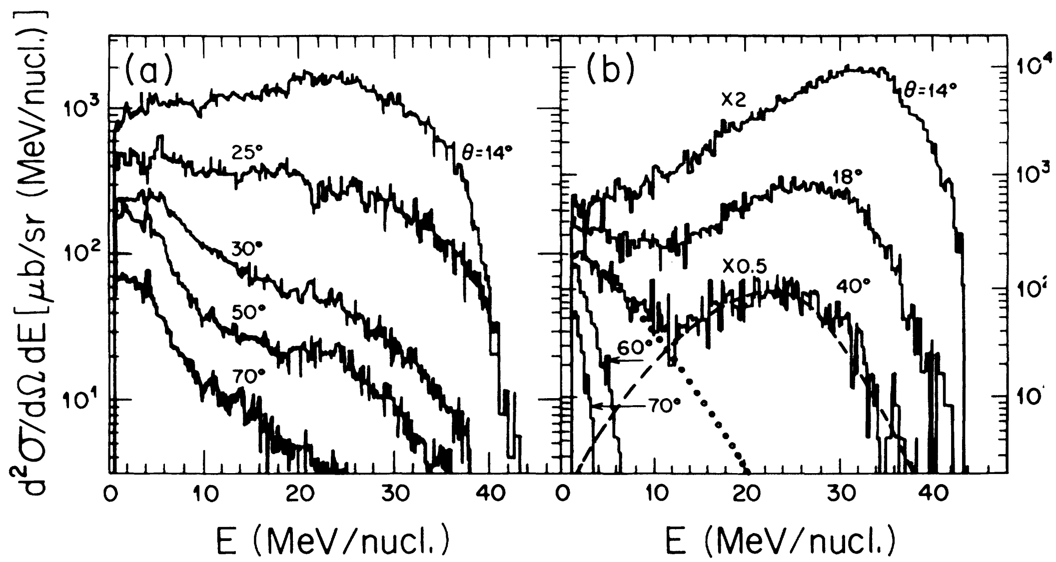

FIG. 1. Angular evolution observed for the energy spectra of (a) ^{6}Li and (b) ^{12}C. The dotted and dashed curves in (b) illustrates the two-component [Eqs. (2) and (1), respectively] decomposition discussed in the text. Some of the spectra have been multiplied by a factor, as indicated, to allow a visual separation of the spectra shown.

posed by Kiss *et al.* [6]. This involves two functions, one for the (projectile-quasielastic) high-energy (HE) group, given by

$$F_{\rm HE}(E/A)=A_{\rm HE}(E/A)^{1/2}e^{B(E/A)} \times\left[1+e^{(E/A-E_0/A)C}\right]^{-1}, \qquad (1)$$

and a second one for the LE-IMF's with the form

$$F_{\rm LE}(E/A)=A_{\rm LE}(E/A)^{1/2}e^{-A(E/A)/T}, \qquad (2)$$

where $A_{\rm HE}$, $A_{\rm LE}$, B, E_0, C, and T are adjustable parameters.

In regions where one component dominates the spectra, the values for the parameters of the other component were extrapolated from the trend of the data deduced from the intermediate angular region, where a satisfactory two-component fit was possible. One example of the decomposition of the spectra is shown (dotted and dashed curves) in the $\theta=40°$ spectrum of Fig. 1(b). This method leads to a two-component decomposition of the angular distributions, as illustrated in the inset of Fig. 2. Assuming a continuous shape, the decomposed angular distribu-

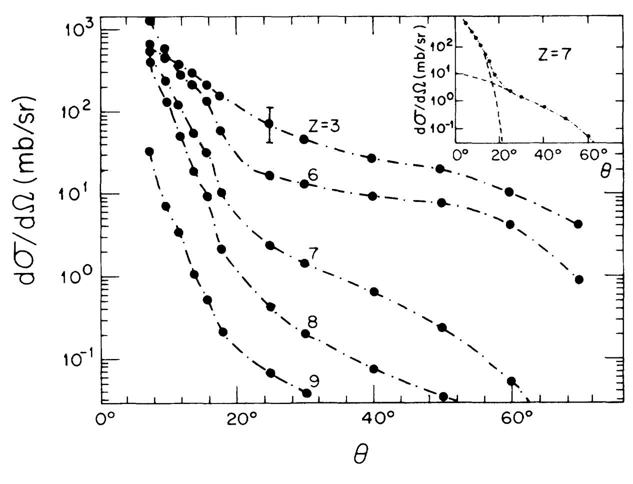

FIG. 2. Energy-integrated angular distribution measured for $3\leq Z\leq 9$ elements. The dot-dashed lines were drawn to guide the eye. The statistical uncertainty associated to each point is smaller than of the data symbols. A $\pm 10\%$ error bar in one of the points represents our estimate for the overall uncertainty due to systematic errors inherent to target thickness and collected beam charge measurements. The inset illustrates the decomposition of the angular distributions resulting from the two-component analysis of the spectra.

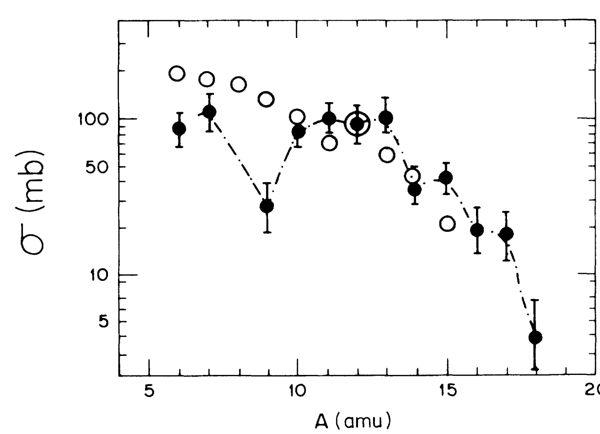

FIG. 3. Observed (solid circles) and predicted (open circles) mass distributions. The model calculations were normalized to the $A=12$ experimental point. The curve joining the experimental points is drawn to guide the eye.

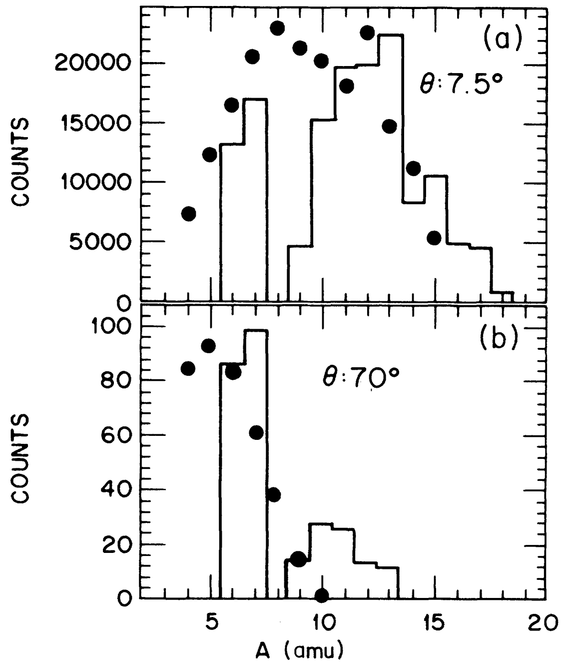

FIG. 4. Measured (histogram) and predicted (solid circles) mass distributions at (a) $\theta=7.5°$ and (b) $\theta=70°$.

tions were integrated within the observed angular range. Following this procedure, the LE-IMF yields were estimated to represent 34% of the measured (≈ 710 mb) reaction yields.

As mentioned in the Introduction, from the point of view of low-energy reaction mechanisms, LE-IMF's are commonly associated with a variety of energy damping [2,6] processes in which a large portion of the kinetic energy available is transformed into excitation of the whole, or a fraction, of the composite system. Among those mechanisms, fusion and/or deep inelastic collisions result in residues having the mean velocity (in the laboratory frame of reference) of the center of mass of the total (projectile+target) system. The residues of these processes are identified [7] in the forward angle IMF spectra because they form a group having a most probable kinetic energy per nucleon $E_r \approx [A_p^2/(A_p+A_t)^2]E_p \cos^2\theta_{\rm lab}$, where A_p and A_t are the projectile and target masses, respectively, E_p is the projectile's incident energy per nucleon, and $\theta_{\rm lab}$ is the observation angle. In ^{16}O + ^{12}C at 38 MeV/nucleon this corresponds to ≈ 12 MeV/nucleon. As shown in Fig. 1 no such group can be identified in the energy spectra.

At these incident energies there are reasons to expect that the fusion components should represent only a small fraction of this yields which form the energy spectra of IMF's. First, the contributions to the compound nucleus cross section are limited by angular momentum. The $29\hbar$ liquid-drop model limit predicted [8] for this system leads to a (sharp cutoff) fusion cross section $\sigma < 100$ mb (i.e., less than 10% of the total reaction cross section deduced from our elastic scattering measurements [9]). The second argument, which also applies to deep-inelastic collisions, is that the energy per nucleon available for damping in this reaction exceeds 8 MeV, implying that the fusion and deep-inelastic collisions are most likely to result in light ($Z \leq 2$) residues.

Regarding incomplete fusion, which involves less energy damping and could result in IMF's having a wide range of energies, it is difficult to conceive why it should result in a group having ≈ 0 MeV/nucleon as its most likely kinetic energy. This is particularly so when we are dealing with a near-symmetric system in which the fraction missing fusion could belong to either the projectile or the target.

In view of the above, to explain the observed production of LE-IMF's, it would be tempting to invoke reaction mechanisms characteristic of higher energy regimes (multifragmentation, coalescence, etc.). However, we would like to propose a simpler explanation for the origin of the LE-IMF yields observed here, namely that they are the target-related "quasielastic" residues. The present data show that quasielastic mechanisms (fragmentation, transfer to the continuum, etc.) are abundant. These are generally identified by the observation of IMF's having masses, and energies per nucleon, close to those of the projectile. Presumably, in each of these interactions a quasielastically scattered target residue is also produced. These yields would, then, be characterized by having a zero mean velocity. Still, since the quasielastic yields present a momentum distribution having a finite width, some target residues may have sufficient energy to leave the target and fulfill the minimum energy requirements of our detection system, particularly in the reversed kinematics situation of the present experiment.

IV. A MODEL

A simple cascade-type reaction model was developed in order to illustrate the similarities between the systematics observed here for the LE-IMF's and what may be expected for target-related quasielastic components. Since the details of the calculations will be given elsewhere [10], we now describe the basic concepts of the model. First, these reactions are assumed to be dominated by nucleon-nucleon (n-n) collisions. Based on a simple reaction model by Harvey [11], the probability for a given nucleus-nucleus (N-N) interaction is calculated by integrating the probability that each nucleon in the projectile would undergo a collision along its trajectory through the target mass distribution. Before (and after) the interaction, the initial (residual) nuclei travel along the corresponding Coulomb orbits. During the collision, the interacting nuclei are assumed to follow straight (parallel to the beam) trajectories. The projectile impact parameter, as well as the location of the projectile nucleons, relative to the projectile center of mass, are generated at random.

Whenever an n-n collision occurs, the kinematics of the colliding nucleons is calculated assuming an isotropic c.m. angular distribution. The probability that each one of these nucleons would rescatter off either the projectile or the target mass distributions is then calculated by integrating along their new trajectories. Should a second collision occur, the rescattered nucleon is assumed to be trapped by the nucleus (projectile or target) with which it

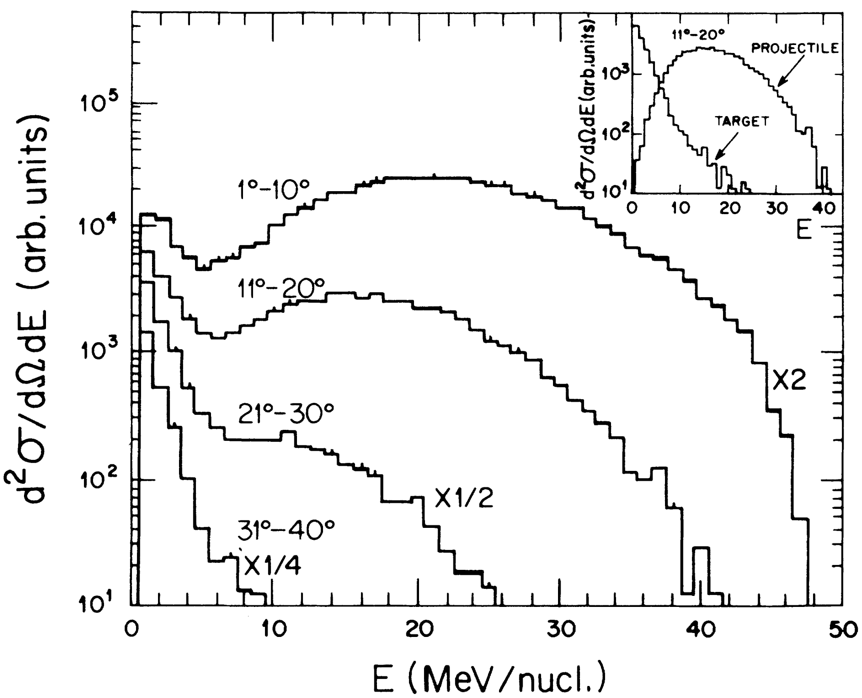

FIG. 5. Cascade model predictions for the angular evolution of the energy spectra of $A=8$ residues. Inset: The predicted $\theta=11°-20°$ spectrum, separated into projectile and target components.

collides; otherwise, the nucleon is allowed to remain free. The momentum of each trapped nucleon is added to the momentum of the center of mass of the recipient nucleus and its relative energy is assumed to be transformed into excitation energy. Once the probability for first and, when appropriate, second collisions are evaluated for every projectile nucleon, the mass, charge, momentum (as a vector), and excitation energy of each primary fragment (one from the projectile and one from the target) are calculated.

In the final stage, the two hot primary reaction residues are allowed to decay by emitting, isotropically, nu-

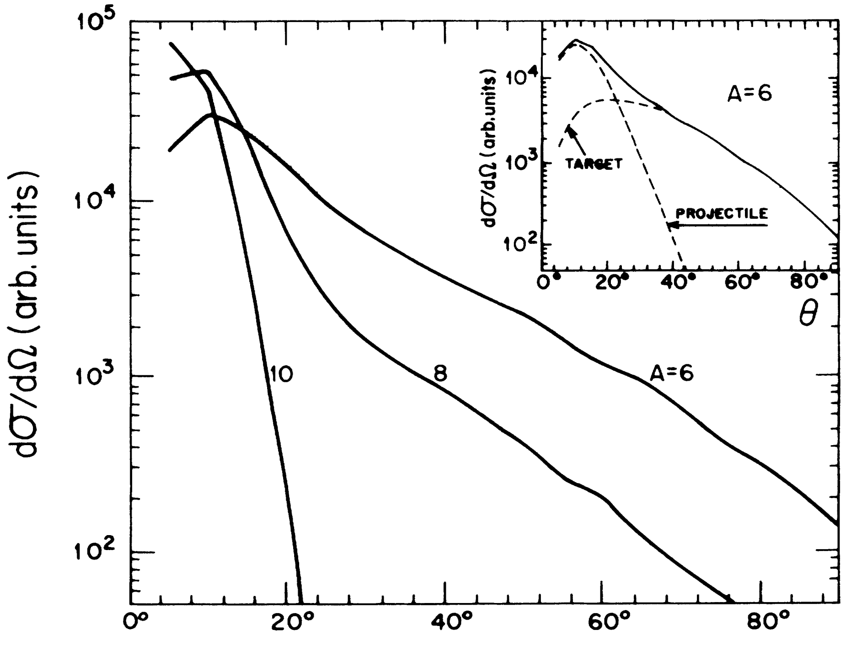

FIG. 6. Predicted energy-integrated angular distributions for $A=6,8,10$ residues. Inset: The predicted $A=6$ angular distribution, separated into projectile and target components.

cleons or alpha particles sequentially, using a simple decay model proposed by Puhlhoffer and Shkeider [12]. The kinematics of each decay is calculated, having the overall effect of a broadening of the energy and angular distributions of the target and projectile residues. The charge, mass, energy, direction, and origin (projectile or target) of the secondary products are recorded in an event-by-event mode. The results of a 1×10^6 event $^{16}O + ^{12}C$ calculation at 38 MeV/nucleon are illustrated in Figs. 3–6.

The spectra predicted by this model for $A=8$ residues [13] are shown in Fig. 5 as a function of angle (integrated in 10° bins, as indicated, to improve statistics). Grossly, the model reproduces the main features of the measured energy spectra [compare Figs. 1(a) and 1(b) with Fig. 5], in particular, the presence of two distinct groups. One of them, having a high mean energy, is dominant at forward angles and the other, with its maximum at the lowest energies, has a more isotropic angular distribution. In the inset of Fig. 5, an origin tag is used to separate the projectile and target components of the $\theta=11°-20°$, $A=8$, calculated spectrum. The overall behavior predicted for energy-integrated angular distributions (Fig. 6) is also similar to that observed experimentally (see Fig. 2). The IMF's having a mass closer to the projectile present a more pronounced forward peaking on their angular distributions. The two-component structure is also present in these predictions. In the inset of Fig. 6 the angular distribution for $A=6$ fragments has been separated into projectile and target residues. The shape of the predicted energy- and angle-integrated mass distribution is compared to the data in Fig. 3. Although the model contains no nuclear structure information, its reproduces the overall mass dependence of the cross section. the shift down in the mean mass observed in the mass distributions between the most forward and the most backward observations can also be understood within this simple model, as illustrated by the solid circles in Figs. 4(a) and 4(b). Thus, based on the similarities between the observations and the predictions of this model, our interpretation is that the origin of the LE-IMF yields observed can be associated to target-related quasielastic components.

V. CONCLUSION

The systematics observed for the intermediate mass fragment singles spectra from the $^{16}O + ^{12}C$ reactions at incident energies of 38 MeV/nucleon were studied. The results indicate that these products can be grossly separated in two, the standard projectile-related quasielastic components and a low-energy group having its maximum yields at, or below, the lowest energy observed. Based on a model, the origin associated with the latter is interpreted as being target-related quasielastic residues.

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