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Angular correlations between heavy and light fragments in the reaction $^{32}S+^{26}Mg$ at $E_{lab}=163.5$ MeV

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Angular correlation measurements between heavy residues ($Z_R=23-13$) and light fragments ($Z_L=2-10$) have been performed for the reaction $^{32}S+^{26}Mg$ at $E_{lab}=163.5$ MeV. The binary nature of the mechanisms competing with fusion-evaporation is evidenced. Linear momentum analysis and velocity plots indicate contributions of binary reactions also for those elements that are generally believed to be produced by fusion-evaporation mechanisms.

I. INTRODUCTION

Heavy-ion collisions at kinetic energies of 2–3 times the Coulomb barrier are generally characterized by the competition between fusion and other damped reaction mechanisms. For composite systems with $A_{CN}=40-60$, fissionlike and deep inelastic[1–3] as well as quasielastic reactions[4–6] have been indicated as main mechanisms in competition with fusion. In some cases,[7] incomplete fusion reaction has also been identified. The onset of the mechanisms competing with fusion is normally associated with the saturation of the fusion cross section with increasing bombarding energy.

In a recent work on the $^{32}S+^{24}Mg$ reactions,[8] Sanders *et al.* suggested that binary fragments product with full equilibration of energy and mass-asymmetry coordinates are due to an asymmetric fission mechanism. This observation pointed out the need of considering also the fusion-fission channel in the competition between fusion and deep inelastic or other reactions that do not proceed through the formation of a compound system.

We have studied in the past [9,10] the fusion cross sections for the $^{32}S+^{24,25,26}Mg$ system by the γ-ray technique showing the saturation of the fusion cross section at $E_{lab}\sim 145$ MeV. The characteristics of the reactions competing with fusion have also been investigated for the reaction $^{32}S+^{26}Mg$ at $E_{lab}=163.5$ MeV by means of inclusive measurement of heavy fragments.[11]

In this work, we report on results of angular correlations between heavy residues ($Z_R=23-12$) and light fragments ($Z_L=2-10$) for the reaction $^{32}S+^{26}Mg$ at $E_{lab}=163.5$ MeV. The aim of this study is to obtain clearer information on the competitions between fusion-evaporation and two-body mechanisms. Measurements of the total linear momentum of two coincident fragments allows one, in fact, to determine the collective properties of the undetected remainder, if any. The momentum distribution of this remainder, the measured momentum deficit, could indicate whether emitted particles have statistical origin or come from direct processes.

II. EXPERIMENTAL PROCEDURE

The experiment was performed at the 16 MV Tandem accelerator facility of Laboratori Nazionali di Legnaro. The beam of ^{32}S ions ($q=11^+$) at energy of 165 MeV was used. Beam current values were in the range 30–100 nA. The bombarded targets consisted of self-supporting Mg, 270 ± 15-$\mu g/cm^2$ thick, with a composition of 97.2% on $A=26$, 1.7% on $A=24$, and 1.1% on $A=25$ isotopes, respectively. Evaporation of a thin (9.5 ± 0.5 $\mu g/cm^2$) ^{197}Au layer on the target was made for normalization purposes. Carbon and oxygen contamination was previously estimated[9] to be as low as ~ 15 $\mu g/cm^2$.

Heavy fragments ($Z=26-13$) were detected by a Bragg Ionization Chamber (BIC). The BIC was connected to a sliding-seal scattering chamber at a distance of 41.5 cm from the target. A circular hole of 30-mm diameter defined the acceptance of the detector $\Delta\Omega=4$ msr. The Bragg Ionization Chamber is fully described elsewhere.[13] In this work the entrance window was 1-μm thick mylar foil. $P10$ at a pressure of 180 Torr was used as counting gas. The z-discrimination power of the BIC was good enough to discriminate very clearly each element of interest in the range $Z=13-23$.

Lighter fragments ($Z\leq 10$) were detected by two ΔE-E telescopes ($\Delta E=10$-μm and $E=500$-μm thick solid-state silicon detectors). They were in the reaction plane, on the opposite side of the beam with respect to the BIC, at a distance of 16 cm from the target, covering a solid angle of $\Delta\Omega=2$ msr.

Angular correlation measurements were performed by detecting the heavy residue R at $\theta_R=-15°$ and the light partner L, detected at angles ranging from $\theta_L=+20°$ to

+70° with an angular step of 5°. The detection angle for the heavy residues is near to the grazing angle for the reaction, ($\approx 13°$), so that a sizeable contribution from two-body inelastic reaction is expected to contribute to the measured tail[11] of the evaporation residues angular distribution.

III. ANALYSIS OF EXPERIMENTAL RESULTS

Figures 1 and 2 show the experimental results in terms of correlation function $W(\theta_{\rm lab})$, defined here as the number of coincidences (Z_R, Z_L) at a given angle $\theta_{\rm lab}$ of the light fragments detector divided by the number of singles of the fragments with (Z_R) in the trigger detector (the BIC). The general behavior of the correlation function $W(\theta_{\rm lab})$ is to peak at $\theta_{\rm lab}=55°-60°$ independently of the particular choice of correlated fragments. The peak in the correlation function indicates a prevalent two-body nature of the reaction. In fact a pure two-body kinematics indicates $\theta_{\rm lab}=40°-90°$ as the correlated angles of the triggering angle for fragments with $Z_R=23-17$ and Q values going from elastic to complete relaxation.

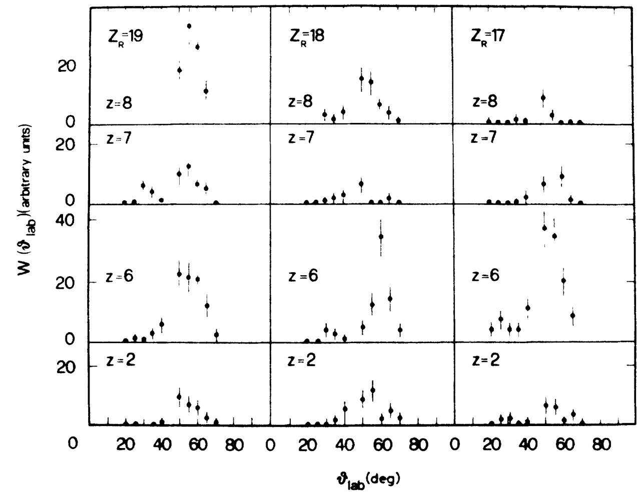

FIG. 2. The same as in Fig. 1, but for $Z_R=19,18,17$.

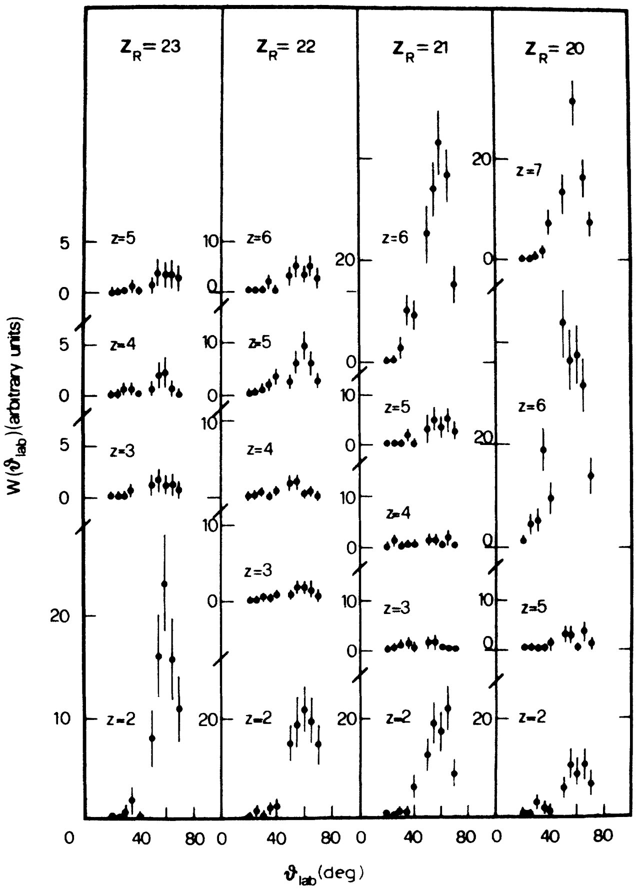

FIG. 1. Angular correlations between heavy fragment Z_R ($Z_R=23-20$) detected at a fixed angle θ_R and the light one ($Z_L=7-2$), detected at variable angle $\theta_{\rm lab}$.

Figure 3 shows the relative cross sections, integrated on the measured θ_L-angular range, for various coincident fragments (Z_R, Z_L). A relevant part of the events are grouped in the region $Z_T=Z_R+Z_L=25-28$, the total charge of the detected fragments being close to that of the composite system. A second important contribution is associated to coincidences between heavy fragments and alpha particles. These events might in principle be associated to evaporation residues after fusion or to sequential decay of fragments after inelastic two-body reactions. The third class of events is given by beamlike fragments ($Z_R=18-12$) in coincidence mainly with carbon or oxygen ions that are therefore associated with large charge deficits.

To obtain a direct proof of the binary nature of the reaction mechanisms competing with fusion, we have ana-

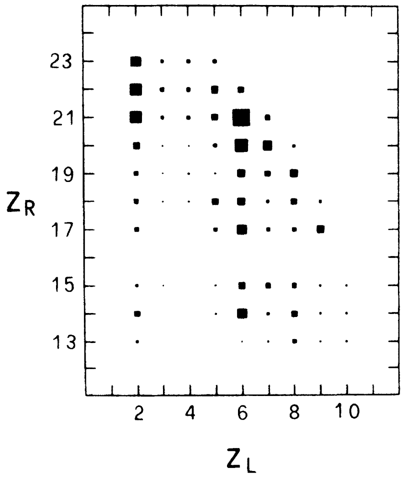

FIG. 3. Cross sections for coincidences between heavy and light fragments (Z_R, Z_L). Square areas are proportional to relative cross sections. The $Z_R=16$ has not been considered in the analysis.

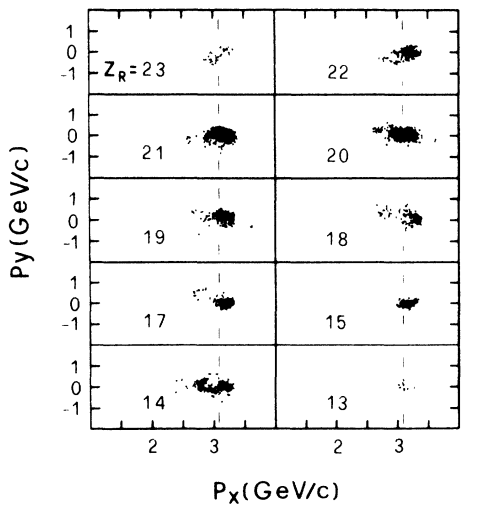

FIG. 4. Measured total momentum distributions for heavy-fragment–light-fragment coincidences. Events in coincidence with $Z_L = 2$ are not included. Dashed lines indicate the position of the c.m. momentum.

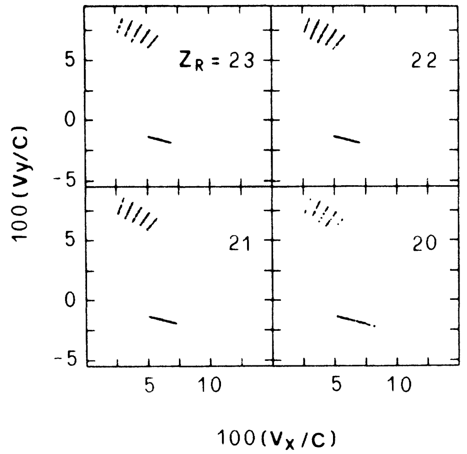

FIG. 6. Velocity plot for experimental coincidence events for heavy fragments with $Z_R = 23$ to $Z_R = 20$, in coincidence with light fragment with $Z_L = 2$.

lyzed the experimental data in terms of total linear momentum deficit.[12] For each (Z_R-Z_L) event we have calculated from the measured kinetic energies the total linear momentum carried by the reaction partners $\mathbf{p}_R + \mathbf{p}_L$. To this end, experimental averaged masses from γ-spectroscopy measurements[9,10] were assumed for $Z = 23-14$ fragments. For lighter fragments, masses corresponding to those of the most abundant isotope were used. Figure 4 reports the results in term of components of the total linear momentum perpendicular p_y and parallel p_x to the beam axis, taking into account all measured events with the exception of those with $Z_L = 2$. It is evident that generally the events lie around $p_y = 0$ and p_x close to the value of ~ 3 GeV/c characteristic of the beam, demonstrating that the relevant reaction mechanism is a binary one, also in the presence of quite a high charge deficit.

In the case of coincidences with $Z_L = 2$, which show sharp peaks in Fig. 1, comparison has been performed by model calculation to ascertain if the alpha particles are statistically evaporated from the compound nucleus or are produced by deexcitation of two primary fragments. Monte Carlo calculations have been performed by using the statistical-model code LILITA (Ref. 14) to simulate the fragments alpha particles coincidences due to the statistical decay of the compound nucleus. Figure 5 shows that the angular distribution of coincidence events in case of evaporation from a compound nucleus is completely different from the experimental one. Because of the strongly focused angular correlation shown by the experimental data, it seems that this alpha emission is produced during a sequential decay of a fully accelerated undetected fragment complementary to the detected Z_R one. This is also evident in Fig. 6 where velocity plots for coincident fragments are shown. It appears that alpha particles (at positive V_y/c in Fig. 6) cannot originate from the detected fragment (at negative V_y/c in Fig. 6), nor from the compound nucleus (at $V_y/c = 0$, $V_x/c = 0.06$). The only possible source is the undetected partner of the heavy detected fragment.

To obtain further information on the amount of energy dissipated, we have calculated the total kinetic energy E_T, in the case of two-body reaction, from the kinetic energy of two coincident fragments. Figure 7 shows the resultant E_T as a function of scattering angle of the detected light fragment, except for $Z_L = 2$. E_T goes from

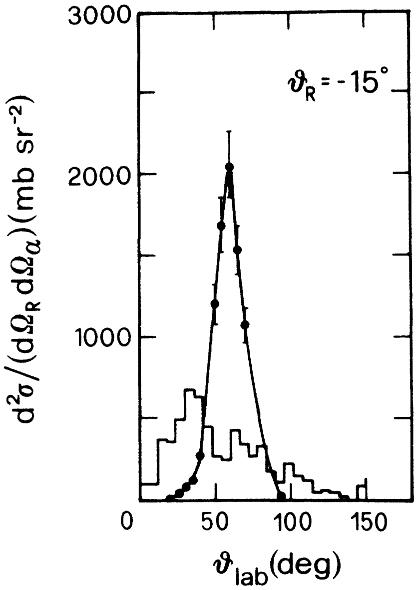

FIG. 5. Angular distribution of events in coincidence with $Z_L = 2$. All contributions coming from $Z_R = 23, 22, 21, 20$ have been summed together. The histogram represents the corresponding statistical calculations given by the LILITA (Ref. 14) code. In these calculations a total fusion cross section of 800 mb and a total number of evaporation events, $N = 3 \times 10^5$, have been assumed. For both heavy and light fragments, the used bins are wide $\Delta\theta = \pm 3°$, $\Delta\phi = \pm 5°$.

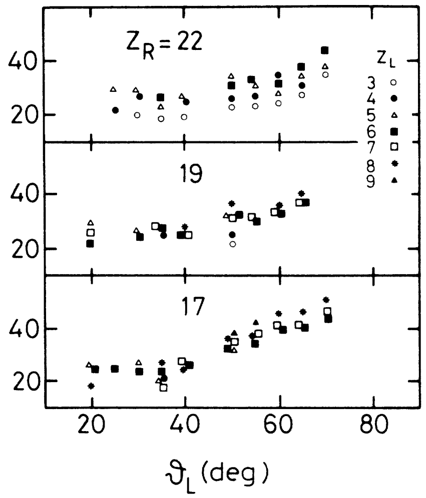

FIG. 7. Total kinetic energy of two coincident fragments, for $Z_R = 22, 19, 17$, as a function of light-fragment detector angle.

quasielastic values associated to backward scattering angles to the deep-inelastic ones when light fragments are emitted forward, showing the well-known evolution of the energy dissipation with the scattering angle. Total kinetic energies $E_T \sim 20-30$ MeV correspond to complete energy relaxation for the exit channels considered in Fig. 7.

We note that fragments with $Z_R = 23$ to $Z_R = 22$, previously associated with a pure fusion-evaporation mechanism,[11] here indicate two-body contribution. A rough estimate of this two-body contribution, obtained by integrating the correlation function, yields only a few percent of the total production cross section at $\theta_{\rm lab} = 15°$, due mainly to events in coincidence with $Z_L = 2$ fragments.

For $Z_R = 21$ previous results have also given indication of a two-body contribution.[11] This cross section is mainly due to coincidences with the $Z_L = 6$ fragment and is of the order of 15 mb, to be compared with the value of 50 mb from single events measurements. On the basis of residue angular distributions,[11] showing essentially a $1/\sin\theta$ behavior, a large part of the yield of $Z_R = 22$ to $Z_R = 20$ could be attributed to a fully equilibrated asymmetric fusion-fission mechanism. Their total contribution, without including the coincidence yield with $Z_L = 2$, corresponds to $\approx 35-50$ mb. A sizeable contribution of a fusion-fission mechanism is also supported by the statistical model CASCADE (Ref. 15) calculations when employing finite-range corrected fission barriers.[16] Therefore, as in the Ref. 8 for the ^{32}S$+^{24}$Mg system, the presence of an asymmetric fusion-fission mechanism can be assumed in this case.

IV. CONCLUSIONS

As a final conclusion of this work, we want to stress that from coincidence measurements between heavy and light fragments, direct evidence of the binary nature of the mechanisms competing with fusion has been obtained for the reaction ^{32}S$+^{26}$Mg at $E_{\rm lab} = 163.5$ MeV. These mechanisms continuously evolve from quasielastic to deep inelastic as the scattering angle of two emerging fragments increases. Their Z-element distribution extends up to overlap partly with the fusion Z distribution. The strongly focused α-particle emission seems to be due to the sequential decay of the undetected complementary partners of the fragment detected at $\theta_{\rm lab} = -15°$. The presence of a fusion-fission contribution to the two-body reaction is also suggested, in analogy with that found for the ^{32}S$+^{24}$Mg system.

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