Source Properties of Intermediate-Mass Fragments Emitted in the Reaction $^{14}N + ^{232}Th$ at $E/A = 35$ MeV

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Triple coincidences between intermediate-mass fragments and angle-correlated binary fission events were measured in the reaction $^{14}N + ^{232}Th$ at $E/A = 35$ MeV. It was found that fragments emitted at backward angles appear to be associated with reactions in which nearly all of the projectile momentum is carried away by the heavy reaction residue and the intermediate-mass fragment. In contrast, fragments emitted at forward angles are accompanied by 20%–30% missing momentum.

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The emission of complex fragments in nuclear reactions well above the interaction barrier is believed to be a signature of highly excited nuclear matter. At relatively low bombarding energies inclusive spectra suggest that these fragments are emitted from a fully equilibrated compound nucleus.[1] For nuclear reactions at intermediate or high energies, particles are emitted prior to the attainment of full statistical equilibrium, rendering the concept of compound nucleus formation and decay inadequate.[2] At these higher energies, complex fragment emission has been associated with more complex phenomena such as a liquid-gas phase transition,[3,4] emission from equilibrated reaction residues,[5] or from nuclear subsystems in local equilibrium,[6–8] the coalescence of nucleons,[9,10] or the development of mechanical instabilities in nuclear matter.[11–13] For reactions at intermediate energies, both equilibrium and nonequilibrium emission mechanisms appear to coexist[8,14,15] analogous to the case for compound and noncompound nuclear emission.[16] The relative probability for these two mechanisms must depend on the projectile energy and/or velocity.

We have investigated the emission of intermediate-mass fragments (IMF's) in the ^{14}N-induced reaction on ^{232}Th in order to characterize the sources from which these fragments are emitted and to investigate whether equilibrium and nonequilibrium components could be associated with different classes of collisions. In order to determine the linear momentum transfer to the heavy reaction residues, we measured triple coincidences between intermediate-mass fragments ($Z \approx 3-13$) and angle-correlated binary-fission events. The measurements reported here were performed at two IMF angle settings: One backward angle, $\Theta_{IMF} = \pm 126°$, which should emphasize ejectiles emitted from an equilibrated targetlike source, and one forward-angle setting, $\Theta_{IMF} = -51°$, which would favor nonequilibrium processes but avoid complications due to projectile fragmentation.

The experiment was performed at the National Superconducting Cyclotron Laboratory of Michigan State University. Angle-correlated fission fragments were detected with two $19 \times 15\text{-cm}^2$ x-y position-sensitive parallel-plate avalanche detectors covering the angular intervals $+59.4° \leq \Theta_A \leq +110/5°$ and $-115.5° \leq \Theta_B \leq -64.5°$, respectively. Intermediate-mass fragments were detected with standard ΔE-ΔE-E silicon-detector telescopes.

The folding-angle distribution between coincident binary-fission fragments can be related to the average momentum vector $\tilde{P}_R$ of the heavy reaction residue through a simple kinematic transformation.[17] We can, therefore, determine the missing momentum,

$$p_m = p_0 - p_R - p_{IMF} \cos\Theta_{IMF}, \tag{1}$$

where p_0 and p_{IMF} denote momentum vectors associated with the incident beam momentum and the momentum of the detected fragment, respectively. Missing momenta different from zero result from preequilibrium particle emission or from the sequential decay of highly excited primary fragments. The present experiment cannot distinguish these two mechanisms.

In Fig. 1 fission-fragment folding-angle distributions in coincidence with Be, C, O, and Ne fragments are shown for the two IMF angle measurements. For comparison the inclusive fission folding-angle distribution for $E/A = 35$ MeV ^{14}N ions is also shown on this plot (the cross-section normalization between the inclusive and exclusive data is arbitrary). Figure 1 demonstrates the strong dependence of the fission-fragment folding angle Θ_{AB} on IMF emission angle. For fixed Θ_{IMF}, the folding-angle distributions exhibit a monotonic dependence on the atomic number of the detected fragment which is largely due to momentum conservation; see also

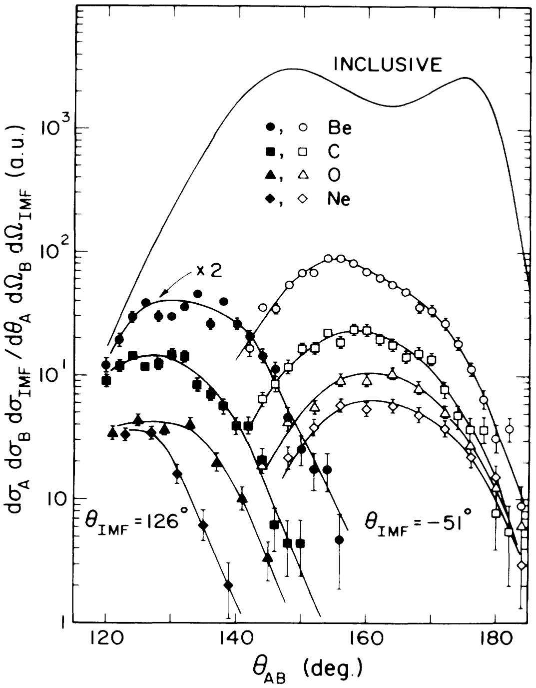

FIG. 1. Fission-fragment folding-angle distributions measured in coincidence with Be, C, O, and Ne fragments detected at $\Theta_{IMF}=-51°$ (open points) and $\Theta_{IMF}=\pm 126°$ (filled points). Solid lines through points are to guide the eye. Upper solid line represents the inclusive folding-angle distribution; its normalization is arbitrary.

Fig. 2.

For a more quantitative analysis, the dependence of the average folding angle, $\langle\Theta_{AB}\rangle$, on the atomic number, Z_{IMF}, of the coincident fragment was determined; see solid points in Fig. 2. The values of $\langle\Theta_{AB}\rangle$ were derived from a moment analysis at forward angles and from Gaussian fits to the back-angle data. Typical errors given in the figure include both statistical and systematic uncertainties. Because of the counting statistics, the errors become larger for heavier fragments. The open points in the figure depict average folding angles calculated for various values of the missing momentum, p_m. For these calculations the direction of the missing momentum was assumed to be parallel to the beam axis; the fragment mass was taken as $A=2Z$; fission mass and energy distributions were determined according to Fatyga *et al.*[18]

At $\Theta_{IMF}=51°$, the missing momentum is of the order of (25–30)%. Apart from the trivial effects due to momentum conservation, no systematic trend with fragment charge can be established. The average missing momentum corresponds to $(28\pm3)\%$ of the projectile momentum, compared to 42% for the total fission cross section.[19,20] For incomplete fusion reactions, the linear momentum transfer to the heavy reaction residue is closely related to the deposition of excitation energy.[21] We estimate average excitation energies of about 320 MeV for sources emitting intermediate-mass fragments at $\Theta_{IMF}=51°$. The observation of nonzero missing momentum is consistent with recent measurements[15] of coincidences between targetlike residues and intermediate-mass fragments for the reaction $^{32}S+Ag$ at $E/A=22.5$ MeV.

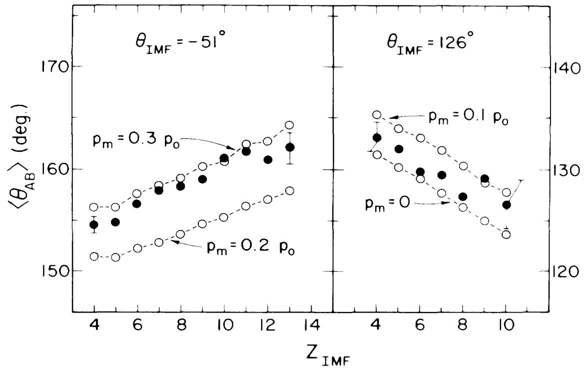

FIG. 2. Average value of the fission-fragment folding angle, $\langle\Theta_{AB}\rangle$, as a function of coincident ejectile atomic number for the two measured IMF angles. Filled points are experimental values determined according to Eq. (1). Open points are calculations based on various values of missing momentum, p_m, as described in text.

The missing momenta are considerably smaller when intermediate-mass fragments are emitted at backward angles $\Theta_{IMF}=126°$. Again, the extracted values are fairly independent of fragment mass. The average value of $\tilde{p}_m=(0.05\pm0.05)p_0$ indicates that these fragments are emitted in highly inelastic collisions in which nearly the entire momentum of the projectile is transferred to the heavy reaction residue. Within the experimental uncertainties, the emission of intermediate-mass fragments at backward angles is consistent with the occurrence of complete fusion of target and projectile, corresponding to an excitation-energy deposition of about 420 MeV.

Figure 3 shows the energy spectra of beryllium and carbon fragments detected at $\Theta_{IMF}=51°$ and 126°. (Since these spectra were measured in coincidence with two fission fragments, contributions from light target contaminants are nonexistent.) At $\Theta_{IMF}=126°$, the energy spectra can be parametrized in terms of the statistical model of Ref. 22 with us assuming emission from an equilibrated compound nucleus formed by the complete fusion of projectile and target. The calculation shown by the dashed line was performed for a temperature of $T=4$ MeV, corresponding to a level-density parameter of $a=(A/8)\ \mathrm{MeV}^{-1}$. At $\Theta_{IMF}=51°$, on the other hand, emission from a fully equilibrated compound nucleus (dashed line) is of minor importance. The solid curve shows a two-source fit with contributions from the fully equilibrated compound nucleus and an additional thermal source of velocity $v\cong 4v_{CN}$, apparent temperature

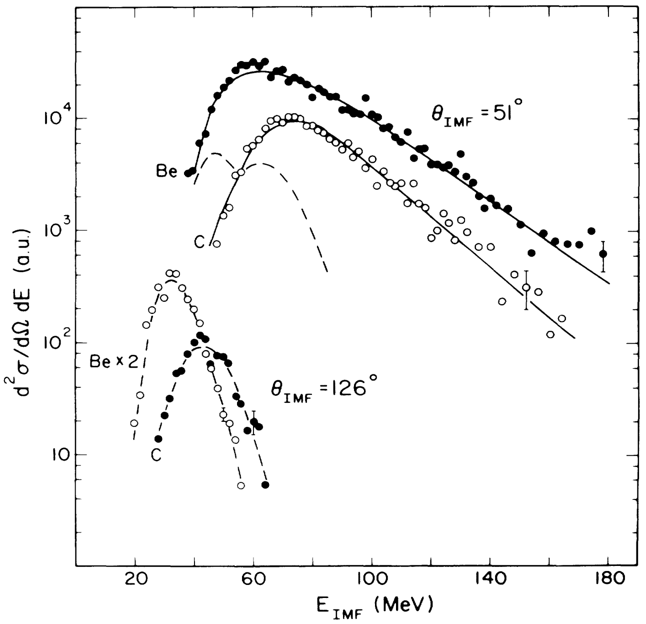

FIG. 3. Energy spectra of beryllium and carbon fragments in coincidence with angle-correlated fission fragments for $\Theta_{IMF}=-51°$ and $\Theta_{IMF}=\pm 126°$. Dashed lines give the results of statistical calculations (Ref. 22) assuming emission from a fully equilibrated compound nucleus. Solid lines are based on a two-source fit with parameters described in text.

$T \approx 13$ MeV, and Coulomb energy of $E_C=0.8V_C$, where V_C denotes the Coulomb barrier for two spherical nuclei.[1,14] The shapes of the energy spectra measured at $\Theta_{IMF}=51°$ are consistent with previous measurements[3,8,15,16] which established the emission of intermediate-mass fragments prior to the attainment of full statistical equilibrium of the composite system.

Several systematic uncertainties exist for the quantitative determination of the excitation-energy deposition and the degree of equilibration in reactions leading to the emission of intermediate-mass fragments. First, the average mass of the detected fragments at forward angles is slightly larger than the value of $A=2Z$ assumed in our analysis. Corrections for this error are of minor importance, resulting in slightly smaller missing momenta at forward angles. Secondly, because of the finite acceptance of our fission detectors, our values for $\langle\Theta_{AB}\rangle$ in coincidence with backward-angle IMF's could be too large. This effect corresponds to an overestimate of the missing momenta for heavier fragments emitted at backward angles, bringing the extracted values closer to zero. The largest quantitative uncertainty has to be attributed to the unknown effects of sequential decay of highly excited primary reaction products. Since the momenta of undetected decay products are included in our definition of the missing momentum, the occurrence of sequential decay will lead to larger missing momenta when the primary reaction products are emitted at forward angles and to smaller missing momenta when they are emitted at backward angles. As a consequence, we may have underestimated the excitation energy deposition for our measurements at $\Theta_{IMF}=51°$ and overestimated it at $\Theta_{IMF}=126°$. If, for example, all ^{12}C fragments resulted from the decay of ^{16}O primary fragments, the missing momenta carried away by the undetected α particle would be of the order of $p_m(\alpha) \approx +(0.08-0.1)p_0$ at $\Theta_{IMF}=51°$ and $p_m(\alpha) \approx -(0.05-0.06)p_0$ at $\Theta_{IMF}=126°$.

Our results demonstrate that the emission of intermediate-mass fragments at backward angles must be attributed to near-equilibrium emission in fusionlike processes in which the missing momentum is surprisingly small when compared to inclusive fusionlike reactions or reactions in which the fragments are emitted at forward angles. These findings suggest that complex fragment emission at backward angles could serve as a reaction filter for the selection of highly excited nuclear systems close to thermal equilibrium.

For ^{3}He-induced reactions on ^{232}Th at $E/A=90$ MeV, large missing momenta ($p_m \approx 0.25p_0$) were observed[23] for reactions in which intermediate-mass fragments were emitted at backward angles ($\Theta_{IMF}=160°$), indicative of particle emission prior to the attainment of full statistical equilibrium of the composite system. The comparison of these results with our experiment suggests that the probability of energy deposition and equilibration in central collisions depends primarily on the incident energy per nucleon (velocity) and on the projectile mass and less on the total center-of-mass energy. The relative velocity between the two colliding nuclei is also a decisive factor for the systematics of the linear momentum transfer in fusionlike collisions as established by inclusive measurements.[19,20] Hence, as long as the incident energy per nucleon remains below $E/A \approx 50$ MeV, complete fusion in central collisions could be a viable concept, even at very high excitation energies. By using heavier projectiles, one could possibly produce long-lived composite nuclei with excitation energies close to the total binding energy of the system.

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