# Polarization, Dynamics, and Nonequilibrium Complex-Fragment Emission

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The sign of the emission angle for nonequilibrium intermediate-mass fragments was determined from the circular polarization of coincident $\gamma$ rays for $^{14}$N-induced reactions on $^{154}$Sm at $E/A=35$ MeV. Positive polarizations, $P_\gamma \leqq 0.3$–$0.4$, are observed for fragments with $3\leqq Z\leqq 6$, consistent with fragment emission after deflection by the attractive nuclear mean field to negative emission angles. These polarizations are small compared to the trends established for nonequilibrium light particles and the expectations of simple dynamical production mechanisms.

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Most fragmentation models assume thermal equilibrium.[1] For incident energies between a few hundred megaelectronvolts and a few gigaelectronvolts, where intermediate-mass fragment cross sections increase strongly with bombarding energy,[2–4] equilibrium models are of limited utility, because many of the fragments are emitted before thermal equilibrium is achieved.[5,6] Models which attempt to describe the nonequilibrium production of fragments[6,7] have only been compared to simple observables such as energy spectra. Such comparisons reveal little of the relationship between reaction dynamics and fragment formation.

To explore this relationship, we have measured the circular polarization of $\gamma$ rays associated with the emission of intermediate-mass fragments for $^{14}$N-induced reactions on $^{154}$Sm at $E/A=35$ MeV. Spectral analysis of similar reactions suggests that many of these fragments are produced well before thermal equilibrium is achieved.[6] Previous polarization measurements for this reaction reveal that nonequilibrium light particles $(p,d,t,\alpha)$ are preferentially deflected to negative scattering angles by the attractive nuclear mean field.[8] Solutions of the Boltzmann equation, plus an additional assumption about composite-light-particle production, provide qualitative agreement with the light-particle data.[8] In this Letter, however, we show that the polarizations for the heavier fragments do not follow the systematic trends established for the light particles. In addition, the polarizations for the heavier fragments are not reproduced by simple dynamical emission models, suggesting that statistical fluctuations may be essential to the fragment emission mechanism.

The measurements were performed at the K500 cyclotron at the National Superconducting Cyclotron Laboratory of Michigan State University. Metallic self-supporting $^{154}$Sm targets of 4 mg/cm$^2$ areal density were bombarded with $^{14}$N ions of 490 MeV incident energy. Two telescopes, each consisting of three Si detectors of 30, 50, and 2000 $\mu$m thickness were placed at the polar and azimuthal laboratory angles of $\theta=35°$, $\phi=0°$ and $\theta=35°$, $\phi=180°$ to detect intermediate-mass fragments $(3\leqq Z\leqq 11)$ at angles much larger than the grazing angle. The circular polarization of coincident $\gamma$ rays emitted along the reaction normal was measured with two forward-scattering polarimeters[9] positioned at $\theta=90°$, $\phi=90°$ and $\theta=90°$, $\phi=270°$. The polarimeters had in-beam analyzing powers of $(0.95\pm 0.1)\%$.[10] In our sign convention, the polarizations are defined with respect to the quantization axis $\mathbf{n}$ defined by $\mathbf{n}=\mathbf{p}_i\times\mathbf{p}_f/|\mathbf{p}_i\times\mathbf{p}_f|$, where $\mathbf{p}_i$ and $\mathbf{p}_f$ are the momentum vectors of the beam and the detected particle, respectively; positive circular $\gamma$-ray polarizations correspond to negative deflection angles and vice versa.

The measured energy spectra of fragments with $3\leqq Z\leqq 6$ and the circular polarization of coincident $\gamma$ rays are shown in Fig. 1. The energy spectra exhibit nearly exponential slopes, indicating that contributions from projectile fragmentation are small. In contrast to the negligible polarizations expected for purely statistical fragment production mechanisms, positive polarizations are observed for all particles, indicating the importance of reaction dynamics. Such positive polarizations are consistent with fragments emission after deflection by the attractive nuclear mean field to negative emission angles. The polarizations increase monotonically with increasing fragment energy. The largest observed polar-

 

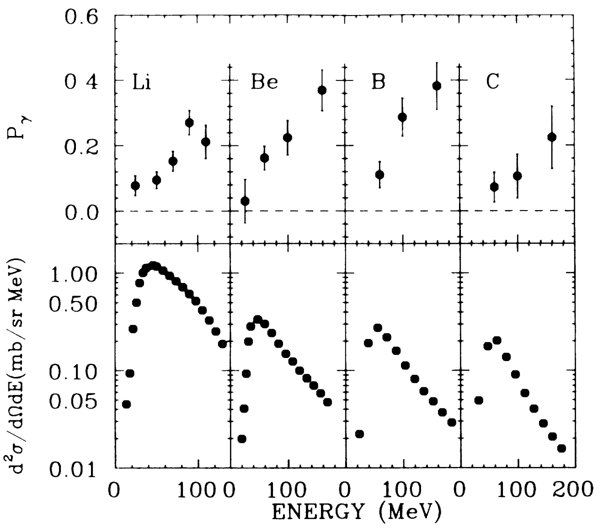


FIG. 1. Energy spectra (lower part) for intermediate-mass fragments emitted at 35° in $^{14}$N-induced reactions on $^{154}$Sm at $E/A=35$ MeV. The corresponding $\gamma$-ray circular polarizations (upper part) are shown as functions of the fragment kinetic energy.

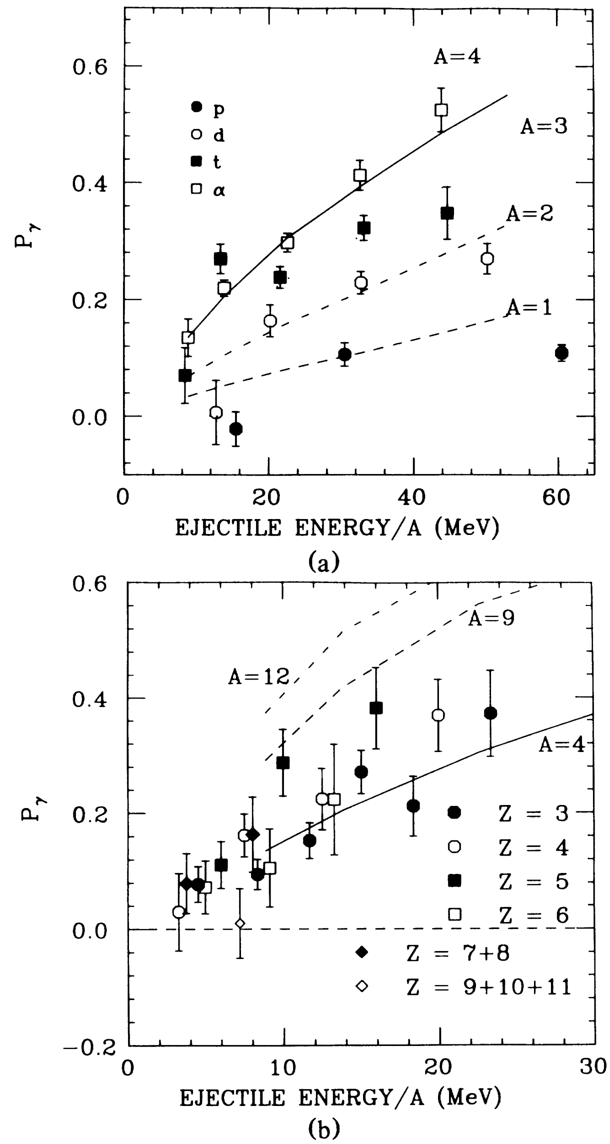


FIG. 2. (a) Polarizations for light particles emitted at 30° as functions of the ejectile energy per nucleon. The lines correspond to coalescence-model calculations described in the text. (b) Polarizations for intermediate-mass fragments emitted at 35° as functions of the ejectile energy per nucleon. The lines correspond to coalescence-model calculations described in the text.

izations, $P_\gamma=0.4$, however, are considerably less than the maximum polarization, $P_\gamma=0.7$–$0.8$, which is consistent with purely negative-angle scattering when one takes into account the contributions from nonaligned spins[11] and from nonstretched $\gamma$-ray transitions.[12] The reduced polarizations for low-energy fragments can partly be attributed to contributions from compound nuclear emission,[4] for which vanishing polarizations are expected. Such processes make negligible contributions to the spectra at energies greater than $10A$ MeV. Since intermediate-mass fragments are preferentially emitted perpendicular to the total angular momentum,[11] $P_\gamma \leqq 0.4$ for $E/A \geqq 10$ MeV implies that more than 20% of these intermediate-mass fragments are emitted to positive angles.

Some insights can be gained by examination of the mass dependence of the $\gamma$-ray polarizations. Figure 2(a) shows the circular polarizations measured[8,10] for nonequilibrium light particles at $\theta=30°$ as functions of the ejectile energy per nucleon. For fixed ejectile velocity, the polarizations are nearly proportional to the ejectile mass. Such a dependence is predicted by phase-space models, such as the coalescence model, in which the cross section for a fragment of mass $A$ is proportional to the $A$th power of the nucleonic phase-space density.[7,13–15] Since the light particles are also preferentially emitted perpendicular to the total angular momentum,[16] one may approximate the circular polarization for a fragment of mass $A$ by taking the difference between positive- and negative-angle cross sections,[17]

$$P_\gamma(\theta_0,E_A,A) \approx f\frac{\sigma_A(-\theta_0)-\sigma_A(+\theta_0)}{\sigma_A(+\theta_0)+\sigma_A(-\theta_0)} = f\frac{\Delta\sigma_A}{2\langle\sigma_A\rangle}, \tag{1}$$

where

$$\langle\sigma_A\rangle = [\sigma_A(-\theta_0)+\sigma_A(+\theta_0)]/2, \quad \Delta\sigma_A = \sigma_A(-\theta_0)-\sigma_A(+\theta_0),$$

and

$$\sigma_A(\pm\theta_0) = [d\sigma_A(\theta,E)/d^3p\Big|_{E=E_A;\theta=\pm\theta_0}$$

is the fragment cross section at the emission angle of $\pm\theta_0$ in the plane perpendicular to the total angular momentum. The constant $f$ takes into account the reduction of the polarization due to dealignment and nonstretched $\gamma$-ray transitions. Assuming the coalescence relation,[14,15] $\sigma_A(\pm\theta_0) = C[\sigma_1(\pm\theta_0)]^A$ ($C$ is a constant which depends on $A$ and the coalescence radius), and equal neutron and proton sections, one obtains

$$P_\gamma(\theta_0,E,A) = f\frac{(\langle\sigma_1\rangle + \Delta\sigma_1/2)^A - (\langle\sigma_1\rangle - \Delta\sigma_1/2)^A}{(\langle\sigma_1\rangle + \Delta\sigma_1/2)^A + (\langle\sigma_1\rangle - \Delta\sigma_1/2)^A}. \quad (2)$$

For $\Delta\sigma_1$ small, $P_\gamma(\theta_0,E,A) \approx AP_\gamma(\theta_0,E/A,1)$, providing polarizations which increase linearly with the fragment mass. Unlike cross sections, polarizations calculated with the coalescence model are insensitive to the coalescence radius. The dashed, dot-dashed, and dotted lines in Fig. 2(a) are obtained by scaling the solid line, drawn here for the $\alpha$ particles, to the protons, deuterons, and tritons, respectively, according to Eq. (2). For these estimates we have taken $f = 0.75$. Except for fragment energies less than $16A$ MeV, where Coulomb effects modify the coalescence relations,[14] the qualitative trends of the measured polarizations and therefore the relative proportions of positive- and negative-angle scattering are well reproduced.

Phase-space models can be combined with dynamical calculations.[7] It is therefore important to know whether such models can also give reasonable descriptions for the heavier fragments. Figure 2(b) shows the $\gamma$-ray polarizations for the heavier fragments, $Z \geqq 3$, as functions of the ejectile energy per nucleon. Here, the solid line describes the polarizations for $\alpha$ particles as in Fig. 2(a). Clearly the polarizations for the heavier fragments do not increase linearly with fragment mass as expected from the trends established by the light-particle measurements. Coalescence-model predictions from Eq. (2) for $^9$Be and $^{12}$C are indicated by the dashed and dash-dotted lines in the figure, respectively. The coalescence model overpredicts the mass dependence of the polarizations for the heavier fragments, yielding polarizations which are substantially larger than those observed for fragments with $Z > 4$ and $E/A > 10$ MeV. Comparisons between the measured and calculated energy spectra likewise reveal reasonable agreement with coalescence-model predictions for light particles[14,18] but poor agreement for fragments of $Z \geqq 3$.[18] Such comparisons, however, do not test coalescence predictions concerning the relative proportions of positive- and negative-angle scattering.

TABLE I. The deflection function (mean scattering angle), mean mass, mean energy per nucleon, and mean angular momentum per nucleon for projectilelike fragments calculated with the Boltzmann equation.

| $b$ (fm) | $\langle A\rangle$ | $\theta_{cl}$ (deg) | $E/A$ (MeV) | $\langle l\rangle/A$ |
|---|---|---|---|---|
| 7.0 | 2 | −53 | 6 | 5 |
| 7.5 | 7 | −27 | 12 | 6 |
| 8.0 | 9 | −19 | 15 | 7 |
| 9.0 | 12 | −2 | 25 | 9 |
| 10.0 | 13 | 6 | 28 | 10 |

While the polarizations for the heavy fragments do not follow the trends established by the light particles, they are comparable to $\gamma$-ray polarizations for heavy fragments detected near the grazing angle in strongly damped reactions at much lower bombarding energies.[12,19] The properties of such fragments have been reproduced by trajectory calculations in which the observed fragment is assumed to be the projectilelike residue.[17,20] Such residues are predicted for large-impact-parameter collisions by time-dependent Hartree-Fock calculations,[21] the Boltzman equation,[22] or nucleon-exchange transport models.[23] Since nucleon-nucleon collisions appear to be important for the present reaction,[8] we have explored this production mechanism with the Boltzmann equation and have calculated the deflection function for projectilelike residues given in Table I. The mean field was modified for these calculations to take into account the Coulomb interaction.[24] Other aspects of these calculations are as described in Ref. 22.

Actual emission angles may fluctuate about the mean angle, $\theta_{cl}$, provided by the deflection function because of the effects of diffraction,[17,25] dynamical dispersion,[17,25] and statistical fluctuations.[26] Following Ref. 17, we have estimated semiclassically the influence of diffraction and dynamic dispersion on the polarization, $P_\gamma(\theta_0, E, A)$, using the equation

$$P_\gamma(\theta_0,E,A) \approx f\frac{\exp\{-[(\theta_{cl}+\theta_0)/\zeta]^2\} - \exp\{-[(\theta_{cl}-\theta_0)/\zeta]^2\}}{\exp\{-[(\theta_{cl}+\theta_0)/\zeta]^2\} + \exp\{-[(\theta_{cl}-\theta_0)/\zeta]^2\}}, \quad (3)$$

where $\theta_0 = 35°$ is the measured scattering angle, $\zeta^2 = 2/\Delta^2 + [(d\theta_{cl}/dl)\Delta]^2/2$, and $\Delta$ is the width of the distribution of exit-channel orbital angular momentum leading to the emission of a fragment with energy $E$. The terms $2/\Delta^2$ and $[(d\theta_{cl}/dl)\Delta]^2/2$ describe the angular spreading due to diffraction and dynamic dispersion to first order, respectively.

Here, $\theta_{cl}$ was taken from the scattering angle of the fragment in Table I with the same energy per nucleon, because secondary processes like coalescence and sequential decay change the mass of the fragment but leave its velocity largely unchanged. For reasonable values of $\Delta$, however, we cannot reproduce the experimental polarizations. Indeed, for $\Delta \approx 4$–20, Eq. (3) predicts $P_\gamma > 0.70$ for $^9$Be at $E = 100$–160 MeV, close to the maximum possible value, $P_\gamma = 0.75$, expected for purely negative-angle scattering with $f = 0.75$. Agreement with the experimental polarizations could still be obtained, however, if the fragments were also dispersed over a much greater angular range by statistical fluctuations.

In summary, we have measured the circular polarization of coincident $\gamma$ rays which accompany the emission of nonequilibrium intermediate-mass fragments in $^{14}$N-induced reactions on $^{154}$Sm at $E/A = 35$ MeV. Positive polarizations, $P_\gamma \leqq 0.3$–0.4, are observed for intermediate-mass fragments, consistent with emission after deflection by the nuclear mean field to negative angles. These polarizations are small compared to the trends established for nonequilibrium light particles. Intermediate-mass fragments may originate through statistical fluctuations that deviate significantly from the ensemble-averaged reaction trajectories described by models such as the Boltzmann equation.[27] The $\gamma$-ray polarizations for the light particles could be reproduced by simple models in which such fluctuations are neglected. For the heavier fragments, however, the comparisons suggest that it may be necessary to take such fluctuations directly into account.

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