Deflection of Nonequilibrium Light Particles by the Nuclear Mean Field

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The sign of the average emission angle of nonequilibrium light particles was determined from the circular polarization of coincident γ rays emitted from residual nuclei for ^{14}N-induced reactions on ^{154}Sm at $E/A = 20$ and 35 MeV. Light particles (p,d,t,α) are preferentially emitted to negative angles. This effect is consistent with deflection of the particles by the attractive nuclear mean field. Numerical solutions of the Boltzmann-Uehling-Uhlenbeck equation demonstrate that the experimental result is sensitive to the interplay between the nuclear mean field and nucleon-nucleon collisions.

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The dynamics of intermediate-energy nucleus-nucleus reactions are governed by the nuclear mean field and by collisions between individual nucleons. Each effect evolves dramatically as the bombarding energy is increased. At low energies ($E/A \leqslant 10$ MeV), the mean field is predominantly attractive and individual nucleon-nucleon collisions are hindered by the Pauli exclusion principle. At much higher energies ($E/A \geqslant 400$ MeV), nucleon-nucleon collisions are frequent and densities may be achieved where the nuclear mean field becomes repulsive.[1] The transition from mean-field–dominated dynamics of low-energy reactions to nucleon-nucleon–dominated dynamics of high-energy reactions is expected to occur at incident velocities comparable to the Fermi velocity where Pauli blocking becomes less effective.

In intermediate-energy nucleus-nucleus collisions, nonequilibrium light particles are observed to be emitted preferentially in the entrance-channel scattering plane,[2] indicating a collective motion in this plane and transverse to the beam axis.[2,3] Microscopic calculations with the Boltzmann-Uehling-Uhlenbeck equation interpret this effect in terms of the deflection to negative emission angles by the attractive nuclear mean field.[1,4] Since the collective motion in the nuclear mean field is damped by individual nucleon-nucleon collisions, the relative importance of positive and negative emission angles is sensitive to the interplay between mean-field dynamics and two-body dissipation.

We have addressed these issues experimentally by determining the sign of the average emission angle of nonequilibrium light particles from the circular polarization of associated γ rays emitted by the residual nucleus for ^{14}N-induced reactions on ^{154}Sm at $E/A = 20$ MeV and $E/A = 35$ MeV. For these mass-asymmetric systems, the light-particle spectra are dominated by nonequilibrium processes.[3,5–7]

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. A metallic self-supporting ^{154}Sm target of 11 mg/cm^2 areal density was bombarded with ^{14}N ions of 280 and 490 MeV energy. Light particles were detected with four ΔE-E telescopes arranged in a doubly symmetric geometry[8] at polar angles of $\theta = 30°$ and 60° with respect to the beam axis and azimuthal angles of $\Phi = 0°$ and 180°. The telescopes consisted of 400-μm-thick surface-barrier detectors and 10-cm-thick NaI detectors and subtended solid angles of $\Delta\Omega(30°) = 44$ msr and $\Delta\Omega(60°) = 53$ msr. The circular polarization of coincident γ rays was measured with two forward-scattering polarimeters[8] positioned at $\theta = 90°$, $\Phi = 90°$ and $\theta = 90°$, $\Phi = 270°$. The polarimeters had in-beam analyzing powers of $(1.30 \pm 0.25)\%$ and $(1.20 \pm 0.25)\%$, at the bombarding energies of $E/A = 20$ and 35 MeV, respectively. Only statistical errors are displayed in the figures.

The measured light-particle energy spectra and γ-ray polarizations are shown in Figs. 1 and 2. The cross sections are forward peaked and the energy spectra exhibit nearly exponential slopes in agreement with the trends established previously for nonequilibrium light-particle emission.[6,7] Positive polarizations are observed at both energies and emission angles. The magnitude of the measured polarization increases with increasing energy and mass of the coincident light particles. No significant dependence on beam energy is observed. For a given particle and energy, the polarization is slightly larger at $\theta = 60°$ than at $\theta = 30°$. In our sign convention,[8] the quantization axis $\mathbf{n}$ is defined by $\mathbf{n} = \mathbf{k}_i \times \mathbf{k}_f / |\mathbf{k}_i \times \mathbf{k}_f|$, where $\mathbf{k}_i$ and $\mathbf{k}_f$ are the momentum vectors of the beam and the detected par-

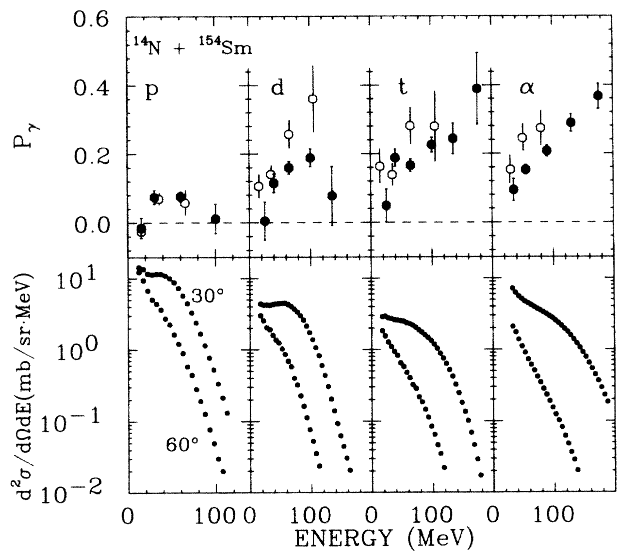

FIG. 1. Circular γ-ray polarizations plotted as a function of particle energies for p, d, t, and α (upper part) for $E/A = 35$ MeV. Closed and open circles correspond to measurements in coincidence with light particles detected at 30° and 60°, respectively. The lower part shows the inclusive energy spectra for the corresponding light particles.

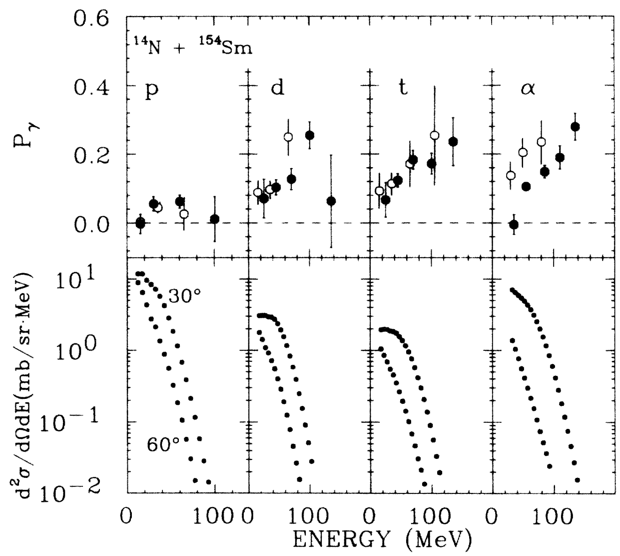

FIG. 2. Circular γ-ray polarizations plotted as a function of particle energies for p, d, t, and α (upper part) for $E/A = 20$ MeV. Closed and open circles correspond to measurements in coincidence with light particles detected at 30° and 60°, respectively. The lower part shows the inclusive energy spectra for the corresponding light particles.

ticle, respectively; positive circular γ-ray polarizations correspond to negative deflection angles and vice versa. Our experiment clearly establishes the preferential emission of nonequlibrium light particles to negative emission angles, consistent with an attractive nuclear mean field and with measurements at lower energies.[9,10] The sign is opposite to what is expected if only shadowing by the residual nucleus were to affect the particle emission.[3] For light-particle energies of $E/A \approx 35$ MeV, P_γ increases approximately linearly with A as would be expected in a coalescence model of light-particle production.

Both the polarization and spin alignment[2] tend to increase with mass and energy of the light particles. In order to estimate whether the magnitude of the measured polarizations is limited by the statistical spin deorientation, we have calculated the spin alignment, $P_{zz} \approx \langle 3M^2/2J^2 \rangle - 0.5$, of the residual nucleus with respect to the reaction normal $\mathbf{n}$. We have estimated P_{zz} using the two schematic parametrizations employed in Ref. 2 which were used to describe the out-of-plane to in-plane ratios of light particles in coincidence with fission fragments for the comparable reaction of ^{14}N + ^{197}Au at $E/A = 30$ MeV.[2] Both parametrizations give similar estimates of P_{zz}. The estimated values of $P_{zz} \approx 0.44$ and 0.77 are consistent with polarizations, $P_\gamma^{\max}$, as large as 0.6 and 0.7,[11] for the emission of protons ($E_p = 30$–50 MeV) and alpha particles ($E_\alpha = 120$ –200 MeV) at $\theta_{\text{lab}} = 60°$. (In these estimates, it is assumed that the presence of nonstretched γ-ray transitions[12] reduces $P_\gamma^{\max}$ by about 20% below the values expected for purely stretched transitions.) These upper bounds are significantly larger than the measured polarizations, indicating that light particles are scattered to both positive and negative emission angles.

Considerable progress has been made recently in treating the dynamics of the nucleon-nucleon collisions in the presence of the mean field generated by the participating nuclei.[1,4,13] We have performed numerical calculations with the Boltzmann-Uehling-Uhlenbeck equation[4,13] for ^{14}N + ^{154}Sm collisions at $E/A = 35$ MeV with impact parameters between $b = 1$ and 10 fm. A Skyrme-type interaction with a compressibility coefficient of $K = 200$ MeV and an isotropic nucleon-nucleon cross section of $\sigma_{NN} = 41$ mb were used. The impact-parameter–averaged azimuthal distributions of nucleons with energies larger than 30 MeV, emitted at $\theta = 30°$ and 60°, are shown in Fig. 3. In the figure, positive and negative scattering angles correspond to $\phi = 0°$–90° and $\phi = 90°$–180°, respectively. The calculations predict the preferential emission of nucleons to negative angles, in qualitative agreement with the experimental observations.

To allow a more quantitative comparison with the data, we have calculated the circular polarization predicted by the Boltzmann-Uehling-Uhlenbeck model. The angular momentum, $\mathbf{J}(b)$, of the residual nucleus (assumed to correspond to nucleons within a radius of 7.5 fm at the collision time of 200 fm/c) was determined for each impact parameter. For simplicity, the residual nucleus was assumed to decay via stretched $E2$ transitions, corresponding to a γ-ray multiplicity of $M_\gamma = J(b)/2$. Integrating over the geometry of the polarimeters,[8] Ω_γ, and averaging over impact parameters b gives for the predicted polarization

$$\langle P_\gamma(\theta)\rangle = \frac{2\pi \sum_b b M_J(b) \int dE \int d\phi\, \sigma_N(\theta,\phi,E) \int d\Omega_\gamma P(\beta) Y(\beta)}{2\pi \sum_b b M_J(b) \int dE \int d\phi\, \sigma_N(\theta,\phi,E) \int d\Omega_\gamma Y(\beta)}. \quad (1)$$

Here, $Y(\beta) = 1 - \cos^4\beta$ and $P(\beta) = 2\cos\beta/(1+\cos^2\beta)$ are the angular distributions of the γ-ray yield and the circular γ-ray polarization, respectively, and $\cos(\beta) = \mathbf{k}_\gamma \cdot \mathbf{J}/k_\gamma J$; $\mathbf{k}_\gamma$ is the momentum vector of the emitted photon and $\sigma_N(\theta,\phi,E)$ is the nucleon differential cross section. The azimuthal integration, $\int d\phi$, averages over different orientations of the entrance-channel reaction plane in the laboratory. Since the relative angles between coincident particles and γ rays are determined by the experimental geometry, the range of the integration, $\int d\Omega_\gamma$, depends only on the relative azimuthal angles, $\Delta\phi = \phi - \phi_\gamma$, between particles and γ rays. The integration, $\int dE$, was performed over energies greater than 30 MeV. At the angles of 30° and 60°, the predicted polarizations are 0.18 ± 0.03 and 0.25 ± 0.03, respectively. The values should be reduced by about 20% if one accounts for nonstretched transitions.[11,12] In comparison, the calculated polarizations, 0.14 and 0.2 at $\theta = 30°$ and $\theta = 60°$, respectively, are larger than the experimentally observed proton polarizations of 0.07 both at $\theta = 30°$ and at $\theta = 60°$. However, the present calculations do not include emission of composite particles which have larger measured polarizations. In accordance with the coalescence picture, one may assess the effects of complex particle emission by evaluating an "effective nucleon polarization" according to the definition

$$P_{\text{eff}}(\theta) = \frac{\sum_i \sum_j A_i \sigma_i(\theta,E_j) P_i(\theta,E_j)}{\sum_i \sum_j A_i \sigma_i(\theta,E_j)}, \quad (2)$$

where A_i, $P_i(\theta,E_j)$, and $\sigma_i(\theta,E_j)$ denote mass, experimentally measured polarization, and cross section for particle i and $i = p,d,t,\alpha$. For particle energies $E/A \geq 30$ MeV, the effective polarizations are $P_{\text{eff}}(30°) = 0.17 \pm 0.03$ and $P_{\text{eff}}(60°) = 0.12 \pm 0.03$. Considering the experimental uncertainties of the absolute calibrations of the analyzing power and the theoretical uncertainties in the relative weights for the composite particles, the deviation between $P_{\text{eff}}(\theta = 60°)$ and the calculated polarization $\langle P_\gamma(\theta = 60°)\rangle$ is not as stringent as the numbers indicate.

In order to illustrate the dependence of the predicted polarizations on the nucleon-nucleon collision dynamics, we have varied the strength of the residual interaction. For simplicity, calculations were only performed for one impact parameter, $b = 6.5$ fm. This impact parameter contributes the largest weight to the polarization integral of Eq. (1). Table I shows the dependence of the predicted polarization on the strength of the nucleon-nucleon scattering cross section.[14] The predicted polarization decreases monotonically for larger values of σ_{NN}. For $\sigma_{NN} = 41$ mb, the polarization is reduced by over a factor of 3 below the value calculated with the mean field alone. Thus the magnitude of the impact-parameter–averaged polarizations calculated with Eq. (1) reflects the balance

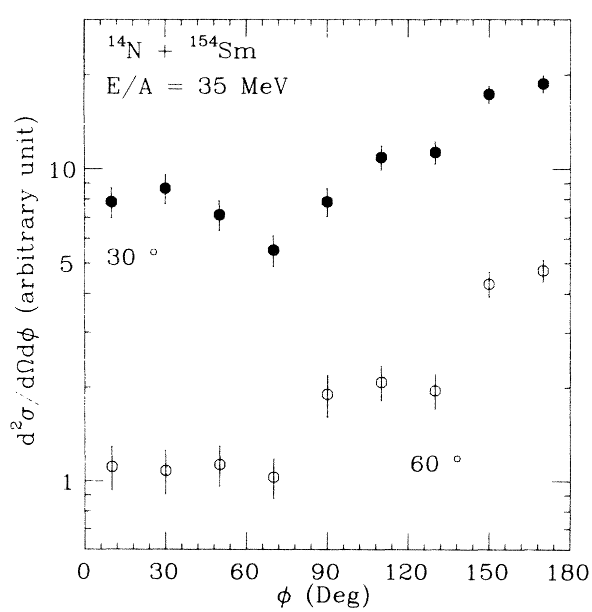

FIG. 3. Azimuthal distribution of nucleons scattered to 30° ± 10° (closed points) and 60° ± 10° (open points) from Boltzmann-Uehling-Uhlenbeck calculations. $\phi > 90°$ corresponds to negative scattering angles and $\phi < 90°$ corresponds to positive scattering angles.

TABLE I. Polarizations predicted by the Boltzmann-Uehling-Uhlenbeck equation using different nucleon-nucleon scattering cross sections σ_{NN}. The calculations were performed for a fixed impact parameter of $b = 6.5$ fm.

σ_{NN} (mb)	$P_\gamma(30°)$
0	0.82 ± 0.08
10.3	0.56 ± 0.04
20.5	0.24 ± 0.08
41.0	0.25 ± 0.07
82.0	0.04 ± 0.10

between deflection by the mean field and randomization of the particle velocities by nucleon-nucleon collisions.

In summary, measurements of the circular polarizations of γ rays in coincidence with light particles indicate that nonequilibrium light particles are predominantly emitted to negative emission angles. Negative emission angles are consistent with the deflection of nonequilibrium light particles by an attractive nuclear mean field. Calculations with the Boltzmann-Uehling-Uhlenbeck equation predict perferential emission to negative angles and suggest that collisions between individual nucleons reduce the polarizations significantly below what might be expected from mean-field dynamics alone.

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