Enhanced Emission of Nonequilibrium Light Particles in the Reaction Plane

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Nonequilibrium light particles were detected in coincidence with two fission fragments for ^{14}N-induced reactions on ^{197}Au at 420 MeV incident energy. Coincident binary-fission events were used to define the reaction plane and to suppress contributions from transferlike peripheral reactions. A strong preference for the emission of nonequilibrium light particles in the fission plane was observed, suggesting the presence of an ordered transverse motion of the emitting source in the reaction plane.

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Particle emission prior to the attainment of global statistical equilibrium of the composite system is well established for intermediate- and high-energy nuclear collisions. Present experimental information on nonequilibrium particle emission in fusionlike reactions is consistent with the concept of statistical emission from a localized region of high excitation.[1-9] Although particle emission from such localized regions of excitation may be expected to be azimuthally anisotropic because of geometrical shadowing or dynamical flow effects, no azimuthal anisotropies have yet been established experimentally. In this Letter we report the first experimental evidence indicating that nonequilibrium particle emission in fusionlike reactions exhibits large azimuthal anisotropies corresponding to preferential emission in the plane perpendicular to the entrance-channel orbital angular momentum.

The experiment was performed at the K500 cyclotron of the National Superconducting Cyclotron Laboratory of Michigan State University. A ^{197}Au target of 0.5 mg/cm^2 areal density was bombarded with ^{14}N ions of 420 MeV incident energy. Triple coincidences between two fission fragments and outgoing light particles, prescaled inclusive light-particle events, and prescaled fission-fission coincidence events were written on magnetic tape and analyzed off line. Coincident fission fragments were detected with two position-sensitive parallel-plate detectors of active area 12×14 cm^2, which were positioned 17 cm from the target at angles of $\theta_{A0}=70°$ and $\theta_{B0}=80°$. Light particles emitted far back of the grazing angle ($\theta_{\text{gr}}\sim 11°$) were detected with two ΔE-E telescopes consisting of silicon ΔE and NaI E detectors. The telescopes had solid angles of 53 and 63 msr and were placed at the angles $\theta_x=55°$, $\phi_x=0°$ and $\theta_x=55°$, $\phi_x=90°$, respectively. Here, θ_x denotes the polar angle measured with respect to the beam axis and ϕ_x denotes the azimuthal angle between the light-particle telescope and the plane defined by the centers of the two fission detectors and the beam axis. In the triple-coincidence data reported in this Letter, the azimuthal angle of one of the fission fragments is constrained to lie within 3.5° of the azimuthal angle corresponding to the center of the fission detector.

For reactions induced on a Au target, fission fragments originate primarily from fusionlike collisions for which the major part of the projectile is absorbed by the target nucleus. To illustrate this point, Fig. 1 shows fission-fragment folding-angle distributions measured for ^{14}N-induced reactions on ^{197}Au at $E/A=30$ MeV. Fission fragments are primarily emitted in fusionlike reactions corresponding to large momentum transfers. In contrast to reactions on ^{238}U,[10] transferlike reactions corresponding to $\theta_A+\theta_B\gtrsim 170°$ are strongly suppressed for reactions on ^{197}Au because of the lower fissility of the targetlike residues.

For simplicity, we will neglect the intrinsic spins of the projectile and target nuclei and the angular momentum of particles emitted prior to fission. In this approximation, the total angular momentum I of the fissioning nucleus is equal to the entrance-channel orbital angular momentum of relative motion between projectile and target nuclei. Semiclassically, the probability distribution, $P(\phi)$, for the angle ϕ between the entrance-channel scatter-

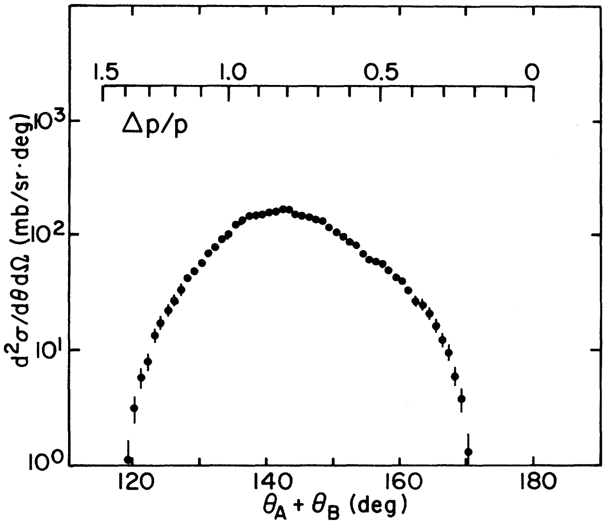

FIG. 1. Folding-angle distributions between coincident fission fragments measured for ^{14}N-induced reactions on ^{197}Au at $E/A = 30$ MeV. The polar angles of the two outgoing fission fragments are denoted by θ_A and θ_B and the average momentum transfer to the target residue, measured in units of the beam momentum, is denoted by $\Delta p/p$.

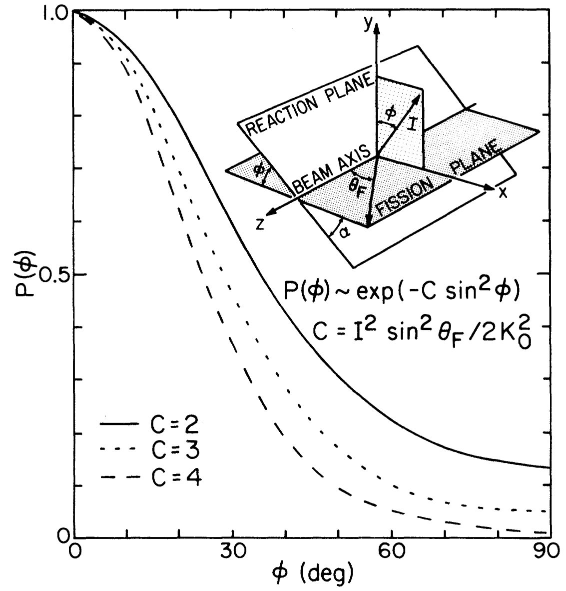

FIG. 2. Characteristic shapes of probability distributions $P(\phi)$ for the fission-fragment plane with respect to the reaction plane.

ing plane[11] and the fission plane (defined as the plane containing the beam axis and the fission fragment velocity vectors) may be expressed as[12]

$$P(\phi) = \text{const} \times \exp[-C \sin^2(\phi)], \tag{1}$$

where $C = I^2 \sin^2\theta_F/2K_0^2$. (For illustration, note the inset of Fig. 2.) The shapes of distributions corresponding to $C = 2$, 3, and 4 are shown in Fig. 2. Since the detailed properties of the fissioning system are not known, C cannot be specified *a priori.*

The energy spectra of light particles detected in and out of plane with two coincident fission fragments are shown by circular and triangular points in Fig. 3. Similar to previous observations for slightly different systems,[1-4] the energy spectra exhibit approximately Maxwellian shapes. However, there is a clear preference for the emission of energetic light particles in the plane of the outgoing fission fragments. To provide a quantitative measure of this enhancement, the ratios of out-of-plane to in-plane energy-integrated coincidence spectra have been plotted in Fig. 4 where the energy integration intervals are indicated by the horizontal bars. The ratios decrease significantly with increasing energy and with increasing mass of the coincident light particles. For the highest-energy alpha particles, azimuthal anisotropies of up to one order of magnitude

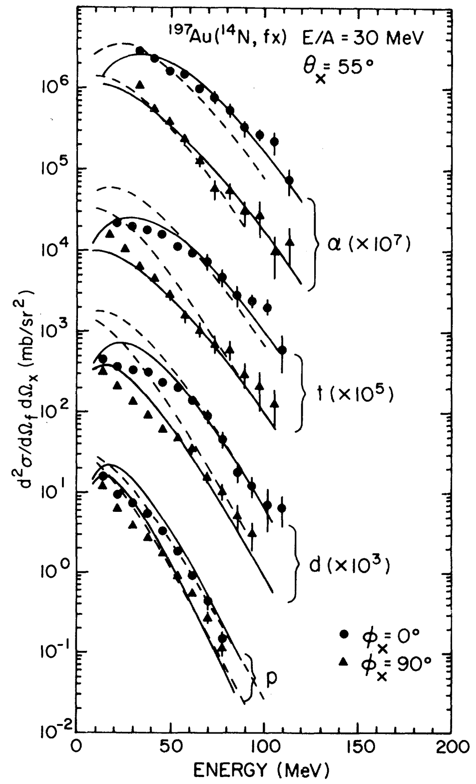

FIG. 3. Energy spectra of p, d, t, and α particles measured in coincidence with fission fragments.

are observed.

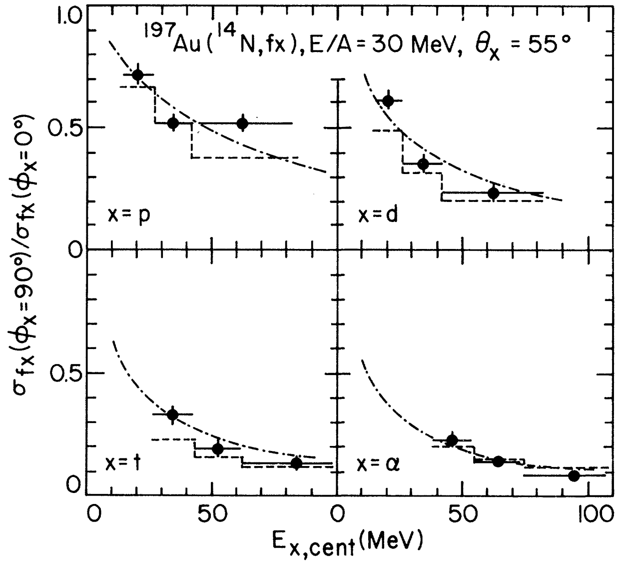

FIG. 4. Ratio of out-of-plane to in-plane coincidences between fission fragments and light particles.

Azimuthally asymmetric angular distributions have been predicted in a variety of reaction models. An enhancement of nonequilibrium light particle emission in a direction perpendicular to the entrance-channel scattering plane could be caused by nuclear shadowing effects[13] or perhaps by hydrodynamic compression effects[14] both of which lead to a preferential flow of nuclear matter in a plane perpendicular to the line connecting the centers of the two colliding nuclei. Our observation of enhanced emission in the fission plane indicates that these effects are of minor importance. On the other hand, an enhanced emission of nonequilibrium particles in the entrance-channel scattering plane might be due to an ordered collective motion of the emitting source in this plane. For illustration, we perform two schematic calculations.

In the first calculation we adopt a model of an emitting source which rotates with angular frequency ω about an axis perpendicular to the entrance-channel scattering plane while moving with a velocity v_0 parallel to the beam axis. In a semiclassical approximation[15,16] the cross section in the laboratory frame may be expressed as

$$\frac{d^2\sigma_x}{dE_x\,d\Omega_x}(E_x,\Theta_x,\Phi_x)=N(E_xE_{\text{c.m.}})^{1/2}\exp\left(\frac{-E_{\text{c.m.}}}{T}\right)\frac{J_1(iA\,(E_{\text{c.m.}}-E_x\sin^2\Theta_x\sin^2\Phi_x)^{1/2})}{iA\,(E_{\text{c.m.}}-E_x\sin^2\Theta_x\sin^2\Phi_x)^{1/2}}, \tag{2}$$

where N is a normalization constant; J_1 denotes the first-order Bessel function; $A=(2m)^{1/2}R\omega/T$; $E_{\text{c.m.}}=E_x+E_0-2E_x^{1/2}E_0^{1/2}\cos\Theta_x$; $E_0=\frac{1}{2}mv_0^2$; E_x and m are the energy and mass of the emitted particle; Θ_x and Φ_x are the polar and azimuthal angles of the emitted particle; and R and T are the radius and temperature of the source.

In the second calculation we assume that the ordered motion is purely translational with a significant velocity component perpendicular to the beam in the entrance-channel scattering plane. We use a moving-source parametrization corresponding to a Maxwellian distribution in a rest frame which moves with the velocity v_0 at the polar and azimuthal angles Θ_0 and $\Phi_0=0$, respectively. In the laboratory frame, the differential cross section is given by

$$\frac{d^2\sigma_x}{dE_x\,d\Omega_x}(E_x,\Theta_x,\Phi_x)=N'E_x^{1/2}\exp\{[-E_x+E_0-2E_x^{1/2}E_0^{1/2}(\cos\Theta_x\cos\Theta_0+\sin\Theta_x\sin\Theta_0\cos\Phi_x)]T^{-1}\}. \tag{3}$$

where N' is a normalization constant.

To utilize Eqs. (2) and (3), it is necessary to incorporate Eq. (1) which relates the experimentally observed fission plane to a distribution of possible entrance-channel scattering plane orientations. Consequently we fold the distributions given by Eqs. (2) and (3) with the probability distribution $P(\phi)$:

$$\frac{d^2\sigma_x}{dE_x\,d\Omega_x}(E_x,\Theta_x,\Phi_x)=\int_0^{2\pi}d\phi\,P(\phi)\frac{d^2\sigma_x}{dE_x\,d\Omega_x}(E_x,\Theta_x,\phi+\Phi_x), \tag{4}$$

where we have taken the convention $\Phi_x=0°$ and $\Phi_x=90°$ for in- and out-of-plane coincidences, respectively.

The results of these calculations are compared to the measurements in Figs. 3 and 4. Calculations with the rotating source appear as solid lines in Fig. 3 and as dashed histograms in Fig. 4. The parameters used in these calculations are $T=5.8$ MeV, $v_0=0.09c$, $C=3$, and $R\omega=0.1c$ for the emission of p, d, and t and $R\omega=0.08c$ for the emission of α particles. The dashed lines in Fig. 3 and the dot-dashed lines in Fig. 4 were calculated on the assumption of a deflected source [Eq. (3)], with the parameters $T = 7$ MeV, $v_0 = 0.1c$, $\Theta_0 = 29°$, and $C = 4$.

Since both of these rather simple models qualitatively describe the data, it is likely that similar agreement could be obtained by other models which superimpose random statistical motion of the participating nucleons upon a transverse collective velocity of approximately $0.05c$. Further measurements are needed to distinguish between these and other possible interpretations and to merge these observations with the accumulating body of experimental data at these energies. We hope that this striking observation will stimulate further development of reaction models which will describe the dynamical and statistical aspects of nucleus-nucleus collisions in terms of more fundamental concepts.

In summary, nonequilibrium light particles produced in fusionlike reactions of $^{14}\mathrm{N} + {}^{197}\mathrm{Au}$ at $E/A = 30$ MeV are preferentially emitted in the entrance-channel scattering plane. The measured azimuthal anisotropies increase significantly for heavier and more energetic particles. The observed in-plane enhancement suggests an ordered transverse motion in the reaction plane superimposed on the random statistical motion of the individual nucleons.

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