Dynamics of Incomplete Fusion Reactions from γ-Ray Circular-Polarization Measurements

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(Received 10 August 1984)

The circular polarization P_γ of deexcitation γ rays has been measured in coincidence with fast charged particles from reactions induced by light heavy ions at $E/A \approx 8$ MeV. Polarizations of up to $|P_\gamma| \approx 0.3$ were observed. The variations of P_γ in sign and magnitude with the particle type, energy, and angle, and with the target mass reveal the effects of the particle-target interaction during a tangential passage along the target nucleus.

PACS numbers: 25.70.Np, 23.20.-g, 25.70.Jj

A variety of dynamical models have been proposed to describe the preequilibrium emission of light particles in heavy-ion reactions at energies of several times the Coulomb barrier energy.[1,2] They may be divided into those which assume statistical emission from an equilibrated hot subsystem (hot-spot,[3] moving-source[4] models) and those which assume emission from the projectile into the continuum either directly (breakup-fusion models[5,6]) or after transfer into states high above the Fermi level of the target nucleus [promptly emitted particles (PEP) or Fermi-jet,[7-9] exciton[10,11] models]. Satisfactory fits to inclusive light-particle spectra were produced with models from each of these groups, in spite of the differences in the underlying physical pictures. This indicates that the forward-peaked angular distributions of the inclusive cross sections and the smooth spectra shapes are not characteristic enough to differentiate between the various approaches.

In this Letter we report further insight into the dynamics of preequilibrium light-particle emission, gained by means of polarization measurements. We studied reactions in which fusion of a substantial part of the projectile with the target is the dominant reaction channel (incomplete-fusion or massive-transfer reactions[1]). In this case, the major part of the incoming angular momentum $\vec{l}_i$ is transferred to the residual nucleus whose spin will therefore point approximately in the direction of $\vec{l}_i$. By measuring the direction of the resulting spin polarization with respect to the reaction normal via the observation of the circular polarization of the deexcitation γ rays, the sign of the emission angle of the light particles can be determined. This information can then be used to distinguish between some of the dynamic reaction models. In a PEP mechanism, e.g., the light particles are emitted from the side of the target nucleus opposite to where it is hit by the projectile, i.e., to negative angles. The same is expected for particles knocked out from the target by a heavy projectile whose radial motion is rapidly stopped on impact.[8] If, on the other hand, the light particles behave as spectators whose trajectory is mainly determined by the Coulomb force, emission to positive angles would result.

Self-supporting samarium and niobium targets of 2–5 mg/cm^2 areal density were bombarded with ^{16}O and ^{14}N beams from the Brookhaven tandem accelerator facility (Table I). Light charged particles were detected and identified in two ΔE-E Si surface-barrier telescopes, subtending solid angles of $\Delta\Omega \approx 30$ msr and mounted in coplanar geometry at equal scattering angles θ_{lab} (see Table I) on either side of the beam axis. Two forward-scattering γ-ray polarimeters were positioned perpendicular to the reaction plane in a double-symmetric detector arrangement.[12] Their in-beam analyzing power was $A = 1.5\% \pm 0.2\%$ for the investigated reactions. The polarization P_γ, deduced from the measured count-rate asymmetries $P_\gamma \cdot A$, will be shown with only statistical errors in the following. The sign of

TABLE I. Investigated reactions.

Projectile	E_{lab} (MeV)	Target	θ_{lab} (deg)
^{16}O	140	^{144}Sm	25
^{16}O	140	^{154}Sm	25,38
^{16}O	110	^{93}Nb	38
^{16}O	120,140	^{93}Nb	25,38
^{14}N	95	^{93}Nb	38

P_γ is defined positive if the photon spin points into the direction of $\vec{k}_i \times \vec{k}_f$, where $\vec{k}_i$ and $\vec{k}_f$ denote the wave vectors of the beam and the observed particle, respectively.

The target chamber was surrounded by an array of seven $7.6 \times 7.6\text{-cm}^2$ NaI detectors, each of them with an efficiency of $\Delta\Omega/4\pi \approx 0.5\%$ for γ rays in the relevant energy range 200 keV $\lesssim E_\gamma \lesssim 1$ MeV. The array was operated in coincidence with light-particle events and was used to study the associated γ-ray multiplicity M_γ. As it turned out, reaction components with low multiplicity, such as breakup after quasielastic interactions or reactions with target contaminants, were efficiently suppressed by the required coincidence with the polarimeter γ rays which effected a weighting of the recorded data in proportion to M_γ.

The results obtained for α particles from the $^{16}O + {}^{144,154}Sm$ reaction and $\theta_{lab} = 25°$ are shown in Fig. 1. Here the data from the bombardment of the two isotopes were summed since no significant isotopic dependence was detected. The trend of P_γ with α-particle energy has a shallow minimum in the energy range of the α particles of near-beam velocity ($E_\alpha \approx 35$ MeV), and negative values of $P_\gamma \approx \approx -0.15$ are observed here. In the $\theta_{lab} = 38°$ data the trend is similar, but P_γ reaches somewhat more negative values ($P_\gamma = -0.28 \pm 0.07$ for 35 MeV $\leqslant E_\alpha \leqslant 50$ MeV). The absolute values of the spin polarization P_z of the γ-decaying nuclei should be about 30% larger than those of P_γ because of the diluting effect of nonstretched γ decay.[13] The negative sign of the polarization indicates positive emission angles as expected for Coulomb deflection. These results are consistent with those from polarization measurements for similar systems, reported by Ishihara *et al.*[14]

Negative polarizations were not observed in the reactions with niobium target. In $^{16}O + {}^{93}Nb$ at 140 MeV and $\theta_{lab} = 25°$, the trend of P_γ with E_α is somewhat similar to that observed for Sm, but shifted towards more positive values (Fig. 2, top). The same trend is also found for $^{14}N + {}^{93}Nb$. At the larger angle $\theta_{lab} = 38°$, the polarization has a positive value in the whole energy range (Fig. 2, bottom). If we average over all data measured with the niobium target and at this angle (cf. Table I), we obtain $P_\gamma = 0.11 \pm 0.02$ (0.20 ± 0.04) for $E_\alpha > 30$ MeV (40 MeV), respectively. If the detection of at least one additional γ ray in the NaI array is required, causing a weighting in proportion to M_γ^2, the values are slightly larger, $P_\gamma = 0.16 \pm 0.02$ (0.28 ± 0.05).

According to the positive sign of P_γ, negative

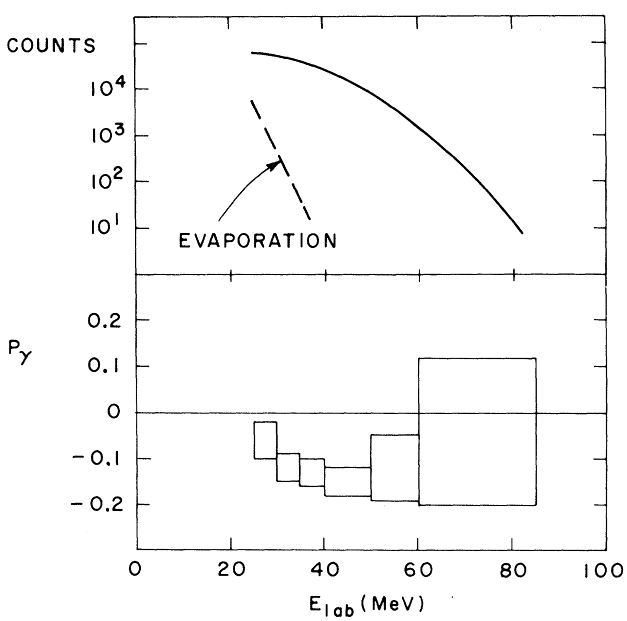

FIG. 1. Inclusive α-particle spectrum (top) and circular polarization P_γ (bottom) of the coincident γ radiation for the reaction $^{16}O + {}^{144,154}Sm$ at 140 MeV ($\theta_{lab} = 25°$). The intensity of the evaporation component, derived from measurements at backward angles, is given by the dashed line.

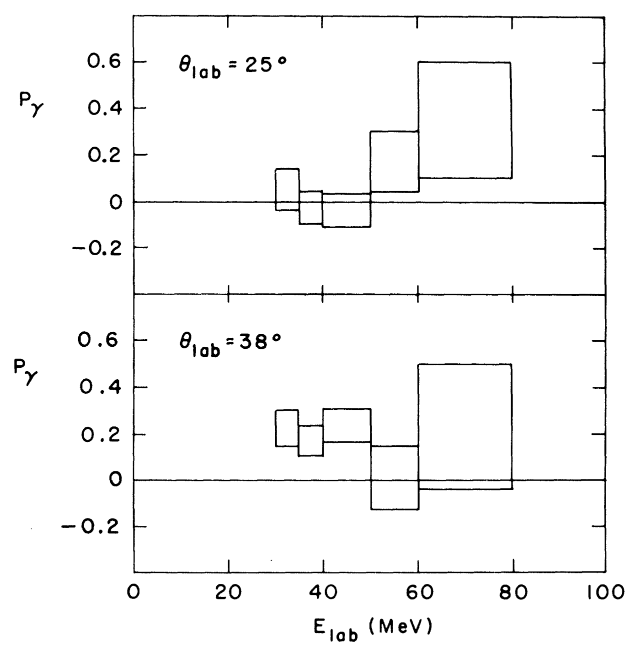

FIG. 2. Circular polarization P_γ measured in coincidence with α particles emitted at $\theta_{lab} = 25°$ (top) and $\theta_{lab} = 38°$ (bottom) for the reaction $^{16}O + {}^{93}Nb$ at 140 MeV.

emission angles dominate in these reactions. They are expected for the PEP and knockout processes, and for the case of deflection in the attractive nuclear field of the target nucleus. Sequential emission from a projectilelike fragment that was scattered to negative angles after a deep-inelastic collision would also focus the light particles to negative angles. The comparatively small cross sections[15] and decay probabilities,[16] as well as kinematic limitations, make it very unlikely, however, that in any part of the α-particle spectra the main yield originates from this process.

The polarizations measured in coincidence with protons are numerically much smaller than those for α particles and are nearly all consistent with zero. This is expected for the lower proton energies where the spectrum is dominated by the evaporation component, but it is also the case at the highest energies ($E_p > 15$ MeV) where the forward-peaked proton component has a considerable intensity (Table II). This result is of particular interest since a substantial spin polarization P_p of the emitted protons was measured by Sugitate *et al.*[17] in a double-scattering experiment conducted for the reaction $^{14}N + ^{93}Nb$ at 95 MeV. The data from both experiments, for the same reaction, are compared in Table II. Apparently P_γ is much smaller than P_p.

There are a variety of conceivable mechanisms that can give rise to the emission of polarized protons.[17] Most of them, however, rely on a dominance of either near- or far-side interactions and therefore would also cause a corresponding polarization of the product nuclei which is not observed. The large values of P_p must therefore originate from some other source, e.g., the spin-orbit coupling in the exit-proton channel. A quantum-mechanical treatment is clearly necessary for a quantitative evaluation of the produced spin polarization. Estimates with a classical trajectory model show that the spin-orbit coupling known from scattering experiments can produce effects with the same sign and of the order of magnitude observed by Sugitate *et al.*,[17] under the assumption that the protons pass close to the target along tangential orbits as they are emitted in the incomplete-fusion process.

TABLE II. Gamma-ray circular polarization P_γ in coincidence with protons, proton spin polarization P_p, and relative intensity I_{fast} of the forward-peaked component in the proton spectra for $^{14}N + ^{93}Nb$ at $E_{\text{lab}} = 95$ MeV.

E_p (lab) (MeV)	P_γ (%)	P_p[a] (%)	I_{fast}[a] (%)
11.9–13.8	-2 ± 3	$+8 \pm 2$	20
13.8–15.4	-2 ± 3	$+10 \pm 6$	27
15.4–17.51	0 ± 4	$+15 \pm 5$	34
17.5–20.2	$+1 \pm 5$	$+17 \pm 7$	45
> 20.2	$+5 \pm 4$	$+20 \pm 7$	

[a]Measured at $\theta_{\text{lab}} = 40°$; from Ref. 17.

The α spectra at energies above 30 MeV are essentially free of evaporation contributions (Fig. 1). The P_γ values from α coincidences thus have a direct bearing on the incomplete-fusion mechanism since other processes that produce fast α particles have very small yields under the present experimental conditions (see above). In the following we will present a classical picture which is consistent with the gross trends of the data. Classical considerations seem adequate for a qualitative discussion since the data are integrated over many nuclear states which effectively average over any particular effects of nuclear structure.

The negative polarizations for beam-velocity α particles and the target with the larger atomic number (samarium) suggest that these particles were emitted near the surface of the target, as the main part of the projectile was captured and, on the average, were deflected to positive angles by the repulsive Coulomb force. In analogy to heavy ions, the maximum deflection angle is given by the grazing angle θ_{gr} for the respective α-particle–target system. We observe negative polarizations only if θ_{gr} is larger than the angle of observation, as in $\alpha + \text{Sm}$ ($\theta_{\text{gr}} \approx 39°$ for $E_\alpha = 35$ MeV). The decreasing effectiveness of the Coulomb force with increasing α-particle energy and decreasing target Z appears as a trend toward more positive polarization values in the data (Figs. 1 and 2). In $^{16}O + ^{93}Nb$ at $\theta_{\text{lab}} = 38°$, i.e., far behind the grazing angle for $\alpha + \text{Nb}$ and $E_\alpha \gtrsim 30$ MeV ($\theta_{\text{gr}} \lesssim 32°$), negative emission angles are prevailing. We therefore interpret the observed Coulomb deflection as largely resulting from the α-particle–target interaction in the exit channel.

In the same picture, one expects particles coming somewhat closer to the target nucleus to be deflected to negative angles by the attractive nuclear force. Since there is no obvious limit on the amount of deflection, this can be the dominant process at the larger angles. Some additional experimental support for such an interpretation of the negative-angle component is found in the γ-ray multiplicity distributions, derived from the number of coincident counts in the NaI array. Within the experimental accuracy, they are identical for $^{16}O + ^{93}Nb$ at

$\theta_{lab} = 25°$ and at 38°, and, for all systems, the multiplicities indicate that the average entrance-channel angular momenta are close to the critical angular momenta as defined by Wilczyński.[18] In that respect, there is no difference between the positive- and negative-angle dominated cases, which again suggests that the observed polarizations are exit-channel phenomena.

In conclusion, we find that the picture of fast-particle emission along tangential trajectories with respect to the target nucleus consistently explains the measured spin polarizations of both the residual nuclei and the emitted fast protons.[17] In particular, the positive values of P_γ and the corresponding negative emission angles for fast α particles, measured with the Nb target, do not have to be taken as evidence for a PEP or knockout process. The data rather emphasize the peripheral character of the incomplete-fusion mechanism in the entrance *and* exit channels. In that sense, they are consistent with breakup-fusion models.

Illuminating discussions with Dr. P. D. Bond and Dr. W. Dünnweber are gratefully acknowledged. This work was supported by the U. S. Department of Energy under Contract No. DE-AC02-76CH00016 and by the Bundesministerium für Forschung und Technologie.

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