P_1 is contributing positively. Work to test such a conjecture is also under way.

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[12]Precisely speaking Γ_b, Γ_d, and ψ all depend on the Q value. This dependence is rather weak, however, and this is neglected in the present calculations for simplicity.

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Gamma-Ray Circular Polarization and Nuclear Spin Orientation in ^{16}O on Ni Reactions at 100 MeV

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The circular polarization of the energy-integrated γ-ray spectra and the angular correlation of discrete γ transitions in coincidence with the light fragments detected at 35° were measured for the reaction 100-MeV $^{16}O + Ni$. A large nuclear spin polarization and at least 80% negative-angle scattering are deduced for deep-inelastic events. The decrease of the circular polarization observed at $Q > -30$ MeV is ascribed to increasing positive-angle contributions to the cross section.

It has been shown that the γ radiation emitted by the excited fragments of deep-inelastic (DI) heavy-ion reactions is circularly polarized and that the sense of rotation of the intermediate complex formed by the colliding nuclei can be determined.[1] In the case of 300-MeV ^{40}Ar on Ag a polarization in the direction of the scattering normal $\vec{k}_i \times \vec{k}_f$ was found which established the predominance of orbiting trajectories leading to negative classical deflection angles. The measured value of about 25% γ-ray circular polarization seems to be rather small, however, since large spin alignment has been observed for the highly excited primary fragments of DI reactions.[2-4] This alignment is interpreted as resulting from the transfer of a considerable part of the orbital angular momentum into intrinsic fragment spins due to tangential friction. A large nuclear spin polarization is therefore expected which should lead to a large γ-ray circular polarization if most of the spin is carried away in cascades of stretched γ transitions.

In general, a γ-ray circular polarization of less than 100% will be found if (i) nonstretched transitions take part in the γ-decay process, if (ii) nonaligned spin is generated either in the primary collision or by the emission of light particles, if (iii) processes with positive and negative scattering angles contribute to the observed cross section (which does not exclude a large alignment), or if (iv) the two fragments emerge with opposite spin directions[5,6] and emit γ radiation of

mutually canceling polarization.

In this Letter we report on a study of the reaction ^{16}O on Ni at 100 MeV which combines the measurements of the circular polarization and the angular correlation of deexcitation γ rays in coincidence with the light fragments. In this way we distinguish the effects of mechanism (iii) from those of (i) and (ii) since in the latter cases a reduction of the polarization will be accompanied by a loss of alignment and hence become apparent in the particle-γ angular correlation of discrete γ transitions. Mechanism (iv) is irrelevant in this case since we find that the light fragments contribute little to the total γ-ray multiplicity. In the case of heavier systems such as Ar + Ag (Ref. 1) and Kr + Ag (Ref. 7) where it has been shown that DI reactions proceed through a sticklike configuration,[8] possibility (iv) also seems to be rather improbable.

In the light-fragment energy spectra from the 100-MeV ^{16}O + Ni reaction a DI component has been observed which is characterized by almost complete dissipation of the energy above the interaction barrier and a forward-peaked differential cross section.[9]

Enriched ^{58}Ni and ^{62}Ni targets of 3 mg/cm^2 thickness were bombarded with 100-MeV $^{16}O^{8+}$ beams of ≈ 30 nA provided by the Munich upgraded model MP tandem Van de Graaff accelerator. Light fragments were detected by heavy-ion telescopes which consisted of an axial-field ionization chamber and a 900-mm^2 solid-state detector subtending an angular range of $35° \pm 5°$. With electronic ΔE-E processing the light-fragment atomic number Z was clearly resolved ($\Delta Z/Z = 0.04$). The symmetric setup used to measure the γ-ray circular polarization has been described previously.[1] For the angular correlation measurements a 120-cm^3 coaxial Ge(Li) detector was used which was placed 9 cm from the target and approximately normal to the recoil direction in the coplanar geometry and normal to the reaction plane in the out-of-plane geometry. Because of Doppler broadening the energy resolution was limited to $\sim 0.5\%$. Furthermore, particle-coincident γ-ray spectra from $E_\gamma = 0.3$ MeV up to 20 MeV were measured in and out of the reaction plane using a 27-cm × 33-cm NaI spectrometer at 72 cm from the target.

The average γ-ray circular polarization P_γ of the energy-integrated γ-ray spectra was evaluated as described in Ref. 1. The results obtained from data with reversed direction of the polarimeter magnetization showed no deviation beyond statistical limits and were averaged. The analyzing power $A_\gamma(E_\gamma)$ of the polarimeter was weighted by the intensity of the γ-ray spectra recorded with the NaI spectrometer. The average value $A_\gamma = (2.5 \pm 0.3)\%$ was found to be independent of Z and the reaction Q value within these limits. This result includes the estimated effects of unpolarized background such as γ radiation scattered from the collimators in the polarimeter and neutron-induced γ radiation. The polarization values P_γ were derived from the measured counting rate asymmetry $P_\gamma A_\gamma$ using $A_\gamma = 2.5\%$. The quoted errors represent the statistical uncertainties of $P_\gamma A_\gamma$.

A drastic change of P_γ with the reaction Q value is observed which for the two strongest Z channels is shown in Fig. 1(b). The values of $+(60 \pm 17)\%$ ($Z = 6$) and $+88^{+12}_{-26}\%$ ($Z = 8$) for the most inelastic groups imply a large fragment polarization along $\vec{k}_i \times \vec{k}_f$. In both reaction channels P_γ decreases to zero with decreasing energy loss and in the $Z = 8$ case P_γ reaches negative values for quasielastic events where a predominance of positive-angle scattering is expected.

The coincident γ-ray spectra recorded with the large NaI detector yield total multiplicities M_γ of 6.3 and 4.5 γ rays per DI event for $Z = 6$ and $Z = 8$, respectively, in accordance with an earlier study.[9] Total fragment spins of $J = 15\hbar$ and $12\hbar$ which have been derived from these values fit well into recent systematics[10] of $M_\gamma(J)$. Since in

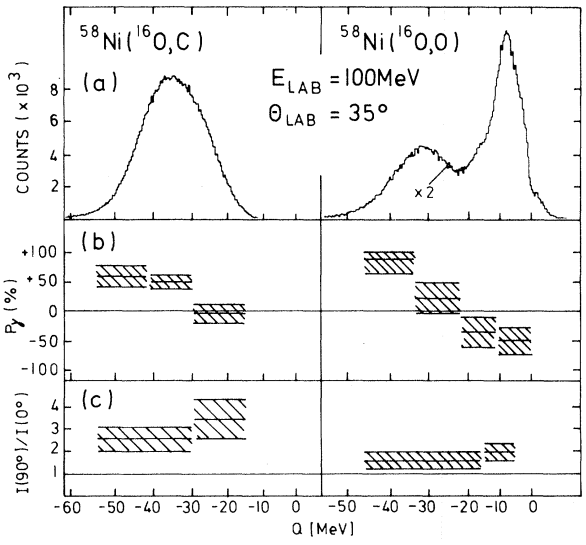

FIG. 1. (a) Particle spectra in coincidence with γ rays, (b) γ-ray circular polarization p_γ, and (c) average in-plane/out-of-plane intensity ratio of the stretched quadrupole transitions listed in Table I. $P_\gamma > 0$ corresponds to a polarization in the direction of $\vec{k}_i \times \vec{k}_f$.

a strongly damped collision $\vec{J}$ points approximately in the direction of the entrance-channel angular momentum $\vec{L}_i$, the positive P_γ, measured for DI events, means $\vec{L}_i \| \vec{k}_i \times \vec{k}_f$ and, hence, negative deflection angles. Transitions in the light $Z = 6$ and 8 ejectiles are clearly seen in the NaI spectra; their multiplicities, however, are only 0.24 ± 0.03 and 0.20 ± 0.04, respectively. Therefore, the measured circular polarization is essentially that of the γ radiation from the heavy fragment.

The in-plane/out-of-plane anisotropies of discrete γ transitions show that down to the last steps of the decay process following the emission of one or two light particles and several γ rays the heavy fragments are still aligned with respect to the scattering normal (Table I).[13] In the DI region the weighted average of the in-plane/out-of-plane intensity ratios of the observed stretched $E2$ transitions is $I(90°)/I(0°) = 2.6 \pm 0.5$ and 1.5 ± 0.4 for $Z = 6$ and 8, respectively. For smaller energy losses a tendency towards larger values is observed similar to that reported[3] for the $^{16}O + ^{27}Al$ reaction [Fig. 1(c)]. For the energy integrated γ-ray spectra the NaI measurements yield a smaller anisotropy of $I(90°)/I(0°) = 1.3$ for $Z = 6$ and $Z = 8$ which may be caused by different multipolarities and nonstretched transitions.

In the $Z = 6$ case it is obvious that the polarization and the alignment exhibit opposite trends as a function of Q. The vanishing polarization for $Q > -30$ MeV is accompanied by a large alignment which means that the polarizations of positive- and negative-angle contributions cancel. This balance is in accordance with indications of two components in the energy spectra found at more forward angles for which optimum quasielastic and DI Q values of -25 and -37 MeV were derived.[14] In the $Z = 8$ case P_γ is a sensitive measure of the relative strength of the two contributions with opposite polarization which evidently correspond to the two groups appearing in the spectra [Fig. 1(a)]. Contributions from positive-angle scattering at $Q > -30$ MeV are also indicated by the polarization data for the nitrogen, fluorine, and neon exit channels.

For DI events the results of the γ-ray circular polarization measurements are summarized in Table II. To avoid quasielastic contributions the corresponding Q ranges were chosen as $Q < Q_C + 18$ MeV $\approx Q_{opt} + 6$ MeV. Here Q_C denotes the Q value corresponding to an exit-channel total kinetic energy equal to the Coulomb energy of touching spheres and Q_{opt} is the optimum Q value for DI events as defined by the maxima in the particle spectra. P_γ is positive for all exit channels. A variation of P_γ with light-fragment Z or with the target isotope may be indicated but cannot be established with the present statistics. All data are consistent with a γ-ray circular polarization of about $+50\%$ for DI events which in the picture of classical orbits implies a lower limit of 75% negative-angle scattering.

To permit an interpretation of this value in view of the measured γ-ray multiplicities and anisotropies we have calculated the average circular polarization and the angular distributions for specific γ-ray cascades. Particular insight

TABLE I. Measured in-plane/out-of-plane intensity ratios $I(90°)/I(0°)$ of deexcitation γ rays following the bombardment of ^{58}Ni with 100-MeV ^{16}O.

Z	$-Q$ (MeV)	γ transition[a]	$I(90°)/I(0°)$[b]
6	13–30	^{58}Ni($2^+ \rightarrow 0^+$)	2.4 ± 1.4
		^{61}Cu($7/2^- \rightarrow 3/2^-$)	4.1 ± 1.1
		^{61}Cu($5/2^- \rightarrow 3/2^-$)	0.6 ± 0.2[c]
	30–54	^{58}Ni($2^+ \rightarrow 0^+$)	2.3 ± 0.8
		^{60}Ni($2^+ \rightarrow 0^+$)	2.6 ± 0.9
		^{61}Cu($7/2^- \rightarrow 3/2^-$)	3.1 ± 1.2
8	7–15	^{58}Ni($2^+ \rightarrow 0^+$)	1.9 ± 0.3
		^{58}Ni($4^+ \rightarrow 2^+$)	2.1 ± 0.7
	15–47	^{56}Fe($2^+ \rightarrow 0^+$)	1.2 ± 0.6
		^{56}Fe($4^+ \rightarrow 2^+$)	1.8 ± 1.1
		^{56}Co($7^+ \rightarrow 5^+$)	1.8 ± 0.8
		^{56}Co($9^+ \rightarrow 7^+$)	1.6 ± 0.8
		^{57}Co($9/2^- \rightarrow 7/2^-$)	1.7 ± 0.6[d]

[a] Transitions between states of lowest excitation energy for given spins.

[b] The effect of the finite solid angles of the detectors is less than 10% in all cases.

[c] $\delta(E2/M1) = +0.35$ (Ref. 11).

[d] $\delta(E2/M1) = -0.26$ (Ref. 12).

TABLE II. Gamma-ray circular polarization for DI events ($Q < Q_C + 18$ MeV). Q_{opt} and Q_C are defined in the text.

Z	$-Q_{opt}$ (MeV)	$-Q_C$ (MeV)	Polarization (%) $^{16}O + ^{58}Ni$	$^{16}O + ^{62}Ni$	Average
5	43	53	10 ± 34	70 ± 22	52 ± 18
6	37	50	53 ± 10	38 ± 9	45 ± 7
7	34	47	72 ± 22	59 ± 18	64 ± 14
8	32	44	58 ± 20	47 ± 17	52 ± 13
9	30	41	70 ± 49	25 ± 39	42 ± 31
10	29	39	21 ± 50	53 ± 42	40 ± 32
5–10			54 ± 8	45 ± 7	49 ± 5

is gained from the examples of (a) a stretched quadrupole cascade starting from a partially polarized initial state with spin j and a Gaussian m-substrate distribution

$$P(m) \sim \exp[-(j-m)^2/2\sigma^2],$$

and of (b) a partially stretched quadrupole cascade involving two $\Delta j = 0$ transitions and starting from a pure $m = +j$ initial state. Orientation along $\vec{k}_i \times \vec{k}_f$ is assumed. The angular distributions are determined by j and σ in the former and by the spin sequence in the latter example. Requiring $I(90°)/I(0°) = 2.6$ (1.5) for the last transition as measured for $Z = 6$ (8) and an initial $j = 10\hbar$ we obtain a γ-ray circular polarization of $P_\gamma = 85\%$ (70%) in case (a) and, on the other extreme, $P_\gamma = 60\%$ (60%) in case (b). These values show that even in the case of pure negative-angle scattering P_γ may be considerably smaller than 100% and they demonstrate the sensitivity of the polarization measurement at polar angles between 20° and 45° to nonstretched quadrupole transitions. Several nonstretched transitions have been identified in the Ge(Li) spectra and also the early statistical γ decay is expected to proceed partly through nonstretched transitions. It therefore seems reasonable to follow example (b) and to interpret the measured average value of $P_\gamma \sim 50\%$ for DI reactions as consistent with pure negative-angle scattering. An interpretation along the line of example (a) which excludes nonstretched transitions leads to a lower limit of at least 80% for the negative-angle component.

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