Evidence for Negative Deflection Angles in ^{40}Ar + Ag Deep-Inelastic Reactions from γ-Ray Circular Polarization Measurements

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We have measured the circular polarization of the deexcitation γ rays following the bombardment of natural Ag targets with 284-MeV and 303-MeV ^{40}Ar ions. A symmetric setup containing two polarimeters normal to the reaction plane was used. From the observed count-rate asymmetry of $+0.65\% \pm 0.15\%$ for deep-inelastic events we conclude that the excited product nuclei are polarized in the direction of the reaction normal $\vec{k}_i \times \vec{k}_f$ which provides evidence for a predominance of negative classical deflection angles.

A common feature of heavy-ion collisions at bombarding energies several MeV/amu above the Coulomb barrier is the occurrence of deep-inelastic (DI) reactions characterized by (i) broad ejectile mass and charge distributions centered close to the projectile, (ii) nearly complete damping of the kinetic energy above the Coulomb barrier, and (iii) angular distributions not symmetric about 90° in the center-of-mass frame. Depending on the value of the bombarding energy relative to the Coulomb barrier the DI differential cross section exhibits either side peaking near the grazing angle or a monotonic decrease for increasing scattering angles.[1] This latter phenomenon has been associated with trajectories winding around the back of the nucleus, i.e., orbiting trajectories leading to negative deflection angles.[2-4] Other explanations, however, involving deflection functions with a second rainbow near 0° and thus avoiding negative deflection angles have also been put forward to explain the data.[5]

This Letter describes an experiment in which the sign of the deflection angle was deduced from the circular polarization of the decay γ rays measured in coincidence with the ejectile, as suggested by Wilczynski.[3] The reaction ^{40}Ar + Ag at about 300 MeV was chosen because it clearly shows a DI group monotonically decreasing with increasing scattering angle and energetically well separated from quasielastic (QE) events near the grazing angle.[6]

To distinguish positive and negative deflection angles one has to know the direction of the orbital angular momentum in the entrance channel. Our attempt to measure this direction is based on the observation that during the heavy-ion collision part of the initial angular momentum is transferred into spin angular momenta of the fragments.[7,8] In a classical picture, this is mainly due to the tangential component of a friction-like force and leads to the same sense of rotation for both residual nuclei as for the orbital motion.[9] The alignment associated with the resulting fragment polarization has been observed.[10,11] In subsequent stages of the reaction process precompound emission and statistical evaporation of light particles reduce the initial polarization but are not expected to change its sign. Even if the nuclear alignment is partly lost, which may be indicated by the small anisotropies found in γ-ray angular distributions,[1] a considerable part of the initial polarization should survive. The remaining angular momentum is carried away by γ decay, and the nuclear polarization appears as a circular polarization if the radiation is observed approximately parallel to the fragment-spin direction. In the case of stretched transitions the γ-ray polarization reaches 100% and it still has a value of 95% at an angle of 45° with respect to the quantization axis. The γ-ray circular polarization has the same sign as the nuclear polarization and, hence, is a measure of the sign of the deflection angle.

The γ-ray circular polarization was measured via Compton forward scattering from magnetized iron.[12] We used two identical polarimeters on opposite sides of the reaction plane which was defined by two identical particle telescopes at $\theta_{lab} = \pm 35°$ (Fig. 1). Each polarimeter consisted of a

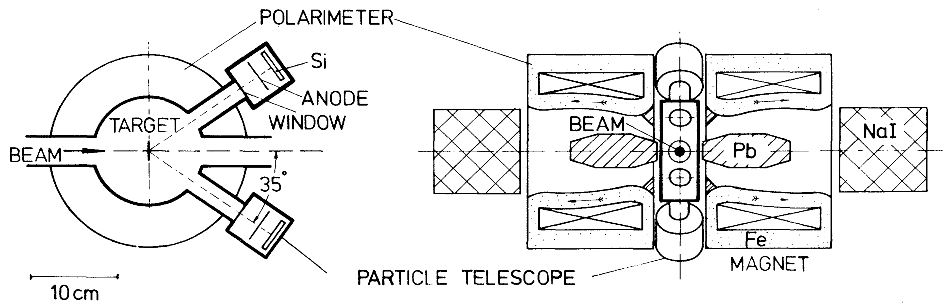

FIG. 1. Detector arrangement. The left-hand side of the figure is a cut of the apparatus along the scattering plane. The right-hand side is a cut containing the scattering normal viewed along the beam direction. The arrows in the magnets indicate the direction of magnetization.

magnet accepting γ radiation at polar angles between 20° and 45° and a 10 cm×10 cm NaI crystal shielded from the direct radiation but detecting the Compton-scattered γ rays. The photomultiplier tubes were Mumetal shielded and electronically stabilized using light-emitting diodes which provided a stable reference line. Using the polarized bremsstrahlung of a ^{90}Sr-^{90}Y source, an analyzing power of 2% to 3% and an overall detection efficiency of about 10^{-3} were measured for γ-ray energies near 1 MeV. The particle telescopes consisted of two axial-field ionization chambers followed by 900-mm^2 surface-barrier Si detectors and extended to scattering angles of 35° ± 5°.

This arrangement allows the simultaneous measurement of four particle-γ coincidence count rates from which the count-rate asymmetry PA can be derived through the expression

$$\frac{N_{11}N_{22}}{N_{12}N_{21}} = \left(\frac{1+PA}{1-PA}\right)^2.$$

Here N_{ij} represents the count rate of particle detector i in coincidence with γ-polarimeter j, P and A denote the γ-ray circular polarization and the analyzing power of the polarimeter, respectively. The solid angles and efficiencies of the four detectors cancel in this ratio. It is also not necessary to change the direction of the iron magnetization in order to obtain PA, and the problem of normalizing successive runs is thus avoided.

Since the effect to be measured is very small we have investigated possible sources of errors. We find that a possible misalignment of the two polarimeters or displacement of the two scattering planes can lead to count-rate asymmetries not larger than ~0.1%. False asymmetries ΔPA arising from the finite size of the beam spot and/or substantial differences in the detection probabilities can occur only in the case of correlated deviations in the particle *and* γ detection. For the DI reaction, we find that these errors do not exceed $|\Delta PA| \approx 0.1\%$ because of the very smooth particle and γ-ray angular and energy distributions. In the case of the QE reaction, the ejectile angular distributions are extremely steep at the chosen scattering angle of 35° (which is about 10° behind the grazing angle) and we find that systematic errors of the order of 1% cannot be excluded.

Natural Ag targets of 2-mg/cm^2 thickness were bombarded with ^{40}Ar beams of 284 and 303 MeV provided by the Unilac heavy-ion facility in Darmstadt. We measured the pulse heights of the particle and γ detectors, the time between particle and γ event, and the time relative to the beam burst. Identification of Z was obtained by inspecting two-dimensional $\Delta E - E$ plots. After the subtraction of randoms all events with light-fragment Z from 11 to 21 (or 24) were accepted and sorted into two different groups representing QE and DI events (Fig. 2).

The asymmetries measured in four different runs are given in Table I. Between runs (2) and (3) the measuring equipment was moved to a new beam line and the two particle telescopes were interchanged. Between runs (3) and (4) the magnetization of the polarimeter was reversed. Since the two bombarding energies are not expected to lead to very different processes we have also averaged all four results to improve the statistical significance. The zero result obtained for random events reflects the proper operation of the data recording system.

For DI events we measure an asymmetry $\langle PA\rangle = +0.65 \pm 0.15\%$. Because of the chosen sign convention this establishes a polarization in the direction of the scattering normal $\vec{k}_i \times \vec{k}_f$ as expected for negative deflection angles (Fig. 2). The

TABLE I. Count rate asymmetries PA of $^{40}Ar + Ag$ for deep-inelastic (DI), quasielastic (QE), and random events. A positive sign corresponds to a polarization in the direction if $\vec{k}_i \times \vec{k}_f$. The quoted errors are those of counting statistics only. For a run, the systematic errors are in the order of 0.1% (DI) and 1% (QE) (see text). The atomic number of light fragments included in the analysis is indicated by Z.

Run	E_{lab} (MeV)	Z	DI (%)	QE (%)	Randoms (%)
(1)	284	11–21	$+0.30\pm0.30$	-2.0 ± 1.3	$+0.1\pm0.5$
(2)	303	11–21	$+0.95\pm0.25$	-4.4 ± 2.6	-0.4 ± 0.5
(3)	303	11–24	$+0.35\pm0.25$	$+0.9\pm2.3$	$+0.1\pm0.2$
(4)	303	11–24	$+1.10\pm0.40$	$+2.0\pm2.4$	-0.2 ± 0.3
Average			$+0.65\pm0.15$	-1.2 ± 1.0	-0.2 ± 0.15

amount of polarization can only be estimated since the in-beam analyzing power is not well known. If we use $A=(2-3)\%$ as obtained with the ^{90}Sr-^{90}Y source we arrive at a polarization $\langle P\rangle \approx 25\%$. This is small compared to $\approx 100\%$ polarization which is expected for a stretched γ cascade from well-aligned nuclei. The polarization also seems to be smaller than the maximum value compatible with an isotropic angular distribution, which we estimate to be about 60% or 80%, assuming pure $E2$ or $E1$ radiation, respectively.

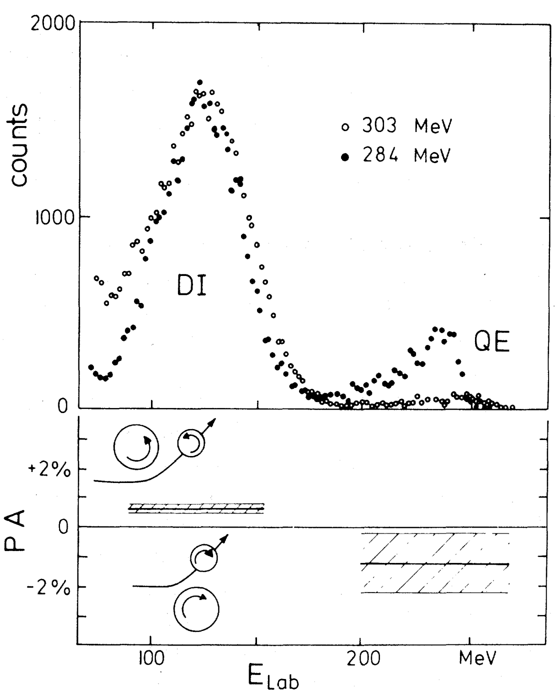

FIG. 2. Coincident energy spectra for ejectiles with $11 \leq Z \leq 21$ (upper part) and count-rate asymmetry PA (lower part). The deep inelastic (DI) group is clearly separated from the quasielastic (QE) group. The counts below about 50 MeV are due to light particles. The sense of rotation of the fragments corresponding to positive and negative PA and, accordingly, to negative and positive deflection angles is indicated.

For QE events we obtain an average value of $\langle PA\rangle = -1.2\% \pm 1.0\%$. Although systematic errors may have averaged out to some extent we believe that further experiments are necessary to corroborate this result. A negative value of PA, i.e., a negative polarization, is expected for positive deflection angles and negative Q values in a classical picture. It is also consistent with the interpretation of the light-fragment polarization measured by Sugimoto *et al.*[13] for the reaction $^{100}Mo(^{14}N, ^{12}B)$.[13]

Summarizing we conclude that this experiment shows the existence of negative classical deflection angles in a deep-inelastic reaction. It is not clear yet whether the small γ polarization is mainly due to canceling contributions (negative- and positive-angle scattering) or whether it follows from a reduction of the nuclear polarization either in the primary process or by light-particle emission.

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Reaction between ^{238}U and ^{238}U at 7.42 MeV/Nucleon

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Inclusive measurements have been performed for the charge, kinetic-energy, and angular distributions of reaction products from ^{238}U + ^{238}U at 7.42 MeV/nucleon. Fission of one or both colliding nuclei is found to dominate. For the surviving U-like fragments, more particle diffusion at a given energy dissipation is observed than in other systems. A search for the production of superheavy elements has yielded an upper cross-section limit of 2×10^{-32} cm^2.

The mechanism of nuclear reactions between very heavy ions is of great current interest.[1-4] We have used the U beam available at the Unilac in Darmstadt to extend such studies to the U+U system. Our motivation has been twofold: (1) to investigate the gross features of the reaction products associated with their charge, total-kinetic-energy, and angular distributions; and (2) to learn about the prospects of synthesizing superheavy elements in this reaction. In this Letter we report on first results of single-particle-inclusive measurements. For U-like fragments surviving fission, we also present an observed correlation between the total-kinetic-energy loss and the amount of nucleon transfer ("diffusion") with a slope much smaller than that observed previously for other systems.[4]

The experiments were performed with a U beam of 7.42 MeV/nucleon and 10^{10} particles/s on a sputtered target of 450 μg/cm^2. Charge and energy distributions of the reaction products were analyzed in a three-section ionization chamber[5] with a Z resolution of effectively $\Delta Z/Z\approx 1/50$. Details of the Z-calibration procedure are given elsewhere.[6] During the run, the chamber was moved in steps of 3° (equal to the acceptance angle) within lab angles of 28°–52°, a finer angular division being possible by the measured time difference between the anode and cathode signals. On the other side of the beam at the relative angle of 86° to the ionization chamber a large surface-barrier detector with an acceptance angle of 16° allowed the detection of kinematic coincidences for binary events. This detector was additionally gated in between macropulses of the Unilac (2–20 ms) to search for α and spontaneous-fission activities of implanted recoil nuclei. A Ge detector was located immediatedly behind the latter detector to measure possible α–x-ray coincidences.

The charge distribution of the single reaction products, integrated over all energies and lab angles 32.5°–44.5°, is shown in Fig. 1. Several striking features are immediately obvious. The