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Observation of spin-aligned secondary fragment beams of ^{14}B

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An alignment of the nuclear spin has been observed for a secondary radioactive beam of ^{14}B produced in the fragmentation of a 60 MeV/nucleon ^{18}O beam impinging onto a ^{9}Be target. The fragments were separated and analyzed in momentum by means of the doubly achromatic spectrometer LISE. The spin alignment was determined through a measurement of the anisotropy of the β-delayed γ-ray emission. The alignment is found to be small in the momentum region corresponding to the peak of the fragmentation yield, whereas it takes a large negative value for the high-momentum tail. This result is discussed in terms of a simple model of projectile fragmentation. The relevance of this result for the determination of nuclear moments far from stability is considered.

I. INTRODUCTION

In recent years high- and intermediate-energy projectile fragmentation reactions have proved their efficiency for the production of light nuclei far from stability. Numerous new nuclei situated at both drip lines have been identified, and a variety of spectroscopic studies on new isotopes have been performed.[1]

It is the scope of the present paper to report on a first observation of spin alignment of the products of projectile fragmentation in the intermediate-energy regime. Indeed, the presence of nonzero spin orientation in projectilelike fragments would enable more detailed spectroscopic investigations such as nuclear moment measurements on exotic nuclei. It would also enhance possibilities for the study of β-decay properties and for applications to solid-state physics.

A measurement of the spin orientation in heavy-ion reactions is also interesting as a source of unique information on reaction mechanisms. Previously, the role of angular momentum in the heavy-ion collisions has been discussed both experimentally[2,3] and theoretically[4,5] in the region of low energies, where the quasielastic and deep-inelastic processes dominate. On the other hand, there has been so far little attention for the spin observables in high-energy collisions, where nucleon-nucleon aspects of interaction are supposedly important and different features of spin-related phenomena may emerge. In the following we present experimental results on spin alignment and discuss a simple model of projectile fragmentation predicting the specific dependence of the spin alignment on the fragment momentum. A related phenomenon of spin polarization is reported elsewhere.[6]

II. EXPERIMENTAL METHOD

The spin alignment was studied for the projectilelike fragment ^{14}B($I^{\pi}=2^{-}$, $T_{1/2}=12.8$ ms, $Q_{\beta}=20.62$ MeV) produced by ^{18}O projectiles impinging at 60 MeV/nucleon onto a ^{9}Be target. The nucleus ^{14}B was chosen because (i) its short lifetime makes it possible to get rid of the spin relaxation effect[7] during the period until the β decay takes place, (ii) the angular distribution of the β-delayed γ rays has a large anisotropy coefficient,[8] and (iii) its high γ energy permits an easy discrimination from low-energy background.

The experimental setup is schematically shown in Fig. 1. A 284-mg/cm^2-thick ^{9}Be target, placed at the entry of the doubly achromatic spectrometer LISE,[9] is bombarded with the ^{18}O^{8+} beam from the GANIL accelerator at a mean intensity of 2.5 μA. The projectilelike fragments are collected at 0° and analyzed by a first dipole magnet according to their magnetic rigidity. This corresponds to a selection in A/Z, light fragments being completely stripped after leaving the thick target at these intermediate (60 MeV/nucleon) energies. An energy degrader, made of wedge-shaped aluminum sheet of an average thickness of 584 mg/cm^2, was inserted in the intermediate focal plane between the two magnets. Correcting the magnetic field of the second dipole for the Z-dependent

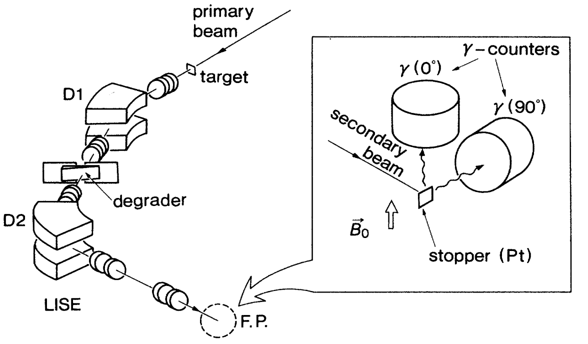

FIG. 1. Experimental setup used.

energy loss allows the achromatic refocusing of almost isotopically pure secondary beams to the final focal point.[10] A removable silicon-surface-barrier detector installed at that point allowed the identification of the secondary beams through a measurement of energy loss and time of flight through the spectrometer. Opening the slit in the intermediate focal plane to a momentum acceptance of $\Delta p/p=4\%$, an intensity of the secondary ^{14}B beam of 4000 pps was measured.

The ^{14}B nuclei were stopped in a Pt foil placed at the final focal point. A static magnetic field $B_0=310$ mT parallel to those of the two dipoles of LISE was applied to the stopper. The 6.09-MeV γ rays consecutive to the β decay of the implanted ^{14}B nuclei were observed by means of two NaI(Tl) scintillation counters (diameter, 15 cm; length, 15 cm) placed at 0° and 90° with respect to the field B_0 which defined the quantization axis. In order to reduce the background contribution, the primary ^{18}O beam was pulsed (18 ms on, 18 ms off) and the γ rays were detected only during the beam-off periods. Furthermore, thick lead collimators with conical openings were placed in front of the γ counters, themselves surrounded by a lead shielding in order to select only γ rays from the implantation region.

The static magnetic field B_0 was switched on and off in cycles of 10 s. Furthermore, a small solenoid was installed around the Pt stopper to produce a small field $B_1=0.5$ mT parallel to the direction of the incoming ^{14}B beam. This induced a spin precession and thus assured equal γ-ray intensity at the two detection angles during the time the B_0 was switched off.

The timing of the different switchings were controlled by a MicroVAX computer, which also acquired the γ spectra and calculated the 0°/90° ratio $R=N_\gamma(0°)/N_\gamma(90°)$ for the static field B_0 being on (or spin alignment preserved) and off (or spin alignment destroyed).

III. DATA ANALYSIS AND RESULTS

The spin alignment produced by the fragmentation reaction in the direction of the beam axis can be expressed (for the case $I=2$) by

$$A=(2a_{+2}-a_{+1}-2a_0-a_{-1}+2a_{-2})/2\ , \quad (1)$$

in terms of the probability a_m of populating magnetic sublevel m. As a result of the spin precession caused by B_0, a new alignment $A'=-A/2$ in the axis parallel to B_0 is established[11] after a short period of time characterized by the transverse-spin relaxation time. Then the angular distribution of the 6.09-MeV γ rays following the β decay of the implanted ^{14}B nuclei is given by[8]

$$W_\gamma(\theta)=1-\tfrac{1}{2}A'P_2\cos\theta\ , \quad (2)$$

where θ denotes the angle of the γ-ray emission relative to the axis of the spin alignment A'. Thus the initial alignment A produced in the projectile fragmentation reaction is deduced from the observed change in the 0°/90° ratio R through

$$A=-\tfrac{8}{3}(R_{\rm on}/R_{\rm off}-1)\ , \quad (3)$$

where $R_{\rm on}$ or $R_{\rm off}$ correspond to the presence or absence of the static magnetic field B_0, respectively.

Figure 2 (upper part) gives the result of this analysis for the spin alignment as a function of the fragment momentum p. In the lower part of Fig. 2, the production yield of ^{14}B is plotted vs p. This yield curve exhibits a broad distribution peaked at a momentum of $p_c=4.47$ GeV/c, closely to the incoming beam velocity. Measure-

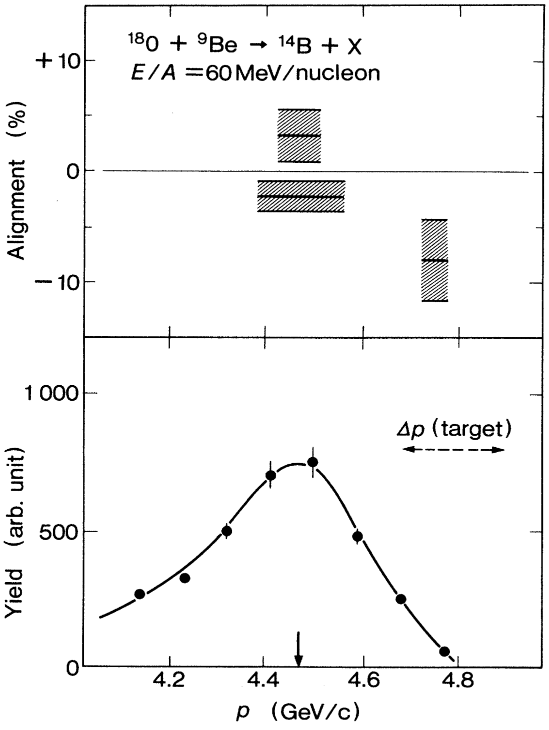

FIG. 2. Observed spin alignment A of ^{14}B produced in the reaction ^{18}O (60 MeV/nucleon) + ^{9}Be. The observed momentum distribution is also shown. Each plotted value of A is averaged over the momentum bin indicated by horizontal bar. The vertical extension of the hatched area corresponds to the uncertainty in A (one standard deviation).

ments of A were made for three different momentum windows, indicated by the horizontal width of the hatched area. Its vertical extension corresponds to the error in the determination of the alignment A, mainly due to counting statistics. Around the peak momentum p_c, small alignments are observed for both a narrow ($\Delta p/p = 2\%$) and a wide ($\Delta p/p = 4\%$) momentum window. The third measurement in the region of the high-momentum tail, at about 6% higher momentum than p_c, yields a negative alignment of substantial size. For a window of $\Delta p/p = 1.1\%$, an alignment of $A = -8.0 \pm 3.7\,\%$ is found.

IV. THEORETICAL INTERPRETATION

A number of experimental studies reveal that the heavy-ion reactions in the intermediate-energy domain share characteristic features of the projectile fragmentation process which typically occurs at high energies. For example, the momentum spectra of the ejectiles emitted at forward angles exhibit a characteristic peak centered near the beam velocity. The width of the peak shows agreement with the Goldhaber formula,[12] provided a smooth variation of the width parameter σ_0 from the high-energy limit $\sigma_0 \cong 85$ MeV/c is allowed.[13]

Several models[12,14,15] have been proposed to reproduce the general features of the projectile fragmentation reaction. These models commonly describe the reaction as a process in which a (cluster of) nucleon(s) in the projectile nucleus is removed from the overlapping volume when the projectile and target collide. The remaining part of the projectile, which is observed as a fragment, is assumed to behave as a "spectator." The momentum distribution of the fragment consequently reflects the motion of the removed cluster in the projectile nucleus before the collision. On discussing the fragment spin, one should also consider the angular momentum carried by the removed cluster in the projectile nucleus. Since the cluster is removed from the projectile surface, the angular momentum also reflects the motion of the cluster, and this generates a relationship between the outgoing momentum and spin of the fragment nucleus.

The consideration can be elaborated into a quantitative form by taking an expression derived in Ref. 15 for the production of a fragment with a longitudinal momentum p_z:

$$\frac{d\sigma}{dp_z} = \int d^2\mathbf{s}\, D(\mathbf{s}) \int dz \int d^2\mathbf{p}_t\, W(\mathbf{s}z;\mathbf{p}_t, p_z - p_{z0}) , \qquad (4)$$

where the momentum vector $\mathbf{p} = (\mathbf{p}_1, p_z)$ of the removed cluster is decomposed into a component p_z parallel to the beam and the transverse part $\mathbf{p}_t$, and the position vector $\mathbf{R} = (\mathbf{s}, z)$ at which the cluster removal takes place is decomposed into z and $\mathbf{s}$ in the same manner. The value of p_z corresponding to the beam velocity is denoted by p_{z0}. In the above expression for the fragmentation cross section, the Wigner transform $W(\mathbf{R};\mathbf{p})$ of the one-body density matrix $\langle \mathbf{r}|\rho|\mathbf{r}'\rangle$,

$$W(\mathbf{R};\mathbf{p}) = \int \frac{d^3\mathbf{x}}{(2\pi)^3} \exp(-i\mathbf{p}\cdot\mathbf{x}) \left\langle \mathbf{R} - \frac{\mathbf{x}}{2|\rho|\mathbf{R}} + \frac{\mathbf{x}}{2} \right\rangle , \qquad (5)$$

represents a "probability" for finding a particle at position $\mathbf{R}$ and momentum $\mathbf{p}$. The weighting function $D(\mathbf{s})$ contains the collision dynamics and confines the process of the nucleon removal to the region of nuclear surface. In the following a form $D(\mathbf{s}) = \delta(|\mathbf{s}| - s_0)$ has been assumed for the weighting function.

For the sake of simplicity, we shall take the example of removing a particle from the $0p$ orbit of the projectile. Describing this orbit by a harmonic-oscillator wave function, we obtain the following expression for the longitudinal momentum distribution:

$$\frac{d\sigma}{dp} = \sum_m \frac{d\sigma_m}{dp} = N \exp[-(b\,\Delta p)^2] \left[1 + \left[\frac{\Delta p}{\Gamma} \right]^2 \right] , \qquad (6)$$

where $d\sigma_m/dp$ denotes the cross section for the component m of the angular momentum $l = 1$, N is a normalization constant, and $\Delta p = p - p_0$ compares the longitudinal momentum p of the fragment to its momentum p_0 defined by the initial beam velocity. Here we have replaced p_z by $p = |\mathbf{p}|$ for simplicity, since the angular distribution of the fragment is well forward peaked (i.e., $|\mathbf{p}_t| \ll p_z$). The width Γ of the distribution may be expressed in forms of $\Gamma = s_0/b^2$, where b denotes the oscillator parameter for the wave function. Since the angular momentum left in the fragment nucleus is opposite to the one of the removed nucleon, the spin alignment A can be expressed by

$$A = [\tfrac{1}{2} - (\Delta p/\Gamma)^2]/[1 + (\Delta p/\Gamma)^2] . \qquad (7)$$

The qualitative behavior of A as a function of p is shown in Fig. 3 where a positive maximum of A occurs at $p = p_0$. The value of A decreases to negative values in the momentum-tail regions. This behavior can be understood intuitively as illustrated in the bottom of Fig. 3: The removal of a nucleon moving parallel to the projectile corresponds to the case $p < p_0$. For peripheral collisions (where $\mathbf{p}_0$ is perpendicular to the radial position vector $\mathbf{R}$ of the nucleon in the rest frame of the projectile), it implies that the nucleon with orbital angular momentum $\mathbf{R} \times \mathbf{p}_0$ is removed leaving the fragment spin in the direction perpendicular to $\mathbf{p}_0$ (negative alignment). An analog argument holds true for $p > p_0$ [Fig. 3(c)]. On the other hand, for $p \cong p_0$ [Fig. 3(b)], the motion of the removed nucleon is perpendicular to $\mathbf{p}_0$ resulting in a positive spin alignment for the outgoing fragment.

In the actual case of the fragmentation of ^{18}O into ^{14}B, one has to consider the contributions from orbital as well as intrinsic-spin angular momenta carried by four removed nucleons in the $0p$ and $1s$-$0d$ orbitals. One must also take into account the fact that the projectilelike fragment (in particular at intermediate energies[16]) might be produced in an excited state and consecutively deexcite through the emission of light particles and γ rays. Consideration of these effects leads to a substantial reduction in size of A. The qualitative behavior of A vs p predicted above, however, is expected to persist. The characteristic features of the experimental result presented in Fig. 2, in particular the negative sign of observed A in the tail region, agrees well with this prediction.

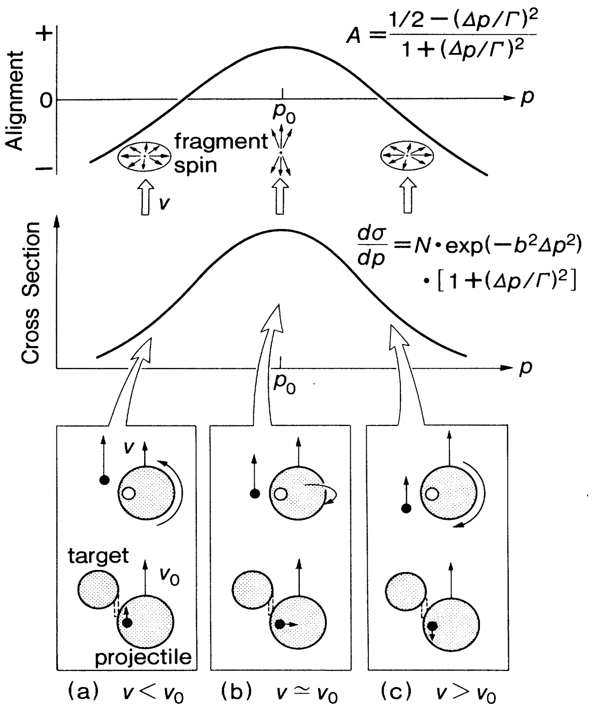

FIG. 3. Predicted behavior of the fragment spin alignment based on a simple projectile fragmentation model. On the bottom, situations for the outgoing velocity (a) $v < v_0$, (b) $v \cong v_0$, and (c) $v > v_0$ are intuitively illustrated, where v_0 denotes the projectile velocity.

V. CONCLUSION

In summary, we have measured for the first time spin alignment of a fragment nucleus ^{14}B in an intermediate-energy projectile fragmentation reaction, ^{9}Be(^{18}O,^{14}B) at 60 MeV/nucleon. The alignment was determined as a function of momentum of the outcoming ^{14}B. The magnitude of the alignment extended up to a value of 8%, which is sufficiently large to be used for a variety of applications.

The observed phenomenon was qualitatively explained within the frame work of standard models of projectile fragmentation reaction. The reaction mechanism, which gave rise to the alignment, should also apply to other spin-orientation phenomena and predicts a large spin polarization of projectile fragments which has a specific dependence on the outcoming momentum. As a matter of fact, a recent experiment[6] on the ^{197}Au(^{14}N,^{12}B) reaction at 40 MeV/nucleon has shown that ^{12}B ejectiles are spin polarized in good accordance with the prediction.

We, however, note an important difference between the alignment and the polarization in terms of reaction mechanism. While the alignment may be essentially determined by the recoil effect, the polarization should be further affected by the balance between the near- and far-side trajectories through which the reaction proceeds. Sizable polarization is predicted to occur only when either of the two types of trajectory dominates over the other.[6] Thus polarization plausibly vanishes, e.g., at higher energies, where the effect of Coulomb deflection becomes relatively weak. On the other hand, the alignment mechanism, which is free from such effects, may persist over the whole range of beam energy including a region of relativistic energies.

This feature is important when one applies the phenomena as a means to produce spin-oriented nuclei. In particular, measurements of nuclear moments of nuclei far from the stability line may be pursued using spin-oriented fragments produced in projectile fragmentation reactions. In such a study, the persistence of the orientation mechanism toward higher energies is crucial, since the production rates of the exotic nuclei increase strongly with the incident energy. It would be highly desirable to examine the phenomena at even higher energies in a future experiment.

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