Spin Polarization of ^{12}B in the Heavy-Ion Reaction ^{100}Mo(^{14}N, ^{12}B)^{102}Ru

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Polarization of product ^{12}B in the reaction ^{100}Mo(^{14}N, ^{12}B)^{102}Ru at 90 MeV was measured as a function of product kinetic energy at the reaction angle of 20°. The polarization was found antiparallel to the vector $\vec{k}_f \times \vec{k}_i$ for higher-energy ^{12}B, while parallel for those with lower energy. The zero crossing occurred at around maximum in the energy spectrum.

Spin polarization of products in a transfer reaction induced by heavy ions, specifically the polarization of ^{12}B in the reaction ^{100}Mo(^{14}N, ^{12}B)^{102}Ru, was measured for the first time. The use of the β-decay asymmetry enabled us to measure the polarization of product $^{12}\mathrm{B}_{\mathrm{g.s.}}$ ($J^\pi = 1^+$; $E_{\beta\max} = 13.37$ MeV; $t_{1/2} = 20.3$ ms). Investigations of such polarization phenomena are useful to elucidate the heavy-ion reaction mechanism. Main interests in the present experiment are (1) whether lighter products show a sizable polarization, (2) how the polarization depends on the reaction Q value, and (3) what kind of model can explain the result.

A pulsed beam of 95-MeV ^{14}N (unpolarized) from the cyclotron at the Institute of Physical and Chemical Research was used to irradiate a ^{100}Mo-(enrichment 95.5%) foil target of 4.8 mg/cm^2 in thickness. The irradiation was cyclic with an on-beam period of 10 ms followed by an off-beam period of 30 ms. The effective incident energy was 90 MeV, since the beam energy loss in the target (tilted) was about 10 MeV. The experimental setup is schematically shown in Fig. 1. Lighter products, emerging from the target chamber in the reaction angle of 20°, impinged into an evacuated stopper chamber through a collimator with an angular spread of $\pm 3.7°$. An aluminum foil with various thickness was inserted between these chambers and used as a degrader of the kinetic energy. Products ^{12}B in a specified range of initial kinetic energy were implanted into a thin platinum stopper, by properly choosing thicknesses of the degrader and the stopper.

β rays from the stopper were detected during the off-beam period by a pair of counter telescopes consisting of two ΔE and one E plastic counters. These telescopes were located above and below the stopper in the direction of expected polarization, i.e., perpendicular to the reaction plane. β rays with energies higher than 3 MeV were detected and the time spectrum was consistent with ^{12}B lifetime. Possible background β emitters with similar lifetime were ^{13}B and ^{12}N, but their yields were known to be insignificant.[1]

The polarization of ^{12}B can be determined from the asymmetry in the β decay. The angular distribution $W(\theta)$ of β rays with respect to the polarization $\vec{P}$ is given as

$$W(\theta) \cong 1 - P\cos\theta,$$

for $^{12}\mathrm{B}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C}_{\mathrm{g.s.}}$ transition. In order to determine the asymmetry free from spurious effects, the direction of ^{12}B spin was controlled by adopting the adiabatic-fast-passage method in NMR during the off-beam period.[2,3] A static magnetic field $\vec{B}_0 = 1.42$ kG was applied normal to the reac-

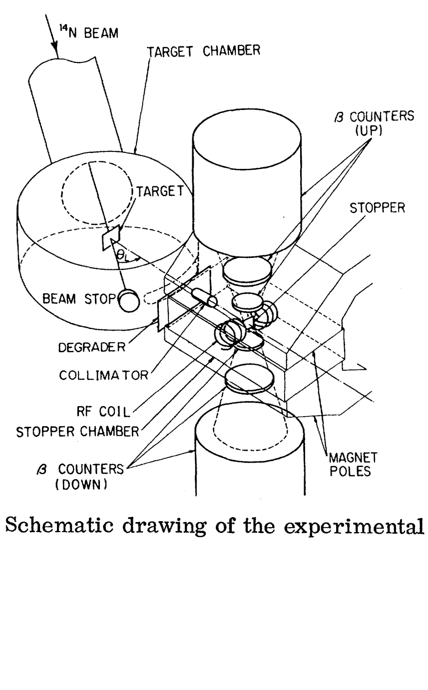

FIG. 1. Schematic drawing of the experimental setup.

tion plane around the stopper, and the NMR was induced by an rf field crossed to $\vec{B}_0$. After every other on-beam period, the rf swept once across the resonance in 5 ms; thus the direction of ^{12}B spin was reversed. At the end of the counting period of 20 ms, the spin was again reversed by applying the rf. In the next period, the rf was applied at off-resonance and the spin direction was unaltered. From the up-down ratio of β-ray counting rates N_{up}/N_{down} at on- and off-resonance periods, the polarization was obtained as $P = (\sqrt{R}-1)/(\sqrt{R}+1)$, where $R = (N_{up}/N_{down})_{off}/(N_{up}/N_{down})_{on}$.

The polarization was essentially preserved during and after the implantation process in the stopper, since the decoupling field $\vec{B}_0$ was present[4] and the spin-lattice relaxation time was known to be much longer than the ^{12}B lifetime in platinum at room temperature.[3,5] It was important to prepare against possible depolarization effects due to hyperfine interactions in ions during flight *in vacuo*. No appreciable depolarization was expected for ^{12}B leaving the target because of predominance in the fully stripped state. After passing through the energy degrader, slower ions captured electrons and depolarization became appreciable for few-electron configurations. In order to eliminate such ambiguous contributions from lower-energy ^{12}B ions, a pair of R measurements were performed by using a thin and a thick platinum stopper. The thin stopper was 5 μm in thickness and stopped ^{12}B ions up to 11 MeV. From the pair of R values, the polarization P was deduced for ^{12}B entering the stopper with energies higher than 11 MeV.

In order to see the adequacy of the present range-energy method, the ^{12}B energy spectrum was measured by detecting β rays. A single broad peak is observed ranging from 40 to 80 MeV as shown in Fig. 2(a). The spectral shape is in good agreement with that obtained by using the silicon-detector telescope.[1]

The polarization obtained is shown in Fig. 2(b) as a function of ^{12}B kinetic energy. The polarization is defined as positive, when it is parallel to $\vec{k}_f \times \vec{k}_i$, where $\vec{k}_f$ and $\vec{k}_i$ are the outgoing and incoming wave vectors, respectively. The measured polarization includes contributions of ^{12}B produced in excited states, through γ de-excitation. The yield of ^{12}B through particle decay of other reaction products, e.g., $^{13}B \to n + {}^{12}B$, $^{13}C \to p + {}^{12}B$, was estimated to be negligible, based on the recent observation of particle-particle correlation.[6]

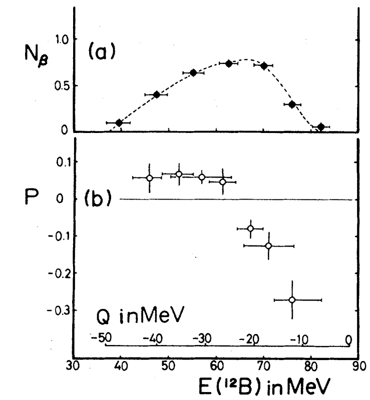

FIG. 2. Energy spectrum (a) in arbitrary scale and polarization (b) of ^{12}B in the reaction $^{100}Mo(^{14}N, {}^{12}B)^{102}Ru$ induced by 90 MeV ^{14}N at 20°, as functions of ^{12}B kinetic energy E and Q value. Horizontal bars indicate energy range pertinent to the measurement. Errors in (b) include those from (1) counting statistics, (2) background subtraction, and (3) correction for depolarization in free ions.

A sizable polarization up to $|P| \simeq 0.3$ is found in the present experiment. For the most energetic part of the spectrum, P is negative and largest. As the energy of ^{12}B decreases, P tends to zero and becomes positive for the lower half of the spectrum. The zero crossing takes place at $Q \sim -23$ MeV, which corresponds roughly to the maximum of the energy spectrum.

According to a macroscopic model introduced by Wilczynski,[7] the polarization of products is expected to be parallel to the incoming orbital angular momentum, and to be parallel to $\vec{k}_f \times \vec{k}_i$ for lighter products along approximately grazing trajectories with small energy dissipation. The experimental result is difficult to explain with this model; the higher-energy part of the spectrum shows the polarization antiparallel to $\vec{k}_f \times \vec{k}_i$.

It is interesting to consider the polarization in terms of a naive microscopic model, following the scheme introduced by Brink.[8] When the (^{14}N, ^{12}B) reaction is assumed to proceed through a simple two-proton transfer, the Q value can be related to the component $\lambda_1\hbar$, normal to the reaction plane, of the angular momentum carried by the transferred pair in the projectile: $Q \simeq \lambda_1\hbar v/R_1 - \frac{1}{2}mv^2 + \Delta V_C$, where v is the speed of the incoming projectile at the instant of collision, R_1 is the radius of the projectile, m is the mass of the transferred pair, and ΔV_C is the difference in the Coulomb barrier between the incoming and outgoing channels. Since the lighter product remains in a hole state of the transferred pair, the sign of polarization should be opposite to that of λ_1. Vanishing polarization is predicted at the Q value, $-(\frac{1}{2}mv^2 - \Delta V_C) \equiv Q_0$, with $\lambda_1 = 0$. As Q increases passing through Q_0, λ_1 changes sign from negative to positive, i.e., positive polarization is expected for $Q < Q_0$, and negative polarization for $Q > Q_0$. The prediction agrees qualitatively with the result of the present experiment. It is interesting to note that the optimum Q value in the energy spectrum roughly coincides with the Q value for $P = 0$. This indicates that the maximum in the cross section occurs for $\lambda_1 = 0$ in accordance with the argument[9] on the optimum Q value.

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Quadrupole Moment of the First Excited 2^+ State of ^{18}O

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The static quadrupole moment Q_{2^+} for the 1.982-MeV 2_1^+ state in ^{18}O has been remeasured via Coulomb excitation. Anomalously large Q_{2^+} values previously published are shown to be erroneous as a result of Coulomb-nuclear interference and other problems eliminated by the present techniques. Both present and previous data are consistent with Q_{2^+} values of $-3.1^{+3.0}_{-2.0}$ ($-0.1^{+3.0}_{-2.0}$) $e\cdot\text{fm}^2$ for constructive (destructive) interference. This result agrees with shell-model and coexistence-model predictions.

The observed coexistence of low-lying rotational bands and spherical states in the closed-shell nuclei ^{16}O and ^{40}Ca has provoked considerable interest in the structure of these nuclei.[1-4] Since existing calculations predict a wide variety of shapes, a knowledge of the shape of these deformed rotational bands would considerably aid in an understanding of their microscopic structure. The $B(E2)$ values within the rotational bands of both ^{16}O and ^{40}Ca are known to be very enhanced, indicating that the bands are strongly deformed. Measurement of static quadrupole moments, for determination of the sign of the deformation, is impractical for ^{16}O and ^{40}Ca because of the high excitation energy and weak $E2$ strengths to the ground state. However, the low-lying energy level spectrum and enhanced $B(E2)$ values in the adjacent two-neutron nuclei ^{18}O and ^{42}Ca suggest the coexistence of low-lying spherical two-neutron configurations and deformed bands similar to those in the adjacent closed core.[1-5] The lowest 2^+ state in ^{42}Ca contains[5] a 58% deformed-core admixture which changes the static quadrupole moment Q_{2^+} from the shell-model value of $+1\ e\cdot\text{fm}^2$ to the large negative value[5] of $-19 \pm 8\ e\cdot\text{fm}^2$. In ^{18}O, the lowest 2_1^+ state appears to have a deformed-core admixture[2-4] of $\sim 12\%$, which means that the maximum change in Q_{2^+} from the shell-model value of $-3\ e\cdot\text{fm}^2$ is -2 $(+2)$ $e\cdot\text{fm}^2$ if the deformed component is prolate (oblate).

Extraordinarily large values of $Q_{2_1^+}$ for ^{18}O were recently measured via Coulomb excitation. These are $-11 \pm 5\ e\cdot\text{fm}^2$ due to Disdier *et al.*[6] and