Michigan State University

National Superconducting Cyclotron Laboratory

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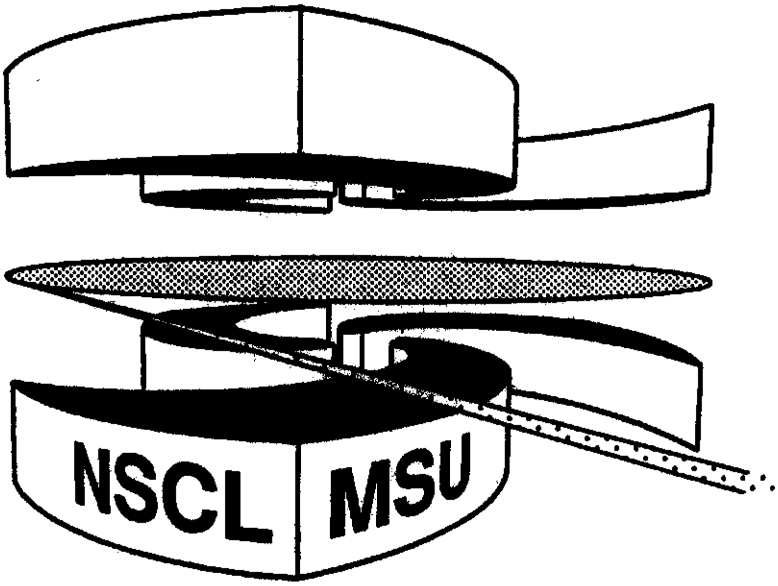

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A program directed towards the measurement of ground state moments in nuclei far from stability has been initiated at the National Superconducting Cyclotron Laboratory at Michigan State University. Spin-aligned fragments are produced at small angles relative to the primary beam axis by intermediate-energy heavy-ion reactions. The fragments are collected and analyzed using the A1200 fragment separator. The β-NMR technique is then used to detect the resonance frequency of the spin-aligned exotic fragments. The results of the first experiments using the β-NMR system recently installed at the NSCL will be reported, including measurements of the polarization of ^{12}B fragments following the reaction of ^{18}O at 80 MeV/A on a Nb target.

INTRODUCTION

Measurements of the ground state moments of exotic nuclei provide important information on the extent to which single-particle and/or collective features dominate the low energy structure of these nuclei. Such measurements, however, are difficult for nuclei far off the line of stability due to the short half-lives of these species. The pioneering experiments by Asahi *et* al. (1), in which they measured the polarization of secondary fragments produced off the central beam axis following intermediate-energy heavy ion reactions, now provide a unique opportunity to measure ground state moments in a variety of light, exotic nuclei. A β-NMR technique can be applied to measure the nuclear hyperfine splitting resonance curve corresponding to the appropriate nuclear moment, where, for the case of a dipole interaction only in an applied magnetic field B, the peak in the resonance curve (given as the Larmour frequency, ν_L) is directly related to the nuclear g factor through the relation $h\nu_L = gB$.

To date, ground state magnetic moments have been measured using the β-NMR technique following intermediateenergy heavy-ion collisions for ^{14,15,17}B and ^{17}N (2,3), ^{9}C and ^{13}O (4), ^{21}F (5), and ^{43}Ti (6). Electric quadrupole moments have also been measured for spin-aligned fragments produced in projectile fragmentation, most recently for ^{14,15}B (7). Through the implementation of a β-NMR apparatus following the A1200 fragment separator at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University, we plan to take advantage of the high quality beams of exotic nuclei presently available at the NSCL to make precise measurements of nuclear magnetic and quadrupole moments for nuclei having Z less than ≈ 40, and with half-lives less than a few seconds. *This* contribution describes the initial experiments used to verify the polarization of fragments following projectile fragmentation end to test the new β-NMR system.

EXPERIMENTAL TECHNIQUE

The β-NMR system used in the initial measurements at the NSCL was similar in many respects to that described by Asahi *et* al. (8). The system resided between the pole faces of a large dipole magnet (pole gap of 10.2 cm), which provided the nuclear Zeeman splitting and the directional holding field for the spin-aligned secondary beams. The detectors consisted of two β telescopes, located at 0’ and 180° with respect to the direction of the holding field of the dipole magnet. The telescopes were each composed of a 4.4 cm × 4.4 cm × 3 mm thick ΔE plastic scintillator and a 5.1 cm × 5.1 cm × 25 mm thick total energy plastic scintillator. Each scintillator detector was coupled to a long (> 56 cm) acrylic light guide to place the photomultiplier tube of each telescope element beyond the fringe field of the dipole magnet. The telescopes were placed 9 mm from the catcher foil, and covered approximately 33% of the 4π solid angle.

The catcher foil for the experiments reported here was a 2.5 cm × 2.5 cm × 250 μm thick Pt foil, annealled at 630° C for 10 hours in air. The foil was mounted between the two β telescopes, and tilted at an angle of 45° relative to the beam axis of the A1200. Surrounding the catcher foil was a set of radiofrequency (RF) coils, which provided the oscillating magnetic field for the resonance measurement. The RF coils were two 30-turn loops (diameter 2.3 cm) of 28 AWG magnet wire, arranged in a Helmholtz-like configuration, with a separation distance of 3.0 cm. The coil inductance was measured to be 77 μH. The RF coils were configured as part of an RCL circuit, which also included a 50 Ω resistor and a variable capacitor to provide the maximum alternating magnetic field by matching the impedance of the circuit to the output impedance (50 Ω) of the RF source.

A secondary beam of ^{12}B ($T_{1/2}$ = 20 ms, $I^{\pi} = 1^{+}$, Q_{β} = 13 MeV) was produced using a primary beam of ^{18}O at 80 MeV/A incident on a 216 mg/cm^2 ^{93}Nb target. The secondary fragments were selected by the A1200 fragment separator (9). Two steering magnets located upstream of the A1200 target position allowed the collection of fragments in the range of +3° to -3° relative to the primary beam axis. The full angular acceptance of fragments in the deflection plane at the target position was approximately 1°. Fragments were also accepted within the range of 1% of the chosen central momentum of the A1200 as defined by momentum slits placed at the first momentum-dispersed image of the device. Beam identification was accomplished at the A1200 focal plane using the energy loss of the fragments measured in a 300 μm Si PIN detector and the fragment time-of-flight (TOF) referenced to the K1200 Cyclotron radiofrequency. A second 300 μm Si PIN was located behind the catcher foil position of the β-NMR apparatus to allow for redundant fragment identification when the catcher foil was removed, again using energy loss and TOF information.

Two data acquisition techniques were employed during the ^{12}B polarization experiments. The first involved pulsing the primary ^{18}O beam from the cyclotron. During beam-on cycles, ^{12}B fragments at 35 MeV/A were directed from the A1200, energy degraded to ≈ 13 MeV/A using Al degrader foils, and implanted into the Pt catcher foil for 20 ms. During the beam-off cycles, which were 40 ms in duration, the RF coils surrounding the catcher foil were energized for the entire beam-off period every other cycle, and β spectra were collected for the ^{12}B spin-polarized fragments. The RF-on spectra were then normalized to the spectra collected during the RF-off condition in order to correct for possible changes in the position of the beam at the catcher foil. Valid β events required signals in both the ΔE and E detectors of a single β telescope within a time period of 100 ns.

In the second data acquisition mode the ^{12}B activity was collected continuously for a given run, with the RF coils energized during the entire run period. This method was employed to test the feasibility of performing, more efficiently, moment measurements for fragments having long (> 10 s) decay half-lifes and spin-lattice relaxation times. Normalization of the β spectra was accomplished by continuously collecting the ^{12}B activity with no signal supplied to the RF coils. This second, or batch, technique had not been employed in the previous β-NMR experiments described in the literature; however, as will be discussed in the following section, the observed magnitude of the destruction of the spin polarization was comparable to that measured using the more conventional beam-on/beam-off acquisition method.

RESULTS AND DISCUSSION

To test the proper operation of the β-NMR system, and also to confirm the observed polarization of fragments following intermediate-energy heavy-ion collisions, we completed two measurements of the polarization of ^{12}B fragments. The first measurement was the reproduction of the resonance curve for ^{12}B. Using a static field of 0.124 T, an incident beam angle of +3° and selecting fragments on the peak of the momentum yield curve, the frequency range from 930–970 kHz was scanned, using a frequency modulation of ± 10 kHz. During this measurement, the batch implantion method described above was employed. The resulting resonance curve is shown in Fig. 1. Fitting this curve to a Lorentzian peak shape, we have extracted a linewidth of 7 kHz, and a Larmour frequency of 947(1) kHz. From the measured Larmour frequency, we deduce a value of 1.002(2) μ_N for the ground state

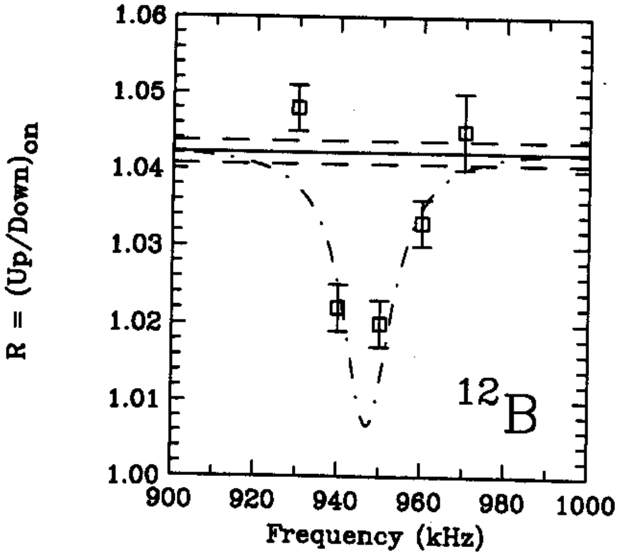

FIGURE 1. Resonance curve for ^{12}B using the batch implantation technique. The frequency modulation employed was ± 10 kHz. The full line is the average Up/Down ratio for all ^{12}B runs when no RF signal was applied to the implanted sample (RF-off). The dashed lines indicate the error attributed to the averaged RF-off ratio. The dot-dash line is a Lorentzian fit to the data, using a peak centroid of 947 kHz and a linewidth of 7 kHz.

magnetic moment of ^{12}B, which agrees well with the adopted value of $+1.00306(^{+15}_{-14})$ μ_N given in Ref. (10).

We also explored the dependence of the observed polarization of the ^{12}B fragments on the longitudinal fragment momentum distribution and on the angle of the emitted fragments. For these measurements, we used the more conventional beam-on/beam-off data acquisition method. The results for ^{12}B fragments are shown in Fig. 2. One can observe that the polarization of ^{12}B fragments has little dependence on fragment momentum in the range from -2% $\leq \Delta p/p \leq$ +2% with the incidence angle of the primary ^{18}O beam at +3.0 degrees to the axis of the A1200, in agreement with the results of Okuno *et al.* (11). In the previous work on the reaction of ^{15}N on ^{93}Nb at 67.3 MeV/A, only a small dependence of the ^{13}B fragment polarization was observed over the same range of fragment momenta. Our result also corroborates the observations of Okuno *et al.* that intermediate mass targets produce non-zero values for the polarization of fragments at the peak in the momentum yield curve (11).

As for the dependence of the ^{12}B polarization on the incident beam angle, we have observed a change in the sign of the polarization of the ^{12}B fragmentswith a change in the direction of the incident angle of the primary ^{18}O beam to -2.5 degrees. This result supports the hypothesis (11) that the mean deflection angle for the projectile-like fragments, and hence the dominance of near- or far-side trajectories, determines the sign of the observed polarization. A null result for an ^{18}O beam at normal incidence was also observed. These results support the preliminary results from GSI obtained for ^{37}K fragments produced following high-energy (500 MeV/A) fragmentation (12).

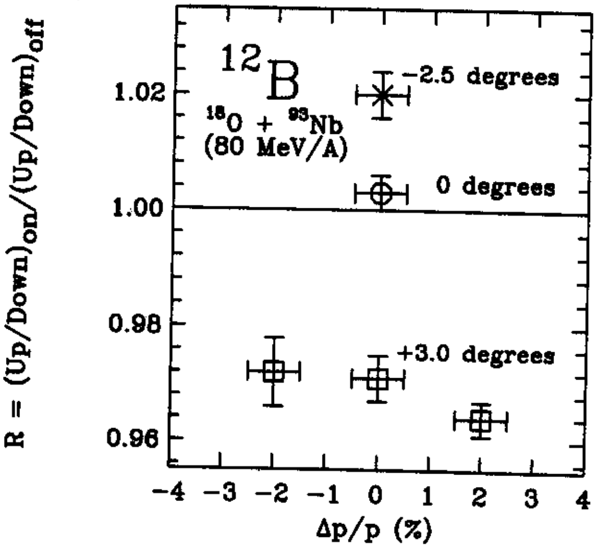

FIGURE 2. Dependence of the observed NMR effect (in %) on the fragment momenta for ^{12}B fragments measured for positive beam deflection (□), negative beam deflection (×), and normal incidence (○) following the reaction ^{18}O + ^{93}Nb at 80 MeV/A. For these measurements, the RF was set to the resonance peak, with a frequency modulation of ± 30 kHz. The value $\Delta p/p$ gives the deviation of the momentum of the ^{12}B fragments from the peak of the momentum yield curve, and the error bars on these values indicate the momentum acceptance of the A1200.

An additional result from these measurements is that the magnitude of the peak of the resonance curve for ^{12}B shown in Fig. 1, which again was measured using the batch implantation method, is similar to that observed using the more conventional beam-on/beam-off data acquisition method (see Fig. 2). This result suggests that the polarization of the ^{12}B fragments is not disturbed by the application of an alternating RF field during fragment implantation. Although the batch implantation technique may provide for more efficient data collection, especially for long half-life species, it may not be as good as the conventional acquisition technique for cancelling systematic errors attributed to changes in beam position on the catcher foil.

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