DEVELOPMENTS IN THE MEASUREMENT OF SPIN-POLARIZED FRAGMENTS USING β-NMR AT THE NSCL

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The measurement of ground state magnetic dipole moments of nuclei far from the line of β stability can provide much needed information on the progression of single-particle states to test current nuclear structure models. Since the observation by Asahi *et al.* [1] that spin-polarized nuclei are produced at angles away from the central beam axis in intermediate-energy heavy-ion reactions, significant progress has been made in the measurement of ground state magnetic dipole moments of light, exotic nuclei. We have successfully implemented the technique of nuclear magnetic resonance on β-emitting nuclei (β-NMR) to measure the *g* factors of spin-polarized secondary fragments at the NSCL [2]. Recent developments to extent this technique to very exotic nuclear systems include the implementation of a multiple adiabatic fast passage technique for β-NMR and the use of thick production targets to improve the yield of spin-polarized nuclei.

1. β-NMR and continuous implantation techniques

We have developed a multiple adiabatic fast passage (AFP) technique for β-NMR as a means of obtaining resonance information for continuously implanted spin-polarized radionuclides. The advantage of multiple AFP with continuous beam implantation is that the duty cycle for the measurement of β decay data is 100%. This provides more efficient data collection, particularly for long-lived species, over the traditional single-pass AFP with beam cycling. Spin-lattice relaxation also plays an important role in the success of a β-NMR measurement. With continuous beam implantation, multiple AFP provides a method in which all times following implantation are probed by the applied radiofrequency (rf).

In the multiple AFP technique [2] a frequency modulated (FM) rf signal is applied to the implanted sample to induce multiple spin flips of the polarized nuclear state. This occurs if the resonance falls within the FM band and if the modulation rate is significantly faster than both the decay half-life and spin-lattice relaxation time. For the initial implementation of this technique, the FM was in the form of a triangle wave. The consequence of this choice is that the net NMR effect using multiple AFP depends on the position of the Larmor frequency within the frequency sweep. For example, should the Larmor frequency occur at the center of the frequency sweep, successive spin flips cause the average polarization to be reduced to zero with complete destruction of the β asymmetry. If the Larmor frequency occurs at an extremum of the FM range, a net resonance will be observed, but the magnitude of the observed effect is reduced.

To overcome this limitation of the multiple AFP technique, FM in the form of a ramp wave has been implemented. The ramp function has the advantage that the spins of a polarized nuclear system will be sampled with equal probability. During the first sweep through the FM range, a single spin flip will occur (as long as the criteria for adiabatic fast passage are met) independent of the position of the Larmor frequency within the FM range. Since the rf signal is returned to the lower extremum at such a fast rate as to have no effect on the spin orientation of the nuclear system, each successive sweep will again produce a single spin flip independent of the position of the Larmor frequency within the FM range.

To test the multiple AFP method employing a ramp modulated rf signal, a spin-polarized secondary beam of ^{12}B was produced by bombarding a ^{93}Nb target with a primary beam of ^{18}O nuclei at 80 MeV/nucleon. The ^{12}B fragments were implanted at room temperature into a 140-μm thick Pt foil annealed at 630 °C for ten hours in air. In this test, beam cycling implantation was used, where the implantation (beam-on) time was 30 ms and the data collection (beam-off) time was 60 ms. During alternate beam-off cycles, a ramp-modulated FM signal was applied to the implanted nuclei. The NMR effect was deduced as the ratio of the counting rates in the 0^o and 180^o β telescopes measured for both the rf-on and rf-off conditions. The calculated Larmor frequency, using the known value of 1.00305 μ_N [3] for the ground state magnetic moment of ^{12}B and the applied magnetic field value of 0.1256 T, was 960 kHz. Three separate measurements were performed: 960 kHz (centered on the Larmor frequency for ^{12}B), 975 kHz, and 1000 kHz, all frequency-modulated at $\pm$20 kHz. The observed NMR effect at each of these frequency settings is shown in Fig. 1. The measured NMR effect for the data collected when the Larmor frequency occurred at the center of the FM ranged was -3.0(7)%. The effect measured at 975$\pm$20 kHz, where the Larmor frequency is at an extremum of the FM range, was -2.3(7)%. This result is consistent with the NMR effect determined at 960$\pm$20 kHz. No effect was measured at 1000$\pm$20 kHz, which was expected as the Larmor frequency lies outside the FM range.

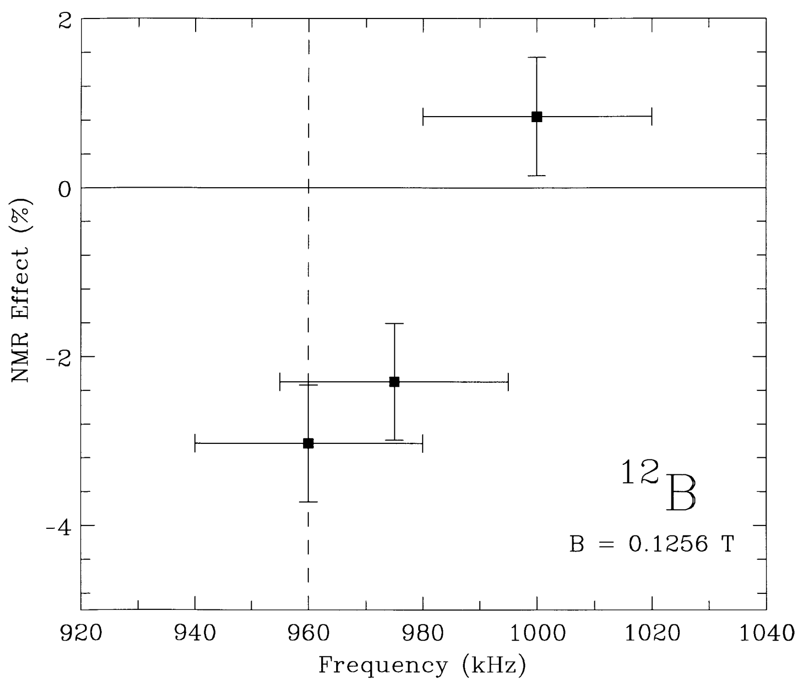

Fig. 1: NMR effect observed for spin-polarized ^{12}B fragments subjected to different rf signals having a fixed, ramp-modulated width of $\pm$20 kHz. The vertical dashed line is the expected position of the Larmor frequency for polarized ^{12}B nuclei in a magnetic field of 0.1256 T.

2. Thick target production of spin-polarized nuclei

In the initial studies of nuclear spin polarization by projectile fragmentation, thin production targets and narrow momentum slits were employed to better define the momentum distribution of the spin-polarized fragments. This was in response to the observation that the magnitude and sign of the spin polarization of fragments produced in intermediate-energy heavy-ion reactions exhibited a strong dependence on the fragment momentum distribution [1]. Further systematic studies [4] revealed that the polarization dependence on the outgoing fragment momentum varied both with the primary beam energy and the atomic number of the target. The most intriguing result from this work was that the polarization trend observed for medium mass targets showed significant polarization at the peak of the momentum yield curve, and that for some beam/target combinations the polarization was nearly constant over a wide momentum range around the central momentum value.

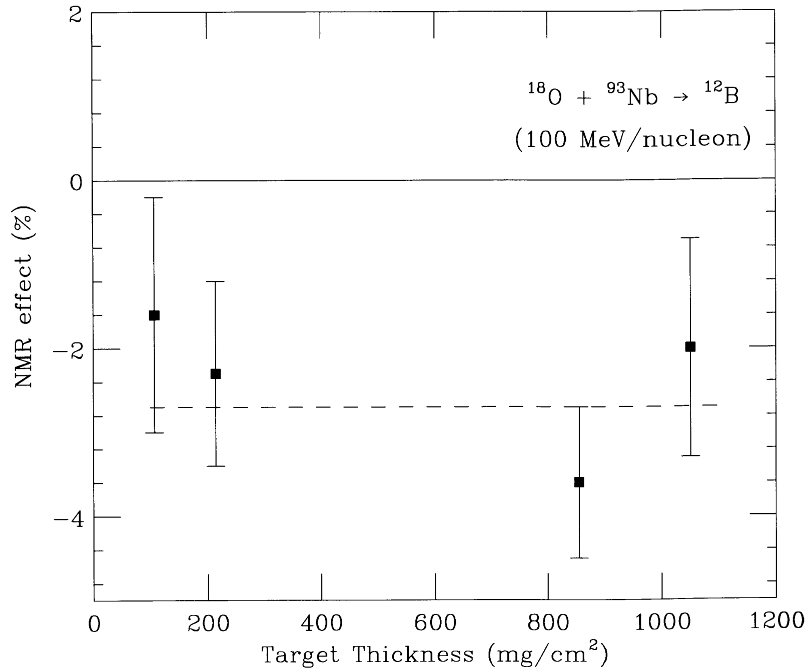

Fig. 2: NMR effect measured for spin-polarized ^{12}B fragments produced by an ^{18}O beam at 100 MeV/nucleon fragmented in Nb targets of varying thickness. The rf frequency applied in each case was 960 ± 10 kHz.

Subsequently, thick targets have been employed for the production of spin-polarized samples for the measurement of ground state *g* factors of several neutron-rich nuclei [5]. The use of thick targets provides a mechanism to enhance the yield of secondary beams having small production cross sections in projectile fragmentation. However, no direct measurement of the polarization dependence on target thickness for a specific primary beam/target combination has been reported.

We have measured the spin polarization of ^{12}B nuclei produced by the fragmentation of ^{18}O projectiles at 100 MeV/nucleon in Nb targets in the range 107 mg/cm^2 to 1055 mg/cm^2. Fragments from this reaction were collected by the A1200 fragment separator at $+2^{o}$ relative to the direction of the primary beam axis. The momentum acceptance was set to 1% using a slit at the first dispersive image of the A1200, and the ^{12}B fragments were separated from other species produced in the reaction using a 425 mg/cm^2 ^{27}Al wedge placed at the second dispersive image of the A1200. The spin-polarized ^{12}B nuclei were implanted into a 250 μm annealed Pt foil at the center of the β-NMR apparatus. An rf signal at 960 kHz (the Larmor frequency for ^{12}B nuclei at the magnetic field setting of 0.1258 T used in this measurement) frequency-moduated at ± 10 kHz using a ramp function was used to determine the magnitude of the NMR effect for each Nb target thickness investigated. Data were also collected at 1000 ± 10 kHz to ensure no NMR effect was observed when off the Larmor frequency.

The NMR effect measured for ^{12}B fragments produced in Nb production targets of 107, 214, 855, and 1050 mg/cm^2 is shown in Fig. 2. The data can be fit by a straight line and indicate an average NMR effect of -2.7% for all targets. This result is consistent with a spin-polarization production mechanism that is independent of the fragment momentum distribution for this specific beam/target combination. The dependence of the spin polarization on the momentum of ^{12}B fragments produced by fragmentation of an 80 MeV/nucleon ^{18}O beam in a 214 mg/cm^2 ^{93}Nb target is shown in Fig. 3. In the range $\Delta p/p$ -4% to $+4\%$, where Δp is the deviation of the ^{12}B momentum away from the momentum p at the peak of the yield curve, the magnitude of the spin polarization is observed to be approximately constant. It is important to note that the shape of the spin polarization versus fragment momentum

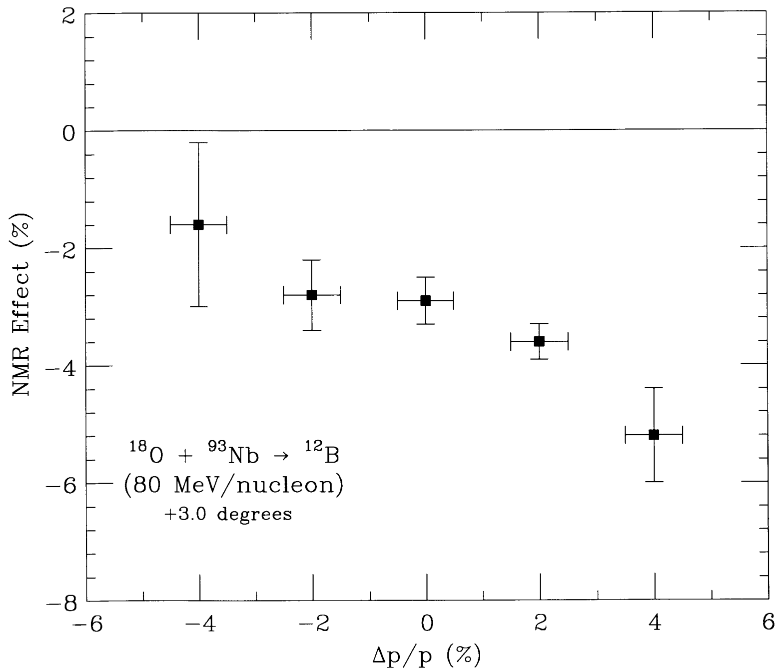

Fig. 3: Dependence of the spin polarization on the momentum of ^{12}B fragments produced by fragmentation of ^{18}O projectiles at 80 MeV/nucleon in a 214 mg/cm^2 Nb target. The *x* error bars indicate the momentum acceptance of the A1200.

curve will depend strongly on the beam and target species, and the primary beam energy. Okuno *et al.* [4] proposed that small values of the parameter $R = \bar{\theta}_{def} / \Delta\theta_F$, where $\bar{\theta}_{def}$ is the mean deflection angle and $\Delta\theta_F$ is the spread in the deflection angle due to the Fermi motion of the projectile nucleus, will result in a spin polarization profile which shows little dependence on the momentum distribution of the fragments. In considering the use of thick production targets for spin-polarization measurements, the selection of a beam, target, and energy combination must be considered carefully to maximize both counting rate and polarization.

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References

1. K. Asahi et al., Phys. Lett. B **251**, 488 (1990)
2. P.F. Mantica et al., Phys. Rev. C **55**, 2501 (1997)
3. P. Raghavan, At. Data Nucl. Data Tables 42, 189 (1989)
4. H. Okuno et al., Phys. Lett. B **335**, 29 (1994)
5. See, for example, H. Ueno et al., Phys. Rev. C **53**, 2142 (1996)