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Pulsed Magnetic Field Method for Measuring Polarization of Radioactive Beams

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A new method has been developed for measuring the magnitude of nuclear spin polarization of a secondary, radioactive beam by making a pulsed magnetic field measurement that does not require advance knowledge of the nuclide's magnetic moment. Using a standard β-NMR apparatus, a magnetic double ratio is determined from the counting rates in 0° and 180' β detectors for magnetic field on and off conditions. This ratio provides direct information on the induced spin polarization of a radioactive beam. A demonstration of the method was performed using spin-polarized ^{12}B nuclei produced by fragmentation of an 80 MeV/nucleon ^{18}O beam in a Nb target.

1. Introduction

Spin polarization of nuclei produced at finite angles with respect to the beam axis in intermediate-energy heavy-ion reactions was first noted by Asahi et *al.* [1]. The observation of substantial spin-polarization for radioactive nuclei produced by projectile fragmentation provides a means for determining nuclear magnetic moments. However, such measurements have been hampered by the fact that the magnitude of the induced spin polarization could not be established prior to performing a successful search for the nuclide's resonance frequency using the technique of nuclear magnetic resonance on beta emitting nuclei (β-NMR). We report a pulsed magnetic field method to determine the magnitude of nuclear spin polarization of a secondary, radioactive beam that does not require knowledge of the nuclide's magnetic moment.

2. Method

In a typical β-NMR experiment, the angular distribution $W(\theta)$ of β particles emitted from a polarized source is measured. The distribution has the general form $W(\theta) = 1 + (v/c)A_1 P\cos\theta$, where v is the electron velocity, c the velocity of light, P is the polarization, A_1 is the directional distribution coefficient, and

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θ is the β emission angle relative to the polarization direction. The angular distribution shows maximum deviation at angles 0° (Up) and 180° (Down). The polarized sample is then exposed to electromagnetic radiation in the radiofrequency (rf) range. If the applied rf is at the Larmor frequency, a redistribution of the magnetic substates occurs, and resonance is achieved. From the position of the Larmor frequency for a pure magnetic interaction, the nuclear g factor can be deduced. Since the β distribution will be isotropic when the rf is tuned to the Larmor frequency, the resonance position is determined as a change in the double ratio

$$R = \frac{(Up/Down)_{\mathrm{rf\ on}}}{(Up/Down)_{\mathrm{rf\ off}}}. \tag{1}$$

R gives *direct* information on the magnitude of induced nuclear spin polarization. However, knowledge of the nuclear magnetic moment is required to identify the position of the Larmor frequency and hence the magnitude of polarization. Recently, a method based on the adiabatic rotation of a magnetic holding field was used to determine the nuclear spin polarization of fragments produced by projectile fragmentation before NMR was observed [3]. We have made a pulsed magnetic field measurement in an attempt to determine the magnitude of spin polarization also without specific knowledge of the ground state nuclear properties. The technique involves determining the magnetic field double ratio

$$MR = \frac{(Up/Down)_{\mathrm{magnet\ off}}}{(Up/Down)_{\mathrm{magnet\ on}}} \tag{2}$$

where the applied magnetic field, providing both the Zeeman splitting and the directional holding field, is pulsed in on/off sequences. When the magnetic field is on, the β directional distribution will be anisotropic if the implanted nuclei have some spin polarization. For the field off period, the quadrupolar interactions may dominate the local field interaction at the location of the impurity in a face-centered cubic host material. This interaction will, in effect, depolarize the nuclear spin system [4] and lead to an isotropic β directional distribution. Therefore, the magnetic field double ratio will deviate from unity if the implanted nuclei are spin-polarized while for unpolarized nuclei, the ratio will be unity. The deviation from unity of the polarized sample provides a direct measure of the magnitude of the induced spin polarization.

3. Application

The method was tested using a spin-polarized ^{12}B beam produced at the National Superconducting Cyclotron Laboratory at Michigan State University. A primary beam of ^{18}O at 80 MeV/nucleon was made incident on a 642 mg/cm^2

niobium foil at the target position of the A1200 fragment analyzer. Radioactive ^{12}B nuclei were collected at +2.5° to the normal primary beam. Fragments within 0.5% of the central momentum were selected and delivered to the NSCL β-NMR apparatus [5]. An annealed 140 μm-thick platinum foil, which has a face-centered cubic lattice structure, was used as a catcher foil.

Initially, a traditional β-NMR experiment was performed to determine the polarization of the ^{12}B fragments. Using an applied magnetic field of 0.1257 T and the known magnetic dipole moment of ^{12}B [6], the Larmor frequency was calculated to be 960 kHz. We performed double ratio measurements (Eq. 1) using continuous implantation and the multiple adiabatic fast passage technique with ramped frequency modulation [7]. The measurements required a triple coincidence between the three detector elements of each β telescope, and the resulting data are shown in Fig. 1a. A polarization $P = 2.3\%$ was deduced from the double ratio at the Larmor frequency.

The magnetic field double ratio was determined for two field values: B = 0.1257 T and B = 0.1725 T. A pulse sequence 30 s field on, 30 s field off was chosen, and the ^{12}B beam was continuously implanted into the platinum catcher foil. Again, a triple coincidence requirement was placed on the β events detected in each scintillator telescope. The resulting magnetic field double ratios are shown as filled symbols in Fig. 1b.

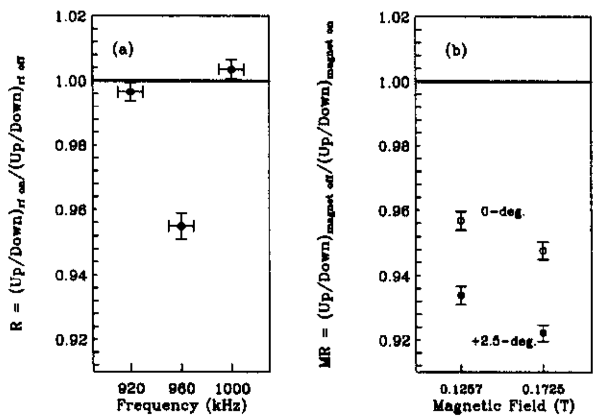

Figure 1. a) Radiofrequency double ratio measurements for ^{12}B in the range of the Larmor frequency for a magnetic holding field B = 0.1257 T and an incident beam angle +2.5°. b) Magnetic double ratio measurements for ^{12}B nuclei produced with an incident beam angle +2.5° (filled symbols) and 0° (open symbols).

The magnetic double ratios exhibit two curious features 1) the magnitude of the effect is larger that observed for the NMR measurement and 2) the values at B = 0.1257 T and B = 0.1725 T are not consistent with one another. The inconsistency in the magnetic double ratios for the two field settings suggested that magnetic field interactions with scintillator photomultiplier tubes may account for the difference between the magnetic double ratios and the double ratio determined by NMR. This was confirmed by measuring the magnetic double ratio as a function of holding field for an isotropic gamma-ray source. To provide a normalization for the magnetic double ratios, the secondary ^{12}B beam was produced at 0°, that is along the incident beam direction. The implanted beam will have no polarization [5], and β emission from this source will be isotropic. The resulting magnetic double ratios determined for $B = 0.1257$ T and $B = 0.1725$ T using an incident beam angle of 0° are shown as open symbols in Fig. 1b. The magnetic double ratios from the non-polarized source (confirmed by NMR) differ significantly from unity, again suggesting a systematic effect that can be traced to the different response of the photomultiplier tubes during the field off and field on collection cycles. This systematic effect can be removed from the data by taking a ratio of the magnetic double ratios for the polarized (beam angle +2.5°) and unpolarized (beam angle 0°) sources.

The normalized magnetic double ratios are approximately 60% of the effect determined from the NMR measurement. This deviation is most likely attributed to the implantation of impurity ^{12}B nuclei in platinum lattice sites where the magnetic interaction strength still dominates the local quadrupolar interactions [4].

In conclusion, we have developed a new method for determining the induced nuclear spin polarization of secondary fragments produced in fragmentation reactions. A magnetic field double ratio deviating from unity was determined for spin-polarized ^{12}B nuclei by performing pulsed magnetic field measurements using a standard β-NMR apparatus. The normalized double ratios were within 60% of the effect measured by NMR. The pulsed magnetic field technique provides a means of maximizing the polarization yield for secondary beams produced by projectile fragmentation reactions. This will afford greater opportunities in the use of polarized radioactive beams for moment measurements in exotic nuclear species.

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