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Magnetic moment of ^{17}Ne using β-NMR and tilted foil polarization

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Abstract

We report on the measurement of the magnetic moment of the ground state of ^{17}Ne. Radioactive ^{17}Ne nuclei were delivered from the high resolution mass separator at ISOLDE onto a high voltage platform at −200 kV and were polarized using the tilted foil polarization method. The polarized nuclei were implanted into a Pt stopper situated in a liquid-helium cooled β-NMR apparatus and the asymmetry destruction of the ensuing β rays was monitored as a function of the rf frequency applied to the polarized nuclei. The measured value of $\mu = 0.74 \pm 0.03$ affirms the $\nu\, p_{1/2^-}$ nature of the ground state of ^{17}Ne and is compared to shell model calculations.

1. Introduction

Magnetic moments of nuclei provide an important input to the understanding of nuclear structure since they can provide precise and unique information regarding the single-particle nature of the particular nuclear level under study. In the last few years, much focus has been drawn to probing nuclear structure at extreme isospin, using the various new developments in rare-isotope-beam facilities and in ancillary detection systems. In particular, measurements of ground-state magnetic moments in short-lived, proton-rich nuclei can shed much light on the evolution of shell structure as approaching the proton drip line. In the β-NMR method, widely used in such measurements in unstable nuclei, the nuclei are polarized using various possible mechanisms such as reaction polarization, optical pumping and low-temperature orientation [1–3]. The resulting asymmetric distribution of decay β-rays is monitored in the presence of an external static magnetic field and a perturbing rf field. The method chosen for polarizing a particular nucleus depends mostly upon properties such as life times and atomic structure. For short-lived nuclei in the ms range, or for elements not readily amenable to laser techniques, the tilted foil method has a broad potential when combined with the β-NMR technique. In the case of the tilted foil technique, atomic polarization is initially induced in ionic electrons by a surface interaction upon the exit of an ion from a thin foil, tilted at an oblique angle with

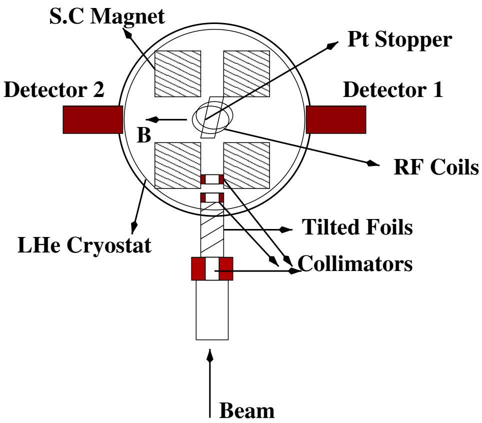

Figure 1. A cross sectional view of the β-NMR setup.

respect to the ionic beam direction. The atomic polarization (in the direction $n \times v$, where n is the unit vector perpendicular to the outgoing surface of the foil and v is the ion velocity vector) is transferred to the nucleus via the hyperfine interaction. The nuclear polarization thus induced can be enhanced, especially for high-spin states, by the use of several foils spaced sufficiently as to allow a significant nuclear precession around the total angular momentum in the flight time between successive foils.

The present experiment utilizes the tilted foil polarization method applied on short-lived nuclei from ISOLDE (CERN) for measuring the magnetic moment of the s-d, $T = 3/2$, ^{17}Ne ($I^{\pi} = 1/2^{-}$, $T_{1/2} = 109$ ms) nucleus that is well-suited for such a measurement. A determination of the magnetic moment of this nucleus is particularly interesting since the magnetic moment of its mirror partner, ^{17}N, is already known [4]. The information for both members of a mirror pair can be used to form the iso-scalar and iso-vector components of the magnetic moment and to compare them to theoretical calculations using the 'free nucleon' and 'effective' operators (see below). While a full picture of $T = 1/2$ mirror nuclei in the s-d shell exists, virtually nothing is known about $T = 3/2$ mirror pairs.

2. Experimental details

The experiment was performed by using the 60 keV ^{17}Ne beam from ISOLDE. A MgO target was heated to high temperature (1000 °C) and bombarded by a 1 GeV pulsed proton beam from the PS-Booster facility at CERN. The spallation reaction products diffused from the target to a plasma ion source via a cold transfer line that ensured that only gas products reach the ion source. The ionized nuclei were extracted at 60 keV and mass-separated by the ISOLDE high-resolution separator (HRS). Typical beam intensities thus obtained were $\approx 10^5$ particle/s. Since the beam energy of 60 keV is not sufficient to pass through the tilted carbon foils without prohibitive multi-scattering effects, the entire experimental setup was mounted on a high voltage platform with an accelerating potential of -200 kV. For the 1^+ charged ^{17}Ne, this corresponds to an energy of 260 keV. A schematic of the setup is shown in figure 1, depicting the various components situated on the high voltage platform such as the superconducting cryostat and the detectors. Several major improvements have been incorporated in the present setup compared to [5, 6]. A new cryostat that houses the superconducting magnet has been constructed and mounted on the high voltage platform. Improved vacuum in the system was helpful in reducing the condensation on the stopper. Typical vacuum was of the order of 10^{-7} mbar. Increased thermal contact between the stopper and the liquid-He cooled Cu block provided temperatures as low as 15 K on the target, as monitored by a thermocouple device. In the present experiment, only one carbon foil of 5-6 μg cm^{-2} at 65° was used. Due to the low spin ($I = 1/2$) of ^{17}Ne, this was deemed sufficient to obtain a degree of polarization [7] close to the saturation value while minimizing losses of the beam reaching the stopper. In a similar setup [5, 6], the tilted foil chamber on the high voltage platform is connected to the superconducting cryostat that provides the holding magnetic field, B, and cools the stopper to low temperature. The polarized ions were allowed to stop in Pt, cooled to 15 K and placed on a linear motion feed-through ladder that provides additional positions for another stopper and for a Faraday cup that is used for beam optimization with a pilot non-radioactive beam. Collimators are placed before and after the foil holder to prevent scattered beam from reaching the stopper. The last collimator is placed inside the magnet housing and remains stationary during the rotation of the foils with respect to the foil holder so as to avoid any artificial asymmetry due to electrons from beam particles scattered off the collimator or the foil holder. The detectors were also externally shielded from radiation originating in the rotating parts. The βs emitted from the decay of ^{17}Ne pass through a thin Al window and are measured in two plastic detectors, kept at 180° apart along the direction of the holding field. The detectors were situated at 8.5 cm from the stopper, subtending a solid angle of 0.025 of 4π. The stopper is surrounded by a rf coil in Helmholtz geometry. A magnetic field of 0.1 T, provided by the superconducting coils, was used as the holding field. The rf field is applied perpendicular to the direction of the holding field. The direction of polarization was changed periodically by rotating the foil holder by a computer controlled micro-stepping motor. The data were collected in four spectra (for two detectors at two foil positions) in a histogramming memory unit placed on the HV platform that was connected to a computer through an ethernet and fibre optic link. The rf was provided by a function generator through a GPIB communication interface.

2.1. β asymmetry determination

The angular distribution of radiation emitted from an axially symmetric ensemble of oriented nuclei is given by

$$W(\theta) = \sum_{\lambda} Q_\lambda B_\lambda A_\lambda P_\lambda(\cos\theta) \tag{1}$$

where B_λ are the orientation parameters, A_λ are the angular distribution coefficients, $P_\lambda \cos(\theta)$ is the Legendre polynomial and Q_λ are the finite-angle attenuation coefficients. The angle θ is measured from the direction of polarization. For parity conserving interactions, only the even terms in λ are non-zero but for electrons from β-decays the leading term in equation (1) is

$$W(\theta) = 1 + Q_1 B_1 A_1 \cos\theta \tag{2}$$

where

$$B_1 = \sqrt{\frac{3I}{(I+1)}\frac{\langle I_z\rangle}{I}}. \tag{3}$$

For the present geometry, the finite-angle parameter Q_1 is close to unity. The $1/2^-$ ground state of ^{17}Ne decays preferentially to two $3/2^-$ levels of ^{17}F at excitation energies of 4.70 and 5.52 MeV, with branching ratios of 0.16 and 0.54, respectively. While the strengths of the corresponding Gamow-Teller and Fermi matrix elements for these transitions are not known, the decay spin sequence yields a geometrical asymmetry parameter A_1 of 2/3.

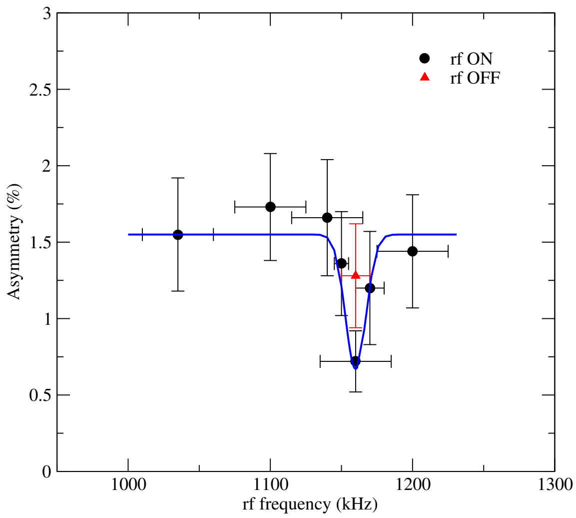

Figure 2. The asymmetry parameter as a function of the rf frequency. The circles represent the asymmetry with rf power 'ON' and the triangle represents the asymmetry obtained with rf power 'OFF'. The solid line is a fit yielding the value of $\mu = 0.74$ nm.

The asymmetry ϵ is defined as

$$\epsilon = \frac{W(0^\circ) - W(180^\circ)}{W(0^\circ) + W(180^\circ)}. \tag{4}$$

In order to avoid systematic errors associated with the efficiencies and dead times of the detectors, a double ratio ρ is defined as

$$\rho = \left[\frac{N(L) \leftarrow}{N(R) \leftarrow} \times \frac{N(R) \rightarrow}{N(L) \rightarrow}\right]^{1/2} \tag{5}$$

where $N(L) \leftarrow$ corresponds, for example, to counts in the detector to the left of the beam with the polarization in the left direction. In the tilted foil polarization experiment, the 'left' and 'right' polarization directions are switched periodically by rotating the foil by 180°. For small $\epsilon(\rho \approx 1)$, the asymmetry is given by

$$\epsilon = \frac{\rho - 1}{\rho + 1}. \tag{6}$$

In an experiment with polarized nuclei the total or partial destruction of the anisotropy of the emitted radiation is probed as a function of the radio frequency to obtain the resonant frequency ν. ν is related to the g-factor through the relation

$$\nu = g\mu_n B_{\text{ext}} \tag{7}$$

where B_{ext} is the external field applied.

3. Results

The measurement was carried out along the lines indicated above; the β asymmetry was monitored as a function of the rf frequency that was applied on the Helmholtz coil surrounding the Pt stopper. Figure 2 presents the asymmetry, determined from the double ratio as given in equations (5), (6) as a function of the rf frequency with a frequency modulation of 2–5%.

Table 1. Comparison of the experimental and theoretical magnetic moments of mirror nuclei ^{17}Ne,^{17}N and ^{15}O, ^{15}N.

		Experimental	WBP Free	WBP Effective
^{17}Ne	1/2−	0.74(3)	0.712	0.795
^{17}N	1/2−	−0.352(2)	−0.333	−0.350
^{17}Ne − ^{17}N	1/2−	1.09(4)	1.045	1.145
^{17}Ne + ^{17}N	1/2−	0.39(4)	0.379	0.445
$\langle S \rangle$		−0.145(5)	−0.159	−0.073
^{15}O	1/2−	0.7189(8)	0.638	0.722
^{15}N	1/2−	−0.28319	−0.264	−0.285
^{15}O − ^{15}N	1/2−	1.003	0.902	1.007
^{15}O + ^{15}N	1/2−	0.437	0.374	0.437
$\langle S \rangle$		−0.083	−0.161	−0.083

The frequency scan was carried out at a fixed magnetic field of 0.1 T and the position of the NMR resonance (manifested in the reduction of the asymmetry) yields the g-factor (as given by equation (7)) to be $g = 1.48 \pm 0.06$ or $\mu = 0.74 \pm 0.03$ for the $1/2^-$ state of ^{17}Ne. The major source of the error stems from the fact that the value of the magnetic field is taken from an off-line calibration of the superconducting coil, resulting in a relatively large systematic error. The experimental value of the asymmetry corresponds to an induced polarization of 2–3%.

We would like to point out that the data presented in figure 2 is taken from the first part of the experiment. After about 36 hours there were indications for an accumulation of condensed rest gas on the stopper that caused Ne atoms to stop in a perturbing environment rather than in the Pt catcher, and the asymmetry results could not be reproduced. We are presently planning improvements in the setup and vacuum system in order to eliminate this problem from future experiments.

The calculations for ^{17}Ne were carried out in a $0\hbar\omega$ p-sd model space with the WBP interaction [9]. For $0\hbar\omega$ the wavefunctions are restricted to two particles in the sd shell and one hole in the p shell. The calculated values are shown in table 1. For comparison we also show the results for the mirror nucleus ^{17}N and for the $A = 15$ mirror pair ^{15}O and ^{15}N, which are just single-hole states in this $0\hbar\omega$ model space. Table 1 also shows the results for the expectation values of the $\langle S \rangle$ operator. The effective M1 operator is that obtained from an analysis of sd-shell nuclei [8], but with an isoscalar spin g-factor for the 0p orbits adjusted to reproduce the $A = 15$ moments. Our goal here is to understand the change between $A = 15$ and $A = 17$, as well as possible effects of the proton halo in ^{17}Ne.

The calculations nicely reproduce the difference between $A = 17$ and $A = 15$ which comes from the coupling of the p-shell hole to the two particles in the sd shell. In comparison to the free-nucleon M1 operator, both $A = 15$ and $A = 17$ show about a 10% enhancement of the isovector moment and a 17% enhancement of the isoscalar moment which translates into a factor of two quenching of the isoscalar $\langle S \rangle$ term. The effective operator, which is designed to reproduce $A = 15$, also reproduces the ^{17}N moment. The value of 0.795 for ^{17}Ne can be decomposed into 0.722 from the 0p-shell neutron hole and 0.073 from the two sd-shell protons. The agreement with experiment for ^{17}Ne could be made exact if the contribution from the two sd-shell protons is reduced from 0.073 to 0.02(4). This change might be related to a reduction in the neutron–proton interaction due to the halo nature of the two sd-shell protons in ^{17}Ne.

The present commissioning of the REX ISOLDE facility provides radioactive beams with energies from 300 keV A^{-1} to 3.2 MeV A^{-1}, allowing heavier mass nuclei to pass through several tilted foils at various charge states and atomic configurations, allowing a selection of beam energy to obtain possibly higher atomic (and hence, nuclear) polarization. The present results therefore pave the way for future determinations of magnetic moments in, e.g., proton-rich nuclei in the Fe–Ga region of the f shell for which virtually no information exists on magnetic moments of $N = Z - 1$ nuclei and of mirror pairs.

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