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GROUND STATE MAGNETIC MOMENTS OF MIRROR NUCLEI STUDIED AT NSCL*

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Progress in the measurement of the ground state magnetic moments of mirror nuclei at NSCL is presented. The systematic trend of the spin expectation value $\langle s \rangle$ and the linear behavior of γ_p *versus* γ_n, both extracted from the magnetic moments of mirror partners, are updated to include all available data.

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1. Introduction

The ground state magnetic dipole moment has sensitivity to the orbital and spin components of the state wave function, and hence serves as an important observable in the study of nuclear structure. In particular, the simultaneous consideration of the magnetic dipole moments of mirror nuclei can provide a framework to test present day nuclear structure models.

Sugimoto [1] showed that if isospin is a good quantum number, the nuclear magnetic dipole moment could be decomposed into isoscalar and isovector components

$$\mu = \left\langle \sum \mu_0(i) \right\rangle_J + \left\langle \sum \mu_3(i) \right\rangle_J , \tag{1}$$

where the sum of the isoscalar μ_0 and isovector μ_3 moments are taken over all nucleons and $\langle \mu \rangle_J$ denotes the expectation value of μ for the state $M = J$, where M and J are the magnetic quantum number and nuclear spin, respectively. The isoscalar magnetic moment represents the sum of the magnetic

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moments of the mirror partners

$$(2T+1)\left\langle \sum \mu_0(i) \right\rangle = \sum_{T_z} \mu(J,T,T_z)\,. \qquad (2)$$

Here T is the total isospin and $T_z = (N-Z)/2$. The left-hand side of Eq. 2 can also be expressed in terms of the isoscalar spin expectation value $\langle s \rangle$

$$\left\langle \sum \mu_0(i) \right\rangle = \frac{J}{2} + 0.38\langle s \rangle\,, \qquad (3)$$

where

$$\langle s \rangle = \left\langle \sum s_z(i) \right\rangle_J \qquad (4)$$

and the constant 0.38 is the sum of the magnetic moments of the bare proton and neutron.

The extreme single-particle limit gives $\langle s \rangle = 0.5$ for odd-A mirror partners whose odd nucleon occupies a single-particle orbital with $j = \ell + s$, where ℓ is the orbital angular momentum. The value $\langle s \rangle = -J/[2(J+1)]$ results for the cases when the odd nucleon resides in an orbital with $j = \ell - s$. Experimentally deduced $\langle s \rangle$ values generally fall within single-particle expectations, except for a few instances that are discussed in detail later.

Buck and Perez [2] analyzed the magnetic moments of mirror nuclei in a different approach. They showed that a plot of the gyromagnetic ratio, $\gamma = \mu/J$, of the odd proton member of the mirror pair γ_p as a function of the gyromagnetic ratio of the odd neutron member γ_n resulted in a straight line. Further scrutiny of this linear dependence of γ_p on γ_n, provided simple expressions for the slope α and intercept β:

$$\alpha = \frac{G_p - g_p}{G_n - g_n}\,, \qquad \beta = g_p - \alpha g_n\,, \qquad (5)$$

where G_x and g_x are the spin and orbital contributions to the g-factor, respectively, with $x = p, n$ for protons and neutrons, respectively. The extreme single-particle model gives $\alpha = -1.199$ and $\beta = 1.000$, while the most recent evaluation of mirror magnetic moments for $T = 1/2$ nuclei by Buck, Merchant, and Perez [3] produced $\alpha = -1.148 \pm 0.010$ and $\beta = 1.052 \pm 0.016$. The small deviation of the experimental moments from the extreme single particle expectation was taken to possibly reflect meson exchange currents and/or small contributions to γ from the even nucleon [2].

Ground state magnetic moment measurements of the neutron-deficient nuclei ^{9}C [4], ^{32}Cl [5], ^{35}K [6], and ^{57}Cu [7] have been completed at NSCL. The results for the odd-A nuclei ^{35}K ($T = 3/2$) and ^{57}Cu ($T = 1/2$) have significantly extended the evaluation of $\langle s \rangle$ and γ_p *versus* γ_n to heavier masses.

In this paper, the experimental approach to magnetic moment measurements at NSCL is described, followed by a summary discussion of the new magnetic moment values for ^{35}K and ^{57}Cu and the resulting systematic trends of mirror moments at higher mass numbers.

2. Magnetic moment measurements at NSCL

Ground state magnetic moments are measured at NSCL using the technique of nuclear magnetic resonance on β-emitting nuclei (β-NMR). Nuclei of interest are produced by bombarding a fixed target with intermediate energy projectiles from the NSCL coupled cyclotrons. The incoming beam is made incident on the target at a small angle relative to the normal beam direction to break the reaction plane symmetry and produce a spin-polarized secondary beam of high-velocity ions. The ion species are mass separated in the A1900 fragment separator [8], with the separator tuned to maximize both the purity and transmission of the desired radioactive isotope. An adjustable slit system located at the A1900 intermediate image is used to select a portion of the momentum distribution of the desired isotopes, which is then transmitted to the β-NMR endstation.

2.1. Spin polarization

The production of spin polarized nuclei in intermediate-energy heavy-ion reactions was first demonstrated by Asahi *et al.* [9], and has been used extensively to measure ground state nuclear moments of short-lived isotopes at RIKEN, GANIL, GSI, and MSU. A classical treatment of the mechanism to describe the nuclear polarization in such reactions [9] considered conservation of linear and angular momentum. The treatment was extended by Okuno *et al.* [10] to account for varying initial reaction conditions. Although good qualitative agreement with experimental measurements was achieved, the magnitude of the observed polarization was typically a factor of three smaller than predictions.

The extension of ground state magnetic moments of mirror nuclei to heavier masses at NSCL was enabled by the establishment of spin polarization in intermediate-energy heavy-ion reactions where a single nucleon is picked up from the target by the fast-moving projectile. The initial measurements of Groh *et al.* [11] showed that large, positive spin polarization is obtained near the peak of the momentum distribution for proton pickup reactions. Subsequent systematic measurements by Turzo *et al.* [12] at GANIL demonstrated the method for neutron pickup as well.

A more accurate prediction of the spin polarization realized in intemediate-energy heavy-ion reactions, both for nucleon removal and pickup, has been developed [13]. Starting with the classical kinematic picture discussed above, a Monte Carlo simulation that included the addition of a more realistic angular distribution of the outgoing fragments, deorientation caused by γ-ray emission, and corrections for the out-of-reaction plane acceptance, was shown to reproduce, both qualitatively and quantitatively, the polarization observed in intermediate-energy reactions. The development of an accurate simulation of the spin polarization process significantly aided the execution of the magnetic moment measurements of ^{35}K and ^{57}Cu described below.

2.2. β-NMR method

The β-NMR system at NSCL consists of a small electromagnet, β detectors, and a radiofrequency (rf) system [14]. The room temperature electromagnet has a pole gap of 10 cm and operates at a maximum field of 0.5 T. The β detectors consist of two plastic $\Delta E - E$ telescopes placed around the sample holder in "up" and "down" positions relative to the orientation of the magnetic field of the electromagnet. The thin telescope element is 0.3-cm thick BC400 plastic scintillator of dimensional area 4.4 $\times$ 4.4 cm, while the thick telescope element is also BC400 scintillator with thickness 2.5 cm and area 5.1 $\times$ 5.1 cm. The scintillators are mounted on BC800 plastic light guides that allow placement of the 12-stage photomultiplier tubes outside the fringing field of the electromagnet. A vacuum chamber can be placed in the pole gap of the electromagnet between the two β detector telescopes. The part of the vacuum chamber above and below the sample holder has been removed and replaced with thin plastic to reduce the attenuation of β particles. The downstream plate of the vacuum chamber is used to mount the sample holder, rf coils, a beam collimator, and a solid-state Si detector for monitoring the secondary beam.

The rf system at NSCL was recently upgraded to allow the simultaneous application of multiple frequencies to the sample without significant loss of power [15]. The frequency-modulated signal from one of up to six frequency generators can be selected by a double-balanced mixer, amplified to a maximum 250 W, and delivered to a high-power rf box containing a bank of vacuum variable capacitors and an impedance matching element (either a 50 Ω resistor or multi-turn transformer). These two elements, along with the rf coil surrounding the sample holder, make up an LCR resonance circuit with a resonance Q factor of ~ 20. Tuning of the LCR for a given frequency is accomplished by setting the variable capacitors via remote controlled stepper motor units. Any combination of capacitors can be selected by way of fast switching relays. The time sequence for applying each frequency and the corresponding capacitance, as well as any necessary secondary beam pulsing, is controlled by a pulse pattern generator.

3. Magnetic moment of the drip-line nucleus ^{35}K

The proton separation energy of ^{35}K is only 80 keV based on the 2003 Atomic Mass Evaluation [16], and its vicinity to the proton drip line may reveal new and interesting nuclear structure features that may be reflected in the ground state magnetic dipole moment. The ^{35}K ions were produced starting with a primary beam of ^{36}Ar at 150 MeV/nucleon via a single proton pickup from a Be target followed by two neutron removal. The ^{35}K production rate was 30 pps/pnA of primary beam. The NMR was scanned between 520 and 620 kHz based on a previous measurement [17]. A resonance signal was observed at frequency 600 ± 10 kHz, corresponding to a magnetic moment $|\mu(^{35}K)| = 0.392 \pm 0.007\ \mu_N$ [6].

4. Magnetic moment of ^{57}Cu

The systematic variation of the ground state magnetic moments of the odd-A Cu isotopes, where neutrons are filling the pf shell, are quenched relative to shell model expectations [18]. In addition, the level structure [19,20] and transition probabilities [21] give a disparate picture of the robustness of the ^{56}Ni double shell closure. The magnetic moment of the one-proton particle nucleus ^{57}Cu is expected to be 2.5 μ_N based on shell models calculations completed in the full pf shell [22]. ^{57}Cu ions were produced by impinging a ^{58}Ni primary beam of energy 140 MeV/nucleon on a Be target. The single-proton pickup reaction and subsequent two neutron removal resulted in a ^{57}Cu production rate of 350 pps/pnA of primary beam. A broad NMR scan was completed between 1400 and 2800 kHz, and a resonance signal was observed at 2050 ± 50 kHz. The deduced magnetic moment value $|\mu(^{57}Cu)| = 2.00 \pm 0.05\ \mu_N$ [7] was nearly 20% smaller than shell model expectations.

5. Isoscalar spin expectation values

The new ground state magnetic moments of ^{35}K and ^{57}Cu dramatically extend the mass range of known mirror partners for $T = 1/2$ and $T = 3/2$ systems. The systematic trend in $\langle s \rangle$ for odd-A mirror nuclei is depicted in Fig. 1. Data are taken from Ref. [23] with the exception of ^{35}K and ^{57}Cu discussed here and ^{23}Al [24] and ^{55}Ni [25], for which signs of μ are taken from theoretical predictions. Nearly all $\langle s \rangle$ values are bounded by the extreme single-particle limits, including the new value $\langle s \rangle = -0.142 \pm 0.020$ deduced for the $A = 35, T = 3/2$ mirror partners, which includes ^{35}K and ^{35}S. It was surprising that the $A = 35, T = 3/2$ system followed the trends established by more well-bounded nuclei, given that ^{35}K exhibits such a small proton binding energy.

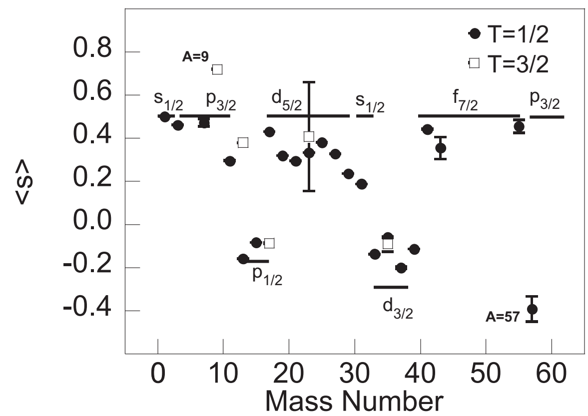

Fig. 1. Isoscalar spin expectation values for mirror magnetic moments. Filled circles are $\langle s \rangle$ values deduced for $T = 1/2$ nuclei, while the open squares are those deduced for nuclei with $T = 3/2$. The limits for $\langle s \rangle$ from the extreme single-particle model are shown by the solid lines.

The two mirror systems whose $\langle s \rangle$ value lies outside the extreme single-particle expectation are those with $A = 9, T = 3/2$ and $A = 57, T = 1/2$. The former disparity has been linked to possible proton intruder configurations in the ground state wave function of ^{9}C [26]. The later has been attributed to a breaking of the ^{56}Ni double-magic core [7].

6. Buck–Perez analysis

While the linear behavior of γ_p *versus* γ_n was demonstrated for $T = 1/2$ nuclei, no such analysis had been performed for $T = 3/2$ nuclei due to the limited experimental data for magnetic moments of $T_z = -3/2$ nuclei near the proton drip line. There are now five $T = 3/2$ mirror pairs whose ground state magnetic moments are known, including the $A = 35, T = 3/2$ system discussed here. The γ_p *versus* γ_n plots for the $T = 1/2$ and $T = 3/2$ mirror nuclei are presented in Fig. 2.

A linear fit for all $T = 3/2$ data shown in Fig. 2 results in slope $\alpha = -1.165 \pm 0.038$ and intercept $\beta = +1.101 \pm 0.037$. The linear trend in γ_p *versus* γ_n for the $T = 3/2$ mirror moments follows that already noted for the $T = 1/2$ data. In addition, the deduced α and β values for the $T = 3/2$ partners agree within errors of the values obtain by Buck *et al.* [3] for the $T = 1/2$ mirror pairs.

Recently, Perez *et al.* [27] extended the treatment of the linear behavior of mirror magnetic moments by using shell model estimates to make small modifications to γ_p and γ_n. The inclusion of contributions of total spin and angular momentum from both odd and even nucleon types improved the fit

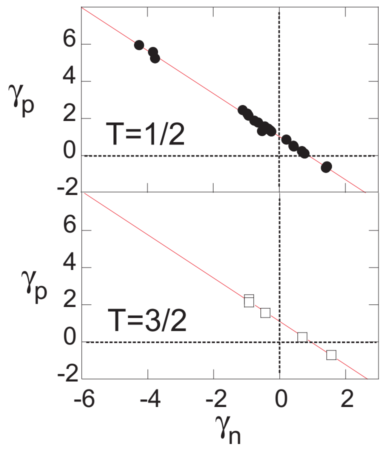

Fig. 2. Plot of gyromagnetic ratios for mirror magnetic moments. Filled circles are for $T = 1/2$ nuclei, while the open squares are those for nuclei with $T = 3/2$. The α and β values deduced from the linear fits shown as the solid lines in the figure are discussed in the text.

to the linear correlations between gryomagnetic ratios of mirror partners, and demonstrated the consistent treatment of γ_p *versus* γ_n for both $T = 1/2$ and $T = 3/2$ mirror pairs.

We note that the two mirror systems at $A = 9, T = 3/2$ and $A = 57, T = 1/2$ that show anomalous behavior in $\langle s \rangle$ as shown in Fig. 1 follow the linear correlation in γ_p *versus* γ_n demonstrated for other known mirror partners. The slope α in the Buck–Perez relation represents a ratio of the neutron and proton spin and orbital g-factors, effectively canceling any systematic spin dependence from the mirror partners, as opposed to relation for $\langle s \rangle$, which will amplify such spin effects. The underlying case for the disparate behavior of the $A = 9, T = 3/2$ and $A = 57, T = 1/2$ mirror moments may lie in the spin contribution from low-ℓ proton orbitals that comprise some part of the ground state wave function of the $T_z = -T$ nucleus.

7. Future initiatives at NSCL

We plan to continue our efforts to extend the measurements of known ground state magnetic moments to heavier nuclei. To this end, we are developing a new laser polarizer beam line [28] that will receive short-lived, low-energy rare isotope beams from the gas catcher system at NSCL. This new experimental set up will be operational in 2011 and will enable β-NMR measurements on refractory elements currently inaccessible at ISOL facilities, where collinear laser spectroscopy and laser polarization measurements have been a staple for many years.

The experimental program on magnetic moments at NSCL has benefitted over the years from contributions by T.J. Mertzimekis, A.E. Stuchbery, D.E. Groh, A.D. Davies, M. Huhta, J.S. Berryman, H.L. Crawford, R.R. Weerasiri, J.B. Stoker, W.F. Rogers, G. Georgiev, D.A. Anthony, and M. Hass. This work was supported in part by the US National Science Foundation grant PHY-06-06007.

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