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Anomalous p-shell isoscalar magnetic moments: Remeasurement of ^{9}C and the influence of isospin nonconservation

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We have remeasured the ground state g factor of ^{9}C using the technique of nuclear magnetic resonance on beta-emitting nuclei (β-NMR) on spin-polarized ^{9}C nuclei produced by the fragmentation of a ^{20}Ne beam at 80 MeV/nucleon in a Nb target. Our new value of $1.396(3)\mu_N$ is consistent with the previously measured value of the ground state magnetic moment of this nuclide. The results of shell model calculations employing isospin-nonconserving (INC) terms in the nuclear Hamiltonian are shown to better reproduce the quenched magnetic dipole moment of ^{9}C and the previously described anomalous isoscalar spin expectation value $\langle\sigma\rangle$ for the ^{9}Li-^{9}C mirror system. [S0556-2813(98)50306-8]

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The magnetic dipole moment is a sensitive probe of the nuclear ground state wave function. Magnetic moments have been measured for nearly all $J\neq 0$ ground states in light nuclei at and near the valley of β stability, and nuclear structure models do well in reproducing these measured moments. As one moves away from the valley of stability, only limited experimental data are available on magnetic moments which may stringently test the predictive power of current theoretical approaches. The ground state g factors of the proton-drip line nuclei ^{9}C and ^{13}O have been measured using spin-polarized radioactive beams and the technique of nuclear magnetic resonance on beta-emitting nuclei (β-NMR), and the results have been reported at recent conferences [1,2]. The deduced ground state magnetic moments of ^{9}C and ^{13}O, $(-)1.3914(5)\mu_N$, and $(-)1.3891(3)\mu_N$, respectively, are significantly quenched with respect to the single-particle Schmidt limit value of $-1.91\mu_N$ expected for a pure $\nu p_{3/2}$ ground state. While the magnetic moment of ^{13}O was shown to agree with simple shell model predictions using Cohen-Kurath wave functions [1], the same calculations were unable to reproduce the small magnetic moment value of ^{9}C. This anomalous value, if verified, may be an indication of unique structure phenomena for the proton drip-line nucleus ^{9}C ($S_p=1.3$ MeV).

The isoscalar spin expectation value, $\langle\sigma\rangle$, has been shown to be a sensitive probe of deviations in the magnetic moments of light, mirror nuclei [3]. The $\langle\sigma\rangle$ deduced from the ^{13}B-^{13}O mirror pair using the known magnetic dipole moment of ^{13}B [4], was shown by Matsuta *et al.* to compare favorably with the observed trends in the $\langle\sigma\rangle$ values extracted for $T=1/2$ nuclei. The $\langle\sigma\rangle$ determined for ^{9}Li-^{9}C using the known value [5] of $+3.4391(6)\mu_N$ for the ground state magnetic moment of ^{9}Li and the small experimental magnetic moment deduced for ^{9}C is 1.44, which lies well outside the $T=1/2$ systematics.

We have remeasured the ground state g factor of ^{9}C using a primary beam and target combination different from Ref. [2] to confirm the anomalous value of the magnetic dipole moment of this nuclide. A secondary beam of spin-polarized ^{9}C was produced at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University by the fragmentation of ^{20}Ne projectiles with an energy of 80 MeV/nucleon in a 107 mg/cm^2 thick ^{93}Nb target to enhance the polarization observed at the peak in the ^{9}C fragment momentum distribution as discussed by Okuno *et al.* [6]. Spin-polarized ^{9}C fragments were collected at $+2.5°$ relative to the beam axis and separated using the A1200 fragment separator [7]. The A1200 was set to select the peak of the momentum yield curve for ^{9}C fragments ($B\rho=1.9370$ Tm), with a momentum acceptance of 1% determined by slits placed at the first dispersive image of the device. A 425 mg/cm^2 Al degrader wedge with an angle of 3.5 mrad was placed at the second dispersive image to separate fragments with a given A/Z ratio. Fragments were identified both at the A1200 focal plane and the experimental endstation by means of the energy loss in 300 μm Si PIN detectors and the fragment time-of-flight relative to the K1200 Cyclotron radiofrequency.

The polarization measurements were performed using the β-NMR technique. The β-NMR apparatus consisted of two β telescopes, an implantation foil, and a set of radiofrequency (RF) coils, all placed between the pole faces of a large dipole magnet. The β telescopes were two 3 mm thick ΔE plastic scintillators and a 2.5 cm thick total E plastic scintillator. The β telescopes were situated 9 mm from the center of the implantation point at 0° and 180° with respect to the direction of the magnetic holding field, covering approximately 33% of the full 4π solid angle. The implantation foil was a 0.25 mm thick Pt foil annealed at 630 °C for 10 hours in air. The foil was tilted to an angle of 45° relative to the direction of the holding field to minimize the attenuation of β particles reaching the scintillator detectors. The Pt foil was kept at room temperature since estimates of the spin-lattice relaxation time (T_1) of ^{9}C in Pt using experimental Knight shift data available for ^{23}Mg in Pt [8] and ^{12}B in Pt [9], as well as theoretical band structure calculations of Matsuta *et al.* [8], suggest $T_1>200$ ms at 298 K. The RF coils were arranged in a Helmholtz-like geometry to produce an

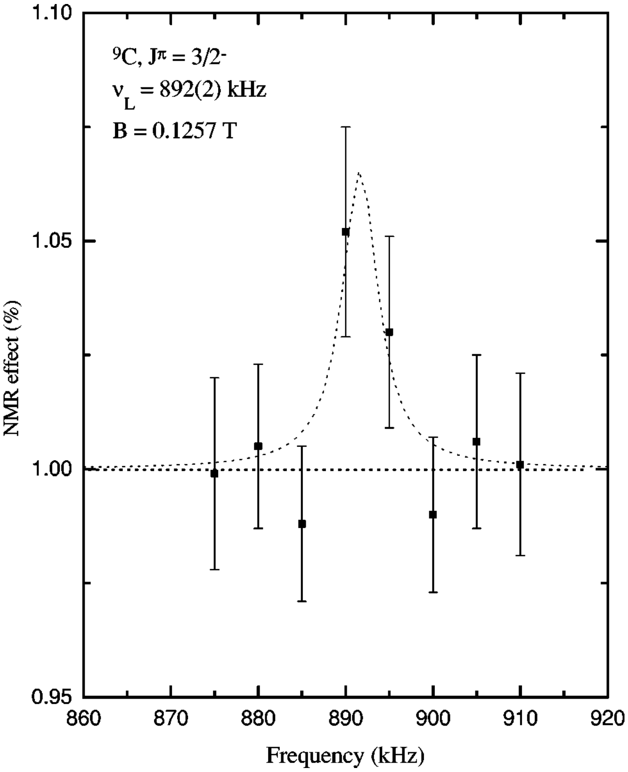

FIG. 1. Resonance curve obtained for ^{9}C. The frequency modulation for each point is ± 10 kHz of the central frequency using a triangle wave form with a 500 Hz repetition rate.

alternating magnetic field of ≈ 0.4 mT perpendicular to the applied field of the dipole magnet. Further details of the β-NMR system are given in Ref. [10].

The resonance curve obtained for ^{9}C is shown in Fig. 1. The data were collected using the multiple adiabatic fast passage technique with continuous beam implantation [10]. In this method, the fragments of interest are continuously implanted while a frequency-modulated (± 10 kHz) RF signal is applied to the sample. A reference signal is collected in a succeeding run with no RF signal applied to the sample. This acquisition method allows for a 100% duty cycle, which is crucial in low count rate experiments such as the one described here, during which the ^{9}C implantation rate was only 2 ions/s.

The data were fitted using a Lorentzian peak shape with a peak centroid of 892(2) kHz and a width of 5 kHz. Using the relation $h\nu_L = g\mu_N B$, where ν_L is the Larmor frequency, $B = 0.1257$ T and $J = 3/2$, we obtained a value of $1.396(3)\mu_N$ for the ^{9}C ground state magnetic dipole moment. The corrections for diamagnetic shielding and the Knight shift for the carbon in platinum system, given in Ref. [1], are smaller than the statistical error in our value for the magnetic moment of ^{9}C. Therefore, these corrections have only been included in the overall error.

Our new measurement is in reasonable agreement with the previous value [1] of $(-)1.3914(5)\mu_N$ for the magnetic dipole moment of ^{9}C, once again suggesting the unique character of this nucleus. Several theoretical studies have recently appeared in the literature that attempted to describe the quenched magnetic moment of ^{9}C and the large deviation of $\langle\sigma\rangle$ for the ^{9}Li-^{9}C mirror partners from the experimental trend established for $T = 1/2$ nuclides. Varga, Suzuki, and Tanihata [11] have used a four-cluster structure for ^{9}Li ($\alpha + {}^3$H$+n+n$) and ^{9}C ($\alpha + {}^3$He$+p+p$) in a microscopic formalism which includes two- and three-cluster arrangements as well in an attempt to describe the small ^{9}C magnetic moment. Although these calculations result in ^{9}C and ^{9}Li systems that are slightly underbound with respect to experiment, the predicted ground state magnetic moment of $+3.43\mu_N$ for ^{9}Li agrees well with the experimental value. The calculated magnetic dipole moment of ^{9}C in the four-cluster model is $-1.50\mu_N$, resulting in the value of $\langle\sigma\rangle = 1.13$ for the ^{9}Li-^{9}C mirror pair, which is smaller than the $\langle\sigma\rangle = 1.44$ observed experimentally.

Kanada-En'yo and Horiuchi have employed an antisymmetrized molecular dynamics approach (AMD) to systematically study the structure and properties of light unstable nuclei, including ^{9}Li and ^{9}C [12]. The calculated ground state moments of ^{9}C and ^{9}Li are -1.53 and $3.44\mu_N$, respectively, in this model which also results in a small value of $\langle\sigma\rangle = 1.08$ as compared to the experimental value of 1.44. In these AMD calculations, the ground state magnetic moments for ^{9}Li and ^{9}C are quite sensitive to the strength of the spin-orbit force, which has the effect of breaking the pairing of nucleon spins. This in turn results in a nonzero contribution of the intrinsic spin of protons and neutrons to the calculated magnetic moments of ^{9}C and ^{9}Li, respectively. Although the strength of the AMD wave functions lies in the independence from effective charges and effective gyromagnetic ratios, a systematic treatment of the carbon isotopes was unable to reproduce the lowest positive parity states of ^{13}C and ^{15}C.

We have performed shell model calculations for ^{9}Li and ^{9}C in an attempt to reproduce the quenched g factor of ^{9}C and the large $\langle\sigma\rangle$ extracted for the ^{9}Li-^{9}C $T = 3/2$ mirror pair. The PTBME interaction of Julies, Richter, and Brown [13], which includes a mass dependence for the two-body matrix elements, was chosen as it reproduces well the level energies and static electromagnetic moments of $0p$-shell nuclides. We employed the simpler, bare g-factors for calculating the magnetic dipole moments of the ^{9}Li-^{9}C and ^{13}B-^{13}O mirror pairs as the results with effective g factors were only slightly different from those derived with the bare nucleon values. The results of the shell model calculations are compared with the experimental magnetic moments in Table I. The present calculations reproduce the experimental magnetic moments and $\langle\sigma\rangle$ for the $A = 13$, $T = 3/2$ mirror partners. The calculated magnetic dipole moment of $-1.44\mu_N$ for ^{9}C contains a significant contribution from the proton intrinsic spin, suggesting a breaking of paired proton spins as was observed in the AMD calculations [12]. The derived value of $\langle\sigma\rangle = 1.09$ for the $A = 9$, $T = 3/2$ partners, although greater than unity, is still well below the experimental value of $\langle\sigma\rangle = 1.44$.

To explore further the large value of $\langle\sigma\rangle$ for the ^{9}Li-^{9}C mirror pair, we extended the shell model calculations described above to include the isospin-nonconserving (INC) processes outlined by Ormand and Brown [14]. The Coulomb interaction should play a significant role in the low-energy structure of loosely bound nuclei near the proton drip-line, and it is important to consider isospin mixing in these systems.

The INC interaction of Ormand and Brown is composed of several parts: (1) the isovector single-particle energies for

TABLE I. The magnetic dipole moments (in units of μ_N) for $T=3/2$ mirror pairs.

Nuclide	Experiment	Shell model PTBME+INC	Shell model PTBME	Extreme S.P.	Cluster model	AMD
^{9}C	$(-)1.3914(5)$[a]	-1.411	-1.437	-1.91	-1.50	-1.53
^{9}Li	$+3.4391(6)$[b]	$+3.360$	$+3.350$	$+3.79$	$+3.43$	$+3.44$
$\langle\sigma\rangle$	1.44	1.18	1.09	1.00	1.13	1.08
^{13}O	$(-)1.3891(3)$[c]	-1.355	-1.355	-1.91	—	—
^{13}B	$+3.1771(5)$[d]	$+3.126$	$+3.124$	$+3.79$	—	—
$\langle\sigma\rangle$	0.76	0.71	0.71	1.00	—	—

[a]From Ref. [2].
[b]From Ref. [5].
[c]From Ref. [1].
[d]From Ref. [4].

the $p_{1/2}$ and $p_{3/2}$ orbitals (two parameters), (2) the Coulomb matrix elements calculated with harmonic-oscillator radial wave functions are scaled by one overall strength parameter, (3) an isovector contribution to the strong interaction which is scaled to the isospin-conserving matrix elements by one parameter, and (4) an isotensor contribution to the strong interaction which is scaled to the isospin-conserving matrix elements by one parameter. The strengths associated with these five parameters are detemined by a least squares fit to 15 b coefficients and 7 c coefficients of the IMME for p-shell configurations in the mass region $A=9-15$, which includes the binding energy data for the $A=9$ $T=3/2$ states studied in this experiment. Although the Coulomb interaction is scaled by a parameter, its value is within a few percent of that expected for the Coulomb interaction between protons. The isovector interaction (-4.2 percent of the isospin-conserving interaction) is required in order to understand the well-known Nolen-Schiffer anomaly for the mirror displacement energies (the b coefficients). The resulting fit reproduces the experimental b coefficients to within 70 keV (rms) and the experimental c coefficients to within 13 keV (rms).

The INC wave functions are obtained in proton-neutron formalism and used to calculate the magnetic moments of the states of interest. For the $A=9$ $T=3/2$ states, the INC interaction allows mixing with the $T=5/2$ states at higher energy. The isospin for the $A=13$ $T=3/2$ states is the highest allowed within the p shell and thus they remain pure in isospin. We have investigated the importance of the four different terms discussed above. Of these the isovector interaction (3), gives the largest change in the $\langle\sigma\rangle$ value.

The results of the calculations employing the PTBME interaction and INC interactions are given in Table I. The present calculations result in a $\langle\sigma\rangle$ value of 1.18 for the ^{9}C-^{9}Li $T=3/2$ mirror pair. Although we have demonstrated that the INC is important for the interpretation of mirror moments, the present calculations do not give the full effect observed experimentally ($\langle\sigma\rangle=1.44$), but they go in the right direction. The effect is actually very small as can be observed by the change in values for the individual magnetic moments in Table I. It is only when the isoscalar magnetic moment is used to obtain the $\langle\sigma\rangle$ value, $\langle\sigma\rangle=\{[\mu(T_z=3/2)+\mu(T_z=-3/2)]-J\}/0.38$, that the effect becomes magnified.

The theoretical magnetic moments given in Table I were obtained with harmonic-oscillator radial wave functions. It is possible to use more realistic Woods-Saxon or Hartree-Fock radial wave functions. However, they do not significantly change the result because the matrix element is diagonal and because the magnetic moment operator has no radial dependence. (There is a larger effect on the Gamow-Teller beta decay matrix elements because it involves the off-diagonal overlap between proton and neutron radial wave functions.)

The Coulomb contribution to the INC is also calculated with harmonic-oscillator radial wave functions, and we note that the present INC interaction is mainly determined from the rather tightly bound nuclei in the upper p shell where the harmonic-oscillator approximation may not be so bad. However, the use of harmonic-oscillator radial wave functions for the Coulomb matrix elements of the more loosely bound light p-shell nuclei (including ^{9}C) may not be so good, and this may be a source of isospin asymmetry beyond the present model.

In summary, we have remeasured the ground state magnetic moment of the proton drip-line nucleus ^{9}C and have confirmed the anomalous value of this moment. Shell model calculations performed using mass-dependent two-body matrix elements are shown to better reproduce the experimental measurement when isospin-nonconserving interactions are included. This suggests the importance of considering Coulomb interactions which lead to isospin mixing in proton drip-line nuclei. However, these calculations were still unable to reproduce the large value of $\langle\sigma\rangle$ for the ^{9}Li-^{9}C mirror partners, and the isospin-nonconserving interactions should be investigated more carefully in the lower part of the p shell. Extending substantially the present shell model calculations by calculating the Coulomb contribution using more realistic wave functions may result in a better understanding of the unusual ground state magnetic moment for the proton drip-line nucleus ^{9}C.

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