Magnetic Moment of the 1^- Ground State in ^{18}N Measured with a New β Level Mixing Nuclear Magnetic Resonance Technique

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The ^{18}N ground state magnetic moment $|\mu| = 0.135(15)\mu_N$ has been measured using a modified β nuclear magnetic resonance technique. The value is compared to shell-model calculations. Spin-aligned ^{18}N projectile fragments were produced in the fragmentation of ^{22}Ne at 60.3 MeV/nucleon. Polarization of the nuclear spins was resonantly induced by a combined magnetic dipole, electric quadrupole, and radio frequency interaction. This is the first application of a new method that allows production of polarized nuclei from spin-aligned projectile fragments, allowing one to measure β asymmetries. The method opens a new range of applications to study static dipole and quadrupole moments of exotic nuclei near the drip lines. [S0031-9007(98)08259-3]

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Nuclear moments provide a stringent test for nuclear models because, in general, they are extremely sensitive to the single-particle structure of valence particles. Comparison of experimental and theoretical nuclear moments can allow refinement of the interaction parameters [1] and provides a test of the models [2]. It becomes especially interesting if one can test nuclear theories close to the drip lines where the single-particle structure is not well established. Since the development of intermediate energy accelerators, followed by in-flight high-resolution recoil spectrometers [3,4], it has become possible to produce exotic nuclei in very clean conditions and in sufficient amounts to allow nuclear moment measurements. Moments of β-decaying ground states are measured via the asymmetric emission pattern of the decay electrons (positrons). e^+/e^- emission is asymmetric with respect to the nuclear spin direction, due to parity violation in the β decay. However, to obtain asymmetric β decay, the ensemble of the desired nuclei needs to be spin polarized (differently populated $|+m\rangle$ and $|-m\rangle$ quantum states, $m = \langle I_z\rangle$). Producing spin-polarized nuclei has been a challenging experimental problem. Several techniques have been developed to polarize short-lived ($\mu s < \tau < s$) β-unstable nuclei after the production process, such as tilted foil polarization [5,6] or optical pumping [7,8]. When exotic nuclei are produced in a projectile fragmentation reaction, spin polarization can be obtained by the reaction itself, provided recoil fragments are selected at a nonzero angle with respect to the primary beam [9]. On the other hand, selecting projectile fragments in the forward direction is much more straightforward, especially at high beam energies where much higher yields are obtained at forward angles. Fragments emitted parallel to the primary beam direction are not spin polarized, but spin aligned (equal population of $|+m\rangle$ and $|-m\rangle$ levels) [10]. In that case, a β-asymmetry measurement is possible only if polarization is induced by the applied hyperfine interactions. This procedure requires interactions that break the up-down symmetry in the quantum system.

To measure the magnetic and quadrupole moment of β-decaying projectile fragments, we apply in this work for the first time a method [11,12] which induces spin polarization starting from a spin-aligned ensemble of forward selected fragment nuclei. The breaking of the symmetry is obtained by applying noncollinear static magnetic dipole and electric quadrupole interactions. The interaction with a static magnetic field allows the determination of the magnetic moment ($\nu_B = g\mu_N B/h$), while the interaction with an electric field gradient induced by a crystal lattice allows the determination of the quadrupole moment ($\nu_Q = eQV_{zz}/h$, for nuclei with $I \geq 1$). At certain values of the static magnetic field, polarization is induced due to the mixing of two hyperfine levels ($|m\rangle$ quantum states). A resonant onset of β asymmetry as a function of the magnetic field is measured, from which the ratio of the magnetic to quadrupole moment of the nuclei can be derived. This technique is known as the "level mixing resonance" (β-LMR) technique and is described extensively in Refs. [11] and [13]. By combining this method with a *modified* "nuclear magnetic resonance" (β-NMR) technique [14,15], both the magnetic moment and the ratio of the quadrupole to magnetic moments can be derived independently in one experiment. This new combined method has been applied to neutron-rich ^{18}N [$I^{\pi} = 1^-$, $Q_{\beta} = 9.4(4)$ MeV, $T_{1/2} = 624(12)$ ms [16]] projectile fragments. We report on the very small magnetic moment of ^{18}N and compare our result to shell-model calculations.

^{18}N nuclei were produced in the fragmentation of a ^{22}Ne beam (60.3 MeV/nucleon) by a ^{12}C foil (349.5 mg/cm^2). A fixed target was mounted in the target chamber in front of the LISE III spectrometer at GANIL [17]. The selection of ^{18}N fragments (at a recoil angle of 0°) was optimized by using an achromatic wedge of ^{9}Be (102.1 mg/cm^2) in the intermediate focal plane and a Wien-filter behind the spectrometer. A nearly pure secondary beam with 94% ^{18}N, 5.5% ^{20}O, and 0.5% ^{16}C was identified by means of time-of-flight versus energy-loss spectra [18]. The secondary nuclei were submitted to two noncollinear static interactions (electric quadrupole and magnetic dipole), in order to obtain a nonequidistant splitting of the m states (Fig. 1a). The electric field gradient for the quadrupole interaction is provided by stopping the fragments in a Mg single crystal. The crystal was mounted on the cold finger of a continuous flow cryostat, allowing the crystal temperature to be varied between 5 and 300 to ± 0.1 K. Our experiment was performed at $T = 40.0(5)$ K in order to reduce the influence of spin-lattice relaxation [19,20]. A vertically oriented static magnetic field was induced by two coils mounted around the vacuum chamber. To measure the magnetic moment using the modified NMR technique, a radio frequency (rf) field with constant frequency $\nu_{\mathrm{RF}} =$ 20 kHz was applied perpendicular to the static magnetic field. This rf field induces transitions between m-quantum states of the ^{18}N ground state at magnetic fields where the rf frequency matches the level splitting (Fig. 1c). The rf frequency was modulated over ± 3 kHz at a ramp frequency of 100 Hz, in order to assure a broad enough resonance as a function of B. Two β telescopes were placed at 0° (UP) and 180° (DOWN) with respect to the static magnetic field, to measure the asymmetry in the β decay (As $= N_{\mathrm{UP}}/N_{\mathrm{DOWN}} - 1$). Each telescope consisted of 1 and 5 mm thick NE102A plastic scintillators, 3×3 cm^2, covering a solid angle of 2.5% of 4π each. Using a thin and a thick detector in coincidence allows reduction of background γ radiation and scattered β radiation in the recorded spectra. To verify the purity of the β detection, we measured the β-decay intensity as a function of time, using a pulsed beam ($T_{\mathrm{on}} = 1$ s and $T_{\mathrm{off}} = 3$ s). The fitted β-decay half-life $T_{1/2} =$ 633(4) ms is in good agreement with the value given in Ref. [16]. No beam pulsing was applied during the measurement of the β asymmetry as a function of the external magnetic field. In a first scan of the field range, the rf field was off, giving rise to a pure level mixing resonance (Fig. 1b) as measured before [20]. In this experiment, however, we oriented the crystal with a small tilt angle ($\beta \approx 1°$) between the c axis and the static magnetic field, in order to induce a very sharp LMR. During a second scan the rf field was on, resulting in a combined LMR-NMR curve. To visualize clearly the influence of the rf signal, we subtracted the pure LMR curve (scan 1) from the combined LMR-NMR (scan 2), giving rise to Fig. 1d. The two resonances that appear can be understood as NMR transitions induced by the modulated rf field. The NMR resonance condition $|E_0 - E_{-1}| = h\nu_{\mathrm{RF}}$ [14] is fulfilled for two static fields B^1_{NMR} and B^2_{NMR} (Fig. 1c) positioned symmetrically around the previously measured level mixing field.

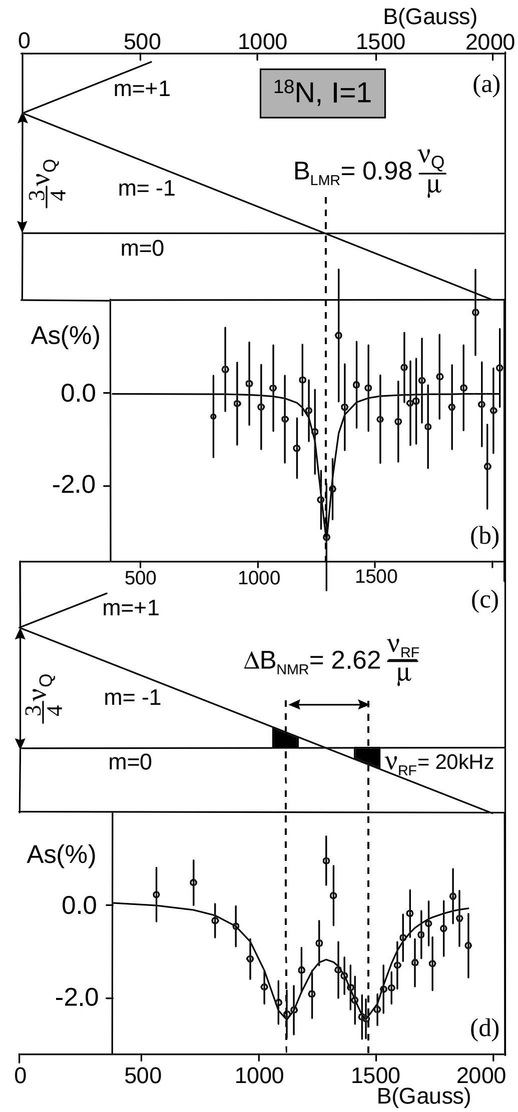

FIG. 1. (a) Hyperfine levels as a function of magnetic field strength B for a nucleus with spin 1, submitted to a combined quadrupole and magnetic dipole interaction. (b) LMR curve for ^{18}N, showing the resonantly induced spin polarization. The resonance field is proportional to the nuclear moment ratio Q/μ. (c) Similar to (a), but with additional rf field, matching level splitting of the $m = 0$ and $m = -1$ quantum states at two NMR resonance fields. (d) Resonances due to the rf field, from which μ can be derived.

The spectra resulting from taking the difference between the pure LMR curve and the combined LMR-NMR scan were fitted to a calculated spectrum that takes into account the LMR and rf interactions. The fit yields directly the magnetic moment $|\mu(^{18}\mathrm{N})| = 0.135(15)\mu_N$. An advantage of measuring a transfer of initial alignment into polarization is the sensitivity of the measurement to the sign of the product $A_1 A \frac{QV_{zz}}{\mu}$. This procedure allows us to derive the sign of the nuclear moment ratio if the sign of the asymmetry parameter A_1, the electric field gradient V_{zz}, and the initial alignment A are known [11,20]. Both theory and experiment confirm a negative sign for the electric field gradient V_{zz} [21]. The asymmetry parameter is calculated to be positive [20] and, based on experimental results for other fragment beams, a positive sign for the alignment is assumed [10,22]. From the measured LMR (Figs. 1a and 1b), we derive the ratio of the quadrupole interaction frequency to magnetic moment with very high precision: $\nu_Q/\mu(^{18}\mathrm{N}Mg) = +1311(7)\ \mathrm{kHz}/\mu_N$, in agreement with our previous result [20]. Using our magnetic moment as derived from the NMR resonances (adopting a negative sign based on theory), we obtain the quadrupole interaction frequency for $^{18}\mathrm{N}(\mathrm{Mg}, T = 40\ \mathrm{K})$: $\nu_Q = -177(20)$ kHz. We measured the electric field gradient at 40 K to be $V_{zz} = -2.68(25) \times 10^{16}\ \mathrm{V/cm}^2$ [23], resulting in a quadrupole moment $Q(^{18}\mathrm{N}, 1^-) = +27(4)$ mb.

Note that the static moments of the ^{18}N ground state have also been measured recently by Ogawa *et al.* at RIKEN, and were published in a conference proceedings [24]. The values for the quadrupole frequency and magnetic moment reported there yield a ratio $\nu_Q/\mu = 223\ \mathrm{kHz}/\mu_N$, which is 6 times smaller than the ratio we derive from the LMR resonance position, seen in three independent LMR measurements ([20] and this work). While the quadrupole resonance measured by Ogawa *et al.* looks very convincing, the technique used to observe the resonance is not straightforward. When subjected to a combined quadrupole and magnetic interaction, this $I = 1$ system has an energy spacing $E_{\pm 1} - E_0 = |h(\nu_B \pm \frac{3}{4}\nu_Q)|$ [12] between the $m = 0$ and $m = \pm 1$ levels. In Ref. [24], two rf frequencies fulfilling the above relation are applied simultaneously to induce these resonant transitions. Note that this approach assumes knowledge of the Larmor frequency ν_B and thus of the magnetic moment. If the Larmor frequency were not properly chosen, it could happen that only one of the applied rf frequencies actually overlaps the resonance and the extraction of ν_Q would consequently be in error. On the other hand, if we use our ratio of ν_Q/μ which we determined very precisely from our LMR resonance, it is possible to deduce the magnetic and quadrupole moment from their applied NQR resonance frequencies ($\nu_{\mathrm{RF}} = 245$ and 355 kHz) at the external field $B_0 = 120.4$ mT [25]. For the lowest frequency, we find a magnetic moment $\mu(\mathrm{Ogawa}) = 0.13\mu_N$ and a quadrupole frequency $\nu_Q(\mathrm{Ogawa}) = 168$ kHz, in good agreement with the values which we derive from our data, and in agreement with the explanation presented above for the discrepancy in the results of the two experiments.

In this work, we focus on the shell-model interpretation of the magnetic moment and its implication on the understanding of structural changes in the neutron-rich N isotopes with $N \geq 8$. Magnetic moments have been calculated in the *psd* model space where the protons are in the $0p$ $(0p_{3/2}, 0p_{1/2})$ shell, and neutrons are in the sd $(0d_{5/2}, 1s_{1/2}, 0d_{3/2})$ shell. The configurations are calculated and discussed relative to a closed-shell $[\pi(0p)^6, \nu(0p)^6]$ configuration for ^{16}O. Calculations were performed with the two effective Hamiltonians (WBP and WBT) obtained in Ref. [26]. Both Hamiltonians use the Wildenthal (USD) two-body matrix elements [2] for the neutron-neutron sd-shell interaction. The proton-proton and proton-neutron interactions were obtained by fitting linear combinations of two-body matrix elements (WBT) or two-body potential strengths (WBP) to the binding and excitation energies of nuclei in the mass region $A = 10-22$ [26].

Both WBP and WBT calculations predict 2^- ground states for ^{16}N and ^{18}N. Experimentally, the ground state of ^{18}N is established as $I^\pi = 1^-$ [16], and theoretically this level occurs at very low excitation energy [16,26]. The dominant component of the $^{18}\mathrm{N}(1^-)$ wave function is $[\pi(p_{1/2})^{-1}] \times [\nu(sd)^3, \frac{3}{2}^+]$, while $^{16}\mathrm{N}(1^-)$ has a rather pure $[\pi(p_{1/2})^{-1}] \times [\nu(s_{1/2})^1]$ configuration. The presence of three neutrons in the $^{18}\mathrm{N}$ $[\nu(sd)^3, \frac{3}{2}^+]$ configuration lowers this 1^- level with respect to the configuration with a $[\nu(s_{1/2})^1]$ component, due to the favored energy of the seniority-three configuration $[\nu(d_{5/2})^3, \frac{3}{2}^+]$. A similar level is found in ^{19}O, the $N = 11$ isotone of ^{18}N, where this $\frac{3}{2}^+$ state occurs experimentally at an excitation energy of 96 keV.

By comparing the experimental and theoretical magnetic moments for the 1^- states in ^{16}N and ^{18}N, one can confirm the configuration change of the lowest 1^- levels. A summary of the calculated and experimental moments is given in Table I. Because the configurations are rather pure (dominant component $> 90\%$), it is possible to calculate the weak-coupled magnetic moments (see Ref. [27]) in terms of those for the individual proton and neutron configurations. Using the theoretical moments for ^{15}N and ^{19}O, the weak-coupling value for the ^{18}N ground state is $\mu_{w,psd}(1^-) = -0.696$. If the experimentally obtained moments for ^{15}N and ^{19}O are used, the value reduces to $\mu_{w,\mathrm{exp}}(1^-) = -0.46(7)$. The full *psd* shell-model calculation with free-nucleon g factors results in a magnetic moment $\mu = -0.119$ with WBT and -0.275 with WBP, to be compared to the present experimental value of $|\mu_{\mathrm{exp}}| = 0.135(15)\mu_N$. The decrease of the magnetic moment between the full values and the weak-coupled value is due to additional terms coming from the interference of the main component with the smaller components involving the $p_{3/2}$ orbital. Comparison of the two values -0.119 (WBT) and -0.275 (WBP) gives an

TABLE I. Calculated and experimental [29,30] magnetic moments of light nuclei. Shell-model calculations are performed in a *psd* shell-model space, using the WBP and WBT effective Hamiltonians. In addition to the full model space results (WBT and WBP), we also give for ^{18}N the pure weak-coupling results obtained with individual *psd* model-space moments (w, psd) and with individual experimental moments $(w, \exp)$.

State	Main configuration	$\mu_{\text{theory}}(\mu_N)$	$\mu_{\exp}(\mu_N)$
^{15}N $\frac{1}{2}^-$	$\pi(p_{1/2})^{-1}$	−0.264	−0.283
^{19}O $\frac{3}{2}^+$	$\nu(sd)^3$	−0.994 (WBP)	−0.72(9)
^{18}N 1_1^-	$[\pi(p_{1/2})^{-1}] \times [\nu(sd)^3\ \frac{3}{2}^+]$	−0.696 (w, psd)	±0.135(15)
		−0.46 $(w, \exp)$	
		−0.275 (WBP)	
		−0.119 (WBT)	
^{18}N 1_2^-	$[\pi(p_{1/2})^{-1}] \times [\nu(sd)^3\ \frac{1}{2}^+]$	−1.90 (WBP)	
^{16}N 1_1^-	$[\pi(p_{1/2})^{-1}] \times [\nu(s_{1/2})^1]$	−2.18 (WBP)	−1.83(13)

indication of the size of the theoretical uncertainty associated with the present *psd* model space Hamiltonians. In contrast, the moment obtained for the configuration of the ^{16}N 1^- state has a much larger value of -2.18 (WBP) and -2.16 (WBT), which are in fair agreement with the experimental value of $\mu(^{16}\text{N}, 1^-) = -1.83(13)\mu_N$. The magnetic moments obtained with effective g factors [2,28] differ from these free-nucleon values by ± 0.10 or less, but the quantitative result depends upon how the effective operator is parametrized, and this will remain the subject for a more detailed analysis.

Thus, we find that the lowest 1^- states in ^{16}N and ^{18}N have very different structures and magnetic moments. The small value obtained experimentally for the ^{18}N magnetic moment nicely confirms this structural change and is in quantitative agreement with the range of theoretical values. On the other hand, theoretical calculations of the quadrupole moment in this model space, calculated with harmonic-oscillator radial wave functions and effective charges of $e_p = 1.3$ and $e_n = 0.4$, give $Q_{\text{theory}} = +18$ mb (WBP) and $+15$ mb (WBT). The effective charges were chosen to reproduce the experimental quadrupole moments of ^{13}B (a pure proton configuration) and ^{17}O (a pure neutron configuration). The theoretical values are considerably smaller than the present experimental result of $+27(4)$ mb, suggesting the need for more refinement in the shell-model predictions for nuclei away from the line of stability.

In conclusion, we have demonstrated that the nuclear magnetic and quadrupole moments provide very sensitive tools to improve our understanding of the structure of nuclei. The new method that has been applied to study the magnetic moment of spin-aligned projectile fragments opens new possibilities to study moments (both dipole and quadrupole) of nuclei near the drip lines produced in fragmentation reactions. Especially for the study of ground state moments (via the asymmetry in the β decay), the method is unique because no initial polarization is needed. Forward scattered spin-aligned fragments (with highest yield) can be used, because spin polarization is induced by the combined level mixing and rf interactions.

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