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Nuclear magnetic moment of ^{19}Ne with possible applications to other radioactive gas isotopes

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We have observed narrow nuclear magnetic resonances in polarized ^{19}Ne stored for several seconds in a Formvar cell. The nuclear polarization is monitored by observing the β-decay asymmetry while the atoms are subjected to an rf driving field. Due to the long observation times and motional averaging, narrow resonance widths are observed. Using this technique we find $\mu(^{19}\mathrm{Ne}) = -1.885\,42(8)\mu_N$. Possible application to other radioactive noble gas isotopes is discussed.

[NUCLEAR STRUCTURE ^{19}Ne; measured μ. Observed motional averaging. Magnetic field stabilizer.]

Measurements of the magnetic moments of radioactive rare gas nuclei pose special problems. Low densities preclude the use of conventional absorption nuclear magnetic resonance (NMR) techniques. Standard atomic beam magnetic resonance methods are of no avail since the ground state electronic spin is zero. In the case of ^{37}Ar, this problem was circumvented by measuring the hyperfine structure of excited atomic states with high resolution optical spectroscopy. However, the precision of this method is limited. (The value obtained is $0.95 \pm 0.20\mu_N$.[1]) Following the discovery of parity violation, Connor measured the magnetic moment of ^{8}Li using the β asymmetry to monitor polarization in an NMR experiment.[2] Dobson and Commins later used the β asymmetry technique to measure the magnetic moment of the rare gas atom ^{19}Ne.[3] In their experiment, nuclear magnetic resonance transitions were induced on a polarized beam of ^{19}Ne; the beam atoms were captured downstream in a cell where their β asymmetry was observed. Since then, the β-asymmetry method has also been used to measure magnetic moments of many other atoms in solids.[4–9]

We have extended the β-asymmetry technique of Dobson and Commins to remeasure the magnetic moment of ^{19}Ne. As in their experiment, ^{19}Ne atoms are polarized by the atomic beam method and are captured in a cell for several seconds. In our experiment, the NMR transitions are induced on the atoms stored in the cell while they induced transitions on atoms in flight. The long sitting time in the cell produces much narrower linewidths than achieved in the previous beam experiment. Dobson and Commins obtained a linewidth of ~20 kHz whereas we have obtained linewidths of ~75 Hz.

An SF_6 target is bombarded with 12 MeV protons from the Princeton cyclotron to produce ^{19}Ne through the reaction $^{19}\mathrm{F}(p,n)^{19}\mathrm{Ne}$. The gas handling system and atomic beam apparatus are illustrated schematically in Fig. 1 and are described in greater detail in Ref. 10. The SF_6 carries the ^{19}Ne to a liquid nitrogen cold trap where the SF_6 freezes out. The ^{19}Ne passes through the trap and is then pumped into the atomic beam source cavity which is maintained at ~37 K by a helium refrigerator. After the ^{19}Ne exists through the source slit, the two polarization states are spatially separated in a "Stern-Gerlach" magnet. A movable slit in the center of the magnet is used to select either of the ^{19}Ne spin states. Polarizations approaching 100% are achieved. Between the spin selection magnet and the experimental area is a small buffer

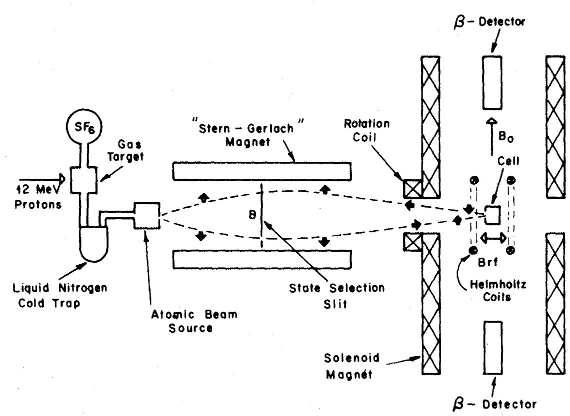

FIG. 1. Schematic diagram of the atomic beams machine. The atomic beam is defined by the source exit slit, the state selection slit, and the cell entrance channel. The rotation coil maintains a smooth transition field between the "Stern-Gerlach" magnet fringing field and the interior solenoid field B_0. B_0 transports the β's from the cell to one of the detectors. B_{rf} is generated by a Hewlett-Packard model 3325A frequency synthesizer and a small amplifier driving the Helmholtz coils.

chamber with a 10.2 cm diffusion pump and a liquid nitrogen cold finger.

Polarized ^{19}Ne enters the cell through a glass capillary array entrance aperture. The ability to maintain polarization in the cell does not depend critically on the cell construction materials. Delrin, Lucite, Mylar, Kapton, Formvar, and glass have all been used successfully. The results described here were obtained using a cell made of a quartz fiber frame supporting thin Formvar walls. The cell volume is 32 cm^3, the sitting time is $\sim$2.5 s, and the relaxation time for polarization is $\gtrsim$20 s.

The ^{19}Ne decays by the process $^{19}\mathrm{Ne} \rightarrow {}^{19}\mathrm{F} + e^+ + \nu_e$. The storage cell is located at the center of a large solenoid which produces a uniform magnetic field $B_0 \approx 1400$ G. This field transports the positrons to two plastic scintillator detectors located at the ends of the solenoid. The orbit diameter of the positrons is less than the inner radius of the solenoid so that virtually all of the positrons are detected. The magnetic field B_0 in the cell region is measured before and after taking asymmetry data using a proton NMR magnetometer. The field is stabilized between NMR measurements by a feedback system with a Rawson-Lush 944 rotating coil gaussmeter as the sensing device (see Fig. 2). The observed stability for $B_0 = 1400$ G is $\pm$0.02 G over a period of several days. A 10 cm radius Helmholtz coil pair provides a uniform rf driving field B_{rf} throughout the cell. rf field strengths range from 1.5 to 30 mG.

The count rates in the two detectors are combined to compute an observed asymmetry Δ defined by $\Delta = (N_1 - N_2)/(N_1 + N_2)$ where N_i is the number of counts in detector i. Any effects which are not correlated with the polarization are removed by reversing the incident ^{19}Ne polarization periodically.

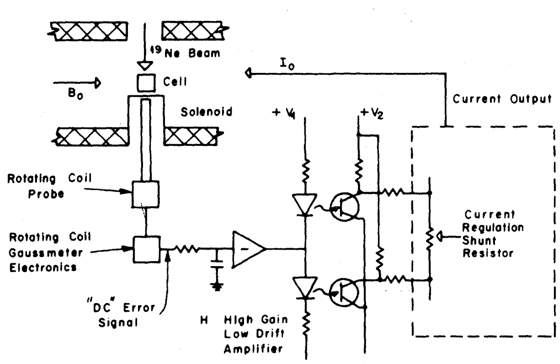

FIG. 2. Feedback system to stabilize B_0. The Rawson-Lush 944 rotating coil Gaussmeter is nulled after the desired B_0 field is set. Then the loop is closed and any change from the null position is compensated for by the feedback network. The amplifier is built around an Analog Devices AD-52K opamp and the optical isolators are Fairchild model FCD-810. The overall loop gain is $\sim$100.

With an angular distribution of the form $\omega(\theta) = 1 + AP\hat{J} \cdot \vec{v}/c$, the polarization P is related to Δ by $\Delta = AP\langle v/c \rangle G$. Here A is the β-asymmetry parameter, v is the velocity of the positron, and G is a factor dependent on detector geometry. In our case, $A \approx -0.04$, $\langle v/c \rangle = 0.92$, and $G \approx 0.5$.

Figure 3 shows the resonance curves obtained at three different rf field strengths. The results are summarized in Table I. After correcting for diamagnetic effects and for the difference between B_0 as measured at the center of the cell and the average of B_0 over the cell we get the result that $\mu(^{19}\mathrm{Ne}) = -1.885\,42(8)\mu_N$. This is in reasonable agreement with the previous value of $\mu(^{19}\mathrm{Ne}) = -1.887(1)\mu_N$,[3] and has a significantly smaller uncertainty. Instabilities in B_0 and uncertainties in the uniformity of B_0, rather than the linewidth, limit the accuracy of our measurement of the magnetic moment.

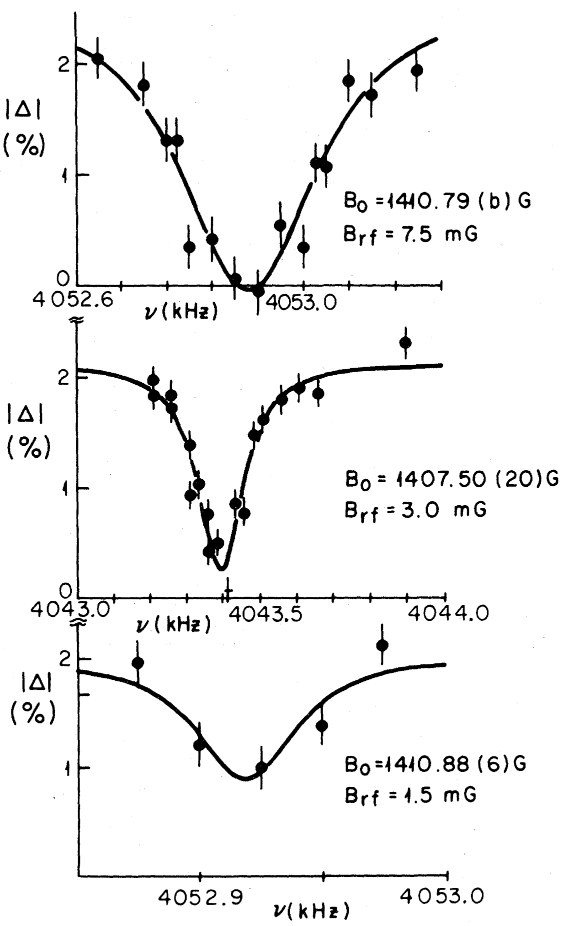

FIG. 3. Resonance lines at several rf field strengths. The 3 mG line was measured without the field stabilizer described in the text. The solid curves represent least squares fits to the data of the four parameter function $\Delta = \Delta_0 + a/[(\nu - \nu_0)^2 + \Gamma^2/4]$. The parameter Δ_0 is constrained to 2.0% in fitting the 1.5 mG data.

TABLE I. Tabulation of results and corrections. Calculations are based on the expression $\mu = (\hbar/2\mu_N)2\pi\nu_0/B_0(1-\sigma)$, where σ is the diamagnetic correction factor; σ (proton in mineral oil) $= 2.78\times10^{-5}$ (Ref. 18); $\sigma(\text{Ne}) = 5.693\times10^{-4}$ (Ref. 22); μ (proton) $= 2.792\,845\,6(11)\mu_N$ (Ref. 23); $\mu_N = 5.050\,824(20)\times10^{-24}$ ergs/G (Ref. 23); $\hbar = 1.054\,588\,7(57)\times10^{-27}$ ergs s (Ref. 23).

	rf field (mG)		
	7.5	3	1.5
ν_0 (proton) (kHz)	6006.90(20)	5992.96(50)	6007.29(20)
B_0 (G)	1410.87(5)	1407.59(12)	1410.96(5)
Corrected B_0 (G)[a]	1410.79(7)	1407.51(13)	1410.88(7)
$\nu_0(^{19}\text{Ne})$ (kHz)[b]	4052.880(7)	4043.396(3)	4052.922(3)
$\mu(^{19}\text{Ne})$ (μ_N)	1.885 47(9)	1.885 44(17)	1.885 37(9)

[a] B_0 is corrected by $-0.08(4)$ G to account for the difference between B_0 measured at the center of the cell and B_0 over the whole cell.
[b] Specified uncertainties in the figures are one standard deviation in the fit to the resonance data.

The rms magnetic field variation (in B_0) over the volume of the cell is measured to be ~0.2 G. This corresponds to a uniformity limited linewidth of 600 Hz. All of the observed resonance lines are narrower than this due to motional averaging of B_0. In our experiment the transit time for atoms to cross the cell is ~50 μs whereas the spin flipping time at $B_{rf} = 1.5$ mG is 0.1 s. Thus an atom makes ~2000 traversals of the cell during a single spin flip and thereby averages the field very effectively. As B_{rf} is decreased, the flipping time increases and the averaging becomes more complete, as shown in Fig. 3.

Motional narrowing was observed by Bloembergen *et al.* in 1948.[11] Anderson[12] and Kubo[13] and, more recently, Watanabe *et al.*[14–16] and Sykes[17] have discussed theoretical models for this narrowing. Resonance lines narrower than one would expect from field inhomogeneities have also been observed using the Ramsey separated field technique in an atomic beam[18,19] and in experiments on optically pumped rubidium vapor.[20]

The solenoid magnet used in this experiment was not specifically designed for good homogeneity and stability. A more uniform and stable magnetic field (B_0) will facilitate the observation of narrower resonance lines. A much more accurate magnetic moment measurement can be obtained if B_0 is measured more accurately. Work is currently proceeding on a uniform field shielded solenoid and an optical pumping magnetometer which will increase the accuracy of this experiment.[21]

The β-asymmetry polarization detection methods and related asymmetry methods can be applied to other noble gas isotopes. The polarization of nuclei which decay via electron capture, such as ^{37}Ar, can be observed using the neutrino asymmetry (detected by observing the recoil ion asymmetry using multichannel plate detectors). We are also working on a measurement of ^{133}Xe using the γ anisotropy to detect the alignment. The narrow resonance lines observed may also be useful as a probe for other more exotic effects such as nuclear electric dipole moments.

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