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Dressed spin of ^{3}He

A. Esler,* J. C. Peng, D. Chandler, and D. Howell
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

S. K. Lamoreaux,† C. Y. Liu,‡ and J. R. Torgerson
Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

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We report a measurement of dressed spin effects of polarized ^{3}He atoms from a cold atomic source traversing a region of a constant magnetic field B_0 and a transverse oscillatory dressing field $B_d \cos \omega_d t$. The observed effects are compared with a numerical simulation using the Bloch equation as well as a calculation based on the dressed atom formalism. An application of the dressed spin of ^{3}He for a proposed neutron electric dipole moment measurement is also discussed.

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The existence of a permanent electric dipole moment (EDM) of an elementary particle such as the neutron is direct evidence for time-reversal (T) symmetry breaking, which implies a violation of CP (charge-conjugation and parity) symmetry assuming CPT invariance [1]. Although CP violation is known to occur in neutral K and B meson systems, it has never been found for hadrons consisting of light quarks only, such as the neutron. Therefore, observation of a nonzero neutron EDM would provide qualitatively new information on the origin of CP violation.

The current experimental upper limit of the neutron EDM (d_n), obtained from an experiment [2] using bottled ultracold neutrons (UCNs), is $|d_n| < 2.9 \times 10^{-26}$ e-cm (90% C.L.); see also Ref. [3]. A new experimental search for the neutron EDM has been proposed using UCNs produced and trapped in a bath of superfluid ^{4}He [4,5]. The experiment searches for a shift of the UCN precession frequency due to the interaction of d_n with an applied electric field.

In the proposed neutron EDM experiment, a small concentration of polarized ^{3}He atoms ($X \sim 10^{-10}$) would be introduced into the superfluid to serve as a comagnetometer. The ^{3}He atoms would also function as a highly sensitive spin analyzer because of the large difference between the n-^{3}He absorption with total spin $J = 0$ compared to $J = 1$ [6]. The absorption reaction $n + {}^3\text{He} \rightarrow p + {}^3\text{H}$ releases 764 keV of total kinetic energy. This recoil energy excites short-lived molecules in the superfluid ^{4}He that emit ultraviolet scintillation light [7]. Consequently, the observed rate of scintillations depends on the relative angle between the UCN and ^{3}He spins. In a transverse magnetic field B_0, the UCN and ^{3}He spins will precess at their respective Larmor frequencies: $\omega_n = \gamma_n B_0$ and $\omega_3 = \gamma_3 B_0$, where γ_i is the gyromagnetic ratio of each species. If the ^{3}He and UCN spins are parallel at time $t = 0$, a relative angle between the spins develops over time because the ^{3}He magnetic moment is larger than that of the neutron ($\gamma_3 \approx 1.1\gamma_n$). Therefore, the rate of scintillations observed is modulated at the difference of the two spin precession frequencies:

$$\omega_{\text{rel}} = (\gamma_3 - \gamma_n)B_0 \approx 0.1\gamma_n B_0. \quad (1)$$

In the presence of a static electric field E parallel to B_0, Eq. (1) gains a term proportional to the neutron EDM:

$$\omega_{\text{rel}} = (\gamma_3 - \gamma_n)B_0 + 2d_n E/\hbar. \quad (2)$$

Eq. (2) shows that ω_{rel} depends only on $d_n E$ in the limit of $B_0 \rightarrow 0$. Alternatively, the experimental signal would become independent of B_0 if the condition $\gamma_3 - \gamma_n = 0$ were satisfied. Spurious signals due to inhomogeneity or slow drifts in the magnetic fields would thereby be eliminated. The UCN and ^{3}He magnetic moments can be modified, and in fact equalized, by the dressed spin effect [4,8,9] in which a particle's effective magnetic moment is modified by applying an oscillating magnetic field $B_d \cos \omega_d t$ perpendicular to B_0. In the weak-field limit ($B_0 \ll \omega_d/\gamma$, or $y \ll 1$, where $y \equiv \gamma B_0/\omega_d$), Polonsky and Cohen-Tannoudji [10] showed that the dressed magnetic moment γ_i' is given by

$$\gamma_i' = \gamma_i J_0(x_i), \quad x_i \equiv \gamma_i B_d/\omega_d, \quad (3)$$

where J_0 is the zeroth-order Bessel function of the first kind and x_i is a dimensionless parameter proportional to the dressing field strength. Using this expression, one can solve for the "critical" dressing field magnitude which makes $\gamma_n' = \gamma_3'$. If this critical dressing field is applied, corresponding to $x_3 = 1.32$ [4], the relative precession between the UCN and ^{3}He [Eq. (2)] vanishes except for the contribution from $d_n E$. In addition, modulating the x parameter with a different frequency ω_{m} causes the observed scintillation rate to have a first harmonic term with amplitude proportional to the neutron EDM and the applied electric field [4].

Modification of the neutron magnetic moment using an oscillatory magnetic field has been demonstrated experimentally by Muskat, Dubbers, and Schärpf [11]. Other authors have described work using excited states of mercury or alkali atoms [12], but the effects of rf spin dressing on ^{3}He nuclei have never been reported. In this article we present results of an experiment on polarized ^{3}He that demonstrate changes of the ^{3}He dressed magnetic moment as predicted by Eq. (3)

*asharp@uiuc.edu.
†Present address: Yale University, New Haven, CT 06520, USA.
‡Present address: Indiana University, Bloomington, IN 47405, USA.

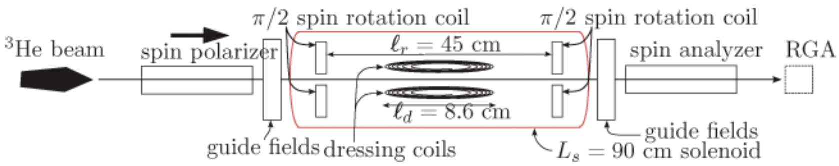

FIG. 1. (Color online) Schematics of the apparatus used for measuring the ^{3}He resonance frequency. In this coordinate system, the beam propagates along $\hat{z}$ and $\hat{x}$ points vertically upward.

for small values of y. Deviations from Eq. (3) are observed for larger values of y. Numerical calculations using both classical and quantum mechanical methods are compared with the experimental results.

We measured the dressed ^{3}He precession frequency using the Ramsey separated oscillatory fields (SOF) method [13] and the experimental apparatus shown in Fig. 1. Cold ^{3}He atoms from an effusive beam source at ~1.0 K were polarized by a strong (7.5 kG) quadrupole magnetic field and entered a 90-cm-long solenoid with 99.5% polarization [14] along the direction of the solenoid field $B_0\hat{z}$. Two pairs of $\pi/2$ coils were placed inside the solenoid to provide the vertical fields $B_r \cos\omega_r t\hat{x}$ required for the SOF method. In addition, an independent pair of coils was located at the middle of the solenoid to provide the vertical dressing field. Downstream of the solenoid, a spin analyzer identical to the quadrupole polarizer transmitted those ^{3}He atoms that were polarized along the $\hat{z}$ direction. A residual gas analyzer (RGA) then counted the flux of the transmitted ^{3}He atoms.

The ^{3}He beam from the source had a thermalized velocity distribution $f(v)$ (a Maxwellian distribution modified by the polarizer's acceptance) that was determined from a measurement of the ^{3}He beam transmission with a single rf coil set at the Larmor frequency. We found that $f(v)$ peaked at $\bar{v} = 155$ ms^{-1} with FWHM = 70 ms^{-1}.

In the dressed spin measurement, the frequency of the rf fields (ω_r) was varied near the ^{3}He Larmor precession frequency, producing oscillations in the transmitted atom flux as shown in Fig. 2 (a detailed discussion of the SOF method is given in Ref. [13]). With the dressing field off, the global minimum in the transmitted flux is observed at the ^{3}He's Larmor frequency (this is the ordinary resonance condition $\omega_r = \omega_0 = \gamma B_0$). The shape of the transmission curve is consistent with the velocity-averaged transition probability calculated using the measured atomic velocity distribution $f(v)$. When the dressing field $B_d \cos\omega_d t\hat{x}$ was applied, the value of ω_r that produced the minimum RGA flux shifted to a different frequency, as demonstrated in Fig. 2. Measurements were performed at two B_0 values (3.36 G and 8.50 G) and the dressing field frequency and magnitude were varied as parameters. Several different dressing field frequencies were investigated for each B_0 setting, and at each frequency the dressing field's magnitude was varied over 10 to 15 values ranging from 0 up to 15–20 G. For each B_0, B_d, and ω_d combination the frequency of the $\pi/2$ coils at which the RGA flux reached its minimum was determined. The results of our measurements are plotted in Fig. 3.

The shifts observed in the ^{3}He resonance frequency are due to changes in the effective magnetic moment of the ^{3}He caused by the dressing field. In the undressed, or "free," case ($B_d = 0$) the transverse components of the ^{3}He spin precess about B_0 at the Larmor frequency $\omega_0 = \gamma B_0$ during the transit time between the two $\pi/2$ rotation coils, which we call t_r. The resonance condition occurs when the spin precesses in phase with the rf field, i.e., $\gamma B_0 t_r = \omega_r t_r$. Modifying the ^{3}He magnetic moment with the dressing field caused the spin to precess with a different frequency in the region of the dressing field, and therefore the observed magnetic resonance occurred at a frequency ω_r' different from the undressed case. Writing γ' for the gyromagnetic ratio of the dressed ^{3}He, the total spin precession of the ^{3}He is a sum of two contributions—the precession inside the dressing field with frequency $\gamma' B_0$ and the free precession with frequency $\omega_0 = \gamma B_0$ outside the dressing region. The resonance occurs when the phase angle of the rf field is equal to the total ^{3}He precession angle,

$$\omega_r' t_r = \gamma B_0(t_r - t_d) + \gamma' B_0 t_d, \tag{4}$$

and the resonance frequency shift $\Delta\omega_r = \omega_r' - \omega_0$ is

$$\Delta\omega_r = B_0(\gamma' - \gamma)\frac{t_d}{t_r} = \omega_0(\gamma'/\gamma - 1)\frac{\ell_d}{\ell_r}, \tag{5}$$

where t_d is the ^{3}He's time of flight through the dressing region of length ℓ_d and ℓ_r is the separation of the two $\pi/2$ fields. Secondary minima in the transmission signal are observed

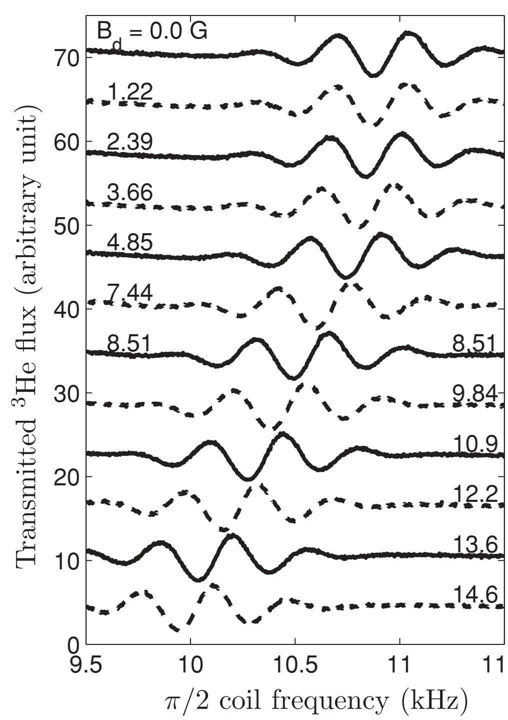

FIG. 2. ^{3}He beam transmission vs SOF frequency showing shift of the resonance frequency with increasing magnitude of the dressing field B_d. Sequential data traces are offset vertically for clarity. In these data $B_0 = 3.36$ G, $\omega_0/2\pi = 10.89$ kHz, and $\omega_d/2\pi = 29.5$ kHz ($y = 0.369$).

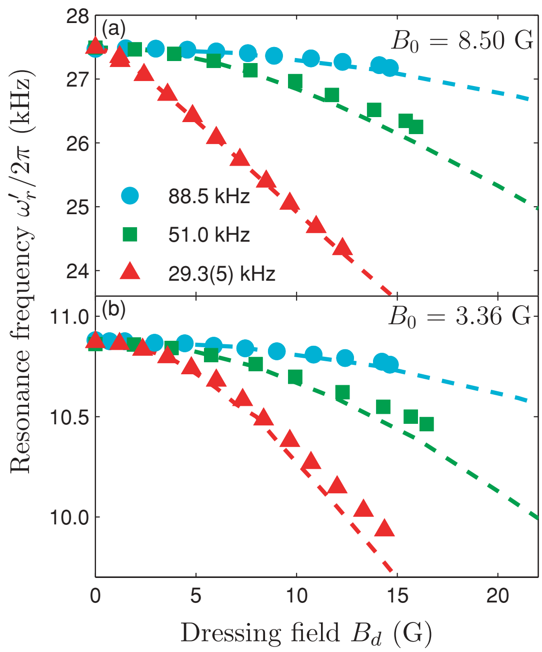

FIG. 3. (Color online) ^{3}He resonance frequency data as a function of B_d for several dressing field frequencies ω_d. (a) $B_0 = 8.50$ G. (b) $B_0 = 3.36$ G. The triangle symbol indicates $\omega_d/2\pi = 29.3$ kHz in (a) and 29.5 kHz in (b). Dashed lines show the results of Bloch simulations for each frequency.

(Fig. 2) when the precession and rf phase difference is an integer multiple of 2π.

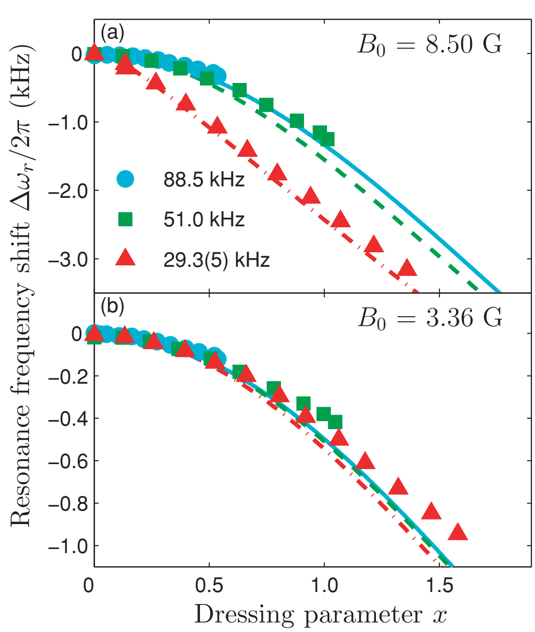

FIG. 4. (Color online) Change of the ^{3}He precession frequency as a function of the dressing parameter $x = \gamma B_d/\omega_d$. The curves show the expected resonance frequency shifts computed from the dressed spin energy spectrum and Eq. (5). The values of y (from top to bottom) in (a) are 0.31, 0.54, and 0.94; in (b), the values are 0.12, 0.21, and 0.37.

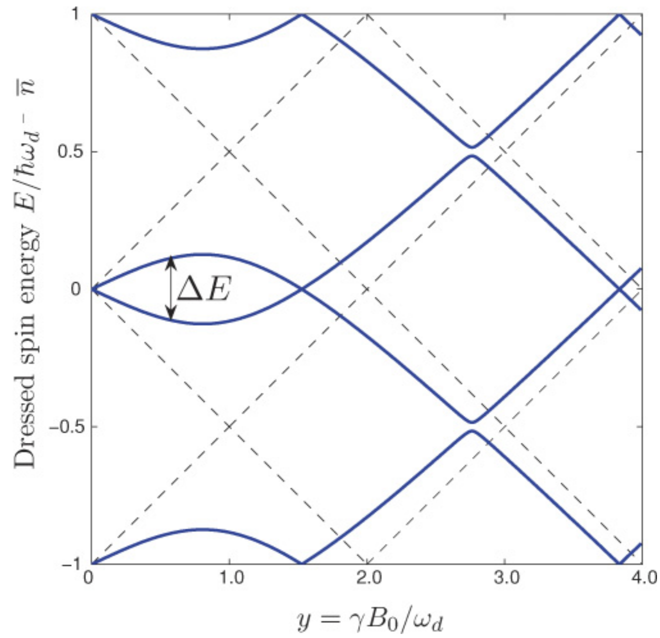

FIG. 5. (Color online) Sample energy diagram of the dressed spin system calculated as a function of y, for dressing parameter $x = 1.57$. Dashed lines indicate the Zeeman splittings in the undressed system ($E_0 = \pm\frac{1}{2}\hbar\omega_0$). The energy scale is given in units of the dressing field photon energy $\hbar\omega_d$.

We have used both classical and quantum-mechanical approaches to interpret the experimental results. In the first case, we numerically integrate the Bloch equation with a fourth-order Runge-Kutta method to propagate the ^{3}He through the solenoid region and determine the final polarization $\boldsymbol{s}\cdot\hat{\boldsymbol{z}}$. We simulated all of the measurements by varying the SOF frequency about the ^{3}He's Larmor frequency and averaging the result over $f(v)$. The resonance curves thus obtained are in good agreement with our experimental data and, in particular, the resonance frequency shifts due to the dressing field are well reproduced, as shown in Fig. 3.

In addition to the classical simulations, we have also interpreted the experimental observations using the dressed atom approach pioneered by Cohen-Tannoudji [8]. The Hamiltonian of a spin-$^1/_2$ particle with gyromagnetic ratio γ subjected to the constant magnetic field $B_0\hat{\boldsymbol{z}}$ and a linearly polarized rf field $B_d \cos\omega_d t\,\hat{\boldsymbol{x}}$ can be written

$$\hat{H} = -\gamma B_0 \hat{S}_z + \hbar\omega_d \hat{a}^\dagger \hat{a} + \lambda \hat{S}_x (\hat{a} + \hat{a}^\dagger), \tag{6}$$

where $\hat{S}_x$ and $\hat{S}_z$ are the spin operators along $\hat{\boldsymbol{x}}$ and $\hat{\boldsymbol{z}}$, respectively ($\hat{S}_z$ having eigenvalues $m_z = \pm\frac{1}{2}\hbar$). The first term of Eq. (6) is the Zeeman interaction, and the second term is the energy of the dressing field with creation and annihilation operators $\hat{a}^\dagger$ and $\hat{a}$. The final term in Eq. (6) describes the coupling of the particle's spin to the photon field with strength $\lambda = \gamma B_d/2\sqrt{\bar{n}}$, where $\bar{n} \gg 1$ is the average number of photons. This interaction term allows the particle to absorb or emit photons, which entails the exchange of energy and angular momentum. Because the rf field is perpendicular to B_0 (and can be decomposed into a superposition of right- and left-handed circularly polarized fields), only $\Delta m_z = \pm\hbar$ transitions are allowed.

In the weak-field regime ($B_0 \ll \omega_d/\gamma$, or $y \ll 1$), Eq. (6) can be solved analytically with the result $\gamma' = \gamma J_0(x)$ [10]. Equation (5) implies that the resonance frequency shift then becomes

$$\Delta\omega_r = \omega_0[J_0(x) - 1]\frac{\ell_d}{\ell_r}, \qquad (7)$$

which only depends on the dressing strength $x = \gamma B_d/\omega_d$. The experimental values of $\Delta\omega_r$ are plotted as a function of x in Fig. 4 for measurements at two different B_0 settings and several values of y. As shown in Fig. 4(b), this "x-scaling" behavior is indeed observed for $\Delta\omega_r$ measured at $B_0 = 3.36$ G, where the y values are small. For data taken at $B_0 = 8.50$ G, deviation from x-scaling is clearly observed for the measurement with $\omega_d/2\pi = 29.3$ kHz ($y = 0.94$), for which the expression $\gamma' = \gamma J_0(x)$ no longer holds.

To understand the observed deviation from x-scaling shown in Fig. 4, we have calculated the dressed spin energy diagram by diagonalizing the full Hamiltonian of Eq. (6). In Fig. 5 we show an example of the dressed energy eigenvalues E as a function of the static field B_0, for a constant dressing field magnitude corresponding to $x = 1.57$, which is the largest value acheived in our measurements. The diagram shows how the Zeeman splitting in the undressed system is modified by the presence of the dressing field [8]. From the energy difference ΔE between the dressed eigenstates, γ' is given by $\Delta E/B_0$ and $\Delta\omega_r$ is calculated using Eq. (5) to obtain the curves in Fig. 4. These results show that the observed deviation from x-scaling can be quantitatively described in this quantum mechanical approach.

In summary, we have measured the modification of the precession frequency of a polarized ^{3}He beam in a constant magnetic field superimposed by a transverse oscillating dressing field. In the weak-field limit ($y = \gamma B_0/\omega_d \ll 1$), the modified gyromagnetic ratio γ' obeys the relation $\gamma' = \gamma J_0(x)$. Deviation from this relation is observed at larger values of y. The observed modification of the ^{3}He effective gyromagnetic ratio can be well described by classical calculations using the Bloch equation as well as by the quantum approach based on the dressed atom formalism. This result supports the proposal to use a dressing field to modify the neutron and ^{3}He precession frequencies in a neutron EDM experiment.

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