Dressed Spin of Polarized $^3$He in a Cell

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Abstract

We report a measurement of the modification of the effective precession frequency of polarized $^3$He atoms in response to a dressing field in a room temperature cell. The $^3$He atoms were polarized using the metastability spin-exchange method. An oscillating dressing field is then applied perpendicular to the constant magnetic field. Modification of the $^3$He effective precession frequency was observed over a broad range of the amplitude and frequency of the dressing field. The observed effects are compared with calculations based on quantum optics formalism.

Key words: dressed spin; polarized $^3$He; neutron EDM
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A non-zero neutron electric dipole moment (EDM) is direct evidence for violations of both parity ($P$) and time-reversal ($T$) symmetries \cite{1,2}. Assuming CPT invariance, $T$ violation also implies $CP$-violation \cite{3}. Observation of a non-zero neutron EDM would provide qualitatively new information on the origin of $CP$-violation, since no $CP$ violation has ever been found for a baryon or a hadron containing light quarks only, like a neutron.

The most sensitive neutron EDM measurement was carried out at the ILL (Institut Laue Langevin) using bottled ultracold neutrons (UCNs) and an upper limit of $|d_n| < 2.9 \times 10^{-26} e \text{ cm}$ (90\% C.L.) was obtained \cite{4}. A non-zero

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neutron EDM will lead to Stark splitting in an electric field. In the presence of parallel (antiparallel) magnetic ($B_0$) and electric ($E$) fields, the Larmor precession frequency ($\omega$) is given by

$$\hbar \omega = 2(\mu_B B_0 \pm d_n E)$$

(1)

where $\mu_B$ and $d_n$ are the neutron magnetic and electric dipole moments, respectively. A shift in the precession frequency which correlates with the direction and magnitude of the electric field would be a signal for the neutron EDM. Two new neutron EDM experiments [5,6] have been proposed using a novel technique [7] of producing and storing UCNs in superfluid $^4$He.

A major challenge of all EDM experiments is to minimize systematic effects arising from the variation of the magnetic field. The technique of dressed spin has been proposed by Golub and Lamoreaux [7] to reduce these systematic effects. A small concentration ($X \sim 10^{-10}$) of polarized $^3$He atoms would be added to the superfluid helium to act as both a spin analyser and a comagnetometer. The relative spin orientation between the UCNs and $^3$He determines the rate of the absorption reaction

$$n + ^3He \rightarrow p + ^3H + 764 \text{ keV},$$

(2)

which has a much larger cross section when the n–$^3$He have a total spin $J = 0$ compared to $J = 1$ [8]. In a 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 $\gamma_i$ is the gyromagnetic ratio of each species. The relative angle between the UCN and $^3$He spin will develop over time ($\gamma_3 \approx 1.1 \gamma_n$), and the rate of the absorption reaction is modulated at the difference of the two spin precession frequencies:

$$\omega_{rel} = (\gamma_3 - \gamma_n) B_0 \approx 0.1 \gamma_n B_0$$

(3)

In the presence of a static electric field $E$ parallel to $B_0$, Eq. 3 gains an additional term proportional to the neutron EDM

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

(4)

For typical values of $B_0 = 10 \text{ mG}$ and $E = 30 \text{ KV/cm}$, Eq. 4 shows that the first term is $\sim 8$ orders of magnitude greater than the second term for a $d_n$ of $10^{-27} \text{ e cm}$. This shows the importance of accurately monitoring the value of $B_0$. An alternative approach is to adopt the dressed-spin technique [7]. In the presence of an oscillating off-resonance magnetic field, $B_d \cos \omega_d t$, perpendicular to $B_0$, the UCN and $^3$He magnetic moments can be effectively modified, and in fact equalized, by the dressing field set at the so-called ‘critical-dressing’ condition. In the high dressing-field frequency limit ($\omega_d \gg \gamma_i B_0$), it
was shown \[14\] that \(\gamma_i\) becomes \(\gamma'_i\) given by

\[ \gamma'_i = \gamma_i J_0(x_i), \quad x_i \equiv \gamma_i B_d/\omega_d \]  

(5)

where \(J_0\) is zeroth-order Bessel function of the first kind. The critical dressing occurs at \(\gamma'_3 = \gamma'_n\) (or \(x_3 = (\frac{2}{\gamma_n}) x_n = 1.323\)), where the modified gyromagnetic ratios for neutron and \(^3\)He are equal. Eq. 4 shows that the EDM signal is then independent of \(B_0\) and not sensitive to the fluctuation and drift of \(B_0\).

Modification of the neutron effective magnetic moment using an oscillating magnetic field has been studied by Muskat \textit{et al.} \[9\] for a polarized neutron beam. More recently, modification of \(^3\)He effective magnetic moment was studied by Esler \textit{et al.} \[10\] using a polarized \(^3\)He atomic beam. Both experiments utilized polarized beam, and no measurements have been reported yet for polarized neutrons or \(^3\)He in a cell. As the proposed neutron EDM experiment will utilize polarized \(^3\)He in a superfluid helium cell, it is of interest to extend the previous study \[10\] to polarized \(^3\)He stored in a cell.

In this paper, we report a measurement of response of polarized \(^3\)He atoms in a room temperature cell to the application of a dressing field. Modification of the \(^3\)He effective precession frequency was observed over a broad range of the amplitude and frequency of the dressing field. The observed shift in the effective precession frequency are found to be in good agreement with theoretical calculations based on quantum optics.

An overall schematic of the apparatus is shown in Fig. 1. A cylindrical Pyrex cell of 2.5 cm radius and 5.7 cm length is filled with 1 torr \(^3\)He gas and located at the center of a pair of 50.8 cm radius Helmholtz coils, which provides \(B_0\) along the \(z\)-axis. Another pair of Helmholtz coils of 25.4 cm radius cancels the vertical component of the Earth field. Four 80-turn rectangular pickup coils of 5.08 cm \(\times\) 6.35 cm are placed in the \(\hat{x} - \hat{z}\) plane surrounding the cell to measure the \(^3\)He precession signal. Two other pairs of coils, the \(B_1\) and the dressing coils, provide oscillatory magnetic fields along the \(x\)-axis. The radius and separation of the \(B_1\) coils are 11.94 cm and 12.7 cm, respectively. For the dressing coils, the radius is 11.94 cm and the separation is 10.8 cm.

The \(^3\)He gas is polarized using the metastability spin exchange method \[11,12\]. An RF field is applied to two electrodes outside of the cell to generate a discharge in the \(^3\)He gas. A GaAs diode laser provides circularly polarized light with wavelength tuned at 1083 nm to pump \(^3\)He atom from the metastable \(^2^3S_1\) \(F = \frac{3}{2}\) states to \(^2^3P_0\) \(F = \frac{1}{2}\) states \((C_9\) transitions). A polarization of \(\sim 20\%\) for \(^3\)He is obtained \[13\].

After \(^3\)He is polarized, the laser and RF discharge are turned off, followed by the application of a short oscillatory pulse at Larmor frequency on the \(B_1\) coil to rotate the \(^3\)He spin from \(\hat{z}\) to the \(\hat{x} - \hat{y}\) plane. The dressing field
\( B_d \cos \omega_d t \hat{x} \) is then applied. Without the dressing field, the \(^3\)He atoms precess at the Larmor frequency \( \omega_0 = \gamma_3 B_0 \). The application of the dressing field modifies the \(^3\)He effective precession frequency.

The time-varying magnetization caused by the \(^3\)He precession will induce an EMF in the pickup coils. The signal from the pickup coils is then analyzed by a lock-in amplifier to measure the rms voltage \( V(t) \) at the reference frequency of the lock-in. For each setting of the dressing field, the reference frequency is varied to locate the maximum output amplitude, which occurs when the reference frequency coincides with the \(^3\)He precession frequency. Fig. 2 shows examples of measurements for several settings of the magnitude of \( B_d \) at \( B_0 = 387.7 \) mG and \( \omega_d/2\pi = 7152.5 \) Hz. As \( B_d \) (or equivalently, \( x \equiv \gamma_3 B_d/\omega_d \)) increases, the \(^3\)He precession frequency clearly shifts to lower values. The widths of the peaks in Fig. 2 are consistent with the 5.3 Hz bandwidth of the lock-in amplifier. The effective precession frequency, \( \omega_{\text{eff}} \), can be determined from the location of maximum amplitude \( A \).

The dressed-spin effects are measured for a range of \( B_d \) and \( \omega_d \). For convenience, two dimensionless parameters are defined:

\[
x \equiv \frac{\gamma_3 B_d}{\omega_d}, \quad y \equiv \frac{\gamma_3 B_0}{\omega_d} = \frac{\omega_0}{\omega_d}.
\] (6)

As will be seen later, the dressed-spin effects are functions of \( x \) and \( y \) only.

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**Fig. 1.** Schematic of the apparatus. See text for description of various components.
Table 1
List of parameters for the various measurements.

| $y$   | $\omega_0/2\pi$ [Hz] | $\omega_d/2\pi$ [Hz] |
|-------|------------------------|------------------------|
| 0.15  | 1271                   | 8473                   |
| 0.3   | 1272                   | 4240                   |
| 0.5   | 1267                   | 2540                   |
| 0.8   | 1271                   | 1588                   |
| 0.9   | 1271                   | 1412                   |

Table 1 lists the values of $B_0(\omega_0)$, $\omega_d$ and $y$ for our measurement. Fig. 3 shows the measured ratios $\omega_{\text{eff}}/\omega_0$ as a function of $x$ and $y$. For a given value of $y$, $B_0$ and $\omega_d$ are fixed and $B_d$ is varied to determine the $x$-dependence of $\omega_{\text{eff}}/\omega_0$. The error bars in Fig. 3 took into account the uncertainties of the $B_d$ calibration, the determination of $\omega_{\text{eff}}$, and the drift in $B_0$.

Fig. 3(a) shows that $\omega_{\text{eff}}$ is smaller than $\omega_0$ when the dressing field frequency is higher than the Larmor frequency ($y = \omega_0/\omega_d < 1$). Also shown in Fig. 3(a) is the zeroth-order Bessel function $J_0(x)$. The data are consistent with the theoretical prediction [14] that $\omega_{\text{eff}}/\omega_0 = \gamma'/\gamma = J_0(x)$ as $y \to 0$. Indeed, the $\omega_{\text{eff}}/\omega_0$ data obtained at $y = 0.15$ are well described by $J_0(x)$. As $y$ increases...
toward 1, large deviations from $J_0(x)$ are observed for $\omega^{eff}/\omega_0$, as shown in Fig. 3(a).

Fig. 3(b) shows $\omega^{eff}/\omega_0$ measured at five different values of $y$ when the dressing field frequencies are lower than the Larmor frequency, namely $y = \omega_0/\omega_d > 1$. In contrast to the results observed in Fig. 3(a), the dressing frequency $\omega^{eff}$ is now larger than $\omega_0$. In the remainder of this paper, we discuss the theoretical calculations for interpreting the observed dressed-spin effects and compare the data with the calculations.

Fig. 3. Ratios of measured effective precession frequency $\omega^{eff}$ over $\omega_0$ as a function of $x$ for (a) $y < 1$ and (b) $y > 1$. The dashed curves are calculations described in the text.
The dressed spin system was first studied by Cohen-Tannoudji et al. [14,15]. The Hamiltonian for a spin-$\frac{1}{2}$ particle with gyromagnetic ratio $\gamma$ in a constant magnetic field $B_0 \hat{z}$ and an oscillatory magnetic field $B_d \cos \omega_d t \hat{x}$ can be written as

$$\frac{\mathcal{H}}{\hbar \omega_d} = \left(\frac{\gamma B_0}{\hbar \omega_d}\right) \hat{S}_z + \hat{a}^\dagger \hat{a} + \frac{\lambda}{\hbar \omega_d} \hat{S}_x (\hat{a} + \hat{a}^\dagger) \equiv \frac{y}{2} \hat{\sigma}_z + \frac{x}{4 \sqrt{n}} \hat{\sigma}_x (\hat{a} + \hat{a}^\dagger),$$

(7)

where $\hat{S}_x$ and $\hat{S}_z$ are the spin operators along $\hat{x}$ and $\hat{z}$, respectively. The first term in Eq. 7 is the Zeeman interaction of the spin with $B_0$, and the second term is the energy of the oscillatory dressing field with creation and annihilation operators $\hat{a}^\dagger$ and $\hat{a}$. The final term in Eq. 7 describes the coupling between the spin of the particle and the dressing field with strength $\lambda = \frac{\gamma B_d}{2 \sqrt{n}}$, where $n \gg 1$ is the average number of photons. This interaction term allows the particle to absorb or emit photons and exchange energy and angular momentum with the dressing field. Because the dressing 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.

Fig. 4. Energy diagram of the dressed spin system calculated as a function of $y$, for dressing parameter $x = 1.323$. Dashed lines indicate the Zeeman splittings in the undressed system ($E_0 = \pm \frac{1}{2} \hbar \omega_0$). The solid lines show the modified energy spectrum due to the dressing field. The energy scale is given in units of the dressing field photon energy $\hbar \omega_d$. 
In the high dressing field frequency limit ($\omega_d \gg \gamma B_0$ or $y \ll 1$), Eq. (7) can be solved analytically with the result $\gamma' = \gamma J_0(x)$ \textsuperscript{14}. The precession frequency becomes

$$\frac{\omega_{\text{eff}}}{\omega_0} = \frac{\gamma' B_0}{\gamma B_0} = J_0(x),$$

which only depends on the dressing strength $x = \gamma B_d/\omega_d$. The modification of $\gamma$ by a factor of $J_0(x)$ under a high frequency dressing field was observed in several experiments \textsuperscript{9,10} including the present measurement (see Fig. 3).

To understand the observed deviation of $\gamma'/\gamma$ from $J_0(x)$ in Fig. 3 for arbitrary dressing parameters $x$ and $y$, we have calculated the energy level diagrams for the dressed-spin system by diagonalizing the Hamiltonian of Eq. (7) \textsuperscript{16}. In the basis of $\langle \cdots, |n + 1, -\rangle, |n, +\rangle, |n, -\rangle, |n - 1, +\rangle, \cdots \rangle$, where $n$ signifies the oscillating quanta of the dressing field and $+/-$ denotes the spin up/down state of $^3$He, the Hamiltonian has the following matrix elements:

$$
\begin{pmatrix}
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdot & n + 1 + \frac{y}{2} & 0 & 0 & \frac{x}{4} & 0 & 0 & \cdot \\
\cdot & 0 & n + 1 - \frac{y}{2} & \frac{x}{4} & 0 & 0 & 0 & \cdot \\
\cdot & 0 & \frac{x}{4} & n + \frac{y}{2} & 0 & 0 & \frac{x}{4} & \cdot \\
\cdot & \frac{x}{4} & 0 & 0 & n - \frac{y}{2} & \frac{x}{4} & 0 & \cdot \\
\cdot & 0 & 0 & 0 & \frac{x}{4} & n - 1 + \frac{y}{2} & 0 & \cdot \\
\cdot & 0 & 0 & \frac{x}{4} & 0 & 0 & n - 1 - \frac{y}{2} & \cdot \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots
\end{pmatrix}
$$

Fig. 4 shows an example of the energy eigenvalue diagram as a function of the parameter $y = \gamma_3 B_0/\omega_d$ for a dressing field magnitude corresponding to $x = \gamma_3 B_d/\omega_d = 1.323$, which corresponds to the condition for critical dressing. A matrix of dimension $46 \times 46$ is diagonalized to obtain the energy eigenvalues for each $x$ and $y$ parameters. The dashed lines are the Zeeman splitting for the undressed system ($x = 0$). Fig. 4 shows how the Zeeman splitting in the undressed system is modified by the presence of the dressing field. Without the dressing field, the gyromagnetic ratio is given by $\Delta E/\hbar B_0$, which is just a constant ($\Delta E/\hbar B_0 = \gamma$) independent of $B_0$. When the dressing field is applied, Fig. 4 shows that $\Delta E$ is changed to $\Delta E'$ and $\gamma$ now becomes $\gamma' = \Delta E'/\hbar B_0$. It is interesting to note that for $y < 1$, $\Delta E' < \Delta E$ and $\gamma'$ is smaller than $\gamma$. In contrast, for $y > 1$, Fig. 4 shows that $\Delta E' > \Delta E$ and $\gamma'$ is now greater than $\gamma$. The striking feature observed in the data shown in Fig. 4, namely, $\omega_{\text{eff}}/\omega_0 = \gamma'/\gamma < 1$ for $y < 1$ and $\omega_{\text{eff}}/\omega_0 > 1$ for $y > 1$, is well described by
this approach.

The dashed curves in Fig. 3 are the calculations for $\omega_{\text{eff}}/\omega_0 = \gamma'/\gamma$ using the quantum mechanical method. The good agreement between the data and the calculation shows that the observed deviation can be quantitatively described in this quantum mechanical approach.

In summary, we have developed the method to measure the modification of the effective precession frequency of polarized $^3$He atoms in a room temperature cell over a broad range of the dressing field parameters. Our study confirms that in the high-frequency limit, the modified gyromagnetic ratio $\gamma'$ obeys the relation $\gamma' = \gamma J_0(x)$. Deviation from this relation was observed for other settings of the dressing field parameters. In particular, we found that when $y > 1$, $\gamma'$ is larger than $\gamma$. The observed modification of the effective $^3$He precession frequency can be quantitatively described by a quantum approach. We plan to extend the measurements to cover the larger $x$ region as well as in superfluid $^4$He cell, which are relevant to the future neutron EDM experiment.

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