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Limits on Possible New Nucleon Monopole-Dipole Interactions from the Spin Relaxation Rate of Polarized $^3$He Gas

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Various theories beyond the Standard Model predict new particles with masses in the sub-eV range with very weak couplings to ordinary matter. A $P$-odd and $T$-odd interaction between polarized and unpolarized nucleons proportional to $\hat{s} \cdot \hat{r}$ is one such possibility, where $\hat{r}$ is the distance between the nucleons and $\hat{s}$ is the spin of the polarized nucleon. Such an interaction involving a scalar coupling $g_s$ at one vertex and a pseudoscalar coupling $g_p$ at the other vertex can be induced by the exchange of spin-0 bosons. We show that measurements of the transverse spin relaxation rate $\Gamma_2$ for polarized gas can be used to set limits on the product $g_s g_p$ for boson masses in the 10 meV to 100 meV range, corresponding to distances from centimeters to micrometers. We present limits from both a reanalysis of previous measurements of $\Gamma_2$ in $^3$He spin exchange cells and from data in a test experiment searching for a change in $\Gamma_2$ upon the motion of an unpolarized test mass. The outlook for more sensitive measurements using this technique is discussed.

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I. INTRODUCTION

The possible existence of new interactions of nature with ranges of macroscopic scale (meters to nanometers) and very weak couplings to matter has begun to attract more scientific attention. Particles which might transmit such interactions are starting to be referred to generically as WISPs (Weakly-Interacting sub-eV Particles) [1] in recent literature. Several theoretical scenarios can generate such interactions. Many theories beyond the Standard Model possess extended symmetries which, when broken at a high energy scale, lead to weakly-coupled light particles with long-range interactions. Several theoretical attempts to explain dark matter and dark energy also produce new long-range interactions. The fact that the dark energy density of order (1 meV)$^4$ corresponds to a length scale of 100 $\mu$m encourages searches for new phenomena around this scale [2, 3].

Long ago Moody and Wilczek [4] considered the form of interactions which could be induced by the exchange of a spin 0 field between fermions with scalar or pseudoscalar couplings. In addition to possible $P$ and $T$-conserving scalar-scalar (monopole-monopole) and pseudoscalar-pseudoscalar (dipole-dipole) interactions, they highlighted an interesting $P$ and $T$ violating scalar-pseudoscalar (monopole-dipole) interaction of the form

$$ V = \frac{\hbar^2 g_s g_p}{8\pi m_n} \frac{\hat{s} \cdot \hat{r}}{r^2} \left( \frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-r/\lambda}, \quad (1) $$

where $m_n$ is the mass and $\hat{s} = \hbar \hat{\sigma}/2$ is the spin of the polarized particle, $\hbar$ is Planck’s constant, $\lambda$ is the interaction range, $\hat{r} = r/r$ is the unit vector between the particles, and $g_s$ and $g_p$ are the scalar and pseudoscalar coupling constants. Axions [5–9] can induce such an interaction. A general classification of interactions between nonrelativistic fermions assuming only rotational invariance [10] uncovered 16 different operator structures involving the spins and momenta of the particles. The monopole-dipole form in equation 1 corresponds to the potential $V_9 + V_{10}$ in the notation of Dobrescu and Mocioiu. This work also summarized the existing experimental constraints known at that time for some of the interactions. Most of the experiments which have been performed to search for such interactions [9, 11–17] are sensitive to ranges $\lambda > 1$ cm.

Recent experimental work seeks to constrain the monopole-dipole interaction at shorter distances. Baessler et al. [12] used the observation of neutron bound states in the Earth’s gravitational potential and the apparent absence of a spin-dependence for the bound state energies to place an upper bound on $g_s g_p$ for length scales of order micrometers, which is the characteristic spatial separation of the bound state wave function from the surface. A spatially inhomogeneous monopole-dipole interaction $\hat{s} \cdot \hat{r}$ (Eq. 1) can also influence the time evolution of a collection of polarized nuclei. Authors [18, 19] used this effect to set limits on the monopole-dipole interaction using the experimentally-measured longitudinal relaxation rate ($\Gamma_1$) of polarized ultracold neutrons (UCN) in a material trap. A similar analysis has been performed for other polarized species: Pokotilovski [13] set a limit using the measured $\Gamma_1$ of optically polarized noble gas. The use of polarized gases to study the monopole-dipole interaction can be found also in other recent works [20, 21].

In this paper we show that the transverse relaxation rate $\Gamma_2$ of the nuclear polarization in optically pumped noble gases can be used to search for the monopole-dipole nucleon-nucleon interaction with a sensitivity that should...
greatly exceed that reached by $\Gamma_1$ measurements. We set a new limit on $g_sg_p$ with this method in the range from 10 μm to about 1 cm. We also show results from a simple test experiment performed as a proof of principle involving the motion of an unpolarized test mass near the polarized gas. Future experiments using this technique which could lead to significant improvements of the constraints along with ideas to avoid possible systematic effects are proposed.

II. THEORY

The transverse relaxation rate $\Gamma_2$ from the monopole-dipole interaction can be calculated in direct analogy with the $\Gamma_2$ of a magnetic moment in a longitudinal magnetic field gradient. We review the results of the theory of spin relaxation of polarized gas in an external longitudinal magnetic field gradient. Consider a cylindrical cell of inside diameter $a$, length $L$, and wall thickness $d_0$ containing polarized gas with a large planar source mass of thickness $d$ and nucleon density $N$ close to the cell (Fig. 1). The external magnetic field, the nuclear polarization, and the cell axis all point along $z$ and are normal to the plate. In the theory of nuclear magnetic resonance (NMR) $\Gamma_1$ (the longitudinal relaxation rate) comes from external interactions in which the polarization is lost, and $\Gamma_2$ (the transverse relaxation rate) comes from the dephasing of the spins. $\Gamma_2$ induced by a longitudinal magnetic field gradient has been evaluated in the literature in the limit of short mean free path for the gas atoms (true at sufficiently high gas pressure) and for $\Gamma_1 \ll \Gamma_2$ to be [22–24]

$$\Gamma_2 \approx \frac{8\sqrt{2}L^4}{175D} |\nabla H_z|^2,$$

(2)

where $D$ is the diffusion coefficient, $H_z$ is the magnetic field along $z$, and $\gamma$ is the gyromagnetic ratio of the dipole. This expression is valid if the mean free path $l$ is much smaller than the size of the cell and if the rotation angle of the spin over a mean free path of a diffusing atom is negligible[23], i.e. $\omega l \ll \bar{v}$, where $\bar{v}$ is the average velocity of the atom, and $\omega$ is the precession frequency of the spin in the external magnetic field. Both of these conditions are met in the measurements discussed below. The thermodynamic parameters which satisfy this condition can be found using the expressions for the mean free path in a gas $l = \frac{k_B T}{\sqrt{2 \pi m d_{0} p}}$ and the average speed $\bar{v} = \sqrt{8k_BT/(\pi m)}$ where $k_B$ is the Boltzmann constant, $T$ is temperature, $p$ is pressure, $d_{m} \approx 0.62 \times 10^{-10}$ m is the diameter of the $^3$He atom, and $m$ is the mass of the atom.

The monopole-dipole interaction varies with distance as shown in Eq. (1) due to its finite range and the surrounding matter will contribute to $\Gamma_1$ and $\Gamma_2$ of the polarized atoms. Since both the external magnetic field and the monopole-dipole interaction are proportional to $\vec{s} \cdot \vec{r}$, the expression (Eq. 2) derived for relaxation in external magnetic field gradients can be directly applied to calculate the contribution of the monopole-dipole interaction to $\Gamma_2$ from interaction with the mass if the mean free path $l$ is much smaller than both the size of the cell and the range of the force $\lambda$. The monopole-dipole interaction potential seen by the polarized gas at position $r(\rho, \theta, z)$ is the integral of Eq. (1) over the volume of the material. In the limit in which the length of the plate is much larger than the dimensions of the cell, the monopole-dipole potential and its gradient are

$$V(r) = g_s g_p N \frac{\hbar^2 \lambda}{4m_n} e^{-z/\lambda}(1 - e^{-d/\lambda}),$$

(3)

$$\frac{\partial V}{\partial z} = g_s g_p N \frac{\hbar^2}{4m_n} e^{-z/\lambda}(1 - e^{-d/\lambda}),$$

(4)

where $N$ is the nucleon density of the matter, and the gradients in the $x$ and $y$ directions vanish. We use Eq. (2), Eq. (4), and $V = \hbar \gamma H_z$ to calculate $\Gamma_2$ as

$$\Gamma_2 = \frac{1}{LS} \int_0^L \Gamma_2(z) S dz$$

$$= \frac{8L^3}{175D} \left[ \frac{g_s g_p N \hbar (1 - e^{-d/\lambda})}{4m_n} \right]^2 \int_0^L e^{-z/\lambda} d\bar{z}$$

(5)

where $S$ is the cross sectional area of the cylindrical cell. After averaging $\Gamma_2$ over the cell volume, one derives a relation between the product of the monopole-dipole couplings $g_s g_p$ and $\Gamma_2$:

$$g_s g_p = \frac{2m_n}{\hbar N L^2} (175D \Gamma_2)^{1/2} f(\lambda),$$

(6)

where

$$f(\lambda) = \left( \frac{L}{\lambda} \right)^{1/2} e^{d_0/\lambda}(1 - e^{-d/\lambda})^{-1}(1 - e^{-2L/\lambda})^{-1/2}.$$

(7)

We believe that measurements of $\Gamma_2$ have the potential for greater sensitivity in probing the monopole-dipole potential for high pressure cells than measurements of $\Gamma_1$. The ratio $\Gamma_1/\Gamma_2$ in the short mean free path limit for polarized atoms in the same magnetic field gradient is[23]

$$\frac{\Gamma_1}{\Gamma_2} \approx \frac{175D^2}{8R^4 \Omega_0^2},$$

(8)

where $\Omega_0$ is the precession frequency of the dipole. Taking the data in Ref. [13] as a typical example, $D = 2.35$ cm$^2$s$^{-1}$, $R = 5$ cm, and $\Omega_0 = 10^5$ s$^{-1}$ for a ratio $\Gamma_1/\Gamma_2 = 1.9 \times 10^{-11}$. $\Gamma_2$ measurements are intrinsically more sensitive and convenient than $\Gamma_1$ measurements in searching for the monopole-dipole interaction.
There is a small error of the cell which is the glass pull-off when the cell was sealed: otherwise the cell is cylindrically symmetric. The mass of the cell wall can also make a contribution to $\Gamma_2$. In this section we describe the constraints on the monopole-dipole interaction obtained from both sources.

The polarized $^3$He gas was contained in a cylindrical cell of internal diameter 21 mm and length 34 mm made of aluminosilicate glass (Fig. 1). The end walls are estimated to be 4 mm thick. It was filled with $^3$He gas at an atomic density of $4.4 \times 10^{19}$ cm$^{-3}$, nitrogen about $1.6 \times 10^{18}$ cm$^{-3}$, and a small amount of Rb (0.1 g) for spin exchange optical pumping [26]. There is a small volume about $\pi \times (0.25 \text{cm})^2 \times 1 \text{cm}$ attached to the center of the cell which is the glass pull-off when the cell was sealed: otherwise the cell is cylindrically symmetric. The $^3$He was polarized by spin exchange optical pumping in an oven to a maximum polarization of $\approx 40\%$ with $\Gamma_1 = 7.9 \times 10^{-6}$ s$^{-1}$. After the cell was fully polarized it was cooled to room temperature and a 200 turn pickup coil was employed to measure $\Gamma_2$ by the standard NMR method of free induction decay (FID). The cell axis was parallel to the main magnetic field of 1.4 mT provided by a Helmholtz coil.

We moved a 8 cm $\times$ 8 cm $\times$ 2 cm polytetrafluoroethylene (PTFE) block back and forth into the position shown in Fig. 1. We measured $\Gamma_2^{(in)}$ 5 times when the PTFE block was near the cell and $\Gamma_2^{(out)}$ 5 times when the PTFE was moved out. The average values for the 5-times-in and 5-times-out data are given by $\Gamma_2^{(in)}$ and $\Gamma_2^{(out)}$, respectively. $\Gamma_2$ decreased from 25.0 s$^{-1}$ to 24.4 s$^{-1}$ during the experiment, which is most likely due to radiation damping[27]. To cancel the $\Gamma_2$ dependence on the polarization of the gas, measurements were conducted with the PTFE block moved in a time sequence (in, out, out, in). We show the difference $\Delta \Gamma_2 \equiv 1 - 1$ in Fig. 2 as one point with an uncertainty $\sqrt{(\Delta \Gamma_2^{(in)})^2 + (\Delta \Gamma_2^{(out)})^2}$. This difference measurement was repeated 50 times. The final $\Gamma_2$ difference and its standard uncertainty (the standard deviation of the mean of the 50 measurements), $\Delta \Gamma_2 = (0.0014 \pm 0.0012)$ s$^{-1}$, are shown as the three red lines.

This result is consistent with the absence of a monopole-dipole interaction between the mass and the polarized $^3$He. The nucleon density of the PTFE is $N = 1.32 \times 10^{24}$ cm$^{-3}$. Using Eq. (6), we obtain a limit on the monopole-dipole coupling strength between the polarized $^3$He nucleus and the nuclei in the mass as a function of the range $\lambda$ which excludes an area in the $(g_s g_p, \lambda)$ plane above the line defined by

$$g_s^{(n)} g_p^{(n)} = 2.8 \times 10^{-21} \Delta \Gamma_2^{3/2} f(\lambda).$$

The constraint obtained from this method is shown in Fig. 3, curve 7.

The material of the cell itself can also cause polarized gas relaxation if the monopole-dipole potential exists. If the dimension of the polarized gas holder is much larger than the coupling range $(L \gg \lambda$ and $a \gg \lambda$), only the two ends have nonzero contribution to the total potential along $z$-axis. Following the same procedure from Eq. (3) to (7), we exclude an area in the $(g_s g_p, \lambda)$ plane above the line defined by

$$g_s^{(n)} g_p^{(n)} = \frac{m_n (350 D \Gamma_2)^{1/2}}{h N L^2} (\frac{L}{\lambda})^{1/2} \frac{1}{(1 - e^{-d_0/\lambda})}.$$
Various experiments have observed very small relaxation rates of polarized high density noble gases. For example, in Refs. [28] and [29] $3.4 \times 10^{19}$ $^{3}$He atoms, $8.1 \times 10^{18}$ $^{129}$Xe atoms, and $1.8 \times 10^{19}$ $^{14}$N$_2$ molecules were sealed in glass cell of internal height 0.75 cm and internal diameter 0.75 cm. A $^{3}$He transverse relaxation rate of $4 \times 10^{-4}$ s$^{-1}$ was observed in the experiment. Taking $D = 1.71$ cm$^2$s$^{-1}$, $d_0 = 0.3$ cm, and $N = 1.31 \times 10^{24}$ cm$^{-3}$, we obtain a line of constraint

$$g_s^{(n)}g_p^{(n)} = 4.2 \times 10^{-22} \Gamma_{2,1}^{1/2} \frac{(L/\lambda)^{1/2}}{(1 - e^{-d_0/\lambda})}.$$  

(11)

The result is shown in Fig. 3, curve 8.

From measurements and theoretical calculations [30], it is known that the polarization of the $^{3}$He nucleus is dominated by the neutron polarization, with only a small contribution from orbital motion and other effects. The composition of both the PTFE used in our measurements and the glass used to set the other limits is dominated by low-mass elements. Therefore the limits shown in Fig. 3 involve the pseudoscalar coupling $g_p$ of the neutron and the scalar coupling $g_s$ of an ensemble of unpolarized matter made of a roughly equal proportion of neutrons and protons.

IV. SYSTEMATIC EFFECTS

In this section we consider some systematic effects which would need to be addressed to perform a more sensitive experiment using this technique. In addition to the contributions to $\Gamma_2$ from external magnetic field gradients and the gradient in the monopole-dipole field from nearby unpolarized objects including the test mass discussed above, we can identify several other contributions to $\Gamma_2$ [22, 25] which we list here along with a qualitative discussion of their possible effect on our proposed search.

1. Radiation damping, i.e., the action of the currents induced in the pickup coils on the $^{3}$He magnetization [31], can perturb $\Gamma_2$ [27, 32]. This effect can be reduced by decreasing the quality factor Q of the pickup coil, the filling factor, and/or the size of the $^{3}$He magnetization. We expect that the dependence of $\Gamma_2$ on $^{3}$He magnetization that we observed in this test experiment could be decreased substantially without greatly reducing the signal to noise ratio. Since $\Gamma_2$ decreases with increasing magnetization if the $^{3}$He is polarized in the higher energy state, measurements with the $^{3}$He polarization reversed can reveal this effect if present.

2. The magnetic moments of the polarized $^{3}$He nuclei produce a magnetic field proportional to polarization of the gas which depends on the shape of the cell and the spatial distribution of the magnetization. This field can possess gradients even if the external magnetic field is uniform. This gradient can be minimized by proper choice of cell geometry: for example, a sphere of spatially uniform magnetization produces no field gradient. The motion of the test mass must not influence, directly or indirectly, the $^{3}$He magnetization distribution in the cell.

3. A finite magnetic susceptibility of the test mass may produce magnetic field gradients and therefore change $\Gamma_2$. A finite electrical conductivity of the test mass can support eddy currents which produce electromagnetic fields that change $\Gamma_2$. Test masses with low magnetic susceptibility and electrical conductivity can be chosen, and materials with different densities but matched magnetic and/or electrical properties can be employed.

4. $\Gamma_2$, which is ultimately limited by $\Gamma_1$, can be affected by collisions with the wall of the cell. Although the surface physics involved is not completely understood, glass surfaces with negligible effects on $\Gamma_1$ [22, 33] and $\Gamma_2$ [24] have been prepared. The motion of the test mass must be performed in such a way as not to modify the spin dependence of the interaction of the polarized $^{3}$He atoms with the internal surfaces of the glass. This seems achievable.

5. The magnitude of the $^{3}$He polarization decreases at a rate determined by $\Gamma_1$ in addition to the losses from tipping the polarization for $\Gamma_2$ measurements, and the $\Gamma_2$ measurements themselves are performed at different times corresponding to different test mass positions. The timescale for residual contributions to $\Gamma_2$ proportional to $^{3}$He polarization are determined by the tip losses and $\Gamma_1$. If $\Gamma_1 \ll \Gamma_2$, the systematic effect induced by this change can be eliminated by optimizing the time sequence of the test mass motion and/or the data analysis. The (in-out),(out-in) analysis sequence employed in our test mea-

![Figure 3: Constraints on the monopole-dipole coupling strength $g_s^{(n)}g_p^{(n)}$: 1. Blue, from Ref.[18]; 2. Purple, from Ref.[13]; 3. Red, by using low density $^{3}$He gas, from Ref. [20]; 4. Black, by using low density $^{3}$He gas, from Ref. [29]; 5. Pink, from Ref.[9]; 6. Black, from Ref.[12]; 7. Green, this work; 8. Black, this work, by reanalyzing the high density $^{3}$He relaxation data in Ref. [28] and [29]; 9. Blue, from Ref. [21], by using low density $^{3}$He gas.](image-url)
measurement, for example, cancels a systematic from a linear time-dependent drift in $\Gamma_2$. More complicated sequences can remove time dependent drifts of arbitrary polynomial order in time.

There is also great room for improvement of the measurement sensitivity. Magnetic shielding can reduce the ambient magnetic field gradients and their fluctuations. The gas density $N$ may be chosen to optimize the diffusion coefficient $D$ for better sensitivity to a particular range of $\lambda$ (Eq. 6), although with decreasing gas density the mean free path $l$ of the atom increases, and the high-pressure requirement ($\lambda \gg l$) may not be fulfilled any longer. Since the monopole-dipole potential vanishes exponentially, a thin windowed cell can be used to allow the test mass to approach the polarized gas closely. It is easy to reverse the magnetic field direction and the direction of the $^3\text{He}$ polarization relative to the magnetic field to confirm the $s \cdot r$ dependence of any signal and reveal any effects due to hysteresis from magnetic impurities in the apparatus. We conclude that the constraints on both the coupling and the range of a possible monopole-dipole interaction using this method can be significantly improved in dedicated experiments.

V. CONCLUSIONS

We propose a method using the dependence of the transverse relaxation rate $\Gamma^T$ of polarized $^3\text{He}$ gas on the position of an unpolarized, nonmagnetic test mass to set more stringent limits on possible monopole-dipole interactions. This method should be much more sensitive than the constraints already obtained from the analysis of longitudinal spin relaxation $\Gamma^L$ measurements. We have performed a simple proof-of-principle measurement using the technique. This method can be applied to search for monopole-dipole interactions with ranges below 1cm. We discussed the possibility of future sensitivity improvements using this method along with strategies to minimize systematic effects.

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