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Phys. Rev. D **83**, 031504 — Published 23 February 2011
DOI: 10.1103/PhysRevD.83.031504

DXR1039

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 $\vec{s}\cdot\vec{r}$ is one such possibility, where $\vec{r}$ is the distance between the nucleons and $\vec{s}$ 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 Γ_2 for polarized gas can be used to set limits on the product $g_s g_p$ for boson masses in the 10μeV to 100 meV range, corresponding to distances from centimeters to micrometers. We present limits from both a reanalysis of previous measurements of Γ_2 in ^{3}He spin exchange cells and from data in a test experiment searching for a change in Γ_2 upon the motion of an unpolarized test mass. The outlook for more sensitive measurements using this technique is discussed.

PACS numbers: 13.75.Cs, 13.88.+e, 14.20.Dh, 14.70.Pw, 14.80.Va

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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 μm 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

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

where m_n is the mass and $\vec{s} = \hbar\hat{\sigma}/2$ is the spin of the polarized particle, $\hbar$ is Planck's constant, λ is the interaction range, $\hat{\mathbf{r}} = \mathbf{r}/r$ 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 $\vec{\sigma}\cdot\vec{r}$ (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 (Γ_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 Γ_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 Γ_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

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greatly exceed that reached by Γ_1 measurements. We set a new limit on $g_s g_p$ 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 Γ_2 from the monopole-dipole interaction can be calculated in direct analogy with the Γ_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) Γ_1 (the longitudinal relaxation rate) comes from external interactions in which the polarization is lost, and Γ_2 (the transverse relaxation rate) comes from the dephasing of the spins. Γ_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]

$$\Gamma_2 \approx \frac{8\gamma^2 L^4}{175D} \left|\nabla H_z\right|^2 , \tag{2}$$

where D is the diffusion coefficient, H_z is the magnetic field along z, and γ 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 ω 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 $l = \frac{k_B T}{\sqrt{2}\pi d_m^2 p}$ and the average speed $\bar{v} = \sqrt{8k_B T/(\pi m)}$ where k_B is the Boltzmann constant, T is temperature, p is pressure, $d_m \simeq 0.62 \times 10^{-10}$ 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 Γ_1 and Γ_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 Γ_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 λ. The monopole-dipole interaction potential seen by the polarized gas at position $\mathbf{r}(\rho,\theta,z)$ 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

$$V(\mathbf{r}) = \frac{g_s g_p N \hbar^2 \lambda}{4m_n} e^{-z/\lambda}(1 - e^{-d/\lambda}), \tag{3}$$

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

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 Γ_2 as

$$\begin{aligned}\Gamma_2 &= \frac{1}{LS}\int_0^L \Gamma_2(z) S \mathrm{d}z \\ &= \frac{8L^3}{175D}\left[\frac{g_s g_p N\hbar(1 - e^{-d/\lambda})}{4m_n}\right]^2 \int_0^L e^{\frac{-2(z+d_0)}{\lambda}} dz\end{aligned} \tag{5}$$

where S is the cross sectional area of the cylindrical cell. After averaging Γ_2 over the cell volume, one derives a relation between the product of the monopole-dipole couplings $g_s g_p$ and Γ_2:

$$g_s g_p = \frac{2m_n}{\hbar N L^2}(175\, D\, \Gamma_2)^{1/2} f(\lambda), \tag{6}$$

where

$$f(\lambda) = \left(\frac{L}{\lambda}\right)^{1/2} e^{d_0/\lambda}(1 - e^{-d/\lambda})^{-1}(1 - e^{-2L/\lambda})^{-1/2}. \tag{7}$$

We believe that measurements of Γ_2 have the potential for greater sensitivity in probing the monopole-dipole potential for high pressure cells than measurements of Γ_1. The ratio Γ_1/Γ_2 in the short mean free path limit for polarized atoms in the same magnetic field gradient is[23]

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

where Ω_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 $\Gamma_1/\Gamma_2 = 1.9 \times 10^{-11}$. Γ_2 measurements are intrinsically more sensitive and convenient than Γ_1 measurements in searching for the monopole-dipole interaction.

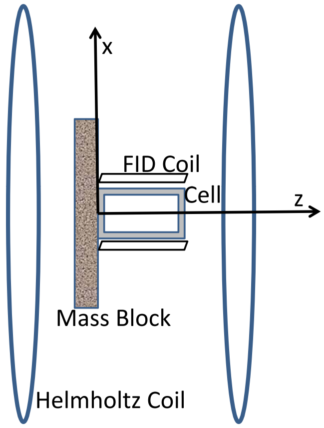

Figure 1: Polarized ^{3}He gas is sealed in a cylindrical cell of diameter a, length L, and wall thickness d_0. A plate of thickness d and transverse dimensions much greater than a is perpendicular to the z-axis. The cell was in the center of a Helmholtz coil, which provided a magnetic field, as well as in the center of another pair of coils with almost the same size as the cell, which were used for free induction decay (FID) NMR measurements.

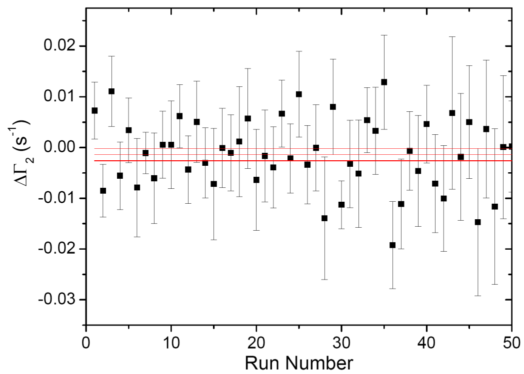

Figure 2: The change in Γ_2 when the PTFE block was moved in and out, denoted by $\Delta\Gamma_2$. The error bars show the standard deviation of the mean for each group of 5 measurements of $\Delta\Gamma_2$.

III. EXPERIMENT AND RESULTS

We conducted a proof of principle for our proposed technique to search for a monopole-dipole interaction by measuring the change in Γ_2 of polarized ^{3}He gas upon motion of a nonmagnetic unpolarized test body near and away from the gas. The mass of the cell wall can also make a contribution to Γ_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 4.4×10^{19} cm^{-3}, nitrogen about 1.6×10^{18} cm^{-3}, and a small amount of Rb (¡0.1 g) for spin exchange optical pumping [26]. There is a small volume about $\pi \times (0.25\,\text{cm})^2 \times 1$ 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 $\simeq 40\%$ 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 Γ_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 $8\,\text{cm} \times 8\,\text{cm} \times 2\,\text{cm}$ 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 $\Gamma_{2,n}^{(in)}$ and $\Gamma_{2,n}^{(out)}$, respectively. Γ_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 Γ_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 $\Delta\Gamma_{2,n} = \Gamma_{2,n}^{(out)} - \Gamma_{2,n}^{(in)}$ in Fig. 2 as one point with an uncertainty $\sqrt{\left(\Delta\Gamma_{2,n}^{(in)}\right)^2 + \left(\Delta\Gamma_{2,n}^{(out)}\right)^2}$. This difference measurement was repeated 50 times. The final Γ_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 λ which excludes an area in the $(g_s g_p,\, \lambda)$ plane above the line defined by

$$g_s^{(n)} g_p^{(n)} = 2.8 \times 10^{-21} \Delta\Gamma_2^{1/2} f(\lambda). \tag{9}$$

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

$$g_s^{(n)} g_p^{(n)} = \frac{m_n (350\, D\, \Gamma_2)^{1/2}}{\hbar N L^2} \frac{(L/\lambda)^{1/2}}{(1 - e^{-d_0/\lambda})}. \tag{10}$$

Various experiments have observed very small relaxation rates of polarized high density noble gases. For example, in Refs. [28] and [29] 3.4×10^{19} ^{3}He atoms, 8.1×10^{18} ^{129}Xe atoms, and 1.8×10^{19} 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 4×10^{-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

$$g_s^{(n)} g_p^{(n)} = 4.2 \times 10^{-20} \Gamma_2^{1/2} \frac{(L/\lambda)^{1/2}}{(1 - e^{-d_0/\lambda})}. \qquad (11)$$

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 Γ_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 Γ_2 [22, 25] which we list here along with a qualitative discussion of their possible effect on our proposed search.

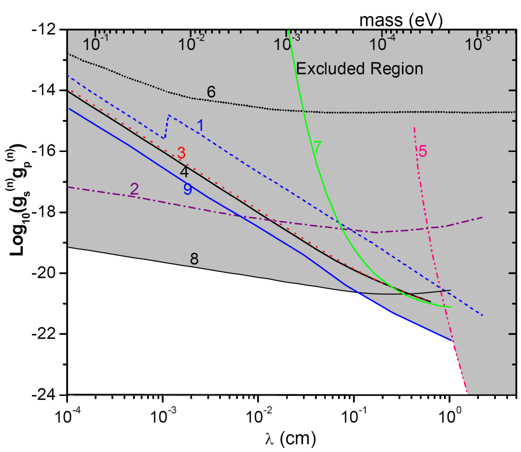

Figure 3: Constraints on the monopole-dipole coupling strength $g_s^{(n)} g_p^{(n)}$: 1. Blue, from Ref.[18]; 2. Purple, from Ref.[13]; 3. Red, by using low density ^{3}He gas, from Ref. [20]; 4. Black, by using low density ^{3}He gas, from Ref. [20]; 5. Pink, from Ref.[9]; 6. Black, from Ref.[12]; 7. 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.

(1) Radiation damping, i.e., the action of the currents induced in the pickup coils on the ^{3}He magnetization[31], can perturb Γ_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 Γ_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 Γ_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 Γ_2. A finite electrical conductivity of the test mass can support eddy currents which produce electromagnetic fields that change Γ_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) Γ_2, which is ultimately limited by Γ_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 Γ_1 [22, 33] and Γ_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 Γ_1 in addition to the losses from tipping the polarization for Γ_2 measurements, and the Γ_2 measurements themselves are performed at different times corresponding to different test mass positions. The timescale for residual contributions to Γ_2 proportional to ^{3}He polarization are determined by the tip losses and Γ_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-

surement, for example, cancels a systematic from a linear time-dependent drift in Γ_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 λ (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}He polarization relative to the magnetic field to confirm the $\vec{s}\cdot\vec{r}$ 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 Γ_2 of polarized ^{3}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 Γ_1 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.

VI. ACKNOWLEDGMENTS

We thank Dr. Y. N. Pokotilovski and Dr. A. K. Petukhov for their inspiring communications. This work was supported in part by NSF PHY-0116146, and the development of polarized ^{3}He apparatus at NIST is supported in part by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under award DE-FG02-03ER46093. The work of WMS was supported in part by the Indiana University Center for Spacetime Symmetries.

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