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Searching for New Spin-Velocity Dependent Interactions by Spin Relaxation of Polarized ^{3}He Gas

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We have constrained possible new interactions which produce nonrelativistic potentials between polarized neutrons and unpolarized matter proportional to $\alpha\vec{\sigma}\cdot\vec{v}$ where $\vec{\sigma}$ is the neutron spin and $\vec{v}$ is the relative velocity. We use existing data from laboratory measurements on the very long T_1 and T_2 spin relaxation times of polarized ^{3}He gas in glass cells. Using the best available measured T_2 of polarized ^{3}He gas atoms as the polarized source and the earth as an unpolarized source, we obtain constraints on two new interactions. We present a new experimental upper bound on possible vector-axial-vector(V_{VA}) type interactions for ranges between $1 \sim 10^8$m. In combination with previous results, we set the most stringent experiment limits on $g_V g_A$ ranging from $\sim \mu$m to $\sim 10^8$m. We also report what is to our knowledge the first experimental upper limit on the possible torsion fields induced by the earth on its surface. Dedicated experiments could further improve these bounds by a factor of ~ 100. Our method of analysis also makes it possible to probe many velocity dependent interactions which depend on the spins of both neutrons and other particles which have never been searched for before experimentally.

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In recent years, various models of new physics beyond the Standard Model have been studied in which new massive particles such as the axion, familon and majoron, *etc.* were theoretically introduced [1]. New macroscopic interactions meditated by WISPs (weakly-interacting sub-eV particles) have also been theoretically proposed. The interaction ranges of these new forces range from nanometers to astronomical distance scales. The fact that the dark energy density is on the order of $(1\ \text{meV})^4$ corresponding to a length scale of $100\ \mu$m also encourages people to search for new physical phenomena around this scale [2]. Various experiments have been performed or proposed recently to search for a subset of these new interactions which could couple to the spin of the neutron/electron[3–11].

The idea that exotic new interactions might be spin/velocity dependent is quite fascinating. For example, the theoretically proposed photinos interact with nuclei only through spin-dependent forces [12]. Ref.[13] analyzed the possible nonrelativistic potentials between spin-1/2 fermions from spin 0 and spin 1 boson exchange and found 16 possible new interactions, 10 of which depend both on the spin states and the relative velocity between particles. Torsion, a twisting of spacetime coupled to intrinsic spin, which has been included in many models which extend general relativity [14, 15], can also induce spin-velocity dependent interactions between an unpolarized source and the spin. Hari-Dass interaction [16] is another example of spin-velocity dependent interactions.

Either for the torsion-induced or the vector-axial-vector (V_{VA}) type interaction, the spin of polarized noble gases like ^{3}He can interact with an unpolarized source through a potential proportional to

$$V = \alpha\vec{\sigma}\cdot\vec{v}, \tag{1}$$

where $\vec{\sigma}$ are the Pauli matrices and $\vec{v}$ is the relative velocity between the spin and the unpolarized source. The parameter α has dimensions of momentum and depends on factors specific to the interaction such as the probe to source distance, the source mass or the nucleon number, *etc.* Since it is known that the spin of the ^{3}He nucleus is dominated by the spin of its unpaired neutron [17], in this paper we interpret constraints on α in terms of neutron properties. To help develop intuition for the physical effects of V it is useful to imagine that V produces an effective pseudo-magnetic field:

$$V = \vec{\mu}\cdot\vec{B}', \tag{2}$$

where $\vec{\mu}$ is the magnetic moment, γ the gyromagnetic ratio of the spin polarized particle, and $\vec{B}' = 2\alpha\vec{v}/\hbar\gamma$ the pseudo-magnetic field.

Spin polarized neutron/atom beams are convenient to probe these spin-velocity dependent interactions since a large relative velocity between the probe and the source can be easily realized. However, the number of the probe particles is limited by the phase space density of the beam. Larger phase space densities of polarized probe particles can be obtained by using ensembles of polarized gases, but the polarized noble gas ensembles which can support sensitive NMR measurements of the spin dynamics needed for this search are usually sealed in glass cells. It would be technically difficult to realize a large relative velocity between the source mass and the probe particles inside delicate glass cells.

Though $\langle\vec{v}\rangle$ is zero for atoms of the glass sealed noble gas, $\langle v^2\rangle$ is not. The nonzero $\langle v^2\rangle$ in the presence of a $\vec{\sigma}\cdot\vec{v}$ type interaction will change the spin relaxation times of polarized noble gases. Although it is a second order effect, in this case there is no need for bulk motion of either the polarized or unpolarized masses in the experiments. Thus it is possible to detect or constrain the new physics by the longitudinal spin relaxation time (T_1) or the transverse relaxation time (T_2) of polarized noble gases. Here T_1 refers to the mean time for a spin polarized ensemble to return to its thermal equilibrium state and T_2 the mean time that polarized spins to lose coherence when processing along the longitudinal main field while the polarization is tipped to the transverse direction [18]. For the best available T_1 [19] and T_2 [20, 21] data, our research indicates that the constraint on α from T_2 is tighter than that from T_1. In what follows, we will first describe how the $\alpha\vec{\sigma}\cdot\vec{v}$ interaction affects the spin relaxation times of the polarized ^{3}He gas, then we will constrain α by using the best available T_2 measured in the experiment. Furthermore, by using this constraint of α and the earth as a source, we obtain new limits on two different types of new interactions, vector-axial-vector interaction (V_{VA}) and a linear combination of the time component of possible torsion fields from the earth.

CONSTRAINING α BY T_1 AND T_2 OF SPIN POLARIZED ^{3}HE GAS

Highly polarized, dense ensembles of polarized ^{3}He gas have been developed over the last few decades for scientific applications in nuclear/particle physics, neutron spin filters and medical imaging [22–24]. There are already some examples using the spin relaxation time to constrain the scalar-pseudo-scalar type [25] interaction which is spin dependent. T_1 is used in Ref.[19] while T_2 in Refs.[21, 26]. Assume the magnetic field is along $\hat{z}$, then using the Redfield theory [21, 27], the longitudinal and transverse relaxation times of the polarized ^{3}He gas due to a randomly fluctuating magnetic field can be expressed as:

$$\Gamma_1 = \frac{1}{T_1} = \frac{\gamma^2}{2}[S_{Bx}(\omega_0) + S_{By}(\omega_0)],$$
$$\Gamma_2 = \frac{1}{T_2} = \frac{\gamma^2}{4}[S_{Bx}(\omega_0) + S_{By}(\omega_0) + 2S_{Bz}(0)], \quad (3)$$

where

$$S_{Bx}(\omega_0) = \int_{-\infty}^{+\infty}\langle B_x(t)B_x(t+\tau)\rangle e^{-i\omega_0\tau}d\tau. \quad (4)$$

Here $\langle ...\rangle$ represents the ensemble average, B_x is the $\hat{x}$ component of the fluctuating magnetic field as seen in the rest frame of the diffusing polarized ^{3}He atom, and $\omega_0 = \gamma B_0$ is the Larmor frequency. Using above formulas, it is easy to see that the pseudo-magnetic field induced by the $\alpha\vec{\sigma}\cdot\vec{v}$ interaction will change T_1 as follows:

$$\Gamma_1 = \frac{1}{T_1} = \frac{4\alpha^2}{\hbar^2}\int_{-\infty}^{+\infty}\langle v_x(t)v_x(t+\tau)\rangle e^{-i\omega_0\tau}d\tau. \quad (5)$$

When the Lamor frequency ω_0 is much larger than $1/\tau_D$ with $\tau_D \propto L^2/D$ (L is the characteristic length of the gas sealed cell in the dimensions transverse to the magnetic field), the autocorrelation function for the velocity is [27]:

$$\langle v_x(t)v_x(t+\tau)\rangle = \langle v_x^2\rangle e^{-\frac{|\tau|}{\tau_c}} = \frac{1}{3}\langle v^2\rangle e^{-\frac{|\tau|}{\tau_c}}, \quad (6)$$

where τ_c is the average collision time of the atoms.

Plugging in the data given in Ref.[19], $\tau_c = 3\times 10^{-10}$s, $T_1^{\rm rem} = 2664$h (1σ value), $\omega_0 = 10^5\text{s}^{-1}$, we obtain an upper limit to α as:

$$\alpha \le 7.7\times 10^{-37}\text{kg}\cdot\text{m}\cdot\text{s}^{-1}. \quad (7)$$

Similarly, the relaxation time T_2 caused by the $\alpha\vec{\sigma}\cdot\vec{v}$ type interaction can be expressed as:

$$\frac{1}{T_2} = \frac{\alpha^2}{\hbar^2}\int_{-\infty}^{+\infty}[\langle v_x(t)v_x(t+\tau) + v_y(t)v_y(t+\tau)\rangle e^{-i\omega_0\tau} + 2\langle v_z(t)v_z(t+\tau)\rangle]d\tau. \quad (8)$$

Here we need to calculate $\langle v_x(t)v_x(t+\tau)\rangle$ under the condition that the magnetic field is small such that Eqn.(6) cannot be applied anymore. According to Refs.[28, 29], we can derive

$$\int_{-\infty}^{+\infty}\langle v_x(t)v_x(t+\tau)\rangle e^{-i\omega_0\tau}d\tau = \omega_0^2 S_x(\omega_0), \quad (9)$$

where $S_x(\omega_0)$ is defined as the Fourier transformation of $\langle x(t)x(t+\tau)\rangle$. Now the problem of finding the velocity autocorrelation function reduces to calculating the position autocorrelation function. The latter can be solved using diffusion theory [21, 27]. For a spherical cell with radius R, it can be shown that:

$$S_x(\omega_0) = 4R^2\sum_n \frac{1}{x_{1n}^2(x_{1n}^2-2)}\frac{\frac{x_{1n}^2 D}{R^2}}{(\frac{x_{1n}^2 D}{R^2})^2 + \omega_0^2}, \quad (10)$$

where x_{1n} are the zeros of the derivatives of spherical Bessel functions [30] and D is the diffusion constant of the ^{3}He gas. The relaxation time T_2 can be finally expressed as

$$\Gamma_2 = \frac{1}{T_2} = \frac{\alpha^2}{\hbar^2}\omega_0^2[S_x(\omega_0) + S_y(\omega_0)]. \quad (11)$$

Now using the data given in Ref.[20], which used a radius of the spherical cell $R = 3$cm with $D = 470\text{cm}^2\cdot\text{s}^{-1}$ and

$\Gamma_2 = 8.0 \times 10^{-7}\mathrm{s}^{-1}$ (1σ value [21]) into Eqn.(11), we obtain an upper limit on α as

$$\alpha \leq 6.9 \times 10^{-37}\mathrm{kg}\cdot\mathrm{m}\cdot\mathrm{s}^{-1}. \tag{12}$$

This upper limit is slightly more stringent than that given by Eqn.(7) and so we are going to use T_2 to constrain the possible spin-velocity dependent new physics. However, the T_1 estimate is simple and direct, and in some more complicated cell geometries one can get a constraint more easily and quickly by using the T_1 estimate.

CONSTRAINING NEW INTERACTIONS USING THE EARTH AS A SOURCE

Vector-axial-vector interaction

Taking advantage of the fact that there are about 10^{42} polarized electrons in the earth, Ref.[10] used the polarized electron spins of the earth as a source to constrain several possible exotic long-range spin-spin interactions. Inspired by this spirit, we notice that there are 10^{51} nucleons in the earth. It might be even more advantageous to use the earth as a source to constrain some spin-velocity dependent interactions. For example, for the vector-axial-vector interaction $V_{VA}(r)$ from the Lagrangian $\mathcal{L}_X = \bar{\psi}(g_V\gamma^\mu + g_A\gamma^\mu\gamma_5)\psi X_\mu$, this parity violating potential has the form:

$$V_{VA}(r) = \frac{\hbar g_V g_A}{2\pi}\frac{e^{-r/\lambda}}{r}\vec{\sigma}\cdot\vec{v}, \tag{13}$$

where $\lambda = \hbar/m_X c$ is the interaction range, m_X the mass of the new vector boson and g_V,g_A the vector and axial vector couplings. Using the earth as a source, the Vector-Axial(V-A) potential generated by the earth on its surface is[31]:

$$V_{VA} = \hbar g_V g_A \rho_N \lambda^2[(1-\frac{\lambda}{R_\oplus})e^{-\frac{\Delta y}{\lambda}} +(1+\frac{\lambda}{R_\oplus})e^{-\frac{2R_\oplus}{\lambda}}]\vec{\sigma}\cdot\vec{v}, \tag{14}$$

where ρ_N is the nucleon number density of the earth, $R_\oplus$ the earth radius, Δy the probe to ground distance. If the force ranges are close to or smaller than the typical $\sim$ 1m distance between the cell and ground, the earth source can be considered as semi-infinite and Eqn.(14) is still valid as we will see later. If the new interaction $V_{VA}(r)$ exists, it will induce the $\alpha\vec{\sigma}\cdot\vec{v}$ interaction on the earth surface and affect the relaxation times of the spin polarized ^{3}He gas. Plugging in $\rho_N = 3.3\times10^{30}\mathrm{m}^{-3}$ and using Eqn.(11), we get

$$g_V g_A \lambda^2[(1-\frac{\lambda}{R_\oplus})e^{-\frac{\Delta y}{\lambda}}+(1+\frac{\lambda}{R_\oplus})e^{-\frac{2R_\oplus}{\lambda}}] \leq 2.0\times10^{-34}\mathrm{m}^2. \tag{15}$$

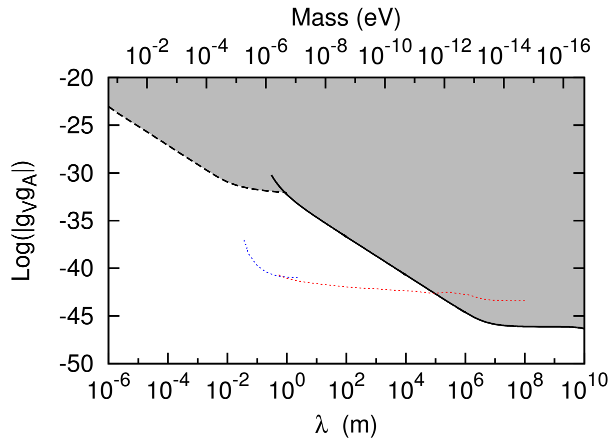

FIG. 1: (Color online)Constraint to the coupling constant product $|g_V g_A|$ as a function of the interaction range λ(new vector boson mass). The bold solid line is the result of this work; The dashed line is the result of Ref.[4]; The blue and red dotted lines are the result of Ref.[33] which were derived by combining g_V of Refs.[34, 35] with g_A of Ref.[9] from separate experiments.The dark grey area is excluded by experiments of previous work [4] and this work, both directly constrain $|g_V g_A|$ in a single experiment.

The derived constraint on $g_V g_A$ is shown in FIG.1. For $\lambda \leq \Delta y$ much smaller than $R_\oplus$, the nonzero Δy limits the practical force range. In this case Eqn.(14) can be approximated as:

$$V_{VA} = \hbar g_V g_A \rho_N \lambda^2 e^{-\frac{\Delta y}{\lambda}}\vec{\sigma}\cdot\vec{v}, \tag{16}$$

which is the same as the V-A potential derived in Ref.[11] for a plane plate in which the thickness goes to infinity.

In comparison with the previous result given by Ref.[4], the constraint derived in this work has no improvement for ranges below $\sim$ 1m. In the long distance limit with $\lambda \gg R_\oplus$, Eqn.(15) becomes:

$$g_V g_A \leq 7.4\times10^{-47}. \tag{17}$$

If the constraint derived from the neutron spin rotation experiment is extended to the long range $\sim 10^8$m, our work improves the existing direct experimental upper bound by as much as $\sim$ 16 orders of magnitude. When comparing with the results of Ref.[33], which were derived by combining g_V in Refs.[34, 35] and g_A in Ref.[9], we get $\sim$ 3 orders of magnitude improvement. The present work gives the best known constraint on $|g_V g_A|$ for ranges between 10^{-6}m to 10^8m. We emphasize that the limits on the vector-axial-vector interaction presented here are derived directly from a single laboratory experiment.

Torsion induced by the earth on its surface

Using neutron spin rotation in liquid helium, Refs.[36, 37] constrained possible "in-matter "torsion for the first time. For torsion mentioned here, we refer to exactly the same type as in Refs.[36, 37]. These works showed that, for nonrelativistic motion of a spin in a torsion field, some time components of the torsion field couple to the spin through the form [36] :

$$V = \zeta\vec{\sigma}\cdot\vec{v}, \tag{18}$$

which has exactly the same form as Eqn.(1). ζ includes all other factors such as the distance, the source mass, *etc.* As in Refs.[36–38], here we only consider the leading order of the torsion background which is a constant. Constraints on Earth-sourced torsion had been discussed in Ref.[38], where rotating the apparatus or comparing the behavior of particles and antiparticles were proposed to detect torsion. We have found that relaxation time of the polarized ^{3}He gas can constrain ζ without moving the apparatus. Using the earth as a source and applying Eqn.(12), it is easy to show that in natural units

$$\zeta = \alpha \leq 1.3\times 10^{-18}\text{GeV}. \tag{19}$$

OTHER APPLICATIONS AND PROPOSED EXPERIMENTS

Applying the method to the axial-axial-vector interaction — It is possible to apply this analysis to other possible spin-velocity interactions. We have tried to constrain the axial-axial-vector interaction(V_{AA}) which also comes from $\mathcal{L}_X$. We find no improvement for ranges above $\sim$ 1m in comparison with Ref.[9].

Using the cell wall as a source– For V_{VA} or V_{AA} and ranges around $\sim$ 1mm, one might think to use the cell wall as a source, as done in Refs.[19, 21]. In this case α is not a constant anymore and cannot be moved out of the ensemble average. We would therefore need to calculate more complicated correlation functions such as $\langle\alpha[x(t),y(t),z(t)]\alpha[x(t+\tau),y(t+\tau),z(t+\tau)]v_x(t)v_x(t+\tau)\rangle$. The situation is simpler for T_1. The correlation time of velocities is $\sim 10^{-10}$s, and on this time scale the atom can only move a distance $\sqrt{\langle v^2\rangle}\tau\sim 10^{-7}$m. In this short distance for the force ranges under consideration, $\alpha(t)$ and $\alpha(t+\tau)$ can be treated as constants and moved out of the ensemble average. We have verified this approximation by Monte Carlo simulations. Using T_1, we obtain constraints for $|g_Vg_A|\sim 3$ orders less stringent than Ref.[4] and for g_Ag_A more than $\sim$ 1 order less stringent than Ref.[3]. For T_2, the situation is much more complicated. If we approximate the spherical cell as a cube, and consider each wall as an infinite plate as in Ref.[21], we could get a constraint for $|g_Ag_A|$. The result is also more than one order less sensitive than the existing constraint. This is not surprising since the relaxation times depend on the interactions through second order processes. At short distances, with a small amount of the source mass as the cell wall, it is hard for the relaxation time method to compete with the first order methods as in Refs.[3–6, 8].

Possibilities of applying the method to spin-spin-velocity dependent interactions— It is also possible to apply this method to search for many other types of spin-spin-velocity interactions. There are 6 different types of these interactions out of the 16 total derived in Ref.[13]. For these interactions, not only a relative velocity between the source and probe is required, but also both the probe and source have to be spin polarized. Thus they are even more difficult to search for experimentally. To the best of our knowledge, most of these interactions have never been experimentally searched for. However, as in Ref.[10], if we use polarized electrons in the earth as a source and the relaxation time method presented in this work, it would be possible to constrain these velocity dependent electron-spin-neutron-spin interactions for the first time.The method presented in this work therefore opens a new path for probing various new interactions which are spin-spin-velocity dependent.

Possible improvement in sensitivity from T_1 — We can try to further improve the sensitivity by dedicated experiments. Either for T_1 or T_2, the key is to constrain α better. For T_1, in the limit that $1/\tau_D \ll \omega_0 \ll 1/\tau_c$ we find that $\alpha\propto\sqrt{n/T_1}$ after optimizing parameters. Since the measured T_1 is already as long as several thousand hours for polarized ^{3}He with cell pressure of $\sim$ 1 bar, it seems that the most promising way to improve the sensitivity is to reduce the gas number density. If n is reduced to $\sim$ 1 mbar, and the conditions for T_1 and ω_0 remain the same as before, the sensitivity could be improved by a factor of $\sim$ 30 if the same long T_1 is observed. Furthermore, we notice that in Ref.[21], by subtracting the relaxation contributed from the magnetic field gradient, the residual T_2 from other sources was improved by about one order of magnitude from $\sim$ 60h to $\sim$ 500h. Although a twice better T_2 was reported in Ref.[39], no improvement in sensitivity can be made without knowing the magnetic field gradients. For T_1, according to our best knowledge, the contribution from the magnetic field gradient has not been subtracted yet. For T_1 measured as long as a few thousand hours, the relative magnetic field gradient, for example $\partial_x B/B_0$ is usually in order of $\sim 10^{-4}\text{cm}^{-1}$. At this level, the gradient contributed relaxation is also in order of $\sim$ 1000h. There could be improvement for the T_1 method by precisely mapping the holding magnetic field. By reducing the gas pressure and mapping the field precisely, we might get an improvement in sensitivity by a factor of $\sim$ 100.

Possible improvement in sensitivity from T_2—A similar result is obtained using T_2: $\alpha\propto\sqrt{n/T_2}$ after optimizing parameters. Since the cell pressure is already as low as a few mbars [20], it is hard to imagine that sensitivity can be increased substantially by further reducing the pressure. Also the diffusion theory will break down for a much lower cell pressure, though the Redfield theory is still valid [29, 40]. On the other hand, lower cell pressure means fewer probing particles, a factor which will eventually dominate. The optimum gas pressure in this case is a theoretically interesting question. One might find the answer by using the theory presented in Refs.[29, 40]. For a ∼mbar cell, if a thousand-hour-long T_2 could be observed the sensitivity could be improved by one order of magnitude.

CONCLUSION

By using the spin relaxation times of polarized ^{3}He gas measured in previous experiments and the earth as a source, we have constrained two types of possible new interactions which are neutron spin-velocity dependent. We found that the best available T_2 relaxation times give slightly better constraints. We derived new experimental limits on possible Vector-Axial type interactions with ranges from ~ 1m to $\sim 10^8$m. At the distance of $\sim 10^8$m, the limit is improved by ~ 16 orders in magnitude in comparison with the previous result of the neutron spin rotation experiment. In combination with the previous result [4] which is more sensitive at short distances, we present the most stringent constraint derived directly from experiments on $g_V g_A$ ranging from $\sim 10^{-6}$m to $\sim 10^8$m (FIG.1). The methods presented in this work open up new possibilities to search for or constrain many possible spin-spin-velocity dependent interactions. By dedicated experiments, an improvement in sensitivity by a factor of ~ 100 might be achieved using these ideas.

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