Searching for Axion Like Particles using Spin Polarized Noble Gases and Other Methods

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Exotic spin dependent interactions can be meditated by ALPs(Axion Like Particle). Not only ALPs are possible candidates for dark matter, but also they might provide the most promising solution to the strong CP problem. Furthermore, recently, various models of new physics beyond the standard model have been studies in which new massive particles such as axion, familon, and majoron, etc. were theoretically introduced. Many of these exotic new interactions are spin dependent. For these interactions to be detected, the source or the probe particles have to be spin polarized. Spin polarized neutron beam, atom beam or noble gases are good probes to detect these new interactions. We proposed to use ^{3}He atom beams to search for three types of new interactions[1]. Using the atom beam method, sensitivities on three different types of spin dependent interactions could be improved by as much as 10^2 to 10^8 over the current experiments at the millimeter range. We Searched for New Spin- and Velocity-Dependent Interactions by spin relaxation of polarized ^{3}He Gas. 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 vectoraxial-vector (VVA) type interactions for ranges between 1 and 10^8 m[2].

1 Introduction

New physics beyond the Standard Model is possible. New interactions meditated by new particles were theoretically proposed in many occasions[3] . New macroscopic interactions meditated by WISPs (weakly-interacting sub-eV particles) is an example. 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 μm also encourages people to search for new physical phenomena around this scale [?]. The Axion is another example. It is not only a possible dark matter candidate but also provides probably the most promising solution to the strong CP problem. 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[4, 5, 6, 7, 8, 9, 10, 11, 1].

2 Another Motivation to Search for New Interactions

The idea that new interactions might be spin dependent is quite fascinating. Except motivations for solving the dark matter and the strong CP problem, there could be another motivation.

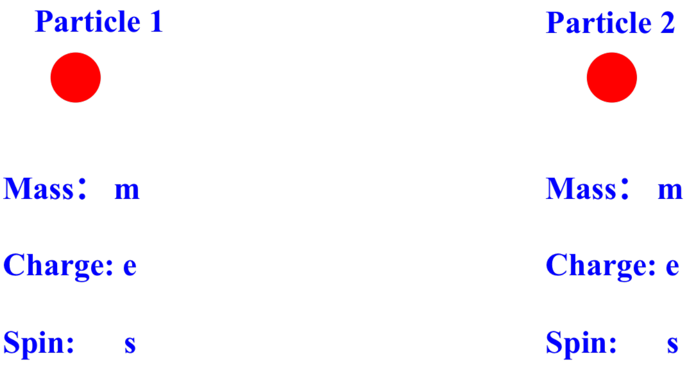

Figure 1: Basic properties of two fundamental particles

As shown in Fig.1, if there are two fundamental particles, what are their most important properties? Probably, they are the mass, charge and spin of the particles.

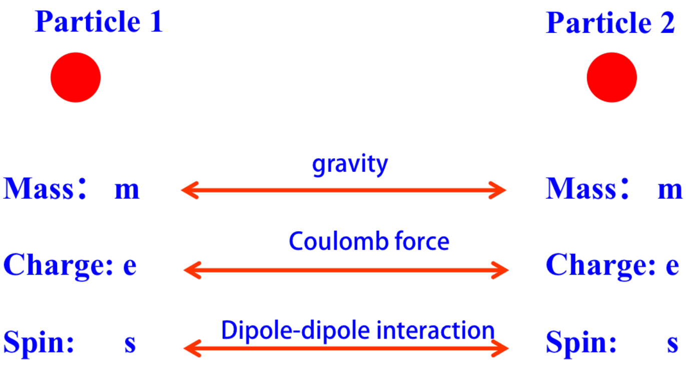

Figure 2: Conventional interactions between two fundamental particles

As shown in Fig.2, for the two fundamental particles, there are conventional interactions which couple their fundamental properties. In more detail, there is gravity which couples the two particles's mass, Coulomb force which couples the two charges and magnetic dipole-diople interaction which couples two spins.

Could it be possible that there are new interactions which can couple different types of the particle properties? As shown in Fig.3, could there be a new interaction which couples the

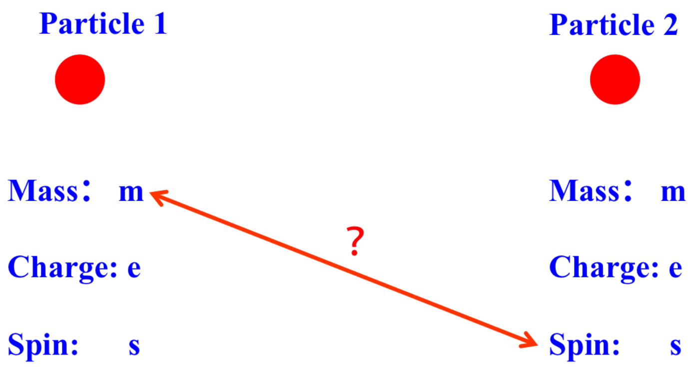

Figure 3: New interactions which can couple different types of properties

mass to the spin of the particles? Considering mixing is not uncommon in modern physics, new experiments measuring the interactions shall be performed to verify if the interactions exist.

3 Several New Spin Dependent Interactions

In Ref.[12], interactions between non-relativistic fermions assuming only rotational invariance can be classified into 16 different operator structures involving the spin and momenta of the particles. For all these sixteen interactions, only one interaction does not require either of the two particles to be spins polarized; six interactions require at least one particle to be spin polarized and the remaining nine require both particles to be spin polarized.

Experimental constraints on possible new interactions of mesoscopic range which depend on the spin of one or both of the particles are much less stringent than those for spin-independent interactions. This is not surprising since macroscopic objects with large nuclear or electron polarization are not easy to arrange outside an environment that includes large magnetic fields, which can produce large systematic effects in delicate experiments. On the other hand the addition of the spin degree of freedom opens up a large variety of possible new interactions to search for which might have escaped detection to date.

Among the six type interactions which only one particle needs to be spin polarized, the scalar-pseudoscalar interaction $V_{SP}(r)(V_{9,10}$ in Ref.[12]'s notation) originated from the coupling $\mathcal{L}_\phi = \bar{\psi}(g_s + i g_p \gamma_5)\psi\phi$[13, 14],or the monopole dipole interaction has begun to attract more scientific attention recently. The interaction between the polarized spin 1/2 fermion of mass m and another unpolarized nucleon can be expressed as:

$$V_{SP}(r) = \frac{\hbar^2 g_S g_P}{8\pi m}(\frac{1}{\lambda r} + \frac{1}{r^2}) \exp(-r/\lambda) \vec{\sigma} \cdot \hat{r} \tag{1}$$

where $\lambda = \hbar/m_\phi c$ is the interaction range, m_ϕ is the mass of the new scalar boson,$\vec{s} = \hbar\vec{\sigma}/2$ is the spin of the polarized particle and r is the distance between the two interacting particles.

While for the vector-axial-vector interaction $V_{VA}(r)(V_{12,13}$ in Ref.[12]'s notation) originated from the coupling $\mathcal{L}_X = \bar{\psi}(g_V\gamma^\mu + g_A\gamma^\mu\gamma_5)\psi X_\mu$, this parity violating interaction has the form:

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

where $\vec{v}$ is the relative velocity between the probe particle and source particle,$\lambda = \hbar/m_X c$ is the interaction range, m_X is the mass of the new vector boson. $V_{VA}(r)$ is the Yukawa potential times the $\vec{\sigma}\cdot\vec{v}$ factor,which makes this interaction quite interesting. Another interaction requiring only one particle to be spin polarized is the axial-axial interaction $V_{AA}(r)(V_{4,5}$ in Ref.[12]'s notation), which is also originated from the $\mathcal{L}_X$ coupling, can be written as:

$$V_{AA}(r) = \frac{\hbar^2 g_A^2}{16\pi mc}(\frac{1}{\lambda r} + \frac{1}{r^2})\exp{(-r/\lambda)}\vec{\sigma}\cdot(\vec{v}\times\hat{r}) \tag{3}$$

All these interactions are in the form of $\vec{s}\cdot\vec{B'}$ where $\vec{B'}$ can be viewed as a pseudo magnetic field[14]. For an unpolarized source mass as a plane plate of thickness d and surface normal vector $\hat{y}$, as in Ref.[15, 14], for a spin polarized probe particle moving with velocity $\vec{v}$, the corresponding pseudo-magnetic fields due to these three interactions can be derived as:

$$\vec{B}_{SP} = \frac{1}{\gamma}\frac{\hbar g_S g_P}{2m}\rho_N \lambda e^{-\frac{\Delta y}{\lambda}}[1 - e^{-\frac{d}{\lambda}}]\hat{y} \tag{4}$$

$$\vec{B}_{VA} = \frac{2}{\gamma}g_V g_A \rho_N \lambda^2 e^{-\frac{\Delta y}{\lambda}}[1 - e^{-\frac{d}{\lambda}}]\vec{v} \tag{5}$$

$$\vec{B}_{AA} = \frac{1}{\gamma}\frac{g_A^2}{4}\rho_N\frac{\hbar}{mc}\lambda e^{-\frac{\Delta y}{\lambda}}[1 - e^{-\frac{d}{\lambda}}]\vec{v}\times\hat{y} \tag{6}$$

where $\Delta y > 0$ is the distance from the probe particle to the sample surface,ρ_N is the nucleon number density of the sample,γ the gyromagnetic ratio of the probing particle.

4 Searching for New Interactions Using Polarized ^3He Beams

In order to further improve the sensitivity of detecting the spin dependent short range interactions, we propose an experiment using nuclear spin polarized ^3He atom beams. Though in principle other spin-1/2 species as ^{129}Xe might also work, the polarized ^3He beam technique is more convenient since it has been well developed and applied to study the surface dynamics in condensed matter physics for many years[16, 17]. Ref.[18] is a very nice review for the recent developments of the so called polarized ^3He spin-echo technique. The schematic drawing of the proposed experiment is shown as Fig.1. The ^3He beam is firstly produced by the standard atomic beam method[**?**] of expanding compressed ^3He gas through a fine nozzle into vacuum. The speed of the beam can be controlled by adjusting the nozzle temperature. Then the beam is polarized by a beam polarizer which is made of hexapole magnets[17]. High intensity ($1.5 \times 10^{14} atoms/s$ reported in Ref.[19]), small size($2mm$ beam diameter at target according to Ref.[19]) and high polarization (more than 90% reported in Ref.[16]) ^3He beams can be produced. The polarized ^3He beam will then fly over the surface of the high density sample as a lead plate. The beam polarization will be rotated by the new spin dependent interactions if exist.

To reduce the background, the sample is firstly shielded with multiple cylindrical layers of high permeability materials as the μ-metal. In this way, the background field could initially be reduced to $\sim 10^{-9}T$[20]. Then the sample is further shielded by several superconducting layers as thin lead foils. The residual field could be reduced to be less than $10^{-11}T$[21]. After passing the sample area, the beam goes through an analyzer which is another series of hexpole magnets[22]. Only the right polarization state atoms are focused and can go through the analyzer to reach the helium detector. To further reduce the background, a double beam design is applied. As shown by Fig.4, another polarized beam produced by the same way will fly over the other sample surface, then it will be analyzed and detected similarly. The new spin dependent interaction signal can be extracted from the rotation difference between the two beam spins. In Ref.[23, 5], the uniformity of the residual background field reaches 10^{-4} level for a $5cm \times 5cm$ beam size. In this work, a higher uniformity is expected since the beam size is much smaller($2mm$ beam diameter). Thus from the difference, at most, a $\sim 10^{-15}T$ background is estimated and it is considered to be the main systematic for the proposed experiment. There are no systematics from the standard model since now the probe particle does not contact with the sample directly.

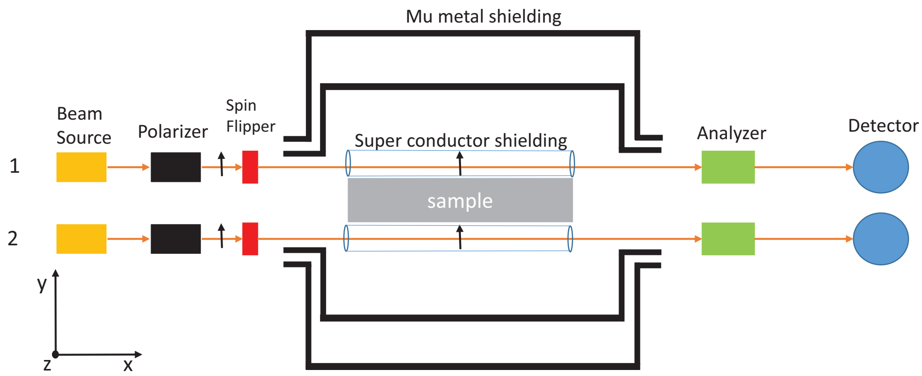

Figure 4: Color online, schematic drawing of the proposed experiment set up,top view .

For different spin dependent interactions, different polarization and beam path arrangements can be made to detect the specified interaction. In more detail, for the interaction $V_{SP}(r)$, the pseudo-magnetic field for beam 1 of Fig.4 is along $+\hat{y}$ direction while for beam 2 $-\hat{y}$ direction.

For $V_{VA}(r)$, the pseudo-magnetic field direction is along the beam moving direction either for beam 1 or beam 2. For $V_{AA}(r)$, the pseudo-magnetic field is along $+\hat{z}$ direction for beam 1 and $-\hat{z}$ for beam 2. To detect V_{SP}, both beam 1 and beam 2 can be set to be polarized along $+\hat{z}$ or $-\hat{z}$ direction. The difference of the spin rotation angles between the two beams will cancel the common background field effect and only leave the pseudo-magnetic field effect since it induces opposite rotation angle for each beam. Since the beams are polarized along $\hat{z}$, the spin rotation difference will not be sensitive to $V_{AA}(r)$ which is along the $\pm\hat{z}$ or $V_{VA}(r)$ which will rotate the two beam polarizations along $\hat{v} = +\hat{x}$ by the same amounts. Similarly, $V_{AA}(r)$ can be detected by setting the both beam polarizations along $+\hat{y}$ or $-\hat{y}$ direction. To detect $V_{VA}(r)$, one of the beam path could be flipped thus the relative velocity between the probe beam and the source sample is reversed. If the beam polarization is along $\hat{y}$ direction, the reversed beam setup will be only sensitive to $V_{VA}(r)$. This beam path reversing feature is possible for the atomic beam techniques since all the components are compact enough while it is not easy to be realized for the neutron beams without losing intensity significantly.

By incorporating background reduction designs as combination shielding by μ-metal and superconductor and double beam paths, the precision of spin rotation angle per unit length could be improved by a factor of $\sim 10^4$. By this precision, in combination with using a high density and low magnetic susceptibility sample source mass, and reversing one beam path if necessary, sensitivities on three different types of spin dependent interactions could be possibly improved by as much as $\sim 10^2$ to $\sim 10^8$ over the current experiments at the millimeter range[1].

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

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 [24]. For the best available T_1 [25] and T_2 [26, 27] 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.

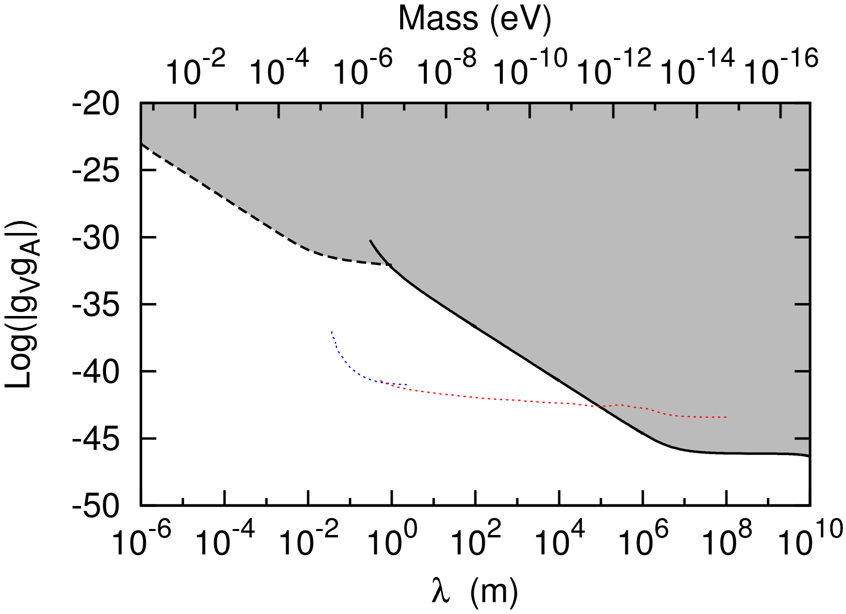

Figure 5: (Color online)Constraint to the coupling constant product $|g_V g_A|$ as a function of the interaction range λ(new vector boson mass). The bold solid line is the result of our previous work[2]; The dashed line is the result of Ref.[5]; The blue and red dotted lines are the result of Ref.[28] which were derived by combining g_V of Refs.[29, 30] with g_A of Ref.[10] from separate experiments.The dark grey area is excluded by experiments of previous work [5] and this work, both directly constrain $|g_V g_A|$ in a single experiment..

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 $\sim$ 1m to $\sim 10^8$m. At the distance of $\sim 10^8$m, the limit is improved by $\sim$ 16 orders in magnitude in comparison with the previous result of the neutron spin rotation experiment. In combination with the previous result [5] 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.5). 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 $\sim$ 100 might be achieved using these ideas.

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