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Constraining short-range spin-dependent forces with polarized helium 3 at the Laue-Langevin Institute

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We have searched for a short-range spin-dependent interaction mediated by a hypothetical light scalar boson with CP-violating couplings to the neutron using the spin relaxation of hyperpolarized ^3He . The walls of the ^3He cell would generate a depolarizing pseudomagnetic field.

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1 Theoretical motivations

Theories beyond the Standard Model (SM) of particle physics generally predict the existence of new phenomena at energies well below the electroweak scale. These new undiscovered particles with masses below 1 eV are called WISPs, which stands for Weakly Interacting Slim Particles.

Since these light particles can arise from the spontaneous breaking of some global symmetry (in the case of spin-0 particles), they are associated with very high energy scales. A well-motivated example is the hypothetical QCD Axion which arises from the global $U(1)$ Peccei-Quinn symmetry, introduced to solve the strong-CP problem [1]. Even if the mass of this particle is supposed very light (sub-eV), the probe energy scale are very large since the symmetry breaking scale parameter f_a lies between 10^9 GeV and 10^{12} GeV. Unlike the Axion, axion-like particles have no relation between their masses, the symmetry breaking scale and their coupling to the SM particles. Other than spin-0 ALPs, new light spin-1 bosons can arise from broken hidden $U(1)$ symmetries and they do not decouple from SM particles even in the limit of vanishing mass.

One way to investigate the coupling of these bosons to fermions is the search for *fifth forces* [2]. When the interaction between two fermions mediated by the exchange of a light boson does not depend on the spin of the two fermions, the force derives from a Yukawa potential with a typical interaction range $\lambda = \frac{\hbar c}{m_0 c^2}$. For a 0.1 eV boson, the corresponding range of the interaction is $2 \mu\text{m}$. Since it corresponds to macroscopic distances, numerous experiments have been realized to probe this fifth force.

Now, instead of pure scalar couplings which give a Yukawa potential, one can consider a pseudoscalar coupling between the boson and the fermions. The interaction becomes *spin-dependent* and cannot be probed by fifth force experiments. We considered a interaction potential between a spin and a (unpolarized) mass [3]

$$V = g_s g_p \frac{\hbar \hat{\sigma} \cdot \hat{r}}{8\pi M c} \left(\frac{m_\phi}{r} + \frac{1}{r^2} \right) \exp(-m_\phi r) \equiv -\vec{\mu} \cdot \vec{b}_a \quad (1)$$

where $\hbar \hat{\sigma}/2$ is the spin of the probe particle, M the mass of the polarized particle, g_s and g_p the coupling constant at the vertices of polarized and unpolarized particles corresponding to a scalar and a pseudoscalar interactions. The potential (1) can be interpreted as a pseudomagnetic field generated by the unpolarized particle on the polarized particle.

Let us consider a ^3He polarized gas contained in a glass cell. The source of the interaction acting on the ^3He is the nucleons in the walls of the cell. Then each helium spin will locally probe an effective pseudomagnetic field

$$b(x) = g_s g_p \frac{\lambda \hbar}{2m\gamma} e^{-x/\lambda} \left(1 - e^{-d/\lambda} \right), \quad (2)$$

with $\gamma/2\pi = 32.4 \text{ Hz}/\mu\text{T}$ the gyromagnetic ratio of the ^3He atoms and d the thickness of the cell walls. The motion of the spins in this inhomogeneous pseudomagnetic field will induce an anomalous depolarization channel, in addition to the usual ones.

In Section II, we will present the principle of measurement. Then the setup will be described in Section III. In Section IV, the analysis procedure will be presented. Finally, the constraints obtained up to now will be shown in Section V.

2 Principle of the measurement

We consider the case of a gas of ^3He polarized atoms with a gyromagnetic ratio γ contained in a glass cell of volume V and immersed in a holding magnetic field $\vec{B}_0 = B_0 \vec{e}_z$. The Larmor precession frequency of the spins is $\omega_0 = \gamma B_0$. In the case of polarized ^3He gas with a high polarization P ($P(t=0) \approx 70 \%$), the gas depolarizes as

$$P(t) = P(t=0)e^{-\Gamma_1 t}, \quad (3)$$

with Γ_1 the longitudinal relaxation rate. Three main mechanisms are expected to contribute to the relaxation: collisions between ^3He atoms, collisions with the cell walls and particles motion in an inhomogeneous magnetic field. The first contribution Γ_{dd} depends on the frequency of atoms collisions and is proportional to the pressure of the gas [4]. The second contribution Γ_w does not depend on the pressure and the polarization of the gas nor on the holding field value. The last contribution Γ_m corresponds to a perturbation of the spins by their motion in an inhomogeneous magnetic field.

In the case of an arbitrary geometry cell immersed in a magnetic field with an arbitrary spatial profile, the relaxation rate can be estimated [5] using the Redfield theory with the relation

$$\Gamma_m = D \frac{\langle (\vec{\nabla} b_\perp)^2 \rangle}{B_0^2}, \quad (4)$$

where D is the diffusion coefficient ($D \approx 1.84 \text{ cm}^2/\text{s}$ in normal condition) and $\langle (\vec{\nabla} b_\perp)^2 \rangle$ corresponds to the average over the cell volume of the squared transverse gradients. This relation is valid in the case of gas with a pressure close to 1 bar, immersed into several μT holding field which is our case. Generally, the magnetic inhomogeneities (small compared with B_0) can be written as a function of the polarization P and the pressure p as

$$\vec{b} = \vec{b}_{\text{ext}} + \vec{b}_{\text{coil}}(B_0) + \vec{b}_{\text{cell}}(P, p), \quad (5)$$

with P the polarization of the gas and p its pressure. The term $\vec{b}_{\text{ext}}$ corresponds to the magnetic inhomogeneities induced by the apparatus environment and $\vec{b}_{\text{coil}}(B_0)$ to the one created by the holding field generator and so is proportional to B_0 . The

last contribution $\vec{b}_{\text{cell}}(P, p)$ is due to the fact that at high pressure and polarization, the ^3He gas behaves as a magnet and generates an inhomogeneous magnetic field proportional to p and P .

Therefore for a given pressure, using (4) and (5), the total longitudinal relaxation rate Γ_1 can be written as

$$\Gamma_1 = a + \frac{b}{B_0} + \frac{c}{B_0^2} + \frac{dP}{B_0} + \frac{eP}{B_0^2} + \frac{fP^2}{B_0^2}, \quad (6)$$

with a , b , c , d , e and f real coefficients. The relaxation contributions induced by walls and atoms collisions are contained in the coefficient a .

In the case of a scalar-pseudoscalar interaction between a ^3He polarized gas and the nucleons in the cell walls, the relaxation rate induced by the motion of the spins into a pseudomagnetic field (2) can be derived using the Redfield theory [6]. Let us consider spherical cells with a radius R . The relaxation rate induced by the pseudomagnetic field generated by the walls of such a cell can be written as

$$\Gamma_{NF} = (\gamma b_a)^2 \frac{\lambda^3}{DR} \frac{1}{(1 + \phi_\lambda^2)^2} \times \left(\sqrt{\frac{2}{\phi_\lambda}} (1 - \phi_\lambda (\phi_\lambda - 2)) + \phi_\lambda^2 - 3 \right), \quad (7)$$

with $b_a = g_s g_p \frac{\lambda \hbar}{2m\gamma} (1 - e^{-d/\lambda})$ and $\phi_\lambda = \gamma B_0 \lambda^2 / D$. Moreover, for $\phi_\lambda \ll 1$, Eq. (7) simplifies into

$$\Gamma_{NF} = (\gamma b_a)^2 \frac{\lambda}{R} \sqrt{\frac{2\lambda^2}{D\omega_0}}. \quad (8)$$

In this regime, the behavior of the relaxation rate with respect to the holding field is very different from the classical relaxation contributions (6). The existence of a new short-range spin-dependent interaction can then be extracted from measurements of the relaxation rate at different values of the holding magnetic field and polarization.

A first test experiment [7] measuring the spin longitudinal depolarization rate as a function of the applied field B_0 was performed in 2010 to demonstrate the sensitivity of the method. A new dedicated experiment is set up at the Institute Laue-Langevin (ILL), improving both (i) the magnetic environment of the experiment and (ii) the measurement of the decay of polarization.

3 Experimental setup description

Our apparatus is designed to provide a large range of possible holding magnetic field B_0 between 3 μT and 300 μT in which the ^3He gas can depolarized. The polarization can be measured using dedicated instruments.

3.1 Magnetic setup

In order to suppress the magnetic inhomogeneities responsible for the depolarization channel Γ_m , the holding field should be as homogeneous as possible. The magnetic setup is composed of a 5 m long and 80 cm diameter solenoid which provides a very homogeneous magnetic field. In order to shield the center of the solenoid where the cell will be set, a μ -metal magnetic shield of 4.5 m long and 96 cm diameter was refurbished from the "n-nbar" experiment [8] which measured the neutron-antineutron oscillation at the ILL. Fig. 1 shows the solenoid inserted into the μ -metal magnetic shield.



Figure 1: Left: Solenoid inserted into the mumetal magnetic shield. Right: Scheme of the spinflip and measurement apparatus. The spherical cell is positioned in contact with the two magnetometers inside the spinflip coil which generates an oscillating magnetic field b_{SF} transversely to the holding magnetic field B_0 .

We mapped the inner magnetic field using a three-axis fluxgate magnetometer, in order to extract the averaged squared transverse gradients $\langle(\vec{\nabla}b_{\perp})^2\rangle$ for different B_0 settings. Typically, $\sqrt{\langle(\vec{\nabla}b_{\perp})^2\rangle}$ is about 2.4 nT/cm to 4 nT/cm for a magnetic field between 2 μ T and 80 μ T. The magnetic relaxation time $T_m = \frac{1}{\Gamma_m}$ is then expected to be longer than 90 h. This long time will directly affect the duration of the experiment and so the precision of the relaxation rate measurement.

3.2 Measurement of the relaxation rates

The spin relaxation of a gas can be determined by periodically measuring the polarization of the gas. We used a direct polarimetry method, first presented by Cohen-Tanoudji [9], which consists in measuring the magnetic field generated by the gas itself and so proportional to its polarization. Close to the cell, this magnetic field can be of the order of tenths of nT at pressures of several bars. The sensors are set at a place where the dipolar field induced by the polarized gas is transverse relative to

the B_0 field, as represented on Fig. 1. The configuration with two fluxgates allows to compensate for the random fluctuations of the environmental transverse fields by taking the difference between the two magnetometer readings, as the dipolar fields created by the polarized ^3He gas at positions 1 and 2 are opposite.

Applying spinflips with a transverse oscillating magnetic field to reverse the polarization (Fig. 1), one can remove magnetic offsets induced by long-term drift of the holding magnetic field or the misalignment of the magnetometers axis with B_0 . Fig. 2 shows typical sequences of "up-down-down-up" ($\uparrow\downarrow\downarrow\uparrow$) measurements of the magnetic field induced by a spherical cell at 4 bar with the two magnetometers. The

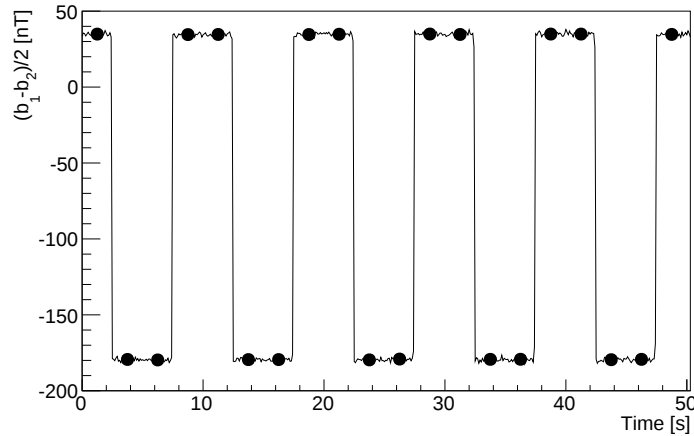


Figure 2: Typical sequence of measurement of the transverse magnetic field generated by a cylindrical cell at 4 bars with two fluxgate magnetometers. The upper (lower) points correspond to the spin up (down) state of the gas.

precision on the polarization measurement extracted from the two fluxgates with a $\uparrow\downarrow\downarrow\uparrow$ sequence is 160 pT. In order to improve this precision, we repeat the polarisation measurement 8 times. For a 1 bar 100 % polarization cell, we have a signal over noise ratio about 1000.

4 Data analysis

In the experiment, we measure the relaxation rate of spin-polarized ^3He gas as a function of the strength of the applied holding magnetic field B_0 . To do so, we used spherical cells filled with polarized ^3He . The details of the 4 Runs obtained up to now are given in Table 1. For each Run, we applied 8 different values of holding field: $\{3 \mu\text{T}, 5 \mu\text{T}, 8 \mu\text{T}, 10 \mu\text{T}, 30 \mu\text{T}, 50 \mu\text{T}, 80 \mu\text{T}, 90 \mu\text{T}\}$. For a given holding field value, the polarization measurements were done every 20 min. When the polarization decreased by 10 %, a different holding field value is used.

Run	Cell	Radius [cm]	Pressure [bar]	Coating	Initial polarization
32	Axion01	6	1	Caesium	70 %
33	Axion01	6	4	Caesium	70 %
34	CCT12	4	4	Rubidium	70 %
35	CCT12	4	1	Rubidium	70 %

Table 1: Main characteristics of the 4 Runs obtained with the apparatus. The value of the indicated initial polarization was measured on the Tyrex installation using an optical method [10].

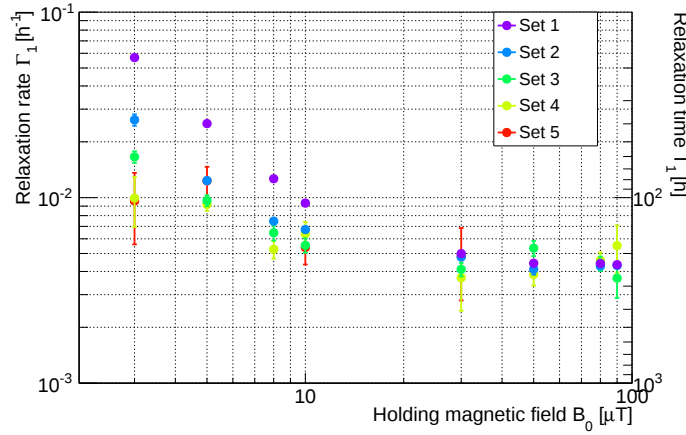


Figure 3: Measurement of the relaxation rates in the Run 32 as a function of the holding magnetic field. Each set corresponds to a series of holding field values.

Using (3), we can extract the relaxation rate Γ_1 and the initial polarization for each magnetic configuration. Fig. 3 presents the measurement of the relaxation rate as a function of the holding field B_0 . The relaxation rate at high magnetic field is about 200 h, which corresponds mainly to relaxation induced by the walls and atoms collisions. At small magnetic field values ($3 \mu\text{T}$), the relaxation is mainly due to gradients which are independent of the holding field value. Since the relaxation rate decreases with the set number (i.e. as the gas depolarizes), the main depolarizing process at low magnetic field and high polarization comes from the magnetic gradients generated by the gas itself.

We can compare the behavior of the relaxation rate with the holding field and the holding field values with the expected standard rate (6). If a new interaction between two nucleons mediated by a pseudoscalar boson exists, a new depolarization channel (7) will add to the standard one and could be detected as an depolarization excess.

However, this analysis method is not optimal since it does not take into account the correlation between the initial polarization value of each magnetic configuration.

A new analysis method is currently under development in order to take into account these correlations.

5 Conclusion

Measuring ^3He hyperpolarized gas relaxation as a function of the holding field is a very sensitive method to search for exotic short-range spin-dependent interactions. A dedicated apparatus was built at the ILL in order to find a new spin-0 boson or to improve the current constraint on its scalar-pseudoscalar couplings. The setup is composed with a solenoid and a mumetal magnetic shield which provide a very homogeneous magnetic field. We hope to reach one order of magnitude improvement in sensitivity compared with the previous experiment [7].

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