Limits on new long-range nuclear spin-dependent forces set with a K - $^3$He co-magnetometer

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A magnetometer using spin-polarized K and $^3$He atoms occupying the same volume is used to search for anomalous nuclear spin-dependent forces generated by a separate $^3$He spin source. We measure changes in the $^3$He spin precession frequency with a resolution of 18 pHz and constrain anomalous spin forces between neutrons to be less than $2 \times 10^{-8}$ of their magnetic or less than $2 \times 10^{-3}$ of their gravitational interactions on a length scale of 50 cm. We present new limits on neutron coupling to light pseudoscalar and vector particles, including torsion, and constraints on recently proposed models involving unparticles and spontaneous breaking of Lorentz symmetry.

Experimental limits on long-range spin-dependent forces mediated by particles other than the photon were first considered by Ramsey [1]. Following his limit on anomalous spin forces between protons, constraints have been set on non-electromagnetic spin forces between electrons [2, 3] and electrons and nuclei [4]. Indirect laboratory limits on spin-dependent forces between nuclei have been set from tests of gravitational interactions [5, 6] and astrophysical considerations have been used to constrain them [7, 8]. However, no direct laboratory searches for anomalous neutron spin-dependent forces have been performed until recently [9]. Laboratory limits on anomalous forces were recently reviewed in [10]. On the theoretical side, in addition to the original motivation for spin-dependent forces mediated by axions [11], a number of new ideas have been explored, including para-photons [12], unparticles [13] and theories with spontaneous Lorentz violation [14].

Here we use a co-magnetometer consisting of overlapping ensembles of K and $^3$He atoms to search for an anomalous interaction with a spin source consisting of a dense nuclear spin-polarized $^3$He gas located approximately 50 cm away. The co-magnetometer arrangement cancels sensitivity to ordinary magnetic fields [15]. After several weeks of integration we obtain a sensitivity of 0.6 aT to an anomalous field affecting only neutrons. For the first time, the spin-dependent $1/r$ potential between particles is constrained below the strength of their gravitational interactions. Our experiment is about 500 times more sensitive and constrains more parameters than a similar recent experiment searching for anomalous neutron spin-dependent forces with a $^3$He-$^{129}$Xe maser that was published after submission of this work [16].

The experimental setup is shown in Fig. 1. The operating principle of the K-$^3$He co-magnetometer has been described elsewhere [15, 16]. Briefly, the atoms are contained in a 2.4 cm diameter spherical cell made from aluminosilicate glass filled with 12 amagats of $^3$He, 46 Torr of N$_2$ for quenching and a small drop of K metal. The cell is heated to 160°C and is placed inside five layer mu-metal shields with a shielding factor of 10$^6$. K atoms are optically pumped with a circularly polarized pump beam generated by an amplified DFB laser. Spin-exchange collisions between K and $^3$He atoms polarize $^3$He spins. The current in the optical amplifier is adjusted with a slow feedback loop to maintain a constant $^3$He polarization of about 3%. Coils inside the magnetic shields cancel residual magnetic fields and create a field in the $\hat{z}$ direction parallel to the pump beam to compensate for the effective magnetic field experienced by K atoms due to nuclear spin magnetization of $^3$He. As a result, the K magnetometer operates in a zero field, where Zeeman resonance broadening due to spin-exchange collisions between alkali-metal atoms is eliminated [17]. The polarization of K atoms in the $\hat{z}$ direction is determined from measurements of optical rotation of a 0.8 mW linearly polarized off-resonant probe beam generated by a DFB laser tuned to 769.64 nm. To achieve angular sensitivity of $7 \times 10^{-8}$ rad/H$_2^{1/2}$ down to 0.1 Hz beam motion due to air currents is minimized by enclosing all optics in nearly air-tight boxes. The probe beam is carefully directed

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FIG. 1: Experimental setup. PD: photodiode, SP: stress plate to control polarization of the probe beam, T: translation stage to shift the probe beam, P: polarizer, PMF: polarization maintaining fiber, OA: Optical Amplifier, LCW: Liquid Crystal Waveplate, PEM: Photoelastic Modulator, $\lambda/4$: quarter-waveplate, LDA: Laser Diode Array.
through the center of the spherical cell to eliminate polarization rotation caused by linear dichroism associated with reflection from tilted surfaces.

After eliminating residual magnetic fields and light-shifts using zeroing routines described in [16], the \( \hat{\chi} \) polarization of K atoms to leading order is given by

\[
P_{x} = \frac{P_{x}^{0}}{R_{tot}} \left( b_{y}^{n} - b_{y}^{e} + \frac{\Omega_{y}}{\gamma_{n}} \right).
\]

Here \( b_{y}^{n} \) and \( b_{y}^{e} \) describe the phenomenological magnetic-like fields in the \( \hat{y} \) direction that couple only to \( ^{3}\text{He} \) nucleus and K electrons respectively. \( P_{x}^{0} \) and \( R_{tot} \) are the K electron spin polarization and relaxation rate, \( \gamma_{c} \) and \( \gamma_{n} \) are the gyromagnetic ratios for electrons and \( ^{3}\text{He} \) nuclei respectively. Since K and \( ^{3}\text{He} \) atoms occupy the same volume, the co-magnetometer is insensitive to ordinary magnetic fields \( (b_{y}^{n} = b_{y}^{e}) \) but retains sensitivity to an anomalous field that only interacts with nuclear spins. Previous limits on neutron-electron spin coupling [4] are three orders of magnitude below our sensitivity. \( \Omega_{y} \) is the angular rotation frequency of the apparatus relative to an inertial frame, providing an example of an interaction that does not couple to spins in proportion to their magnetic moments. We verified the calibration of the co-magnetometer to 10% accuracy by inducing small rotations of the optical table. We also verified that the co-magnetometer is insensitive to quasi-static magnetic fields in all directions, with the worst suppression factor equal to \( 6 \times 10^{-4} \) in the \( \hat{z} \) direction. A typical noise spectrum of the co-magnetometer for \( b_{y}^{n} \) field is shown in Fig. 2. The sensitivity is equal to 0.75 \( \text{fT/Hz}^{1/2} \) at the 0.18 Hz modulation frequency of the spin-source.

The anomalous field that the co-magnetometer measures is created by optically pumped \( ^{3}\text{He} \) nuclear spins. A cylindrical cell with 4.3 cm ID and 12.8 cm length is filled with K, 20 Torr of \( ^{3}\text{He} \) and 12 atm of \( ^{3}\text{He} \) at room temperature. The cell is heated to 190 °C and held in a magnetic field of 7.8 G. A broad-area laser diode array tuned to the D1 K resonance with external grating feedback is used for optical pumping, delivering approximately 2 W of power to the cell. The nuclear spin direction is reversed every 2.8 sec by Adiabatic Fast Passage (AFP) using a combination of amplitude ramp and frequency sweep of a transverse oscillating magnetic field. With a maximum oscillating field amplitude of 0.5 G and total sweep time of 80 msec, we achieve AFP losses of less than \( 2.5 \times 10^{-6} \) per flip. A liquid crystal waveplate reverses the direction of circular polarization of the pump beam synchronously with the direction of nuclear polarization. Nuclear polarization is measured using the frequency shift of the Zeeman resonance in the spin source correlated with \( ^{3}\text{He} \) spin reversals [18]. At steady state during data acquisition, the polarization of the spin source was 15%, corresponding to \( 9 \times 10^{21} \) fully polarized \( ^{3}\text{He} \) atoms. The co-magnetometer cell was located 48.7 cm away from the center of the spin source cell in the direction of \( -25° \) and azimuth of 222°.

A solenoidal coil wound on the surface of \( ^{3}\text{He} \) cell along its entire length generates a magnetic field pattern similar to that of uniformly polarized \( ^{3}\text{He} \). We measure the magnetic field close to the cell with a fluxgate magnetometer and adjust the current in the coil, which is reversed synchronously with AFP flips, to reduce the magnetic field correlated with spin reversals by a factor of 10. By running a much larger current in the solenoid, we estimate the leakage of the magnetic field of the spin source into the co-magnetometer signal and limit such systematic effect to be less than \( 4 \times 10^{-3} \) aT.

Systematic effects can also arise through parasitic cross-talk between the electronics of the spin source and those of the co-magnetometer. We eliminate all electrical connections between them, with time synchronization achieved by an opto-coupled signal. Every few days we manually change the polarity of the holding field in the spin source and rotate a quarter-waveplate in the pump beam, which reverses the correspondence between direction of the spins and the state of the electronics. We also occasionally flip the direction of the spin polarizations in the co-magnetometer, changing the sign of its signal.

The data are collected in records of 200 sec, after which the \( B_{z} \) magnetic field and \( ^{3}\text{He} \) polarization feedback in the co-magnetometer are adjusted, and the polarization of \( ^{3}\text{He} \) in the spin source is measured. Approximately every 70 min automated routines are executed to zero all magnetic fields and the probe beam lightshift in the co-magnetometer. The data for each record are passed through a digital band-pass FFT filter to remove irrelevant frequency components, the time intervals corresponding to definite spin state are selected, and their mean and uncertainty are calculated. An average of a 3-point moving correlation gives the co-magnetometer signal correlated with the state of the spin source. Fig. 3 summarizes about one month of data taken with the spin source in the \( \hat{y} \) direction, oriented vertically in the lab. The anomalous coupling \( b_{y}^{n} \) is measured to be 0.05 aT \( \pm \ 0.56 \) aT with a reduced \( \chi^{2} \) of 0.87. The data taken for different orientations of the spin source and the co-magnetometer are consistent with each other. Measure-
FIG. 3: Spin-correlated measurement of $b^y_n$ for spin source in the $y$ direction. Each point represents an average over approximately one day. Up and down triangles indicate opposite directions of the spin source, filled and empty triangles indicate opposite directions of the co-magnetometer. Inset Top: Histogram of values for each 200 sec-long record closely follows a Gaussian distribution. Inset Bottom: Data plotted vs. sidereal time of day, showing no significant variation.

FIG. 4: Constraints on a pseudoscalar boson coupling to neutrons as a function of the boson mass. The solid line is from this work and thin dashed line is from [6] for Yukawa coupling only. Thick dashed line is from $^3$He-$^{129}$Xe maser [8], while the dotted line is a limit for protons set by Ramsey [11].

Constraints performed with the spin source oriented in the $z$ direction give similar results $b^z_n = -0.14 \pm 0.84$ aT. In the $^3$He nucleus, the neutron is polarized to 87%, protons have -2.7% polarization, with the rest of the nuclear spin given by orbital angular momentum [19]. For simplicity we focus only on anomalous neutron spin-dependent potential $V_{n,p}^\mu \sigma_n$ in the analysis, setting $\mu = m, b^y_n = 0.87 V_{n,p}^\mu$.

Constraints on pseudoscalar boson coupling. The coupling $g_{\mu}$ of a pseudoscalar boson $\phi$ with mass $m$ to a fermion $\psi$ with mass $M_n$ can be introduced using either a Yukawa or a derivative form:

$$L_{Yuk}^{\mu} = -ig_{\mu} \bar{\psi} \gamma^\mu \psi \phi$$

$$L_{De}^{\mu} = \frac{g_{\mu}}{2M_n} \bar{\psi} \gamma^\mu \gamma^5 \psi \partial^\mu \phi$$

Both forms lead to the same $1/r^3$ single-boson exchange potential [11]:

$$V_3 = \frac{g_{\mu}^2}{16\pi M_n^2} \left[ \hat{\sigma}_1 \cdot \hat{\sigma}_2 \left( \frac{m}{r^2} + \frac{1}{r^4} \right) - \left( \hat{\sigma}_1 \cdot \hat{r} \right) \left( \hat{\sigma}_2 \cdot \hat{r} \right) \left( \frac{m^2}{r^2} + \frac{3m}{r^4} + \frac{3}{r^6} \right) \right] e^{-mr}$$

where $r$ is the distance between the spins and $\hbar = c = 1$. In Fig. 3 we show our 1σ limit on $(g_{\mu}^n)^2/4\pi$ as a function of the boson mass. For a massless boson we obtain $(g_{\mu}^n)^2/4\pi < 5.8 \times 10^{-10}$, a factor of 500 better than recent limit in [4]. Ramsey’s limit on proton spin-dependent forces is $(g_{\mu}^p)^2/4\pi < 2.3 \times 10^{-8}$ [3, 6], but these limits do not apply to the derivative form that would be expected for Goldstone bosons, such as the axion. There are also astrophysical constraints on $g_\mu$ in this range from the strength SN 1987A signal in the Kamiokande detector [7] and metallicity of stars [8]. A more reliable astrophysical limit comes from a null search for axion emissions from the Sun at 14.4 keV M1 transition in $^{57}$Fe which constrains $(g_{\mu}^p + 0.09 g_{\mu}^n)^2/4\pi < 7 \times 10^{-13}$ [20].

Constraints on couplings to light vector bosons. Spin-dependent forces can also be mediated by spin-1 particles. A para-photon that couples to fermions through dimension-six operators is considered in [12, 21]. It leads to a potential similar to (3) but suppressed by 4 powers of a large mass scale $M$. Our measurement constraints $M/\sqrt{g_{\mu}} > 13$ GeV, higher than limits from electron spin-dependent forces. For a generic dimension-four coupling of a light $Z'$ boson with mass $m_{Z'}$, $L = \bar{\psi} \gamma^{\mu}(g\gamma_{\mu} + \gamma_5 g\Lambda)\psi Z'_\mu$, in addition to (3) with $g_{\mu}$ replaced by $(g_A^2 + g_B^2)$, there are two more potentials [21]:

$$V_1 = \frac{g_A^2}{4\pi r^2} (\hat{\sigma}_1 \cdot \hat{\sigma}_2) e^{-m_{Z'}r}$$

$$V_2 = -\frac{g_B^2}{4\pi M_n} \left( \hat{\sigma}_1 \times \hat{\sigma}_2 \right) \cdot \hat{r} \left( \frac{1}{r^2} + \frac{m_{Z'}}{r} \right) e^{-m_{Z'}r}$$

Table I summarizes the bounds from our experiment in the limit of a massless spin-1 particle. To explicitly constrain $V_2$ we collected data with the spin source aligned in the $z$ direction. The constraint on $g_A^2/4\pi$ represents 0.2% of the gravitational interaction between neutrons, for the first time constraining coupling to a massless spin-1 torsion field [22] below gravitational level.

Constraints on unparticle couplings to neutrons. A new physical entity dubbed unparticle with unusual properties, such as absence of a well-defined mass, has attracted a lot of attention [13]. An exchange of unparticles can generate long-range forces that vary as $1/r^{2d-1}$ where $d$ is a non-integer scaling dimension [23]. Spin-dependent forces are particularly sensitive to an axial coupling of unparticles to fermions $L = C_A \bar{\psi} \gamma^{\mu} \gamma_5 \psi U_{\mu}$. For $C_A = c_A \Lambda^{2-d}$ with $\Lambda = 1$ TeV we obtain constraints...
The first term gives a spin-dependent $1/r$ potential, while the second term in a frame moving with velocity $\vec{v}$ relative to the preferred frame leads to an anisotropic spin interaction $\vec{\sigma} \cdot \vec{v}$ considered in [25]. In a moving frame, the spin-dependent force has a complicated behavior with a “shock wave” that can develop behind the spin source [14]. The shape of the signal at the detector as a function of time depends on the orientation of $\vec{v}$ relative to the vector $\vec{r}$ from the source to the detector. For $M_\pi r > 1$ the signal can average to zero over a day but has a distinctive shape as a function of sidereal time of day. We calculated the signal shape assuming $\vec{v}$ corresponds to the velocity of Earth relative to the Cosmic Microwave Background radiation. The limit on the amplitude of the signal is determined by fitting the data plotted vs. sidereal time of day, shown in bottom inset of Fig. 3. The bounds on $M_\pi/F$, shown in Table I for a few values of $M_\pi$, reach below the strength of gravitational interactions. For comparison, limits on anisotropic neutron spin interactions [26] constrain $M_\pi/F < 4 \times 10^{-17}$ for $M_\pi = 10^{-3}$ eV. We note that our limits are in the regime where other operators in the theory could be large and non-linear interactions in the source could be significant. The limits can be extended to larger $M_\pi$ by alignment of $\vec{r}$ so $\vec{r} \cdot \vec{v}$ passes close to $-1$, where the interaction retains its strength even for large $M_\pi$.

In summary, we performed a direct search for anomalous neutron spin-dependent forces using an alkali-metal noble-gas co-magnetometer and a $^4$He spin source. We set limits on couplings to several new particles, some below the strength of gravitational interactions. We achieved an energy resolution of $10^{-25}$ eV, significantly higher than in other atomic physics experiments [27], demonstrating the potential of the co-magnetometer for future precision measurements.

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| Couplings to light spin-1 bosons |
|----------------------------------|
| $V_1: \xi g_\Lambda^2/(4\pi)$ |
| $V_2: g_\xi g_\Lambda^2/(4\pi)$ |
| $V_3: (g_\Lambda^2 + g_\xi^2)/(4\pi)$ |
| $1.2 \times 10^{-41}$ |
| $3.9 \times 10^{-26}$ |
| $5.8 \times 10^{-10}$ |

Axial coupling to unparticles with $\Lambda = 1$ TeV

$d$: 1 1.25 1.33 1.5

$c_A$: $1 \times 10^{-20}$ $9 \times 10^{-16}$ $3 \times 10^{-14}$ $6 \times 10^{-11}$

Coupling to Lorentz-violating Goldstone boson

$M_\pi$(eV): $3 \times 10^{-4}$ $1 \times 10^{-3}$ $3 \times 10^{-3}$ $1 \times 10^{-2}$

$M_\pi/F$: $2.1 \times 10^{-20}$ $2.6 \times 10^{-20}$ $2.1 \times 10^{-20}$ $2.9 \times 10^{-20}$

TABLE I: Bounds on neutron coupling to new particles.

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