Limits on New Long Range Nuclear Spin-Dependent Forces Set with a K-^{3}He Comagnetometer

G. Vasilakis, J. M. Brown, T. W. Kornack, and M. V. Romalis

Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

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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 2×10^{-8} of their magnetic or less than 2×10^{-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.

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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 nonelectromagnetic 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 paraphotons [12], unparticles [13], and theories with spontaneous Lorentz violation [14].

Here we use a comagnetometer 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 comagnetometer 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 [9].

The experimental setup is shown in Fig. 1. The operating principle of the K-^{3}He comagnetometer 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 μ-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 $\hat{x}$ direction is determined from measurements of optical rotation of a 0.8 mW linearly polarized off-resonant probe beam gen-

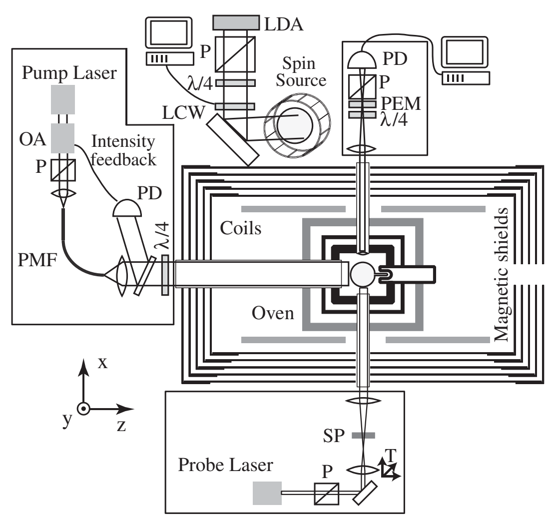

FIG. 1. Experimental setup. PD: photodiode, SP: stress plate to control polarization of the probe beam, T: translation stage to shift the probe beam, P: polarizer, PMF: polarization maintaining fiber, OA: optical amplifier, LCW: liquid crystal wave plate, PEM: photoelastic modulator, $\lambda/4$: quarter–wave plate, LDA: laser diode array.

erated by a DFB laser tuned to 769.64 nm. To achieve angular sensitivity of 7×10^{-8} rad/Hz$^{1/2}$ 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 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 $\hat{x}$ polarization of K atoms to leading order is given by

$$P_x^e = \frac{P_z^e \gamma_e}{R_{\rm tot}}\left(b_y^n - b_y^e + \frac{\Omega_y}{\gamma_n}\right). \tag{1}$$

Here b_y^n and b_y^e describe the phenomenological magnetic-like fields in the $\hat{y}$ direction that couple only to ^{3}He nucleus and K electrons, respectively. P_z^e and $R_{\rm tot}$ are the K electron spin polarization and relaxation rate, γ_e and γ_n are the gyromagnetic ratios for electrons and ^{3}He nuclei, respectively. Since K and ^{3}He atoms occupy the same volume, the comagnetometer 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 3 orders of magnitude below our sensitivity. Ω_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 comagnetometer to 10% accuracy by inducing small rotations of the optical table. We also verified that the comagnetometer is insensitive to quasistatic magnetic fields in all directions, with the worst suppression factor equal to 6×10^{-4} in the $\hat{z}$ direction. A typical noise spectrum of the comagnetometer for b_y^n field is shown in Fig. 2. The sensitivity is equal to 0.75 fT/Hz$^{1/2}$ at the 0.18 Hz modulation frequency of the spin source.

The anomalous field that the comagnetometer measures is created by optically pumped ^{3}He nuclear spins. A cylindrical cell with 4.3 cm ID and 12.8 cm length is filled with K, 20 Torr of N_2 and 12 atm of ^{3}He at room temperature.

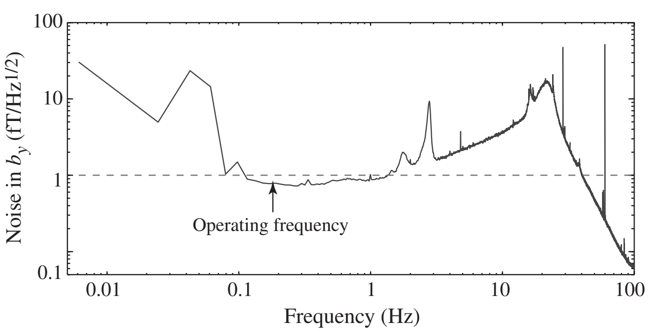

FIG. 2. Frequency spectrum of the comagnetometer noise in measurement of b_y^n. The broad peak at 20 Hz is the resonance of the coupled spin ensemble, peaks at 2 and 3 Hz are due to mechanical resonances of the floating optical table, and the peak at 0.05 Hz is due to the cycle time of a cooling system.

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 2.5×10^{-6} per flip. A liquid crystal wave plate 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}He spin reversals [18]. At steady state during data acquisition, the polarization of the spin source was 15%, corresponding to 9×10^{21} fully polarized ^{3}He atoms. The comagnetometer cell was located 48.7 cm away from the center of the spin-source cell in the direction with altitude of $-25°$ and azimuth of 222°.

A solenoidal coil wound on the surface of ^{3}He cell along its entire length generates a magnetic field pattern similar to that of uniformly polarized ^{3}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 comagnetometer signal and limit such systematic effect to be less than 4×10^{-3} aT.

Systematic effects can also arise through parasitic cross-talk between the electronics of the spin source and those of the comagnetometer. We eliminate all electrical connections between them, with time synchronization achieved by an optocoupled signal. Every few days we manually change the polarity of the holding field in the spin source and rotate a quarter–wave plate 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 comagnetometer, changing the sign of its signal.

The data are collected in records of 200 sec, after which the B_z magnetic field and ^{3}He polarization feedback in the comagnetometer are adjusted, and the polarization of ^{3}He in the spin source is measured. Approximately every 70 min automated routines are executed to zero all magnetic fields and the probe beam light shift in the comagnetometer. The data for each record are passed through a digital bandpass 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 comagnetometer signal correlated with the state of the spin source. Figure 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 χ^2 of 0.87. The data taken for different orientations of the spin source and the comagnetometer are consistent with each other. Measurements performed with the spin source oriented in the $\hat{z}$ direction give similar results $b_y^n = -0.14 \pm 0.84$ 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 $V_a^n \sigma_n$ in the analysis, setting $\mu_{^3\mathrm{He}} b_y^n = 0.87 V_a^n$.

Constraints on pseudoscalar boson coupling.—The coupling g_p of a pseudoscalar boson ϕ with mass m to a fermion ψ with mass M_n can be introduced using either a Yukawa or a derivative form:

$$\mathcal{L}^{\mathrm{Yuk}} = -i g_p \bar{\psi} \gamma^5 \psi \phi \quad \text{or} \quad \mathcal{L}^{\mathrm{Der}} = \frac{g_p}{2M_n} \bar{\psi} \gamma_\mu \gamma^5 \psi \partial^\mu \phi. \tag{2}$$

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

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

where r is the distance between the spins and $\hbar = c = 1$. In Fig. 4 we show our 1σ limit on $(g_p^n)^2/4\pi$ as a function of the boson mass. For a massless boson we obtain $(g_p^n)^2/4\pi < 5.8 \times 10^{-10}$, a factor of 500 better than recent limit in [9]. Ramsey's limit on proton spin-dependent forces is $(g_p^p)^2/4\pi < 2.3 \times 10^{-5}$ [1]. For a Yukawa form of interaction, two-boson exchange leads to limits on g_p from tests of gravitational forces, $(g_p^n)^2/4\pi < 2.5 \times 10^{-8}$ [5,6], 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_p 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 $(g_p^n + 0.09 g_p^p)^2/4\pi < 7 \times 10^{-13}$ [20].

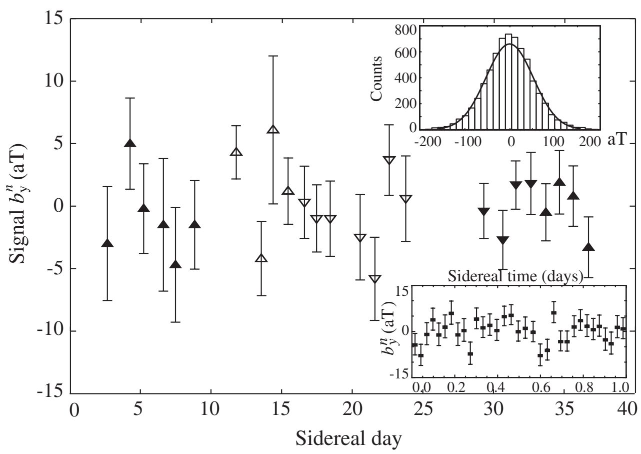

FIG. 3. Spin-correlated measurement of b_y^n for spin source in the $\hat{y}$ direction. Each point represents an average over approximately one day. Up and down triangles indicate opposite directions of the spin source, filled and empty triangles indicate opposite directions of the comagnetometer. Inset 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.

Constraints on couplings to light vector bosons.—Spin-dependent forces can also be mediated by spin-1 particles. A paraphoton 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 $M/\sqrt{c_n} > 13$ GeV, higher than limits from electron spin-dependent forces. For a generic dimension-four coupling of a light Z' boson with mass $m_{z'}$, $\mathcal{L} = \bar{\psi}\gamma^\mu(g_V + \gamma_5 g_A)\psi Z'_\mu$, in addition to (3) with g_p^2 replaced by $(g_A^2 + g_V^2)$, there are two more potentials [21]:

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

$$V_2 = -\frac{g_V g_A}{4\pi M_n}(\hat{\sigma}_1 \times \hat{\sigma}_2) \cdot \hat{r}\left(\frac{1}{r^2} + \frac{m_{z'}}{r}\right) e^{-m_{z'} r}. \tag{5}$$

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 $\hat{z}$ 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 prop-

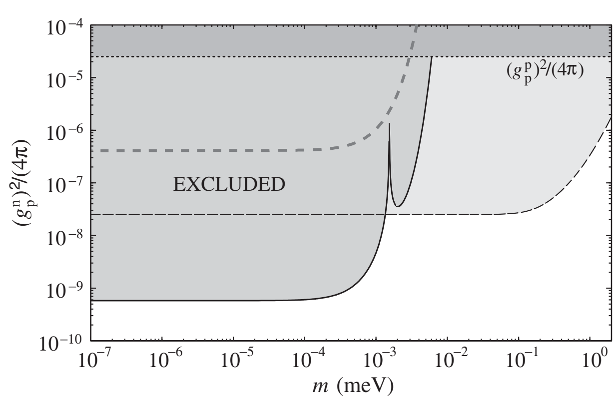

FIG. 4. Constraints on a pseudoscalar boson coupling to neutrons as a function of the boson mass. The solid line is from this work and thin dashed line is from [6] for Yukawa coupling only. The thick dashed line is from ^{3}He-^{129}Xe maser [9], while the dotted line is a limit for protons set by Ramsey [1].

TABLE I. Bounds on neutron coupling to new particles.

Couplings to light spin-1 bosons				
	V_1: $g_A^2/(4\pi)$	V_2: $g_V g_A/(4\pi)$	V_3: $(g_A^2+g_A^2)/(4\pi)$	
	1.2×10^{-41}	3.9×10^{-26}	5.8×10^{-10}	
Axial coupling to unparticles with $\Lambda = 1$ TeV				
d:	1	1.25	1.33	1.5
c_A:	1×10^{-20}	9×10^{-16}	3×10^{-14}	6×10^{-11}
Coupling to Lorentz-violating Goldstone boson				
M_π(eV):	3×10^{-4}	1×10^{-3}	3×10^{-3}	1×10^{-2}
M_π/F:	2.1×10^{-20}	2.6×10^{-20}	2.1×10^{-20}	2.9×10^{-20}

erties, 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 noninteger scaling dimension [23]. Spin-dependent forces are particularly sensitive to an axial coupling of unparticles to fermions $\mathcal{L} = C_A \bar{\psi}\gamma^\mu\gamma_5\psi\,\mathcal{U}_\mu$. For $C_A = c_A\Lambda^{1-d}$ with $\Lambda = 1$ TeV we obtain constraints on c_A shown in Table I as a function of d. These limits are similar to the ones obtained from electron spin-dependent force [23] and gravitational measurements [24] and are much stronger than those from astrophysics.

Constraints on coupling to Goldstone bosons associated with spontaneous breaking of Lorentz symmetry.—The dynamical effects of a Goldstone boson π associated with spontaneous breaking of the Lorentz symmetry down to spatial rotations in a preferred frame have been recently explored [14]. Such a particle would have an unusual quadratic dispersion relationship $\omega = k^2/M_\pi$ and its leading order coupling to fermions is spin dependent

$$\mathcal{L} = \frac{1}{F}\bar{\psi}\gamma^\mu\gamma^5\psi\,\partial_\mu\pi + \frac{M_\pi^2}{F}\bar{\psi}\gamma^0\gamma^5\psi. \qquad (6)$$

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 $\hat{\sigma}\cdot\vec{v}$ 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 $M_\pi v r > 1$ 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_π/F, shown in Table I for a few values of M_π, reach below the strength of gravitational interactions. For comparison, limits on anisotropic neutron spin interactions [26] constrain $M_\pi/F < 4\times10^{-17}$ 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 nonlinear interactions in the source could be significant. The limits can be extended to larger M_π 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_π.

In summary, we performed a direct search for anomalous neutron spin-dependent forces using an alkali-metal noble-gas comagnetometer and a ^{3}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 comagnetometer for future precision measurements.

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