Experimental search for an exotic spin-spin-velocity-dependent interaction using an optically polarized vapor and a rare-earth iron garnet

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We report an experimental search for an exotic spin-spin-velocity-dependent interaction between polarized electrons of Rb atoms and polarized electrons of a solid-state mass, violating both the time-reversal and parity symmetries. This search targets a minute effective magnetic field induced by the interaction. A spin-exchange relaxation-free (SERF) magnetometer based on an optically polarized Rb vapor is the key element for both a source of polarized electrons and a high-sensitivity detector. A dysprosium iron garnet (DyIG) serves as the polarized mass, with an extremely small magnetization at the critical temperature around 240 K and a high spin density. To reduce the magnetization, one of major systematic effects, a home-built cooling system controls the mass temperature. This search is the first application of DyIG since it was proposed as a polarized mass to explore exotic spin-dependent interactions. The experiment set the most stringent limit on the electron-electron coupling strength in the centimeter interaction range, in particular $g_V^3 g_V^3 < 10^5$ at $\lambda = 2$ cm.

Recent searches for exotic spin-dependent interactions between fermions are growing, especially because of the interest of the quantum information science for the high energy physics [1]. The idea of the exotic interactions was first proposed by Moody and Wilczek [2] through new spin-0 boson exchange and later expanded by Dobrescu and Mocioiu [3] including the interaction potentials depending on the relative velocity between two interacting fermions through new spin-1 boson exchange. These new bosons provide sensitive observable for alternative theories beyond the Standard Model of particle physics that can solve several mysteries in fundamental physics. For example, the strong charge-parity problem in quantum chromodynamics can be resolved by introducing the spin-0 axions [4]. The cold dark matter can be composed of the axions [5] or the spin-1 dark photons [6–8]. Several theoretical concepts including the string theory, the hierachy problem, dark energy, and unparticles [9] also predict the existence of such new bosons [10] which can mediate the exotic spin-dependent interactions.

Most experiments have mainly focused on static spin-dependent interactions, including $V_2$, $V_3$, $V_{0+10}$ and $V_{11}$ (adapting the numbering conventions in Ref. [3]), using spectroscopy [11], electron-spin-polarized torsion-pendulum, magnetometry, atomic parity non-conservation, and electric dipole moment measurement [12,13,14]. A few searches for spin-velocity-dependent interactions using unpolarized masses has been performed based on polarized $^4$He relaxation [13,14], cold neutron beams [15,16], magnetic stripes [17], and spin-exchange relaxation-free (SERF) magnetometers [18,19].

Investigating spin-spin-velocity-dependent interactions (SSVDIs), on the other hand, is relatively challenging because the spin-polarized masses can generate a spurious interaction signal (i.e., a magnetic signal). Some experiments have been performed: Hunter et al. first applied polarized geoelectrons with a $^{199}$Hg-Cs magnetometer [20], Ji et al. used a K-Rb SERF magnetometer with SmCo$_5$ spin sources [21]; and at the atomic scale from an analysis of spin-exchange interactions [22]. However, these experiments were sensitive at a long distance between the sources and the probes due to the mass magnetic field, or at an extremely small distance based on the comparison with the theory calculation.

In this letter we explore a SSVDI at a distance in centimeters:

$$V_{15} = -g_V^3 g_V^3 \frac{\hbar^3}{8\pi m_e^2 c^2} 	imes \left\{ (\hat{\sigma}_1 \cdot (\hat{v} \times \hat{r})) (\hat{\sigma}_2 \cdot \hat{r}) + (\hat{\sigma}_1 \cdot \hat{r}) (\hat{\sigma}_2 \cdot (\hat{v} \times \hat{r})) \right\} 	imes \frac{1}{(\lambda^2 r^3 + 3 \lambda^2 + 3 \lambda^3)} e^{-\lambda/\lambda},$$  \(1\)

where two interacting particles are electrons with spin unit vector $\hat{\sigma}_1$ and $\hat{\sigma}_2$, and the mass ($m_e$); their relative distance and relative velocity are $\hat{r}$ and $\hat{v}$; $\hbar$ is the reduced Planck constant; $c$ is the speed of light; and $\lambda$ is the interaction length. $g_V^3$ is the vector electron coupling [12,23] with the spin-1 dark photon [24]. Note that $V_{15}$ violates both the time-reversal and parity symmetries. We investigated the $V_{15}$ based on our recently proposed experimental approach (proposal in Ref. [25] and applications in Refs. [18,19]) using SERF magnetometers that serve as both a source of spin-polarized electrons and a high-sensitivity detector. The $V_{15}$ between SERF spin-polarized electron spin $\hat{\sigma}_1$ with the gyromagnetic ratio $\gamma$ and electron spin of a spin-polarized mass $\hat{\sigma}_2$ generates an effective magnetic field $\vec{B}_{\text{ef}}$ that...
can interact with the SERF electron, similarly as the ordinary magnetic field: \[ V_{15} = \Delta E = \gamma \hbar \sigma_1 \cdot B_{\text{eff}} \] where \( \Delta E \) is the energy shift of the SERF spin-polarized electrons. The \( B_{\text{eff}} \) is our target signal to be measured with the SERF magnetometer.

For the SERF magnetometer, we utilized the QuSpin cm-scale magnetometer based on an optically polarized \(^{87}\text{Rb}\) 3 mm cubic vapor cell [27] (for more detail, see Refs. [18] [19] [28]). The cell was heated to \( \sim 160 \) °C to elevate an Rb atom density to \( \sim 10^{14} \text{ cm}^{-3} \).

A rare-earth iron garnet (dysprosium iron garnet, Dy\(^{3+}\)Fe\(^{2+}\)Fe\(^{3+}\)O\(_3\), DyIG) was employed as the spin-polarized mass. Our experiment is the first application of DyIG since it was recently proposed for spin-polarized masses due to its near-zero magnetization at the critical temperature around 220–240 K (suppressing systematic effects) and its high spin density of about \( 10^{26} \text{ m}^{-3} \) (improving the experimental sensitivity to the interaction) [29]. The DyIG is a ferrimagnet in which three sublattices contribute to the net magnetization: Dy\(^{3+}\) ions occupy dodecahedral sites in the garnet lattice; and Fe\(^{3+}\) ions occupy octahedral and tetrahedral sites [29]. The magnetic moments of Dy\(^{3+}\) are nominally aligned with the octahedral ion moments but anti-aligned with the tetrahedral ion moments. As any ferrimagnetic material, DyIG hold the net magnetization only below the Curie temperature. At the critical temperature below the Curie temperature, the two opposing Dy\(^{3+}\) and Fe\(^{3+}\) moments become equal, resulting in a zero net magnetic moment and hence magnetization. The total spin excess per molecule is estimated to be 0.6 at the critical temperature [23] so that the electron spin density of DyIG is \( 1.7 \times 10^{26} \text{ m}^{-3} \).

The DyIG polycrystalline sample of 8 mm diameter, 1.7 mm length, and 0.32 g mass (the inset of Fig. [1]) was synthesized at Indiana University by the conventional solid-state reaction method [30]. The sample was spin-polarized in a 2 T magnet in several hours to ensure the fully saturated electron spins. Its magnetic property was characterized using the Quantum Design susceptometer system [31]. Figure 1 shows the sample magnetic moment as a function of temperature, which indicates the critical temperature of 240 K.

A dominant systematic effect in our experiment is the stray magnetic field generated from the spin-polarized DyIG sample. According to Fig. [1] mitigating the sample field was possible by lowering the sample temperature to the critical temperature with a cooling system, as discussed below. Further mitigation was achieved with additional magnetic shields made of \( \mu \)-metal and ferrite; however, the shields led to a increased distance between the SERF magnetometer and the DyIG sample.

Figure 2(a) shows a schematic of the experimental setup at Los Alamos National Laboratory to probe \( V_{15} \) and photos of main elements. Because the SERF magnetometer operates in low-field environments, it was located inside a magnetically shielded room (MSR), and also compensation coils were added at the magnetometer head to additionally cancel the fields from magnetic sources inside the MSR. The main body of the cooling system—a chiller (PolyScience IP-100) that can achieve the temperature as low as 180 K in a liquid cryostat and an alcohol liquid bucket that contains a submersible pump for liquid circulation—was located outside the MSR in order to avoid their magnetic noise. For the design simplification, the cooling system components except the chiller were wrapped by flexible thermal insulation made of aerogel and fiberglass. In such an open environment, the chiller could cool the liquid in the bucket as low as 230 K. The liquid circulated through 2 m-long transport hose made of 1 cm-diameter PVC clear tubing that was connected to a plastic fitting placed inside the MSR through a hole with 6.35 cm radius on the MSR wall. The fitting contains a cold finger of a sapphire rod with 1 cm diameter and 5 cm length provided by Egorov Scientific. For the mass cooling, the DyIG mass was attached at the end of the sapphire rod with a high thermal conductivity (34.6 W/m/K) and a low magnetic susceptibility (\( -2.1 \times 10^{-7} \); thus, no systematic magnetic signal is generated). The mass was concentrically aligned with the SERF Rb vapor cell. For the mass motion, a motor (Haydonkerk EC042B-2PM0-804-SP), located outside the MSR and enclosed by an one-layer \( \mu \)-metal box, was connected to the fitting through a G-10 rod. The cold finger/mass assembly was enclosed by a plastic cylindrical box filled with 5 mm-thick aerogel sheet.

A temperature sensor (Lake Shore DT-670-SD) was mounted on the transport hose near the liquid bucket to monitor the liquid temperature. It was observed that the temperature was around 235 K with the drift of 4 K for one day due to the ambient temperature variation.
We observed that the mass temperature was a few degrees higher than the liquid temperature, thus close to the critical temperature of 240 K. Although the mass was cooled down to around the critical temperature, the residual field from the mass was measured to be \( \sim 1 \mu T \) and the field drift caused by the temperature drift deteriorated the performance of the SERF magnetometer. To this end, the cold finger/mass assembly was surrounded by an open thin one-layer \( \mu \)-metal box and an open ferrite box additionally enclosed the SERF magnetometer, as shown in Fig. 2(a). This configuration resulted in the increase of the distance between the nearest surfaces of the Rb vapor cell and the mass, \( \delta r \), up to 7.5 cm.

Figure 2(b) illustrates a schematic of the configuration of the SERF Rb vapor with spins oriented along the \( x \)-axis and the DyIG mass with spins oriented along the \( z \)-axis. In order to generate the relative velocity term in \( V_{15} \), the mass was rotated by the motor with a constant angular velocity \( \omega \). The mass rotation in this configuration induces the target \( B_{\text{eff}} \) along the \( z \)-axis that can be precisely measured by the SERF magnetometer, sensitive to the \( z \) field component with the intrinsic field sensitivity of 15 fT/Hz\(^{1/2}\) at low frequency below 100 Hz. The distance \( \delta r = 7.5 \) cm.

The suppression of the systematic effects (SERF dc offset on the order of \( \mu T \); mass residual field on the order of \( \mu T \)) was achieved by continuously alternating the mass rotation between clockwise and counterclockwise to subtract the magnetometer signals because the sign of \( B_{\text{eff}} \) is reversed for the opposite rotations, unlike the systematic effects. The motor outputed a trigger signal indicating the rotation direction, enabling to distinguish the direction in the magnetometer signals. Figure 3(a) shows standard magnetometer signals in the time domain together with motor trigger signals, both of which simultaneously recorded, that represent two full cycles of the mass rotation reversal. In one cycle, the mass was rotated with \( \omega = 0.242 \) rad/s for 1 s and then with \( \omega = -0.242 \) rad/s for 1 s. Due to the acceleration/deceleration times and the delay time after each mass rotation in the motor, one cycle elapsed 2.3 s.

To obtain the magnitude of \( B_{\text{eff}} \) from the magnetometer signals, only data points within the yellow shaded regions (the last 25% of data without the regions of the motor deceleration and delay, marked as the gray shaded regions) in each half cycle were used [see Fig. 3(a)] in order to diminish the effects originating from motor acceleration such as mass vibration and also to ensure stable mass rotation with the constant angular velocity. The magnetometer signals between the opposite mass rotations were effectively subtracted using the drift-correction algorithm (for more detail see Refs. \[18, 19\]). The algorithm re-
The statistical sensitivity of dominant systematic effects have been mitigated below the experimental sensitivity $\Delta E$ of $2.92 \times 10^{-19}$ eV.

The limit to $g^e_V g^e_V$ of the interaction $V_{15}$ was derived using the Monte Carlo method to average the interaction potential in Eq. [4] at different interaction ranges (for more detail, see Refs. [18, 19, 26]), plotted in Fig. 3 (red solid curve). The other experimental constraints on $g^e_V g^e_V$ have been derived from the experiments based on the $^{199}$Hg-Cs co-magnetometer with polarized geoelectrons [20, 32] (not shown) and the K-Rb SERF magnetometer with SmCo$_5$ spins [21] (blue solid curve) for the long interaction range $>1$ m. Our experiment sets a new limit on $V_{15}$ in the interaction range from $10^{-3}$ to $10^{-1}$ m with the data collection time of 29.4 h.

In conclusion, we probed the exotic parity- and time-reversal-odd SSVDI $V_{15}$ between SERF spin-polarized electrons and DyIG spin-polarized electrons, and set the most stringent constraint on the electron-electron coupling strength at the centimeter interaction range. The result indicates that this experiment is able to explore the remaining SSVDIs by proper mass movements. The interaction range in this experiment was limited by the field drift of the spin-polarized mass. For a shorter interaction range, a reduction of the mass field drift should be achieved by developing a vacuum cooling system with a thermal feedback loop. For a longer data collection time thus further enhancement in the experimental sensitivity, the motor system should be improved by using an air bushing to reduce friction during the mass motion and a better alignment between the mass and the motor.

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