Searching for New Spin-Dependent Interactions with SmCo$_5$ Spin Sources and a SERF Comagnetometer

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We propose a novel method to search for possible new macro-scale spin- and/or velocity-dependent forces (SVDFs) based on specially designed SmCo$_5$ spin sources and a spin exchange relaxation-free (SERF) comagnetometer. A simulation shows that, by covering a SmCo$_5$ permanent magnet with a layer of pure iron, a high net spin density source of about $1 \times 10^{22}$ cm$^{-3}$ could be obtained. Taking advantages of the high spin density of this iron-shielded SmCo$_5$ and the high sensitivity of the SERF, the proposed method could set up new limits of greater than 10 orders of magnitude more sensitive than those from previous experiments or proposals in exploring SVDFs in force ranges larger than 1 cm.

Searches for anomalous spin- and/or velocity-dependent forces (SVDFs) have drawn considerable attentions in the past few decades. Various theories beyond the Standard Model have predicted weakly coupled scalar, pseudo-scalar, vector, or axial-vector bosons with light masses$^{[1–3]}$. It is believed that these light bosons may be the answers to many fundamental questions related to, for examples, the CP or CPT violation$^{[4, 5]}$, Lorentz violation$^{[6]}$, and the dark matter$^{[7]}$ etc. Obviously, how to experimentally set limits on coupling constants of such bosons or even find them is an important step for human beings to further understand the mother nature.

The light bosons, if exist, can mediate long-range exotic two-body interactions. As part of the SERF comagnetometer, several layers of $\mu$-metal cover the K$^3$He glass cell to reduce the possible ambient magnetic fields, and make the system work in the so-called SERF regime. The right side in Fig. 1 schematically. The left side is a SERF magnetometer, several layers of $\mu$-metal cover the K$^3$He glass cell to reduce the possible ambient magnetic fields, and make the system work in the so-called SERF regime. The right side in Fig. 1 is the iron-shielded SmCo$_5$ (ISSC). The ISSC can move in different ways, which will be introduced in details later. The ISSC is also covered with $\mu$-metals to further reduce the magnetic flux leakage from the SmCo$_5$ even after the iron-shielding.

To get a SERF comagnetometer work, the glass cell is normally heated to about 160$^\circ$C to achieve a sufficiently high alkali vapor density. The leading order of the alkali atoms’ polarization in $x$ direction is given by$^{[12]}$:

\[
P'_x = \frac{P^e_{\gamma_e}}{R_{tot}} (b^e_y - b^e_y),
\]

where $P^e_{\gamma_e}$ is K electrons’ polarization along the $i$-axis, $b^e_y$ and $b^e_y$ are the magnetic-like field in $y$ direction seen by the $^3$He nucleus and the K electrons respectively, $R_{tot}$ is the K electron’s relaxation rate, and $\gamma_e$ is the gyromagnetic ratio for the K electrons. Therefore, if the SVDFs exist, and couple to neutrons or electrons, the corresponding effective fields $b^e_y$ or $b^e_y$ can be detected by the SERF.
The magnetic moment of the Sm$^{3+}$ is the spin contribution of the magnetic moments of Sm in the SmCo$_5$, i.e., $M_{\text{Sm}} = \sigma_{\text{Sm}}^{2e}$, where $\sigma_{\text{Sm}}^{2e}$ is the spin ratio of Sm to Co, and $\mu_B$ is the Bohr magneton. The minus sign of $B_\text{Fe}$ means the magnetization of the iron, $f_{\text{Fe}} = 0.957$ is the spin contribution of the magnetic moments in Fe$^{3+}$ [22, 23]. The magnetism in pure iron mainly comes from the spin magnetic moment of the 3$d$ electrons because the orbital magnetic moment of the 3$d$ electrons can be quenched in the inhomogeneous crystalline electric field [24]. For pure iron magnetized to 10 kGs, its spin density is about $n_{\text{Fe}} = 8.2 \times 10^{22}/\text{cm}^3$.

Even $\mu$-metals may have higher spin densities [25], we prefer pure iron due to its simple structure which potentially affects the data analysis of the SVDF searching experiments.

**FEA Simulation**— With the FEA method, we simulated the magnetization distribution and then the spin density distributions in the ISSC. The main optimized input parameters are listed in Tab. II. The structure under simulation is shown in Fig. 2. The “net” electron spin of this ISSC can be written as $N_{\text{net}} = \int n_{\text{SmCo}}dV_{\text{SmCo}} + \int n_{\text{Fe}}dV_{\text{Fe}}$, where $V_{\text{SmCo}}$ and $V_{\text{Fe}}$ are the volumes of SmCo$_5$ and Iron respectively. According to the FEA simulation (shown in Table II), the net electron spin of this structure is $8 \times 10^{26}/\text{h}/2$, while at the same time the magnetic field can be cancelled to very close to zero (about 0.5 Gs at a distance 5 cm away from the pure iron).

This special feature is mainly due to the fact that Sm’s 4$f$ electrons and Co’s 3$d$ electrons in SmCo$_5$ have large orbital magnetic moments, while Fe 3$d$ electrons’ orbital...
magnetic moments are quenched. Therefore, it is possible to reduce the outside magnetic field close to zero, while at the same time keep the total net electron spins non-zero.

There are some other spin materials which are chosen or proposed for SVDF searches, for example, Alnico, dysprosium iron garnet (DyIG), and GGG etc[17 20 27]. The Alnico has higher spin densities, but its orbital magnetic moment is too low[20] to benefit this experiment. The garnet-DyIG and GGG crystals have also been used in the SVDF search experiments. However, fabrication of those crystals are difficult, especially for large-size crystals, which limits their applications. Due to the simple structure, stable property, and high spin density, the ISSC is an excellent spin material for SVDF searches.


table 1. the optimized rotating axises and orientations of \( \sigma \parallel \beta \) and \( \sigma \parallel \gamma \) when estimate the sensitivities of the different SVDF terms with the proposed setup.

| Terms | \( V_2 \) | \( V_3 \) | \( V_{9+10} \) | \( V_{11} \) | \( V_{9+7} \) | \( V_{14} \) | \( V_{15} \) | \( V_{16} \) |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Rotating axis | \( y \) | \( y \) | \( x \) | \( y \) | \( x \) | \( y \) | \( y \) | \( y \) |
| \( \sigma \parallel \beta \) | \( +z \) | \( +x \) | \( +z \) | \( +z \) | \( +y \) | \( +y \) | \( +z \) | \( +z \) |
| \( \sigma \parallel \gamma \) | \( +z \) | \( +x \) | \( +z \) | \( +z \) | \( -y \) | \( -y \) | \( +z \) | \( -x \) |

Estimations of New Limits for SVDFs– By using the ISSC designed above and a SERF comagnetometer, the sensitivities of SVDF searches could be estimated.

Mathematically, there are 16 terms of SVDFs[14]. Here we list the representative 8 terms which are spin-dependent (\( V_2 \) in Eq.1, \( V_3 \), \( V_{9+10} \), and \( V_{11} \)) as well as spin-and-velocity-dependent forces (\( V_{6+7} \), \( V_{14} \), \( V_{15} \), and \( V_{16} \)):

\[
\begin{align*}
V_3 &= f_3 \frac{\hbar^2}{4\pi m_1 m_2 c} \left[ \left( \sigma_1 \cdot \sigma_2 \right) \left( \frac{1}{\lambda r^2} + \frac{1}{r^3} \right) - \left( \sigma_1 \cdot r \right) \left( \sigma_2 \cdot r \right) \left( \frac{1}{\lambda r^2} + \frac{3}{\lambda r^2} + \frac{3}{r^3} \right) \right] e^{-r/\lambda}, \quad (5)
V_{6+7} &= -f_{6+7} \frac{\hbar^2}{4\pi m_\mu c} \left[ \left( \sigma_1 \cdot v \right) \left( \sigma_2 \cdot r \right) \right] \left( \frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda}, \quad (6)
V_{9+10} &= \frac{f_{9+10} \hbar^2}{8\pi m_\mu} \left( \frac{1}{\lambda r^2} + \frac{1}{r^3} \right) e^{-r/\lambda}, \quad (7)
V_{11} &= -f_{11} \frac{\hbar^2}{4\pi m_\mu} \left( \left( \sigma_1 \times \sigma_2 \right) \cdot r \right) \left( \frac{1}{\lambda r^2} + \frac{1}{r^3} \right) e^{-r/\lambda}, \quad (8)
V_{14} &= \frac{f_{14}}{4\pi} \left( \left( \sigma_1 \times \sigma_2 \right) \cdot v \right) \left( \frac{1}{r} \right) e^{-r/\lambda}, \quad (9)
V_{15} &= -\frac{f_{15} \hbar^3}{8\pi m_1 m_2 c^2} \left\{ \left( \sigma_2 \cdot r \right) \left[ \sigma_1 \cdot \left( v \times r \right) \right] + \left( \sigma_1 \cdot r \right) \left[ \sigma_2 \cdot \left( v \times r \right) \right] \right\} \left( \frac{1}{\lambda r^2} + \frac{3}{\lambda r^2} + \frac{3}{r^3} \right) e^{-r/\lambda}, \quad (10)
V_{16} &= -\frac{f_{16} \hbar^2}{8\pi m_\mu c^2} \left\{ \left( \sigma_2 \cdot v \right) \left[ \sigma_1 \cdot \left( v \times r \right) \right] + \left( \sigma_1 \cdot v \right) \left[ \sigma_2 \cdot \left( v \times r \right) \right] \right\} \left( \frac{1}{\lambda r^2} + \frac{1}{r^2} \right) e^{-r/\lambda}, \quad (11)
\end{align*}
\]

where \( f_i \) is the dimensionless coupling constant between particles, \( m_1 \) and \( m_2 \) are their respective masses, \( m_\mu \) is their reduced mass.

By optimizing the rotational axises of the ISSCs, one can obtain maximum sensitivities for different terms of the SVDFs. The ISSCs rotational axises for different SVDF terms are listed in Tab. I. The main input parameters, which are conservative, are listed in Tab. II.

According to Eq. 3, we take the effective magnetic field for electron as \( B_{eff}^{(e)} = b'_y \), while for neutron, \( B_{eff}^{(n)} = b'_y/0.87 \), due to the limited neutron polarization of 87% in a \(^3\)He nucleus[22 23].

The estimated results are shown in Fig. 3. In \( \lambda > 0.1 \) m, even with conservative input parameters, the proposed method could highly improve the sensitivities of these types of the SVDF searches. For example, the limits of \( f_{10}^{(en)} \), and \( f_{16}^{(en)} \) can be improved by over 10 orders of magnitude in \( \lambda < 1000 \) m compared with the current best limits[20]. For the constrains of the possible new “dipole–dipole interaction” \( f_3^{(en)} \) and \( f_{6+7}^{(en)} \), this proposal could be more than 7 orders of magnitude better than the current records[29 30] at around \( \lambda = 1000 \) m. For the limits of \( f_{9+10} \) and \( f_{12}^{(en)} \), this proposal could be more than 3 orders of magnitude better than other proposals[17 27]. For other terms of the SVDFs for electron-electron (ee) and electron-nucleon (en) couplings, the proposed method can also be several orders of magnitude better than other corresponding best limits up to date.

Summary– The experimental searches for new macro scale SVDFs are important for testing theories beyond the Standard Model. High spin density and easily handling materials are critical for SVDF-search experiments. We propose the ISSC structure, i.e. a SmCo5 permanent magnet covered with pure iron, for the SVDF studies. In this new structure, the magnetic field could be highly reduced, while at the same time a large amount of net electron spin polarization can be achieved. By using this

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**Table II.** Input parameters for the FEA simulation.

| Parameter | Value |
|-----------|-------|
| The SERF’s center to the ISSCs’ center | 0.7 m |
| Distance between the two ISSCs | 0.6 m |
| Rotating frequency | 5 Hz |
| Soft iron’s relative permeability | 12000 |
| SmCo5 Magnetization | 10 kGs |
| The SERF’s sensitivity | 1 fT/Hz^{1/2} |
| Data taking time | 2 weeks |
| The soft Iron’s Nucleon density | 4.7 × 10^{21} cm^{-3} |
| The SmCo5’s Nucleon density | 5.1 × 10^{21} cm^{-3} |
ISCC structure, together with the highly sensitive SERF comagnetometer, the sensitivities for detecting different terms of SVDFs are discussed. This new approach has sensitivities as large as 10 orders of magnitude higher compared with those from previous experiments or proposals, which makes it a promising method in new experiments searching for spin-dependent interactions.

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FIG. 3. Comparisons of the limits set by this proposal and others in literatures. The input parameters, which are conservatively assumed, are shown in Tab. I & II. The “ee” (“en”) labeled here means the coupling between electron and electron (neutron). The references for different terms of the SVDFs are: $V_2$ from Ref. 31 [35], $V_3$ from Ref. 26 [30] 31 [33], $V_{6+7}$, $V_{14}$, $V_{15}$, and $V_{16}$ from Ref 29, $V_{9+10}$ are from Ref 20, 28, 29, 44, 43, and $V_{11}$ from Ref 31 [32].