New Limits on Exotic Spin-Dependent Interactions at Astronomical Distances

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Exotic spin-dependent interactions involving new light particles address key questions in modern physics. Interactions between polarized neutrons (n) and unpolarized nucleons (N) occur in three forms: $g_S^N g_P^n \boldsymbol{\sigma}\cdot\boldsymbol{r}$, $g_V^N g_A^n \boldsymbol{\sigma}\cdot\boldsymbol{v}$, and $g_A^N g_A^n \boldsymbol{\sigma}\cdot\boldsymbol{v}\times\boldsymbol{r}$, where $\boldsymbol{\sigma}$ is the spin and g's are the corresponding coupling constants for scalar, pseudoscalar, vector, and axial-vector vertexes. If such interactions exist, the Sun and Moon could induce sidereal variations of effective fields in laboratories. By analyzing existing data from laboratory measurements on Lorentz and CPT violation, we derive new experimental upper limits on these exotic spin-dependent interactions at astronomical ranges. Our limits on $g_S^N g_P^n$ surpass the previous combined astrophysical-laboratory limits, setting the most stringent experimental constraints to date. We also report new constraints on vector-axial-vector and axial-axial-vector interactions at astronomical scales, with vector-axial-vector limits improved by ~12 orders of magnitude. We extend our analysis to Hari Dass interactions and obtain new constraints.

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Introduction.—Axions, predicted by the Peccei-Quinn (PQ) mechanism [1–3], can induce spin-dependent interactions [4]. The originally proposed axions were quickly ruled out due to the broken energy scale of the electroweak scale; however, new models with higher broken energy scales were subsequently proposed. Axions can have arbitrarily small mass and weak couplings to ordinary matter because the scale at which the PQ symmetry is broken can be arbitrarily large [5]. Thus, axions might mediate interactions in ranges from nanometers to astronomical distances. Though the PQ mechanism was originally proposed to solve the strong CP problem, the axions, which are light, weakly interacting, and pseudoscalar, are also considered as possible candidates for cold dark matter. New interactions might also be mediated by vector particles such as the paraphoton (dark, hidden, heavy, or secluded photon) [6,7], Z' boson [8], graviphoton [9], etc., or even unparticles [10]. Reference [11] proposed 16 different types of new interactions, 15 of which are spin dependent. Non-Yukawa exotic interactions due to the dark or hidden sector were also proposed recently [12,13]. As early as 1980, Fayet [14,15] pointed out that the new U(1) vector bosons, characterized by small masses and weak couplings to ordinary matter, could be generated through the spontaneous breaking of supersymmetric theories. Searching for the new interactions mediated by the new particles is related to the strong CP problem, dark matter, dark energy, and finding evidence of supersymmetry, which is among the most important unsolved problems in modern physics [16].

Particles with similar properties as axions, predicted by various generalized theories, are usually called axionlike particles (ALPs) [8]. If they exist, ALPs (ϕ) can generate a new interaction through the coupling to a fermion ψ, $\mathcal{L}_\phi = \bar{\psi}(g_S + i g_P \gamma_5)\psi\phi$, where g_S (g_P) is the scalar (pseudoscalar) coupling constant [4]. The scalar-pseudoscalar (SP) interaction between a polarized neutron and an unpolarized nucleon can be expressed as

$$V_{SP} = \frac{\hbar^2 g_S^N g_P^n}{8\pi m_n}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)\exp(-r/\lambda)\boldsymbol{\sigma}\cdot\hat{r}, \qquad (1)$$

where $\lambda = \hbar/m_\phi c$ is the interaction range, m_ϕ is the mediator mass, $\boldsymbol{\sigma}$ is the spin operator of the polarized neutron, m_n is the neutron mass, N (n) represents the nucleon (neutron), and r is the distance between the two interacting particles. This interaction could also be generated from $\mathcal{L}_\phi = g_S\bar{\psi}\psi\phi + g_P/(2m)\bar{\psi}\gamma_\mu\gamma_5\psi\partial^\mu\phi$ [4,17,18], which includes a derivative term. Such a term appears in the axion models [19]. Notably, the SP interaction generated from the derivative coupling between axions and fermions is discussed in Ref. [20]. Thus, studying this interaction can be used to investigate not only ALPs but also axions. Recently, the SP interaction has begun to attract more attention [21–27]. For example, Wei *et al.* [28] proposed a laboratory experiment scheme that could surpass the astrophysical limit for the SP interaction. Laboratory limits become closer and closer to the limits derived by combining g_S^N from the torsion balance experiment and g_P^n from SN1987A; however, all the existing limits are less stringent than the combined astrophysical-laboratory ones at astronomical distances.

Vector-axial-vector (VA) and axial-axial-vector (AA) interactions can be derived from a general Lagrangian $\mathcal{L}_X = X_\mu \bar{\psi}(g_V \gamma^\mu + g_A \gamma_5 \gamma^\mu)\psi$ in the nonrelativistic limit, where X is a new vector particle and g_V (g_A) is the vector (axial-vector) coupling constant. The interactions between a polarized neutron and an unpolarized nucleon can be expressed as

$$V_{\mathrm{VA}} = \frac{\hbar g_V^N g_A^n}{2\pi} \frac{\exp(-r/\lambda)}{r} \boldsymbol{\sigma} \cdot \boldsymbol{v}, \tag{2}$$

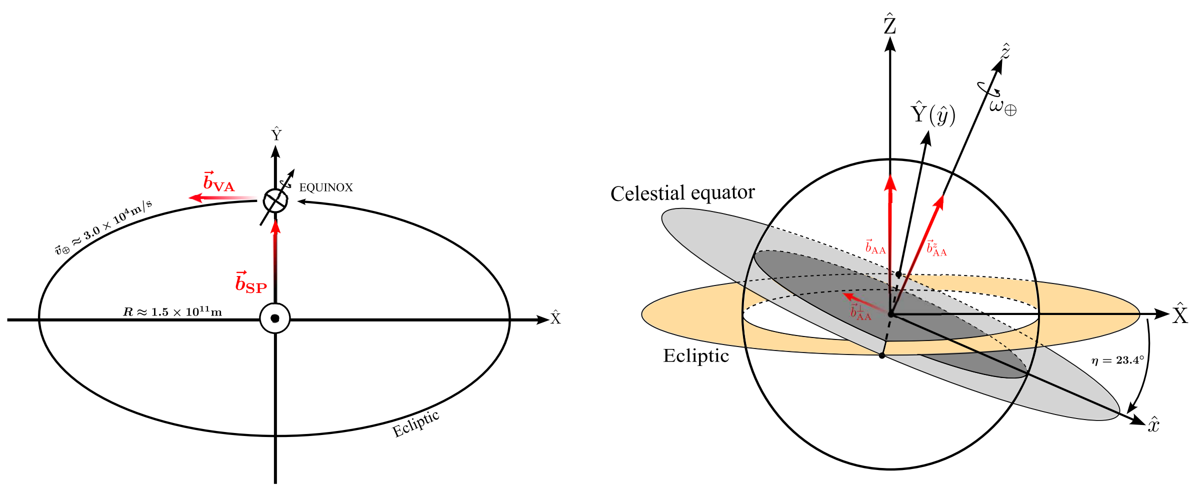
$$V_{\mathrm{AA}} = \frac{\hbar^2 g_A^N g_A^n}{16\pi m_n c} \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) \exp(-r/\lambda) \boldsymbol{\sigma} \cdot (\boldsymbol{v} \times \hat{r}), \tag{3}$$

where $\boldsymbol{v}$ is their relative velocity. Many studies have been carried out to look for the new interactions, detecting either the macroscopic forces or the torques exerted on the polarized probe spins. For example, Leslie *et al.* [29] proposed experimental schemes to detect the new spin-dependent interaction between a polarized source and a mechanical oscillator. For another example, Ding *et al.* [30] used a microfabricated magnetic structure as a polarized source and then tried to detect the AA interaction at the range of $\sim$ microns sensed by a gold-sphere cantilever. Many groups have been searching for the new interaction through its rotating effects as a effective magnetic field on the polarized spin. The VA and AA interactions between different combinations of fermions have been investigated already, such as electron-nucleon [30–33], neutron-nucleon [34–36], electron-electron [37], and electron-antiproton [38]. Studies on these exotic interactions involving muons were performed very recently [39].

Since the signal induced by new interactions is tiny, using a large mass source and modulating the signal to a high frequency are crucial for the detection. A mass source with vast constituents could make the signal measurable. By modulating the signal, on the one hand, the signal-to-noise ratio can be increased with the decrease of the noise bandwidth. On the other hand, the $1/f$ noise can be significantly reduced at high frequencies. In this Letter, treating the Sun and the Moon as mass sources and using Earth's rotation as a modulation, we obtain new limits on exotic spin-dependent SP (1), VA (2), and AA (3) interactions at astronomical distances.

The basic idea.—All three types of spin-dependent interactions are in the form of $\boldsymbol{s} \cdot \boldsymbol{B}'$, where $\boldsymbol{B}'$ can be viewed as a kind of effective magnetic field. Searching for these interactions becomes a problem probing the effective field acting on polarized spins. We first illustrate the basic idea using the Sun as the source mass. In the Sun-centered frame shown in Fig. 1(a), the aforementioned new interactions can generate effective magnetic fields at Earth's center as [40]

$$\begin{aligned}
\boldsymbol{B}'_{\mathrm{SP}} &= \frac{\hbar g_S^N g_P^n N_\odot}{4\pi m_n \gamma_n}\left(\frac{1}{\lambda R} + \frac{1}{R^2}\right)\exp(-R/\lambda) \\
&\quad \times [\cos(\Omega_\oplus t)\hat{X} + \sin(\Omega_\oplus t)\hat{Y}], \\
\boldsymbol{B}'_{\mathrm{VA}} &= \frac{g_V^N g_A^n N_\odot}{\pi \gamma_n}\frac{\exp(-R/\lambda)}{R} \\
&\quad \times [-\Omega_\oplus R \sin(\Omega_\oplus t)\hat{X} + \Omega_\oplus R \cos(\Omega_\oplus t)\hat{Y}], \\
\boldsymbol{B}'_{\mathrm{AA}} &= -\frac{\hbar g_A^N g_A^n N_\odot}{8\pi m_n c \gamma_n}\left(\frac{1}{\lambda R} + \frac{1}{R^2}\right)\exp(-R/\lambda)\Omega_\oplus R\hat{Z},
\end{aligned} \tag{4}$$



(a) (b)

FIG. 1. (a) The Sun-centered frame. The relative size of the Sun and Earth is not to scale. (b) Earth-based frame. We take $\hat{z}$ along with Earth's rotation axis. The angle between the ecliptic plane and Earth's equatorial plane is $\eta = 23.4°$. The red arrows represent the directions of effective fields of three types of spin-dependent interactions generated by the Sun's nucleons.

where R is the distance from Earth to the Sun, γ_n is the gyromagnetic ratio of the neutron, $\Omega_\oplus$ is Earth's orbital angular frequency, and $N_\odot$ is the total nucleon number of the Sun. For a laboratory frame on Earth as shown in Fig. 1(b), the effects of Earth's rotation can be taken into account via the Euler rotations. We first rotate the frame by the angle $\omega_\oplus t$ about the $\hat{Z}$ axis, where $\omega_\oplus$ is Earth's rotation frequency, and then rotate about the $\hat{Y}$ axis by an angle η, which is Earth's obliquity. In the laboratory frame, we will observe effective time-varying fields as

$$\boldsymbol{b}_{\mathrm{SP}} = \frac{\hbar g_{\mathrm{S}}^{N} g_{\mathrm{P}}^{n} N_\odot}{4\pi m_n \gamma_n}\left(\frac{1}{\lambda R} + \frac{1}{R^2}\right)\exp(-R/\lambda)\begin{bmatrix} \cos\eta\cos(\Omega_\oplus t)\cos(\omega_\oplus t) + \sin(\Omega_\oplus t)\sin(\omega_\oplus t) \\ -\cos\eta\cos(\Omega_\oplus t)\sin(\omega_\oplus t) + \sin(\Omega_\oplus t)\cos(\omega_\oplus t) \\ \sin\eta\cos(\Omega_\oplus t) \end{bmatrix}, \tag{5}$$

$$\boldsymbol{b}_{\mathrm{VA}} = \frac{g_{\mathrm{V}}^{N} g_{\mathrm{A}}^{n} N_\odot}{\pi\gamma_n}\frac{\exp(-R/\lambda)}{R} v_\oplus \begin{bmatrix} -\cos\eta\cos(\omega_\oplus t)\sin(\Omega_\oplus t) + \sin(\omega_\oplus t)\cos(\Omega_\oplus t) \\ \cos\eta\sin(\omega_\oplus t)\sin(\Omega_\oplus t) + \cos(\omega_\oplus t)\cos(\Omega_\oplus t) \\ -\sin\eta\sin(\Omega_\oplus t) \end{bmatrix}, \tag{6}$$

$$\boldsymbol{b}_{\mathrm{AA}} = \frac{\hbar g_{\mathrm{A}}^{N} g_{\mathrm{A}}^{n} N_\odot}{8\pi m_n c\gamma_n}\left(\frac{1}{\lambda R} + \frac{1}{R^2}\right)\exp(-R/\lambda) v_\oplus \begin{bmatrix} \sin\eta\cos(\omega_\oplus t) \\ -\sin\eta\sin(\omega_\oplus t) \\ -\cos\eta \end{bmatrix}, \tag{7}$$

where $v_\oplus = \Omega_\oplus R$ is the orbital speed of Earth. As the most straightforward case, $\boldsymbol{b}_{\mathrm{AA}}$ clearly shows effective magnetic fields rotating in the laboratory frame at Earth's rotation frequency. Although $\boldsymbol{b}_{\mathrm{SP}}$ and $\boldsymbol{b}_{\mathrm{VA}}$ appear more complicated due to their mixture with Earth's orbital rotation, the situation can be greatly simplified by considering the fact that $\omega_\oplus \gg \Omega_\oplus$.

In summary, if the exotic spin-dependent interactions exist, the perpendicular components of the effective fields induced by the Sun are modulated by Earth's rotations; thus, we could observe its signal in the laboratory. Although the frequency of Earth's rotation is not high, its frequency modulation effect on the nuclear precession in the comagnetometer makes precision measurements on these new interactions possible (see Supplemental Material [40]).

Constraining the exotic spin-dependent interactions at astronomical distances.—Dual-species comagnetometers are convenient for detecting the tiny signals caused by new spin-dependent interactions, since the two components occupy the same space and common-mode background field noise can be mostly canceled. In principle, we can separate the sidereal modulated signal from the noisy background during precise measurements. The ultrahigh sensitivity of the comagnetometer to the magnetic field changes has an extensive implementation in new physics detection, including electric dipole moments, *CPT* and Lorentz violation, spin-gravity interaction, and so on [45–48]. This comagnetometer method has been used to search for the constant cosmic background field due to Lorentz violation by detecting the sidereal variants of the field observed in the laboratory frame on Earth in Refs. [49,50], where a ^{129}Xe + ^{3}He comagnetometer and a K + ^{3}He one were, respectively, adopted. Stringent constraints on the components of the constant field perpendicular to Earth's rotation axis at a similar level were obtained.

We find that the limits on exotic spin-dependent interactions induced by the Sun can be obtained by using the Lorentz violation searching results. For example, for the experiment described in Ref. [49], the $\Omega_\oplus t$ in Eqs. (5)–(7) approximately equals $\pi/2$, given that the experiment was performed for ~10 days when Earth was around the vernal equinox. The sidereal oscillating effective field $\boldsymbol{b}_\perp$ perpendicular to Earth's rotation axis can be detected as [40]

$$\begin{aligned} \boldsymbol{b}_{\mathrm{SP}\perp} &= \frac{\hbar g_{\mathrm{S}}^{N} g_{\mathrm{P}}^{n} N_\odot}{4\pi m_n \gamma_n}\left(\frac{1}{\lambda R} + \frac{1}{R^2}\right)\exp(-R/\lambda) \\ &\quad \times [\sin(\omega_\oplus t)\hat{x} + \cos(\omega_\oplus t)\hat{y}], \\ \boldsymbol{b}_{\mathrm{VA}\perp} &= \frac{g_{\mathrm{V}}^{N} g_{\mathrm{A}}^{n} N_\odot}{\pi\gamma_n}\frac{\exp(-R/\lambda)}{R} v_\oplus \cos\eta \\ &\quad \times [-\cos(\omega_\oplus t)\hat{x} + \sin(\omega_\oplus t)\hat{y}], \\ \boldsymbol{b}_{\mathrm{AA}\perp} &= \frac{\hbar g_{\mathrm{A}}^{N} g_{\mathrm{A}}^{n} N_\odot}{8\pi m_n c\gamma_n}\left(\frac{1}{\lambda R} + \frac{1}{R^2}\right)\exp(-R/\lambda) v_\oplus \sin\eta \\ &\quad \times [\cos(\omega_\oplus t)\hat{x} - \sin(\omega_\oplus t)\hat{y}]. \end{aligned} \tag{8}$$

Using the result of Ref. [49], at the 95% confidential level (CL), we could derive

$$|\boldsymbol{b}_\perp| < 0.023 \text{ fT}. \tag{9}$$

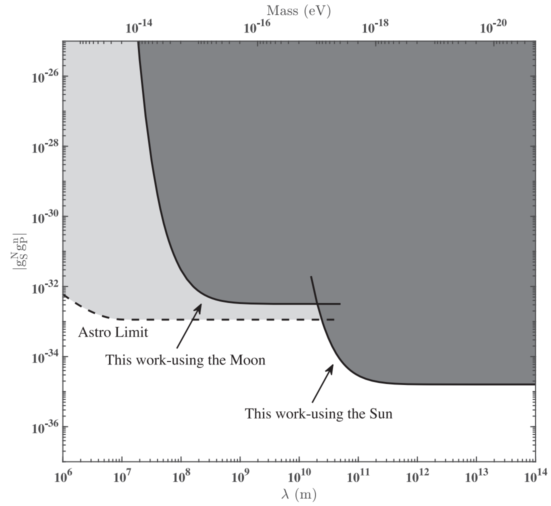


FIG. 2. Constraint to the coupling constant product $|g_S^N g_P^n|$ as a function of the interaction range λ (the mediator mass). The solid lines are the result of this Letter; the left line uses the Moon as the source, and the right line uses the Sun. The dashed line is the result of Refs. [18,51], which was derived by combining g_S^N of weak equivalence with g_P^n from SN1987A. The dark gray area is excluded by the result of this Letter and the light gray one is excluded by the result of Refs. [18,51].

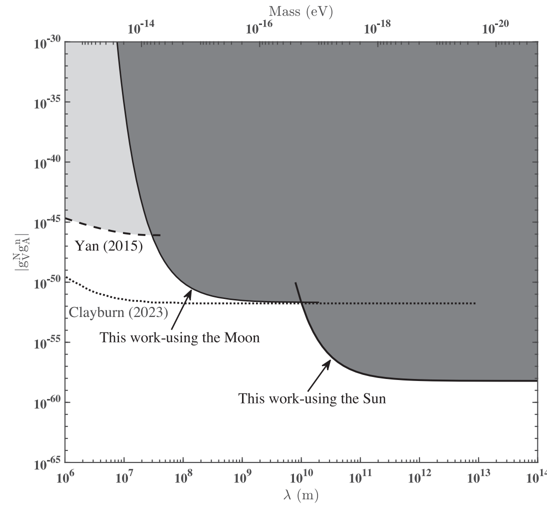


FIG. 3. Constraint to the coupling constant product $|g_V^N g_A^n|$ as a function of the interaction range λ (the mediator mass). The solid lines are the result of this Letter; the left line uses the Moon as the source, and the right line uses the Sun. The dashed line is the result of Ref. [36]. The dark gray area is excluded by the result of this Letter and the light gray one is excluded by the result of Ref. [36]. The dotted line is the result of Ref. [52].

Plugging in all the known parameters such as $\eta = 23.4°$, $N_\odot \approx 1.2 \times 10^{57}$, $R = 1.5 \times 10^{11}$ m, and $v_\oplus \approx 3.0 \times 10^4$ m/s, we can obtain the constraints on the SP (1), VA (2), and AA (3) interactions between polarized neutrons and unpolarized nucleons.

The derived constraint on $|g_S^N g_P^n|$ is shown in Fig. 2. For $\lambda \gtrsim 2 \times 10^{10}$ m, it gives the most stringent limit on $|g_S^N g_P^n|$. For $\lambda > 10^{12}$ m, our bounds $|g_S^N g_P^n| < 1.6 \times 10^{-35}$ (95% CL). Previously, the most stringent constraints on $|g_S^N g_P^n|$ were astrophysical-laboratory limits that combined astrophysical constraints on g_P^n from SN1987A with the laboratory ones on g_S^N from the weak equivalence principle experiment. This Letter improves the existing upper bound by as much as ~70 times. In particular, the new limits on the scalar-pseudoscalar coupling combination exceed the combined astrophysical-laboratory limits for the first time.

Our constraint on $|g_V^N g_A^n|$ is shown in Fig. 3. For $\lambda \gtrsim 3 \times 10^7$ m, it gives the most stringent limit on $|g_V^N g_A^n|$. For $\lambda > 10^{12}$ m, our bounds $|g_V^N g_A^n| < 7.1 \times 10^{-59}$ (95% CL). Previously, the most stringent constraint on $|g_V^N g_A^n|$ near the interaction range under consideration was given in Ref. [36]. If the previous result can be extended to the range of $\sim 10^{12}$ m, the present Letter improves the existing upper bound by as much as 12 orders of magnitude.

The obtained constraint on $|g_A^N g_A^n|$ is shown in Fig. 4. For $\lambda \gtrsim 10^7$ m, it gives the first limit on $|g_A^N g_A^n|$. For $\lambda > 10^{12}$ m, our bounds $|g_A^N g_A^n| < 8.1 \times 10^{-31}$ (95% CL). It is the only known constraint on $|g_A^N g_A^n|$ to us at the astronomical ranges.

We can apply the same analyzing method by using the Moon as a source. In this case, we shall consider errors due to several systematic effects. We show details of the analysis in the Supplementary Material [40]. We also plotted the results using the Moon in Figs. 2–4.

Furthermore, the spin-gravity interaction proposed by Leitner and Okubo [53] and later generalized by Hari Dass [54] can also be strictly constrained. Assuming *CPT*

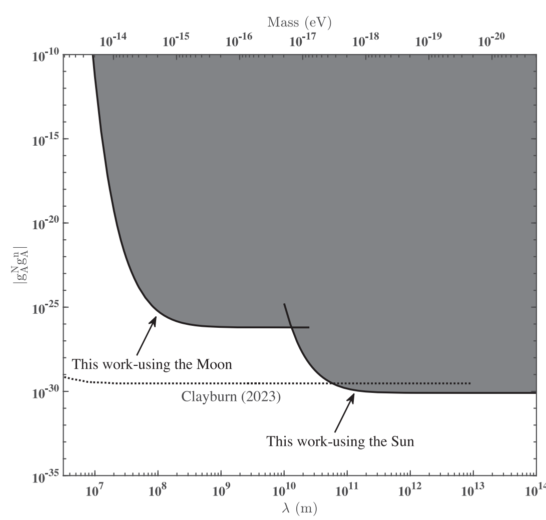


FIG. 4. Constraint to the coupling constant product $|g_A^N g_A^n|$ as a function of the interaction range λ (the mediator mass). The solid lines are the result of this Letter; the left line uses the Moon as the source, and the right line uses the Sun. The dark gray area is excluded by the result of this Letter. The dotted line is the result of Ref. [52].

invariance, two types of discrete symmetry violation spin-gravity potentials are constructed as

$$V(r) = \frac{G_N M\hbar}{2}\left(\alpha_1 \frac{\boldsymbol{\sigma}\cdot\hat{r}}{cr^2} + \alpha_2 \frac{\boldsymbol{\sigma}\cdot\boldsymbol{v}}{c^2 r^2}\right), \tag{10}$$

where G_N is the Newton constant of gravitation, M is the mass of the gravity source, and α_1 (α_2) is a dimensionless constant. These potentials are the starting point of many low-energy experiments [55,56]. They also provide a direct way to test symmetry violation and the equivalence principle in general relativity [54,57]. Using the Sun as the mass source, we derive the limits on α as

$$|\alpha_1| < 2.2\times 10^2\,(95\%\ \mathrm{CL}),$$
$$|\alpha_2| < 2.4\times 10^6\,(95\%\ \mathrm{CL}). \tag{11}$$

When comparing with the results of Ref. [58], our limit on α_1 improves the existing one by ~11 times, and on α_2 we get an improvement of ~4 orders of magnitude.

Conclusion and discussion.—By using the Sun and the Moon as sources, Earth's rotation as modulation, and the existing laboratory limits on the Lorentz and *CPT* violation at distances of astronomical scales, we have constrained three types of possible new interactions between polarized neutrons and unpolarized nucleons. We derived new limits on the SP interaction with ranges from $\sim 2\times 10^{10}$ to $\sim 10^{14}$ m. At the distance of $\sim 10^{12}$ m, the limit is improved by ~70 times compared to the previous combined astrophysical-laboratory limit. This result is the first time the limits from a single laboratory experiment exceed the combined astrophysical-laboratory ones for the SP interaction. We obtained new limits on the VA interaction with ranges from $\sim 3\times 10^7$ to $\sim 10^{14}$ m. At the distance of $\sim 10^{12}$ m, the limit is improved by ~12 orders of magnitude in comparison with the previous result of ^{3}He spin relaxation experiment. We derived the first limits on the AA interaction with ranges from $\sim 10^7$ to $\sim 10^{14}$ m. We also constrained the Hari Dass spin-dependent interactions and obtained new limits on them.

How can we extend the current Letter to include other particles, such as electrons and muons? One possibility is to employ the beam method proposed in Refs. [39,59], which uses superconducting magnetic shielding to create a region with zero background field. By directing spin-polarized particle beams through this region and detecting sidereal variations in polarization along the direction perpendicular to Earth's rotation axis, we can investigate spin-dependent new interactions induced by the Sun for the probing electrons, muons, etc.

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Note added.—Recently, Ref. [60] reports improved limits on $g_S^N g_P^n$ in the interaction range of 10^6–10^{10} m, and Ref. [52] reports limits on $g_V^N g_A^n$ and $g_A^N g_A^n$ in the interaction range of $\sim 10^{13}$ m, as shown in Figs. 3 and 4.

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