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Improved limits on long-range parity-odd interactions of the neutron

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We show that a previous polarized ^{3}He experiment at Princeton, plus Eöt–Wash equivalence-principle tests, constrain exotic, long-ranged ($\lambda > 0.15$ m) parity-violating interactions of neutrons at levels well below those inferred from a recent study of the parity-violating spin precession of neutrons transmitted through liquid ^{4}He. For $\lambda > 10^8$ m the bounds on $g_A g_V$ are improved by 11 orders of magnitude.

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Yan and Snow [1] recently inferred bounds on the coupling strength, $g_A^n g_V^{^4\mathrm{He}}$, of exotic, long-range, parity-violating interactions of neutrons from an experiment that studied the parity-violating spin rotation of polarized neutrons transmitted through liquid ^{4}He. Substantially tighter limits on several closely related quantities can be found by combining bounds on $|g_A^\mathrm{n}|^2$ and on $|g_V|^2$ set by previous experiments to obtain

$$|g_A^n g_V| = \sqrt{|g_A^n|^2 |g_V|^2}. \tag{1}$$

It is convenient to define

$$g_V^\pm = (g_V^\mathrm{p} + g_V^\mathrm{e} \pm g_V^\mathrm{n})/\sqrt{2}, \tag{2}$$

so that $g_V^{^4\mathrm{He}} = 2\sqrt{2} g_V^+$.

We take our bounds on $|g_A^\mathrm{n}|$ from a Princeton optical-pumping experiment with polarized ^{3}He detector and sources [2,3] that probed the neutron spin-spin interaction,

$$V_{12}^{\sigma\cdot\sigma} = \frac{(g_A^n)^2}{4\pi r}(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2) e^{-r/\lambda}, \tag{3}$$

because the neutron in ^{3}He carries most of the nuclear spin.

Our bounds on $|g_V|^2$ come from results of equivalence-principle tests [4,5] that tightly constrain Yukawa interactions of the form

$$V_{12} = \frac{(g_V)^2}{4\pi r} e^{-r/\lambda} = V_G(r)\tilde{\alpha}\left[\frac{\tilde{q}}{\mu}\right]_1 \left[\frac{\tilde{q}}{\mu}\right]_2 e^{-r/\lambda}, \tag{4}$$

where, in the second relation (conventionally used to analyze equivalence-principle results [5]), V_G is the Newtonian potential, $\tilde{\alpha}$ is a dimensionless strength to be determined by experiment, and a general vector "charge" of an atom with proton and neutron numbers Z and N can be parameterized as

$$\tilde{q} = \cos\tilde{\psi}[Z] + \sin\tilde{\psi}[N], \tag{5}$$

where $\tilde{\psi}$ characterizes the vector charge with

$$\tan\tilde{\psi} = \frac{g_V^n}{g_V^p + g_V^e}. \tag{6}$$

Note that $\tilde{q}^\pm$ correspond to charge parameters $\tilde{\psi} = \pm\pi/4$. The results of this analysis are shown in Figs. 1 and 2. The $|g_V|^2$ constraint obtained from the Hoskins *et al.* inverse-square test [6] would be imperceptible in Figs. 1 and 2 because of the rapid weakening of the $|g_A^n|^2$ constraint [2,3] for $\lambda < 0.2$ m.

The experimental results of Refs. [2–5] place especially tight bounds on $g_A^n g_V^n$, the strength of a parity-violating neutron-neutron interaction. For this purpose we use Eqs. (4) and (5) with $\tilde{\psi} = \pi/2$ (i.e. $\tilde{q} = N$). The differing sensitivities of the results in Figs. 1–3 follow from the varying properties of the assumed charges. In Fig. 1, $\tilde{q}^+$ is proportional to the atomic mass number so that the $\tilde{q}/\mu$ ratio difference of the various equivalence-principle test-body pairs arises principally from the relatively small

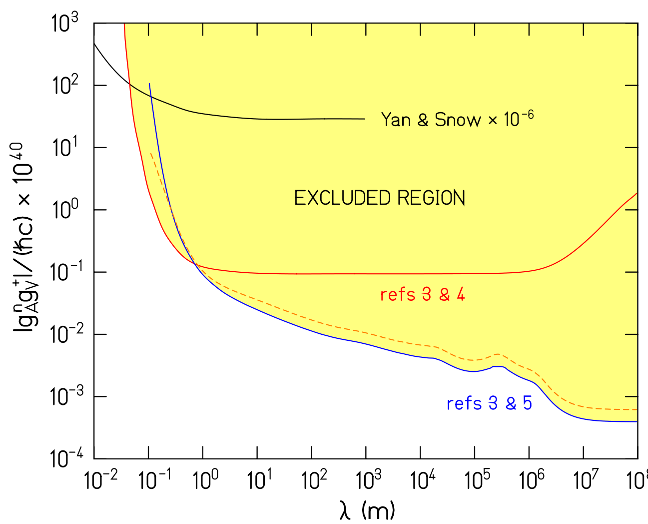

FIG. 1 (color online). Comparison of Yan and Snow's 1σ constraints on $|g_A^n g_V^+|$ [1] with those inferred from Princeton neutron spin-spin studies [2] and Eöt–Wash equivalence-principle tests with bodies falling toward a massive ^{238}U laboratory source [4] or in the field of the entire Earth [5]. Our analysis of the Eöt–Wash data assumes that $\tilde{q}^- = 0$. Yan and Snow's upper bounds are divided by 6 orders of magnitude so that they can be displayed on the same scale. The dashed line shows our constraint with no assumptions about the charge parameter $\tilde{\psi}$.

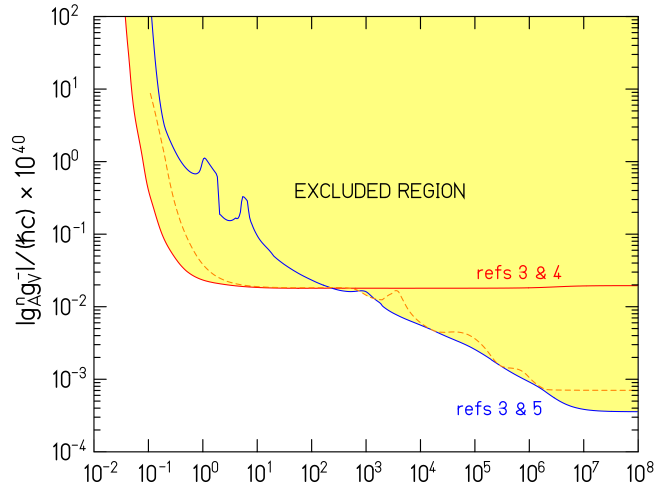

FIG. 2 (color online). 1σ constraints on $|g_A^n g_V^-|$ assuming that $g_V^+ = 0$. The Ref. [5] constraint is weaker and has more structure than in Fig. 1 because the Earth consists largely of materials with $N \approx Z$. The undulations in the conservative bound (dashed line) occur where contributions to the source model (e.g., crust, mantle, or core) with different compositions and densities change the value of $\tilde{\psi}'$ that determines the greatest lower bound.

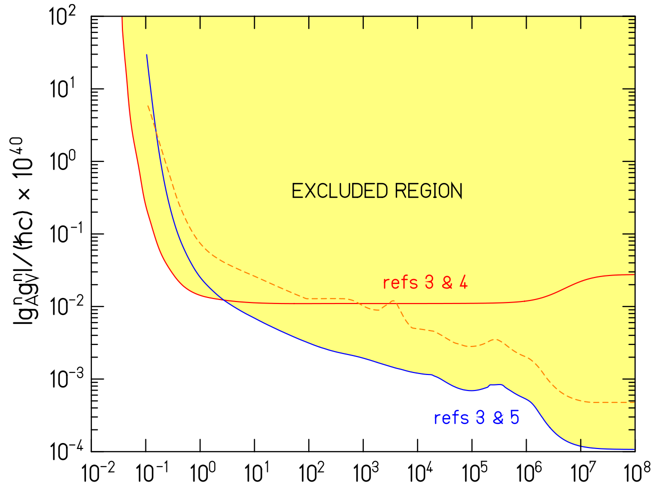

FIG. 3 (color online). Solid lines show 1σ constraints on $|g_A^n g_V^n|$ assuming that $g_V^p + g_V^e = 0$. The dashed line is a conservative constraint that makes no assumptions about $\tilde{\psi}$.

variation in BE/Mc^2 where BE is the nuclear binding energy and M the atomic mass. In Fig. 2 cancellation occurs between neutrons and protons because $N \approx Z$. The tightest limits occur in Fig. 3 because $\tilde{q}$ has no cancellations and $\tilde{q}/\mu \approx N/(Z+N)$ varies substantially for different test body materials.

We can do a completely general analysis by relaxing the assumptions made above about particular values of the charge parameter $\tilde{\psi}$. For example, to establish the most conservative bound on g_V^n ($\tilde{\psi} = \pi/2$) at a given value of λ, we fit the equivalence-principle constraints [4,5] at that λ for the entire range of $\tilde{\psi}'$ values to obtain $\tilde{\alpha}(\lambda, \tilde{\psi}')$, the functional dependence of $\tilde{\alpha}$ on $\tilde{\psi}$, and compute the conservative bound on $[g_V^n(\lambda)]^2$ from the greatest lower bound on

$$4\pi G u^2 \tilde{\alpha}(\lambda, \tilde{\psi}') \cos^2(\tilde{\psi} - \tilde{\psi}'), \tag{7}$$

where G is the Newtonian constant and u is the atomic mass unit. This strategy requires equivalence-principle data with at least 2 different composition dipoles and 2 different attractors to avoid situations where either the charge of the attractor, or the charge-dipole of the pendulum, vanishes at a particular value of $\tilde{\psi}$. The results are shown as dashed lines in Figs. 1–3.

The strategy employed above can also be used to find constraints on $|g_A^n g_V^\pm|$ for $\lambda < 1.5 \times 10^{-2}$ m by taking $|g_V|^2$ from the inverse-square law tests of Hoskins *et al.* [6] and Kapner *et al.* [7] and $|g_A^n|^2$ from the cold-neutron experiment of Piegsa and Pignol [8], but the sensitivity of the cold-neutron work is not sufficient to give a result that is competitive with Yan and Snow's.

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