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 $g_{A}^n g_{V}^n$ are improved by a 11 orders of magnitude.

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Yan and Snow\cite{yan} recently inferred bounds on the coupling strength, $g_{A}^n g_{V}^n$ 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 $|g_{A}^n|^2$ and on $|g_{V}^n|^2$ set by previous experiments to obtain

$$|g_{A}^n g_{V}^n| = \sqrt{|g_{A}^n|^2 |g_{V}^n|^2} \cdot (1)$$

It is convenient to define

$$g_{V}^\pm = (g_{V}^n + g_{V}^0)/\sqrt{2}, \quad (2)$$

so that $g_{V}^{3\text{He}} = 2\sqrt{2} g_{V}^\pm$.

We take our bounds on $|g_{A}^n|$ from a Princeton optical-pumping experiment with polarized $^3$He detector and sources\cite{princeton1,princeton2} that probed the neutron spin-spin interaction

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

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

Our bounds on $|g_{V}^n|^2$ come from results of equivalence-principle tests\cite{yan,pra1} that tightly constrain Yukawa interactions of the form

$$V_{12} = \frac{(g_{V}^n)^2}{4\pi r} e^{-r/\lambda} = V_G(r) \tilde{\alpha} \left[ \frac{\tilde{q}}{\mu} \right]_1 \left[ \frac{\tilde{q}}{\mu} \right]_2 e^{-r/\lambda}; \quad (4)$$

where, in the second relation (conventionally used to analyze equivalence-principle results\cite{pra2}), $V_G$ 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

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

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

$$\tan \tilde{\psi} = \frac{g_{V}^0}{g_{V}^n + g_{V}^0}. \quad (6)$$

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 $|g_{V}^n|^2$ constraint obtained from the Hoskins et al. inverse-square test\cite{pra3} would be imperceptible in Figs. 1 and 2 because of the rapid weakening of the $|g_{A}^n|^2$ constraint\cite{pra1,pra2} for $\lambda < 0.2$ m.

The experimental results of Refs. 2\cite{pra1} and 3\cite{pra2} 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\cite{yan} and 2\cite{pra1,pra2} follow from the varying properties of the assumed charges. In Fig. 1, $\tilde{q}^\pm$ is proportional to the atomic mass number so that the $\tilde{q}/\mu$ ratio difference of the various equivalence-principle

FIG. 1: [Color online] Comparison of Yan and Snow’s 1$\sigma$ constraints on $|g_{A}^n g_{V}^n|\cite{yan}$ with those inferred from Princeton neutron spin-spin studies\cite{pra1} and Eöt-Wash equivalence-principle tests with bodies falling toward a massive $^{238}$U laboratory source\cite{pra2} or in the field of the entire earth\cite{pra3}. Our analysis of the Eöt-Wash data assumes that $\tilde{q}^\pm = 0$. 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 \( |g_A^u g_V| \) assuming that \( g_V^u = 0 \). 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.

test-body pairs arises principally from the relatively small 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 \( g_V^u (\tilde{\psi} = \pi/2) \) at a given value of \( \lambda \) we fit the equivalence-principle constraints \[4, 5\] at that \( \lambda \) 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 \( |g_V^u(\lambda)|^2 \) from the greatest lower bound on

\[
4\pi Gu^2 \tilde{\alpha}(\lambda, \tilde{\psi}') \cos^2(\tilde{\psi} - \tilde{\psi}') ,
\]

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 \( |g_A^u g_V| \) 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 \( |g_A^u|^2 \) 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.

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

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[1] H. Yan and W.M. Snow, Phys. Rev. Lett. 110, 082003 (2013).
[2] G. Vasilakis, J. M. Brown, T. W. Kornack and M. V. Romalis, Phys. Rev. Lett. 103, 261801 (2009).
[3] G. Valilakis, PhD Thesis, Princeton University, 2007.
[4] G. L. Smith, C. D. Hoyle, J. H. Gundlach, E. G. Adelberger, B. R. Heckel, and H. E. Swanson, Phys. Rev. D 61, 022001-1 (1999).
[5] T.A. Wagner, S. Schlammingter, J. H. Gundlach and E. G. Adelberger, Class. Quant. Grav. 29, 184002 (2012).
[6] J. K. Hoskins, R. D. Newman, R. Spero, and J. Schultz, Phys. Rev. D 32, 3084 (1985).
[7] D. J. Kapner, T. E. Cook, E. G. Adelberger, J. H. Gundlach, B. R. Heckel, C. D. Hoyle and H. E. Swanson, Phys. Rev. Lett. 98, 021101 (2007).
[8] F. M Piegsa and G. Pignol, Phys. Rev. Lett. 108, 181801 (2012).
[9] G. Raffelt, Phys. Rev. D 86 015001 (2012).
