Limits on a *CP*-violating scalar axion-nucleon interaction

Georg Raffelt
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
(Received 9 May 2012; published 5 July 2012)

Axions or similar hypothetical pseudoscalar bosons may have a small *CP*-violating scalar Yukawa interaction g_s^N with nucleons, causing macroscopic monopole-dipole forces. Torsion-balance experiments constrain $g_p^e g_s^N$, whereas $g_p^N g_s^N$ is constrained by the depolarization rate of ultra-cold neutrons or spin-polarized nuclei. However, the pseudoscalar couplings g_p^e and g_p^N are strongly constrained by stellar energy-loss arguments and g_s^N by searches for anomalous monopole-monopole forces, together providing the most restrictive limits on $g_p^e g_s^N$ and $g_p^N g_s^N$. The laboratory limits on g_s^N are currently the most restrictive constraints on *CP*-violating axion interactions.

DOI: 10.1103/PhysRevD.86.015001 PACS numbers: 14.80.Va, 06.30.Gv, 11.30.Er

I. INTRODUCTION

The Peccei-Quinn mechanism for explaining the absence of *CP*-violating effects in QCD leads to the prediction of axions, new pseudoscalar bosons with a very small mass [1,2]. Such particles would mediate new macroscopic forces between spin-polarized bodies (dipole-dipole forces), which however are hard to measure because they compete with magnetic interactions. Monopole-dipole and monopole-monopole forces will also arise if axions have small *CP*-violating scalar interactions with nucleons [3]. Axions were invented to explain the absence of *CP* violation in QCD and indeed residual *CP*-violating standard-model effects will be extremely small [4]. However, new sources of *CP* violation may well exist and provide neutron and nuclei electric dipole moments and *CP*-violating axion-nucleon interactions with a phenomenologically interesting magnitude [5–7].

A new force on macroscopic scales would be a major discovery of fundamental importance. Precision tests of Newton's inverse square law and of the weak equivalence principle have a long tradition [8,9]. Besides looking for new forces between bulk matter (monopole-monopole forces), one can also look for "unnatural parity" monopole-dipole forces. The hypothesis of *CP* violation in axion interactions provides one motivation, but of course the measurements themselves are agnostic of the underlying theory.

Torsion-balance experiments can look for new forces between bulk matter and a body with polarized electrons. They are interpreted in terms of the pseudoscalar interaction g_p^e of a new boson ϕ (for example the axion) and the scalar interaction g_s^N with nucleons. One derives constraints on the product $g_p^e g_s^N$, depending on the assumed range $\lambda = 1/m_\phi$ of the new force. (We always use natural units with $\hbar = c = 1$.) Another class of experiments studies the spin depolarization of nuclei or neutrons under the influence of the surrounding bulk matter, providing limits on the product of scalar and pseudoscalar interaction with nucleons $g_p^N g_s^N$. Likewise, one can study the relative procession frequencies of atoms or look for an induced magnetization in a paramagnetic salt.

We here show that the scalar and pseudoscalar couplings are individually constrained, leading to more restrictive limits on the product $g_s g_p$ than provided by the current generation of monopole-dipole force experiments. The scalar nucleon interaction $(g_s^N)^2$ is best constrained by searches for anomalous monopole-monopole forces. The pseudoscalar interaction g_p^e is constrained by the energy loss of white dwarfs and globular-cluster stars, g_p^N by the neutrino signal duration of SN 1987A. There also exist direct laboratory bounds on the pseudoscalar couplings from dipole-dipole force experiments, but the results are not yet competitive with stellar energy-loss limits.

We juxtapose the constraints on $g_s g_p$ thus derived with those from monopole-dipole force measurements. This comparison provides a benchmark for the required sensitivity improvements for the direct force experiments to enter unexplored territory in parameter space.

In Sec. II we briefly review the astrophysical limits on new boson interactions. In Sec. III we summarize experimental limits on the scalar nucleon interaction. In Sec. IV we juxtapose our limits on $g_s g_p$ with those from monopole-dipole experiments and briefly mention limits on dipole-dipole forces in Sec. V. In Sec. VI we interpret the results for axions and conclude in Sec. VII.

II. ASTROPHYSICAL LIMITS

A. Electron coupling

We assume that electrons couple to a low-mass boson ϕ through a derivative coupling $(C_{e\phi}/2f_\phi)\bar{\psi}_e\gamma^\mu\gamma_5\psi_e\partial_\mu\phi$ where f_ϕ is some large energy scale, in the case of axions the Peccei-Quinn scale f_a, and $C_{e\phi}$ a numerical coefficient. This is usually equivalent to the pseudoscalar interaction $-\mathrm{i}g_p^e\bar{\psi}_e\gamma_5\psi_e\phi$ with $g_p^e = C_{e\phi}m_e/f_\phi$. This interaction allows for stellar energy losses by the Compton process $\gamma + e \to e + \phi$ and bremsstrahlung $e + Ze \to Ze + e + \phi$ [10,11].

The brightness of the tip of the red-giant branch in globular clusters constrains various cooling mechanisms of the degenerate core before helium ignition, and in particular reveals [12]

$$g_p^e \lesssim 3 \times 10^{-13}. \tag{1}$$

This limit pertains to particles with $m_\phi \lesssim 10$ keV so that their emission is not suppressed by threshold effects.

White-dwarf cooling would be accelerated by ϕ emission [13]. Isern and collaborators have found that the white-dwarf luminosity function fits better with a small amount of anomalous energy loss that can be interpreted in terms of ϕ emission with $g_p^e \sim 2 \times 10^{-13}$ [14]. The period decrease of the pulsating white dwarf G117-B15A also favors some amount of extra cooling [15]. The interpretation in terms of ϕ emission is of course speculative and we adopt Eq. (1) as our nominal limit.

For completeness we mention that the scalar electron coupling can be similarly constrained [10,16]

$$g_s^e \lesssim 1.3 \times 10^{-14}. \tag{2}$$

This limit is more restrictive because the emission process does not suffer from electron spin flip.

B. Nucleon coupling

The pseudoscalar nucleon coupling, defined analogous to the electron coupling, allows for the bremsstrahlung process $N + N \to N + N + \phi$ in a collapsed supernova core. However, the measured neutrino signal of SN 1987A reveals a signal duration of some 10 s and thus excludes excessive new energy losses [17]. The emission rate suffers from significant uncertainties related to dense nuclear matter effects [18] and amounts to an educated dimensional analysis [11]. Assuming equal ϕ couplings to protons and neutrons one finds [10]

$$g_p^N \lesssim 3 \times 10^{-10}. \tag{3}$$

In typical axion models, the interaction with neutrons can actually vanish.

The scalar interaction is not well constrained by this method because nucleon velocities are relatively small. Moreover, if the neutron and proton couplings are equal, nonrelativistic bremsstrahlung of scalars vanishes. The most restrictive astrophysical limit arises from the energy loss of globular-cluster stars through the process $\gamma + {}^4\mathrm{He} \to {}^4\mathrm{He} + \phi$ [10,16,19]

$$g_s^N \lesssim 0.5 \times 10^{-10}. \tag{4}$$

This limit is quite restrictive because the electric charges and the scalar nucleon couplings each add coherently.

III. SCALAR BARYON INTERACTIONS

We next consider a long-range Yukawa force mediated by a scalar ϕ that couples with equal strength g_s^N to protons and neutrons. For small m_ϕ, restrictive limits derive from precision tests of Newton's inverse square law. The new Yukawa potential is traditionally expressed as a correction to Newton's potential in the form

$$V = -\frac{G_N m_1 m_2}{r}(1 + \alpha e^{-r/\lambda}), \tag{5}$$

where, in terms of the atomic mass unit m_u,

$$\alpha = \frac{(g_s^N)^2}{4\pi G_N m_u^2} = 1.37 \times 10^{37} (g_s^N)^2. \tag{6}$$

The force range is

$$\lambda = m_\phi^{-1} = 19.73\ \mathrm{cm}\ \frac{\mu\mathrm{eV}}{m_\phi}. \tag{7}$$

In the literature, one usually finds plots of the limiting α as a function of λ; for a recent review see Ref. [9].

New scalar interactions with nucleons can be probed in different ways. Stellar energy-loss arguments are most effective for boson masses so large that the interaction range is too short for laboratory tests. Next, one can search for deviations from the inverse-square law behavior of the overall force between bodies. At the largest distances, tests of the weak equivalence principle are most effective, i.e., one searches for force differences on bodies with different composition and in this way isolates the nongravitational part [9]. The results of such experiments can be interpreted in different ways, depending on the assumed property of the new force. We only consider scalar forces interacting with baryon number, but of course one can go through the same arguments for other assumptions.

Following the numbers of curves in Fig. 1, at the shortest distances (1) the stellar energy-loss limit of Eq. (4) beats

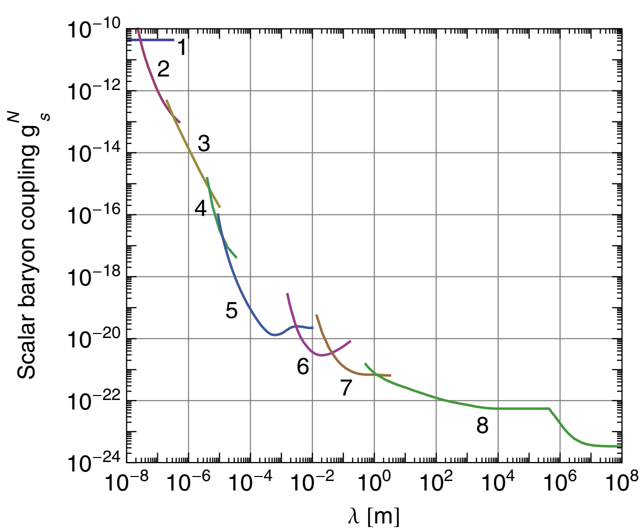

FIG. 1 (color online). Limits on the scalar ϕ coupling to baryons. Curve 1 derives from stellar energy loss [10,16]. Curves 2–6 depend on tests of Newton's inverse square law [20–24]. Curves 7–8 derive from testing the weak equivalence principle [25,26].

laboratory limits. (2) At distances around 10^{-7} m, the Casimir measurements of Decca *et al.* are most relevant [20], (3) followed around the μm scale by those of Sushkov *et al.* at Yale [21]. (4) At the 10-μm scale, Geraci *et al.* of the Stanford group have reported limits on deviations from Newton's law using cryogenic microcantilevers [22]. (5) Torsion-balance tests of the inverse-square law conducted by the Eöt-Wash Collaboration (Kapner *et al.*) provide the best limits in the 10-μm–few-mm range [23]. (6) In the cm range, the Irvine group's (Hoskins *et al.*) torsion balance inverse-square tests dominate [24]. For larger distances, one has to rely on tests of the equivalence principle where we assume that ϕ couples only to baryon number. (7) In the submeter range, we use the Eöt-Wash limits of Smith *et al.* [25], and (8) at yet larger distances those of Schlamminger *et al.* [26].

IV. MONOPOLE-DIPOLE FORCES

A. Electron-nucleon interaction

The most restrictive limit on $g_s^N g_p^e$ arises from the long-range force limits on g_s^N shown in Fig. 1 and the astrophysical limit on g_p^e limit of Eq. (1). We show the product as the lower thin black line in Fig. 2. We recall that for deriving the limits on g_s^N it was assumed that the scalar coupling applies only to baryon number, whereas the pseudoscalar coupling applies to electrons.

Constraints from searches for monopole-dipole forces with torsion pendulums using polarized electrons are shown in Fig. 2. (1) The most recent constraints in the mm range were derived by Hoedl *et al.* with a dedicated apparatus [27]. (2) In the cm range, the best constraints are from the older measurements of the Tsing Hua University group (Ni *et al.*) using a paramagnetic salt in a rotating copper mass [28]. (3) At 10 cm we show constraints derived by Youdin *et al.* by comparing the relative precession frequencies of Hg and Cs magnetometers as a function of the position of two 475-kg lead masses with respect to an applied magnetic field [29]. (4) In the meter range and above, the torsion pendulum measurements of the Eöt-Wash Collaboration (Heckel *et al.*) provide the most restrictive limits [30], except in a gap at 10–1000 km. (5) Here we fall back on stored-ion spectroscopy (Wineland *et al.*) [31].

B. Nucleon-nucleon interaction

The most restrictive limit on $g_s^N g_p^N$ also arises from the long-range force limits of Fig. 1 together with the SN 1987A limit on the pseudoscalar coupling of Eq. (3). We show the product as a thin black line in Fig. 3.

The most restrictive direct experimental limit at short distances arises from measurements of the depolarization of the ^{3}He nucleus. We show the limits of Petukhov *et al.* [32] as curve 1 in Fig. 3. (2) In the cm range and above, the precession of Hg and Cs (Youdin *et al.*) provide the best limits [29]. (3) We also show constraints from the precession and depolarization of ultra-cold neutrons (Serebrov *et al.*) [33].

Constraints from gravitational bound states of ultra-cold neutrons [34] are at the moment not competitive, but may hold significant promise for the future [35].

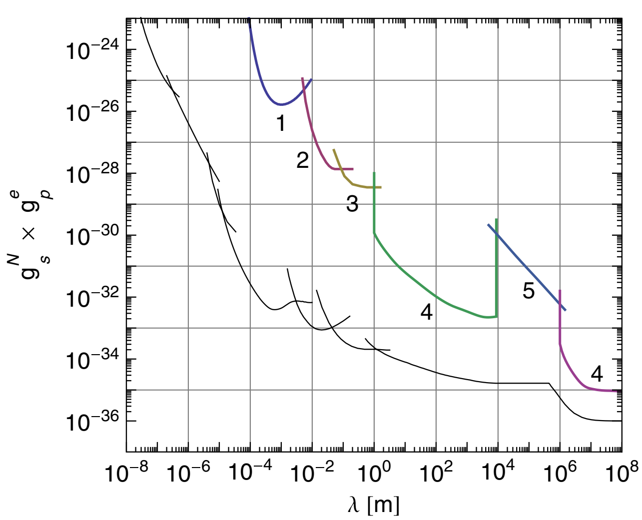

FIG. 2 (color online). Upper limits on $g_s^N g_p^e$. The thin black line represents the g_s^N limits of Fig. 1 multiplied with the astrophysical g_p^e limit of Eq. (1). The experimental curves 1–5 constrain monopole-dipole forces [27–31].

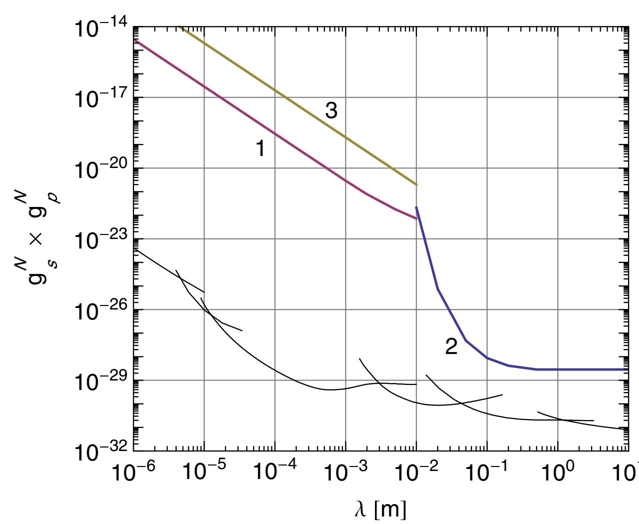

FIG. 3 (color online). Upper limits on $g_s^N g_p^N$. The thin black line represents the g_s^N limits of Fig. 1 multiplied with the SN 1987A limit on g_p^N of Eq. (3). Curve 1 is the experimental limit from ^{3}He depolarization [32], curve 2 is from mercury precession [29], and curve 3 is from ultra-cold neutrons [33].

V. DIPOLE-DIPOLE FORCES

Dipole-dipole forces have been constrained by laboratory experiments, although the results are less restrictive than the corresponding astrophysical limits. For the pseudoscalar neutron coupling one finds $g_p^n < 0.85 \times 10^{-4}$ for $m \lesssim 10^{-7}$ eV based on a K-^{3}He comagnetometer [36]. For the pseudoscalar electron coupling, the most recent Eöt-Wash torsion balance spin-spin experiment yields $g_p^e < 3 \times 10^{-8}$ for $m \lesssim 10^{-6}$ eV [37].

VI. AXION INTERPRETATION

These limits on the various scalar and pseudoscalar couplings of a hypothetical low-mass boson can be interpreted specifically in terms of QCD axions where the interaction strengths and mass are closely correlated apart from model-dependent numerical factors.

One characteristic of axions is the relation $m_a f_a \sim m_\pi f_\pi$ between their mass m_a, decay constant f_a, pion mass $m_\pi = 135$ MeV, and pion decay constant $f_\pi = 92$ MeV. A CP-violating scalar interaction can be expressed as [3,6]

$$g_s^N \sim \Theta_{\rm eff} \frac{f_\pi}{f_a} \sim \Theta_{\rm eff} \frac{m_a}{m_\pi}, \tag{8}$$

where $\Theta_{\rm eff}$ measures CP-violating effects. Taking this relation as defining $\Theta_{\rm eff}$ we show in Fig. 4 (top) the g_s^N limits translated into limits on $\Theta_{\rm eff}$ as function of m_a.

Axions with m_a exceeding about 1 eV are excluded by cosmological hot dark matter bounds [38] and m_a exceeding about 10 meV by the energy loss of SN 1987A. The meV range would be favored by anomalous white-dwarf cooling (Sec. II A). It is interesting that Fig. 4 (top) shows greatest sensitivity at this "axion meV frontier" [39]. However, even in this range the $\Theta_{\rm eff}$ sensitivity is far from realistic values because limits on neutron and nuclear electric dipole moments imply $\Theta_{\rm eff} \lesssim 10^{-11}$ [6,7].

The pseudoscalar axion-electron interaction is $g_p^e = C_e m_e/f_a \sim C_e(m_e/f_\pi)(m_a/m_\pi)$, where C_e is a model-dependent coefficient. Overall we therefore have

$$g_s^N g_p^e \sim \Theta_{\rm eff} C_e \frac{m_e}{f_\pi}\left(\frac{m_a}{m_\pi}\right)^2. \tag{9}$$

Using this relation we translate the $g_s^N g_p^e$ limits of Fig. 2 into $C_e\Theta_{\rm eff}$ and show the result in Fig. 4 (middle).

Likewise, the pseudoscalar axion-nucleon interaction is $g_p^N = C_N m_N/f_a \sim C_N(m_N/f_\pi)(m_a/m_\pi)$ so that

$$g_s^N g_p^N \sim \Theta_{\rm eff} C_N \frac{m_N}{f_\pi}\left(\frac{m_a}{m_\pi}\right)^2. \tag{10}$$

Translating the $g_s^N g_p^N$ limits of Fig. 3 into limits on $C_N\Theta_{\rm eff}$ leads to Fig. 4 (bottom).

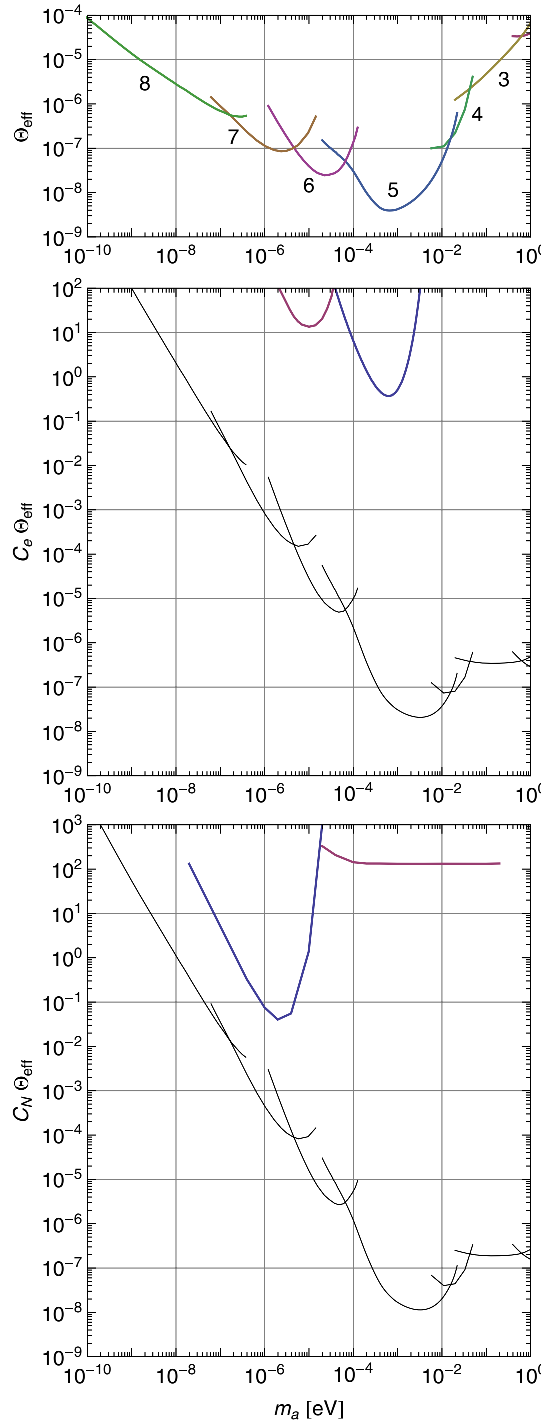

FIG. 4 (color online). Long-range force limits translated to the effective CP-violating axion parameter $\Theta_{\rm eff}$. Top panel: g_s^N of Fig. 1 and Eq. (8). Middle panel: $g_s^N g_p^e$ of Fig. 2 and Eq. (9). Bottom panel: $g_s^N g_p^N$ of Fig. 3 and Eq. (10).

For the moment any of these limits are far from the phenomenologically interesting range. In a more detailed analysis, one should include differences of the axion coupling to protons and neutrons.

VII. CONCLUSIONS

We have interpreted existing laboratory limits on anomalous monopole-monopole forces into limits on the scalar interaction g_s^N of a new low-mass boson ϕ with baryons. We have combined them with stellar energy-loss limits on the pseudoscalar ϕ coupling with electrons g_p^e and nucleons g_p^N and have derived the most restrictive limits yet on the products $g_s^N g_p^e$ and $g_s^N g_p^N$. These constraints are more restrictive than laboratory searches for anomalous monopole-dipole forces. Of course, pure laboratory searches remain of utmost importance, especially if they can eventually overtake the astrophysical results.

ACKNOWLEDGMENTS

I thank Hartmut Abele, Peter Fierlinger, and John Ellis for discussions at the symposium "Symmetries and Phases of the Universe" (February 2012) that motivated this work, Eric Adelberger for discussions at the workshop "Vistas in Axion Physics" (April 2012), and Maxim Pospelov and Seth Hoedl for thoughtful comments on the manuscript. Partial support by the Deutsche Forschungsgemeinschaft under Grant No. EXC-153 and by the European Union Initial Training Network "Invisibles" PITN-GA-2011-289442 is acknowledged.

[1] R. D. Peccei, Lect. Notes Phys. **741**, 3 (2008).

[2] J. E. Kim and G. Carosi, Rev. Mod. Phys. **82**, 557 (2010).

[3] J. E. Moody and F. Wilczek, Phys. Rev. D **30**, 130 (1984).

[4] H. Georgi and L. Randall, Nucl. Phys. B **276**, 241 (1986).

[5] R. Barbieri, A. Romanino, and A. Strumia, Phys. Lett. B **387**, 310 (1996).

[6] M. Pospelov, Phys. Rev. D **58**, 097703 (1998).

[7] M. Pospelov and A. Ritz, Ann. Phys. (N.Y.) **318**, 119 (2005).

[8] E. Fischbach and C. Talmadge, Nature (London) **356**, 207 (1992).

[9] E. G. Adelberger, J. H. Gundlach, B. R. Heckel, S. Hoedl, and S. Schlamminger, Prog. Part. Nucl. Phys. **62**, 102 (2009).

[10] G. G. Raffelt, *Stars as Laboratories for Fundamental Physics* (University of Chicago Press, Chicago, 1996); Annu. Rev. Nucl. Part. Sci. **49**, 163 (1999).

[11] G. G. Raffelt, Lect. Notes Phys. **741**, 51 (2008).

[12] G. Raffelt and A. Weiss, Phys. Rev. D **51**, 1495 (1995).

[13] G. G. Raffelt, Phys. Lett. B **166**, 402 (1986).

[14] J. Isern, E. García-Berro, S. Torres, and S. Catalán, Astrophys. J. **682**, L109 (2008); J. Isern, L. Althaus, S. Catalán, A. Córsico, E. García-Berro, M. Salaris, and S. Torres, arXiv:1204.3565.

[15] J. Isern, E. García-Berro, L. G. Althaus, and A. H. Córsico, Astron. Astrophys. **512**, A86 (2010); A. H. Córsico *et al.*, arXiv:1205.6180 [Mon. Not. R. Astron. Soc. (to be published)].

[16] J. A. Grifols and E. Massó, Phys. Lett. B **173**, 237 (1986); J. A. Grifols, E. Massó, and S. Peris, Mod. Phys. Lett. A **4**, 311 (1989).

[17] G. Raffelt and D. Seckel, Phys. Rev. Lett. **60**, 1793 (1988); M. S. Turner, Phys. Rev. Lett. **60**, 1797 (1988); R. Mayle, J. R. Wilson, J. R. Ellis, K. A. Olive, D. N. Schramm, and G. Steigman, Phys. Lett. B **203**, 188 (1988); **219**, 515 (1989).

[18] H. T. Janka, W. Keil, G. Raffelt, and D. Seckel, Phys. Rev. Lett. **76**, 2621 (1996); C. Hanhart, D. R. Phillips, and S. Reddy, Phys. Lett. B **499**, 9 (2001).

[19] G. Raffelt, Phys. Rev. D **38**, 3811 (1988).

[20] R. S. Decca, D. López, E. Fischbach, G. L. Klimchitskaya, D. E. Krause, and V. M. Mostepanenko, Eur. Phys. J. C **51**, 963 (2007).

[21] A. O. Sushkov, W. J. Kim, D. A. R. Dalvit, and S. K. Lamoreaux, Phys. Rev. Lett. **107**, 171101 (2011).

[22] A. A. Geraci, S. J. Smullin, D. M. Weld, J. Chiaverini, and A. Kapitulnik, Phys. Rev. D **78**, 022002 (2008).

[23] D. J. Kapner, T. S. Cook, E. G. Adelberger, J. H. Gundlach, B. R. Heckel, C. D. Hoyle, and H. E. Swanson, Phys. Rev. Lett. **98**, 021101 (2007).

[24] J. K. Hoskins, R. D. Newman, R. Spero, and J. Schultz, Phys. Rev. D **32**, 3084 (1985).

[25] G. L. Smith, C. D. Hoyle, J. H. Gundlach, E. G. Adelberger, B. R. Heckel, and H. E. Swanson, Phys. Rev. D **61**, 022001 (1999).

[26] S. Schlamminger, K.-Y. Choi, T. A. Wagner, J. H. Gundlach, and E. G. Adelberger, Phys. Rev. Lett. **100**, 041101 (2008).

[27] S. A. Hoedl, F. Fleischer, E. G. Adelberger, and B. R. Heckel, Phys. Rev. Lett. **106**, 041801 (2011).

[28] W.-T. Ni, S.-S. Pan, H.-C. Yeh, L.-S. Hou, and J.-L. Wan, Phys. Rev. Lett. **82**, 2439 (1999).

[29] A. N. Youdin, D. Krause, K. Jagannathan, L. R. Hunter, and S. K. Lamoreaux, Phys. Rev. Lett. **77**, 2170 (1996).

[30] B. R. Heckel, E. G. Adelberger, C. E. Cramer, T. S. Cook, S. Schlamminger, and U. Schmidt, Phys. Rev. D **78**, 092006 (2008).

[31] D. J. Wineland, J. J. Bollinger, D. J. Heinzen, W. M. Itano, and M. G. Raizen, Phys. Rev. Lett. **67**, 1735 (1991).

[32] A. K. Petukhov, G. Pignol, D. Jullien, and K. H. Andersen, Phys. Rev. Lett. **105**, 170401 (2010).

[33] A. P. Serebrov *et al.*, JETP Lett. **91**, 6 (2010).

[34] S. Baessler, V. V. Nesvizhevsky, K. V. Protasov, and A. Y. Voronin, Phys. Rev. D **75**, 075006 (2007).

[35] T. Jenke, P. Geltenbort, H. Lemmel, and H. Abele, Nature Phys. **7**, 468 (2011).
[36] G. Vasilakis, J. M. Brown, T. W. Kornack, and M. V. Romalis, Phys. Rev. Lett. **103**, 261801 (2009).
[37] E. Adelberger, Presentation at ''Vistas in Axion Physics,'' http://www.int.washington.edu/talks/WorkShops/int_12_50W/People/Adelberger_E/Adelberger.pdf.
[38] S. Hannestad, A. Mirizzi, G. Raffelt, and Y. Wong, J. Cosmol. Astropart. Phys. 08 (2010) 001; D. Cadamuro, S. Hannestad, G. Raffelt, and J. Redondo, J. Cosmol. Astropart. Phys. 02 (2011) 003.
[39] G. G. Raffelt, J. Redondo, and N. Viaux Maira, Phys. Rev. D **84**, 103008 (2011).