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Screening of long-range leptonic forces by cosmic background neutrinos

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The absence of dispersion effects of the SN 1987A neutrino pulse has been used to constrain novel long-range forces between neutrinos and galactic baryonic or nonbaryonic matter. If these forces are mediated by vector bosons, screening effects by the cosmic neutrino background invalidate the SN 1987A limits and other related arguments.

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The $\overline{\nu}_e$ signal observed from the supernova (SN) 1987A lasted for a few seconds [1] so that one can derive limits on a variety of effects that would have caused a significant dispersion. The most thoroughly studied case is that of an assumed neutrino mass which would introduce a time delay relative to massless neutrinos of $\delta t/t = m_\nu^2/2E_\nu^2$ [2]. With a δt of a few seconds, the time of flight to the SN of $t = 50\,\mathrm{kpc}/c \approx 5\times10^{12}\,\mathrm{s}$, and energies spread over several 10 MeV one arrives at a mass limit $m_\nu \lesssim 20\,\mathrm{eV}$. Another interesting case is the limit on a putative neutrino charge because the motion on curved paths in the galactic magnetic field would also lead to a dispersion $\delta t/t \propto E_\nu^{-2}$ [3]. Yet another case is an assumed energy-dependent velocity of massless particles due to a fundamental length scale [4].

We presently take a second look at attempts to limit novel long-range forces which would bend the neutrino trajectories and thus also lead to a dispersion $\delta t/t \propto E_\nu^{-2}$ [5]. The force was assumed to be mediated by massless vector bosons coupled to a novel neutrino charge q_ν which may represent, for example, a leptonic interaction. The source of the force is the electrons of the galaxy or perhaps the protons or dark matter particles with a charge q_e, q_p, or q_x. Depending on the nature of the source particles and their distribution in the Milky Way, a limit

$$|q_{e,p,x}q_\nu| \lesssim 3\times10^{-40} \times \begin{cases} 1 & \text{for } e,\, p, \\ m_x/m_p & \text{for dark matter} \end{cases} \quad (1)$$

was derived [5]. For dark matter particles the mass m_x appears because the mass density, not the number density of dark matter particles, is fixed by the galactic rotation curves.

By assumption, in this scenario neutrinos carry a novel charge q_ν which must be opposite between ν_e and $\overline{\nu}_e$ as in normal electromagnetism. Because the cosmic neutrino background is likely CP symmetric, it constitutes a neutral plasma with regard to the new charge and interaction. Therefore, one expects that a source for the new force such as a star or a galaxy will be screened according to the standard Debye-Hückel theory and the bound (1) will be invalid. Similarly, screening effects will invalidate the time delay argument between ν_e's and $\overline{\nu}_e$'s discussed in Ref. [6].

A very strong bound on a leptonic charge coupling, $\alpha_L \equiv q_L^2/4\pi \lesssim 10^{-49}$, follows from high-precision tests of the equivalence principle [7]. At first sight this limit is also invalidated by the possible screening due to background neutrinos [8] so that the strongest bound would come from $\nu_e e$ scattering, $\alpha_L \lesssim 10^{-12}$, and from limits on the energy loss of horizontal-branch stars [9], $\alpha_L \lesssim 3\times10^{-29}$. However, a more detailed analysis based on the stability (or better to say, existence) of macroscopic bodies permits one to conclude that $\alpha_L \lesssim 10^{-36}$ [10].

The effect of screening on the bound (1) strongly depends on the spatial distribution of the source particles in the galaxy. We first consider the case where they are normal visible matter so that the neutrino path from the SN 1987A, which occurred in the Large Magellanic Cloud at a distance of about 50 kpc, lies mostly outside of the source charge distribution which is concentrated in the central region of the Milky Way. In this case the "Coulomb field" created by this charge along the neutrino path from SN 1987A to us is effectively screened by the background neutrinos so that practically no bound on their interaction strength can be obtained.

If the ν_e's are nearly massless, even the cosmic background sea remains relativistic today at an effective temperature $T_\nu \approx 1.9\,\mathrm{K}$. The Debye screening scale in a relativistic plasma is by dimensional analysis $k_D \approx q_\nu T_\nu$ so that a typical screening radius is

$$k_D^{-1} \approx 3\times10^{-23}\,\mathrm{kpc}/q_\nu. \quad (2)$$

It is not important that the neutrino phase space distribution be precisely thermal. Also, screening occurs even though the background neutrinos are a collisionless gas. If $q_\nu \gtrsim 10^{-23}$, the screening radius is less than 3 kpc and so the neutrinos from SN 1987A would not have felt a force to bend their path. Put another way, $q_\nu \gtrsim 10^{-23}$ remains allowed by the SN 1987A argument. If in Eq. (1) one assumes that $q_{e,p}$ is of the same order as q_ν, then

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there is no meaningful SN 1987A bound at all. What remains excluded is a combination of a very small q_ν with a much larger $q_{e,p}$.

If the neutrinos are massive so that they are nonrelativistic today, the screening radius would be even smaller because their total number density is fixed at about $100\,\mathrm{cm}^{-3}$. If they have nonrelativistic velocities, they can be polarized even more easily by a "test charge."

An interesting bound survives if the source of the new field is dark matter particles. Their density distribution in the galaxy probably behaves as r^{-2} up to a distance of about 100 kpc. The equation which governs the screening behavior as a function of galactocentric distance can be written as

$$dQ_\nu/dr = k_D(Q_S - Q_\nu), \tag{3}$$

where $Q_\nu(r)$ is the charge of the cosmic background neutrinos inside the radius r and $Q_S(r)$ is the same for the source particles. For a localized source charge distribution we have $Q_S = Q_0$ and the total charge is exponentially screened, $Q_{\mathrm{tot}} = Q_S - Q_\nu = Q_0 e^{-k_D r}$. If the dark matter acts as a source, we use $Q_S \propto r$ and the total charge inside the halo is compensated only with an accuracy $(R_0 k_D)^{-1}$ where R_0 is the boundary radius of the source charge distribution. The solution of Eq. (3) then has the form

$$Q_{\mathrm{tot}}(r) = Q_S(r)(k_D r)^{-1}(1 - e^{-k_D r}). \tag{4}$$

Here, the factor $Q_S(r)(k_D r)^{-1}$ is a constant because of the assumed behavior $Q_S \propto r$. Correspondingly, the bound (1) for dark matter particles now takes the form

$$q_x < 10^{-17}(m_x/m_p)(r/\mathrm{kpc}) \approx 10^{-16}\, m_x/m_p. \tag{5}$$

This result does not depend on the neutrino "charge" q_ν.

If the background neutrinos are nonrelativistic, the Debye length is smaller and the bound is weaker. The exact suppression factor depends on the neutrino velocity dispersion.

We have implicitly assumed that the universe is neutral with respect to the new charge. If the mass of the corresponding intermediate boson is exactly zero, this is the only possibility because any nonzero cosmic charge density would drastically change cosmology. For a nonzero boson mass, even if it is very small, this may not be true and a cosmic charge asymmetry is possible. Even in this case one would expect screening effects to operate on galactic scales.

Our argument relies on the assumption of oppositely charged neutrinos and antineutrinos, i.e., that the new force is mediated by vector particles. A force mediated by spin-0 or by spin-2 particles is always attractive. Because there is only one conserved rank-2 tensor (the energy-momentum tensor), any force mediated by massless spin-2 particles is identical to gravity. Unless one wishes to consider low-mass bosons as a mediator of the novel force, this leaves only the scalar case as a realistic option for an unscreened galactic-scale force.

A scalar force between a static source and relativistic fermions is suppressed by a Lorentz factor m_ν/E_ν. Therefore, in this case the bound (1) is degraded correspondingly; for massless neutrinos there would be no bound. If neutrinos do have a small mass, they may partially cluster on galactic scales even though they do not contribute the dominant part of the dark matter. In this case they may be the dominant source for the force affecting the propagation of supernova neutrinos.

In a recent paper [11] the dispersion of neutrinos from a future supernova near the galactic center was discussed under the assumption that the galactic dark matter consists of ν_τ's with a mass in the 100 eV range. Again, if the force between these dark matter neutrinos and those from a SN is mediated by a vector force, there will be no novel dispersion effect because the distribution of galactic dark matter neutrinos is likely CP symmetric so that no net charge survives. Even if there were a cosmic CP asymmetry of order, say, the baryon asymmetry, the galaxy would tend to repel surplus charges to its surface. Within the galaxy the "neutrino plasma" likely would be neutral.

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[1] C. B. Bratton *et al.*, Phys. Rev. D **37**, 3361 (1988); K. S. Hirata *et al.*, *ibid.* **38**, 448 (1988).

[2] G. I. Zatsepin, Pis'ma Zh. Eksp. Teor. Fiz. **8**, 333 (1968) [JETP Lett. **8**, 205 (1968)]; T. J. Loredo and D. Q. Lamb, in *Proceedings of the 14th Texas Symposium on Relativistic Astrophysics,* 1988, edited by E. Fenyves [Ann. N.Y. Acad. Sci. **571**, 601 (1989)]. See also the references therein.

[3] G. Barbiellini and G. Cocconi, Nature (London) **329**, 21 (1987).

[4] K. Fujiwara, Phys. Rev. D **39**, 1764 (1989).

[5] G. Fiorentini and G. Mezzorani, Phys. Lett. B **221**, 353 (1989); J. A. Grifols, E. Massó, and S. Peris, *ibid.* **207**, 493 (1988); Astropart. Phys. **2**, 161 (1994).

[6] S. Pakvasa, W. A. Simmons, and T. J. Weiler, Phys. Rev. D **39**, 1761 (1989).

[7] L. B. Okun, Yad. Fiz. **10**, 358 (1969) [Sov. J. Nucl. Phys. **10**, 206 (1969)].

[8] G. A. Zisman, Uch. Zap. Leninab. Gos. Pedagog. Inst. No. 386, 80 (1971); V. M. Goldman, Z. A. Zisman, and R. Ya. Shaulov, Temat. Sb. Leninab. Gos. Pedagog. Inst. (1972); A. K. Ciftci, S. Sultansoi, and S. Türköz, Ankara University Report No. AU-94-03-HEP (unpublished).

[9] 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).

[10] S. I. Blinnikov, A. D. Dolgov, L. B. Okun, and M. B. Voloshin, Report No. HEP-PH/9505444 (unpublished).

[11] R. A. Malaney, G. D. Starkman, and S. Tremaine, Phys. Rev. D **51**, 324 (1995).