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Limits on neutrino electromagnetic properties — an update

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Abstract

Limits on neutrino electromagnetic properties from laboratory experiments and astrophysical arguments are reviewed with an emphasis on the currently favored range of small neutrino masses. We derive a helioseismological limit on the charge and dipole moment for all flavors of $e_\nu \lesssim 6\times10^{-14}e$ and $\mu_\nu \lesssim 4\times10^{-10}\mu_\mathrm{B}$ (Bohr magneton). The most restrictive limits remain those from the plasmon decay in globular-cluster stars of $e_\nu \lesssim 2\times10^{-14}e$ and $\mu_\nu \lesssim 3\times10^{-12}\mu_\mathrm{B}$.

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1. Introduction

The idea that neutrinos could interact by means of an intrinsic magnetic dipole moment is as old as the idea of neutrinos themselves [1]. Of course, in the modern framework of the particle-physics standard model, neutrino dipole moments strictly vanish due to the left-handed nature of the weak interaction, and even neutrino-mass-induced dipole moments are too small to be of any experimental or astrophysical significance [2,3]. On the other hand, nontrivial extensions of the standard model such as left–right symmetry can lead to interesting values for neutrino electromagnetic couplings.

In the late 1980s this possibility was widely discussed because of two astrophysical motivations. The Homestake solar neutrino data seemed to show a significant time variation in correlation with indicators of solar magnetic activity [4,5], leading to a revival of the idea that magnetic spin-precession of left-handed (active) neutrinos into right-handed (sterile) states was responsible for the

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solar neutrino problem [6]. Second, the neutrino observations from supernova (SN) 1987A ignited broad interest in the role of neutrinos in the SN phenomenon where large magnetic fields are known to exist and where magnetic spin precessions between active and sterile states can both change the physics of SN explosions and the neutrino signature from such an event [5]. Lev Okun wrote and co-authored several papers on these topics [7–11], which in turn triggered much activity to derive new limits on neutrino electromagnetic couplings, including some papers by the present author [12–14].

The original motivation for speculating about large neutrino dipole moments has never completely disappeared — the Homestake data continue to be analysed for possible time variations in a very recent series of papers [15,16]. Magnetically induced spin-flavor oscillations continue to provide a viable solution of the solar neutrino problem [17–19], and remain potentially important in SN physics [20–24]. Therefore, the present Festschrift in Lev Okun's honor offers a timely opportunity to review where we stand today with our empirical knowledge of neutrino electromagnetic properties.

2. Plasmon decay in stars

Neutrino dipole or transition moments allow for several interesting processes (Fig. 1). For the purpose of deriving limits, the most important case is $\gamma \to \nu\bar{\nu}$ which is kinematically allowed in a plasma because the photon acquires a dispersion relation which roughly amounts to an effective mass. Even without anomalous couplings, the plasmon decay proceeds because the charged particles of the medium induce an effective neutrino–photon interaction. Put another way, even standard neutrinos have nonvanishing electromagnetic form factors in a medium [25,26]. The

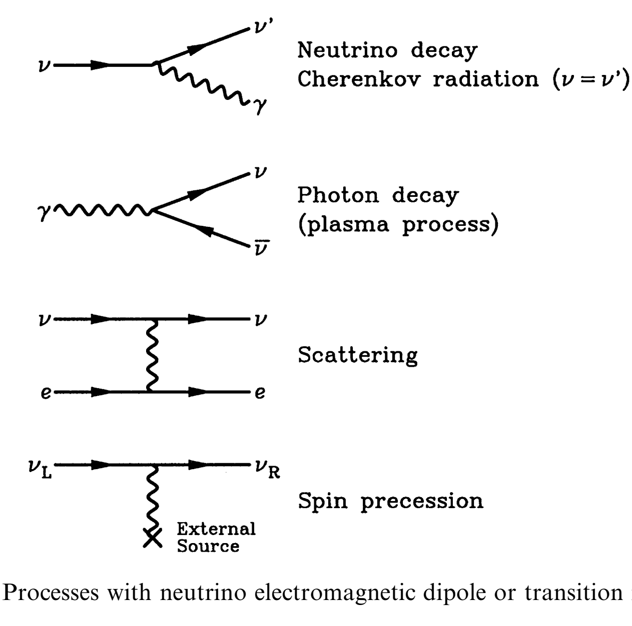

Fig. 1. Processes with neutrino electromagnetic dipole or transition moments.

standard plasma process [14,27,28] dominates the neutrino production in white dwarfs or the cores of globular-cluster red giants, which turn out to be the most sensitive laboratories to constrain neutrino dipole moments.

The plasma process was first used by Bernstein et al. [29] in a seminal paper to constrain neutrino electromagnetic couplings. They calculated the energy-loss rate of the Sun due to the $\gamma \to \nu\bar{\nu}$ process under the assumption that neutrinos couple to photons either through a small charge e_ν or else through a magnetic dipole moment μ_ν. If this energy loss exceeded the solar luminosity, the Sun would have burnt out before reaching its observed age. Today, helioseismology allows for tighter constraints which are found to be $e_\nu \lesssim 6 \times 10^{-14} e$ and $\mu_\nu \lesssim 4 \times 10^{-10} \mu_B$ where e is the electron charge and $\mu_B = e/2m_e$ the Bohr magneton (Appendix A).

A more significant improvement is provided by other stars, notably the properties of globular-cluster stars. Nonstandard neutrino losses would delay the ignition of helium in the degenerate cores of low-mass red giants. Several observables in the color-magnitude diagram of globular clusters allow one to derive a restrictive limit on the core mass at helium ignition, corresponding to the requirement that the new energy-loss rate must not exceed the standard losses by more than a factor of a few. One thus finds the limits [12–14]

$$\mu_\nu \lesssim 3 \times 10^{-12} \mu_B \quad \text{and} \quad e_\nu \lesssim 2 \times 10^{-14} e \ . \tag{1}$$

More recent discussions of these arguments modify details of the astrophysical analysis, but arrive at virtually the same results [5,31]. A slightly more restrictive limit based on the "mass-to-light ratio" of RR Lyrae stars [32] is probably too optimistic. The white-dwarf luminosity function provides a limit of about $10^{-11} \mu_B$, not much weaker than the globular-cluster bound [33].

Naturally, the significance of Eq. (1) could be improved with modern and detailed observations of the color-magnitude diagrams of globular clusters. However, with the plasmon-decay method even a limit of $10^{-12} \mu_B$ would be difficult to achieve, and surely one could not move beyond this value — the anomalous energy loss simply becomes too small to make any measurable difference.

The stellar energy-loss argument includes all neutrino final states which are light enough to be emitted, i.e. with $m_\nu \lesssim 5$ keV for globular-cluster red giants and white-dwarfs. The current evidence for neutrino oscillations from the solar and atmospheric neutrino anomalies as well as the LSND experiment together with experimental limits on m_{ν_e} and cosmological arguments suggest that all neutrino masses are in the eV-range or smaller. Therefore, the stellar-evolution limits most likely apply to all flavors.

The μ_ν limit pertains equally to electric dipole moments and to electric and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.

3. Supernova 1987A

Supernova 1987A provides another energy-loss limit, applicable only to Dirac magnetic or electric dipole or transition moments. The structure of the electromagnetic dipole interaction couples neutrino states of opposite helicity. Therefore, neutrinos which are trapped in a SN core flip their helicity in electromagnetic interactions, taking them into nearly sterile right-handed states which escape directly from the inner SN core. This anomalous energy-loss channel short-circuits the standard diffusive energy transfer and thus shortens the measurable signal of left-handed $\bar{\nu}_e$'s, in conflict with the observed duration of the SN 1987A signal. In an early paper [34], a limit

$$\mu_\nu(\text{Dirac}) \lesssim 3\times 10^{-12}\mu_{\rm B} \tag{2}$$

was derived. It was confirmed by a simple estimate in Ref. [5] and by a recent detailed investigation where the spin-flip rate was calculated by thermal field-theory methods [35]. Another early paper [36] found a much more restrictive limit which should be viewed as too optimistic.

The temperature in a SN core was taken to be about 30 MeV. Depending on the equation of state it may be much larger, in which case this energy-loss channel would be important for much smaller dipole moments.

The right-handed neutrinos emerging directly from the inner SN core have much higher average energies than the ones emitted from the neutrino sphere. They can spin-precess back into active states in the galactic magnetic field and would thus become visible in the detectors which measured the SN 1987A neutrino signal. The absence of such anomalous high-energy events yields another limit [34,37]

$$\mu_\nu(\text{Dirac}) \lesssim 1\times 10^{-12}\mu_{\rm B}\ . \tag{3}$$

The oscillation length for magnetic spin-precession does not depend on the neutrino energy so that the Earth could have been in a node of the oscillation pattern, providing a loop-hole from this constraint.

If neutrinos had a small charge they would be deflected by the galactic magnetic field. The absence of an energy-dependent dispersion of the SN 1987A $\bar{\nu}_e$-signal thus leads to a limit [4,38]

$$e_{\nu_e} \lesssim 3\times 10^{-17} e \tag{4}$$

in analogy to the well-known SN 1987A limit on m_{ν_e}.

4. Big-bang nucleosynthesis

Spin-flip collisions would also populate the sterile Dirac components in the early universe and thus increase the effective number of thermally excited neutrino degrees of freedom at the time of big-bang nucleosynthesis. Full thermal equilibrium attains for $\mu_\nu(\text{Dirac}) \gtrsim 6\times 10^{-11}\mu_{\rm B}$ [39,40]. In view of the SN 1987A and globular-cluster limits this result assures us that big-bang nucleosynthesis remains undisturbed.

5. Radiative decay and Cherenkov effect

A neutrino mass eigenstate ν_i may decay to another one ν_j by the emission of a photon, where the only contributing form factors are the magnetic and electric transition moments. The inverse radiative lifetime is found to be [2,3]

$$\tau_\gamma^{-1} = \frac{|\mu_{ij}|^2 + |\varepsilon_{ij}|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3$$
$$= 5.308\ \mathrm{s}^{-1}\left(\frac{\mu_{\rm eff}}{\mu_{\rm B}}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{\rm eV}\right)^3 , \qquad (5)$$

where μ_{ij} and ε_{ij} are the transition moments while $|\mu_{\rm eff}|^2 \equiv |\mu_{ij}|^2 + |\varepsilon_{ij}|^2$. Radiative neutrino decays have been constrained from the absence of decay photons of reactor $\bar\nu_e$ fluxes [41], the solar ν_e flux [42,43], and the SN 1987A neutrino burst [47–51]. For $m_\nu \equiv m_i \gg m_j$ these limits can be expressed as

$$\frac{\mu_{\rm eff}}{\mu_{\rm B}} \lesssim \begin{cases} 0.9\times 10^{-1}\ ({\rm eV}/m_\nu)^2 & \text{Reactor } (\bar\nu_e)\ , \\ 0.5\times 10^{-5}\ ({\rm eV}/m_\nu)^2 & \text{Sun } (\nu_e)\ , \\ 1.5\times 10^{-8}\ ({\rm eV}/m_\nu)^2 & \text{SN 1987A (all flavors)}\ , \\ 1.0\times 10^{-11}\ ({\rm eV}/m_\nu)^{9/4} & \text{Cosmic background (all flavors)}\ . \end{cases} \qquad (6)$$

The SN 1987A limit is based on the nonobservation of excess counts in the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission Satellite which happened to switch into calibration mode about 223 s after the neutrino burst. Therefore, as stated here the SN 1987A bound applies only to $m_\nu \lesssim 40$ eV where the full γ-ray burst would have been captured.

For higher neutrino masses one can still derive limits from SN 1987A if one takes the short GRS time window into account. Comparable limits in the higher-mass range were derived from γ-ray data of the Pioneer Venus Orbiter (PVO) instrument which had a much longer exposure time [52]. For $m_\nu \gtrsim 0.1$ MeV, decay photons would still arrive years after SN 1987A. In 1991 the COMPTEL instrument aboard the Compton Gamma Ray Observatory looked at the SN 1987A remnant for about 0.68×10^6 s, providing the most restrictive limits in this mass range [53,54]. However, neutrinos with such large masses no longer seem particularly plausible so that we forego a detailed discussion of these bounds. They are difficult to represent in a compact form because neutrinos with a mass exceeding about 30 eV must have nonstandard invisible decay channels in order to conform to well established upper limits on the cosmic matter density. Therefore, the radiative decay limits depend on the nonradiative decay width, introducing an unavoidable further parameter — see [5] for a detailed discussion.

The decay of cosmic background neutrinos would contribute to the diffuse photon backgrounds, excluding the shaded areas in Fig. 2. The dark-shaded area was added only very recently by the observation of TeV γ-rays from the active galaxies Markarian 421 and 501. The lack of flux attenuation by the pair process $\gamma_{\rm TeV}\gamma_{\rm infrared} \to e^+e^-$ has provided new limits on the cosmic density of infrared photons and thus to neutrino radiative decays [45]. The envelope of these limits is well approximated by the dashed line in Fig. 2, corresponding to the bottom line in Eq. (6). More restrictive limits obtain for certain neutrino masses above 3 eV from the absence of emission features from several galaxy clusters [55–57] and from the observation of singly ionized helium in the diffuse intergalactic medium [58].

For low-mass neutrinos, the m_ν^3 phase-space factor in Eq. (5) is so punishing that the globular-cluster limit is the most restrictive one for m_ν below a few eV, i.e. in the mass range which today

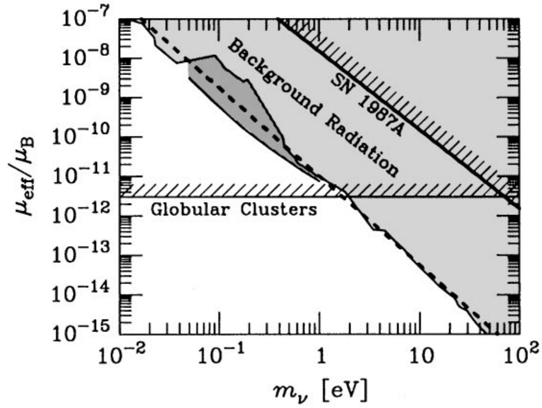

Fig. 2. Astrophysical limits on neutrino transition moments. The light-shaded background-radiation limits are from Ressell and Turner [44], the dark-shaded ones from Biller et al. [45] and Raffelt [46], the dashed line is the approximation formula in Eq. (6), bottom line.

appears favored from neutrino oscillation experiments. Turning this around, the globular-cluster limit implies that radiative decays of low-mass neutrinos do not seem to have observable consequences.

Another form of "radiative decay" is the Cherenkov effect $\nu \to \nu + \gamma$ involving the same initial- and final-state neutrino. This process is kinematically allowed for photons with $\omega^2 - k^2 < 0$, which obtains in certain media (for example air or water) or in external magnetic fields. The neutrino may have an anomalous dipole moment, but there is also a standard-model photon coupling induced by the medium or the external field. Thus far it does not look as if the neutrino Cherenkov effect had any strong astrophysical or laboratory significance — for a review of the literature see [59].

6. Laboratory limits

Laboratory limits on neutrino dipole moments arise from measurements of the ν–e-scattering cross section. The current limits are

$$\mu_\nu < \begin{cases} 1.8\times 10^{-10}\mu_{\rm B} & \text{for } \nu_e \text{ [60]}\,, \\ 7.4\times 10^{-10}\mu_{\rm B} & \text{for } \nu_\mu \text{ [61]}\,, \\ 5.4\times 10^{-7}\mu_{\rm B} & \text{for } \nu_\tau \text{ [62]}\,, \end{cases} \tag{7}$$

see also the Review of Particle Properties [63]. These limits apply also to electric dipole moments and to electric and magnetic transition moments. For example, the limit on μ_{ν_e} applies to all transition moments which connect ν_e to another flavor. It should be noted, however, that the scattering amplitudes from electric and magnetic dipole moments can interfere destructively, providing a loop-hole from these limits [64].

An improvement of the μ_{ν_e} limit to something like $3\times10^{-11}\mu_B$ is to be expected from the MUNU experiment which has been installed at the Bugey nuclear reactor [65,66]. Other projects aiming at a similar sensitivity are in a much earlier stage of development [67–69].

The only electromagnetic from factor for which laboratory measurements provide more restrictive limits than astrophysical arguments is the ν_e electric charge. If electric charge conservation is assumed to hold in β processes such as neutron decay, one finds

$$e_{\nu_e} \lesssim 3\times10^{-21}e\ . \tag{8}$$

This limit is based on a bound for the neutron charge of $e_n = (-0.4 \pm 1.1)\times10^{-21}e$ [70] and on the neutrality of matter which was found to be $e_p + e_e = (0.8 \pm 0.8)\times10^{-21}e$ [71].

7. Conclusions

The recent evidence for neutrino oscillations from the solar and the atmospheric neutrino anomaly and from the LSND experiment indicate that the neutrino mass differences are very small, at most in the eV range. Moreover, the absolute neutrino mass scale cannot exceed a few eV as indicated by the tritium decay limits on the ν_e mass and by cosmological arguments. Therefore, speculations about neutrino masses far in excess of a few eV are becoming more and more unattractive.

If neutrino masses are indeed that small, it is no longer possible to invoke threshold effects to avoid the stellar plasmon-decay limits on neutrino dipole moments and electric charges. Moreover, Fig. 2 illustrates that for neutrino masses below about 2 eV the stellar limits on transition moments are more restrictive than those from searches for radiative decays. Turning this around, if neutrino masses are indeed below a few eV one cannot expect neutrino radiative decays to have any observable consequences.

The current round of experiments to improve the laboratory limits on μ_{ν_e} will not be able to come even close to the globular-cluster limit so that a positive discovery would indicate extremely serious problems with our understanding of low-mass stars. Barring this unlikely possibility, one cannot hope to discover neutrino dipole moments anytime soon in a laboratory experiment. On the other hand, unless a completely new argument is put forth, the stellar-evolution limits have probably gone about as far as they can, although one could still achieve a significant reduction of their uncertainties.

The possibility that neutrino dipole or transition moments in the general $10^{-12}\mu_B$ range play an important role in astrophysical environments with large magnetic fields cannot be ruled out in the foreseeable future. Scenarios with magnetic spin-flavor oscillations in the Sun, supernovae, active galactic nuclei, or the early universe are in no danger of being ruled out anytime soon!

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Appendix A: Helioseismological limit

The interior of the Sun is a nonrelativistic plasma where the neutrino energy-loss rate per unit volume from transverse-plasmon decay is approximately given by [5]

$$Q = (8\zeta_3/3\pi)T^3 \times \begin{cases} \alpha_\nu \omega_P^2/4\pi & \text{Charge}\,, \\ (\mu_\nu^2/2)(\omega_P^2/4\pi)^2 & \text{Dipole Moment}\,, \\ (C_V^2 G_F^2/\alpha)(\omega_P^2/4\pi)^3 & \text{Standard Model}\,. \end{cases} \tag{A.1}$$

Here, $\zeta_3 \approx 1.202$ refers to the Riemann Zeta function, $\alpha_\nu = e_\nu/4\pi$ is the neutrino fine-structure constant, C_V the vector–current coupling constant between neutrinos and electrons, G_F the Fermi constant, and $\omega_P = 4\pi\alpha n_e/m_e$ is the plasma frequency with n_e the electron density. Natural units with $\hbar = c = k_B = 1$ are used. Longitudinal-plasmon decay is not important for these conditions.

Integrating these energy-loss rates over a standard solar model yields $L_\nu = (e_\nu/e)^2 3.2\times 10^{25}$ $L_\odot$ and $L_\nu = (\mu_\nu/\mu_B)^2 6.0\times 10^{17}$ $L_\odot$ (solar luminosity $L_\odot$), respectively. Helioseismology requires that a new energy-loss channel of the Sun does not exceed about 10% $L_\odot$ [30], leading to $e_\nu \lesssim 6\times 10^{-14} e$ and $\mu_\nu \lesssim 4\times 10^{-10}\mu_B$.

The globular-cluster limit on e_ν is not much more restrictive than this result, while one gains a lot for μ_ν. The reason is that the energy-loss rate per unit mass for the e_ν case does not depend on the matter density, while for the μ_ν case it depends linearly on ρ. The cores of low-mass red giants before helium ignition are about 10^4 times denser than the Sun, explaining the improvement of the μ_ν limit.

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