Title
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Journal
Physics Letters B, 275(3-4)

ISSN
0370-2693

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Publication Date
1992

DOI
10.1016/0370-2693(92)91621-f

Peer reviewed

Physics Letters B 275 (1992) 487–490
North-Holland

PHYSICS LETTERS B

Limits on magnetic moments of heavy neutrinos from nucleosynthesis

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Received 24 October 1991; revised manuscript received 28 October 1991

Dirac neutrinos with masses in the MeV range and having "standard model" magnetic moments are known to violate the cosmological ^{4}He bound. We calculate the value of the magnetic dipole moment of Dirac neutrinos in the mass range 5–35 MeV which would allow for consistency with the inferred primordial abundances of ^{2}H, ^{3}He, ^{4}He and ^{7}Li.

The inferred primordial production of ^{4}He from astronomical observations, coupled with the theory of light isotope production in the early universe, remains one of the most widely used constraints on extensions to the standard model of electroweak interactions [1–3] (for a review of these constraints see ref. [4]). We will investigate the constraint imposed by primordial nucleosynthesis considerations on the magnetic dipole moment of Dirac neutrinos in the mass range 5–35 MeV. Introducing a right-handed field transforming as a gauge singlet under $SU(2)_L \otimes U(1)_Y$ allows us to form a Yukawa coupling that provides a Dirac mass term for the neutrino in the standard model. Neutrinos with MeV masses are known to have dire consequences for primordial nucleosynthesis provided their lifetimes are long enough ($\tau_\nu > \sim 1$ s) for them still to be present at the epoch of nucleosynthesis. The additional energy density contributed by the neutrino mass leads to an overproduction of ^{4}He [5].

It is known, however, that a large magnetic dipole moment could circumvent this overproduction, due to the enhanced annihilation and subsequent depletion of massive neutrinos through the electromagnetic channel $\bar{\nu}\nu \to e^+e^-$ [6]. It is the purpose of this letter to investigate this possibility in detail, and to determine the critical values of the magnetic dipole moment which would allow Dirac neutrinos in the

[1] Supported by NSF grant No. NSF-PHY-88-17296.
[2] Supported in part by NSF grant PHY-8914379 and IGPP grant number LLNL-90.
[3] Supported by US Department of Energy W-7405-ENG-48 at LLNL.
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mass range 5–35 MeV and lifetimes $\tau_\nu > \sim 1$ s to remain consistent with the inferred primordial abundances of the light isotopes.

The evolution of the scale factor R of the universe is described by a simple first order differential equation,

$$\left(\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2 + k = \tfrac{8}{3}\pi G\rho R^2 \,, \tag{1}$$

where ρ is the energy density of the universe and k is a dimensionless constant which measures the curvature of space ($k=0, \pm 1$). For all times which will be of interest to us

$$k \ll \tfrac{8}{3}\pi G\rho R^2 \,, \tag{2}$$

and eq. (1) can be rewritten:

$$H^2(t) = \left(\frac{1}{R}\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2 = \tfrac{8}{3}\pi G\rho \,, \tag{3}$$

where we have introduced the Hubble parameter $H(t)$. An important point to note here is the direct dependence of the universal expansion rate on the energy density.

In the context of the standard big-bang the energy density of the universe at the nucleosynthesis epoch is approximately given by

$$\rho = \rho_{\nu_i} + \rho_\gamma + \rho_l \,, \tag{4}$$

where ρ_{ν_i}, ρ_γ and ρ_l are the energy densities due to neutrinos, photons and charged leptons, respectively (we include the antiparticles in these densities). At the temperatures of primordial nucleosynthesis only the electron contributes significantly to the charged lepton energy density. The contribution from each massless neutrino species, i, is

$$\rho_{\nu_i} \approx \tfrac{7}{8}\cdot\tfrac{1}{15}\pi^2 T_\nu^4 \,, \tag{5}$$

where T_ν is the neutrino temperature. The energy densities of photons ρ_γ and relativistic charged leptons ρ_l are given by

$$\rho_\gamma = \tfrac{4}{7}\rho_l = \tfrac{1}{15}\pi^2 T_\gamma^4 \,, \tag{6}$$

where T_γ is the photon temperature. For temperatures above ~ 1 MeV the neutrinos and photons are in thermal equilibrium ($T_\nu = T_\gamma = T$). Using the above equations the relation between temperature and time in the early universe can be derived:

$$T \approx 1.6 g_{\mathrm{eff}}^{-1/4}\left(\frac{t}{10^{-6}\,\mathrm{s}}\right)^{-1/2} \mathrm{GeV} \,, \tag{7}$$

where $g_{\mathrm{eff}}(T)$ represents the effective number of relativistic species,

$$g_{\mathrm{eff}}(T) = \sum_{\mathrm{Bose}} g_{\mathrm{Bose}} + \tfrac{7}{8}\sum_{\mathrm{Fermi}} g_{\mathrm{Fermi}} \,. \tag{8}$$

If massive neutrinos are present at the epoch of nucleosynthesis then the additional mass will contribute to the total energy density of the universe as given by eq. (4). This contribution can be written as

$$\rho_{\mathrm{m}} = 4\int \mathrm{d}E_\nu\, n_\nu(E_\nu) E_\nu \,, \tag{9}$$

where $n_\nu(E_\nu)$ is the number density of the massive neutrino species in the energy interval E_ν to $E_\nu + \mathrm{d}E_\nu$. As both helicity states of the massive neutrino are thermally equilibrated for masses greater than ~ 300 keV [7] (even for vanishing magnetic moment) they both contribute to the energy density. The factor 4 arises from the two spin degrees of freedom and from the fact that we are adding both particles and antiparticles. The number of neutrinos is determined from the solution to the Boltzmann equation:

$$\frac{\mathrm{d}n_\nu}{\mathrm{d}t} = -\sigma_{\mathrm{A}}|v|[n_\nu^2 - (n_\nu^{\mathrm{eq}})^2] - \frac{3}{R}\frac{\mathrm{d}R}{\mathrm{d}t} n_\nu \,, \tag{10}$$

where n_ν^{eq} is the equilibrium number density of massive neutrinos [found by integrating $n_\nu(E_\nu)$], σ_{A} is the total neutrino–antineutrino annihilation cross section, and v is the relative velocity of the annihilating neutrinos.

For a massive neutrino with a large magnetic moment, the cross section for annihilation into an e^+e^- final state is given by

$$\sigma^{\mathrm{e}} = |A^{\mathrm{Z}} + A^{\mu}|^2 \,, \tag{11}$$

where A^{Z} and A^{μ} are the amplitudes for s-channel annihilations through the Z^0 and γ (with magnetic moment coupling) respectively. In the limit where the electromagnetic channel dominates the cross section for annihilation into e^+e^- it can be shown that

$$\sigma^{\mathrm{e}} = \frac{\mu_0^2\alpha^2\pi}{6m_{\mathrm{e}}^2}\left(\frac{1-4m_{\mathrm{e}}^2/s}{1-4m_\nu^2/s}\right)^{1/2}\left(1+8\frac{m_\nu^2}{s}\right)\left(1+2\frac{m_{\mathrm{e}}^2}{s}\right), \tag{12}$$

where μ_0 is the magnetic moment of the neutrino in units of Bohr magnetons, s is the square of the four-momentum transfer ($s=4m_\nu^2$ for $T \ll m_\nu$), and m_ν and m_e are the neutrino and electron mass, respectively. In the other limit where the electromagnetic amplitude is negligible we have the usual weak annihilation channel to the e^+e^- final state with a cross section $\sigma^e = G_F^2 m_\nu^2/8\pi$. In addition to the e^+e^- final states, annihilations through Z^0 exchange into lighter neutrino species can occur (individual quark channels require $m_\nu > m_\pi$, the pion mass). The spin averaged cross section for annihilation into $\bar{\nu}_e\nu_e + \bar{\nu}_\mu\nu_\mu$ is

$$\sigma^\nu = \frac{G_F^2 m_\nu^2}{2\pi}, \tag{13}$$

where G_F is Fermi's constant and we have assumed that $m_\nu \gg T$ at freeze-out. The total annihilation cross section is $\sigma^A = \sigma^e + \sigma^\nu$.

The extra energy density contributed by Dirac neutrinos with masses in the range 5–35 MeV is determined through eqs. (9)–(13). The effect on the expansion rate of the universe is then determined through eqs. (3)–(7). The big bang nucleosynthesis code described in detail in ref. [8] was modified to accommodate the presence of massive neutrinos. The code was then run assuming two massless neutrino species and one massive neutrino within the quoted mass range. In contrast to standard big bang nucleosynthesis, where only one free parameter, the baryon-to-photon ratio η, exists, we have an additional parameter, μ_0.

Adopting the analysis of ref. [9] we have the following constraints on the inferred primordial abundances of the light elements: $Y \leqslant 0.24$; $(D+{}^3He)/H \leqslant 1.1\times10^{-4}$; and $^7Li/H \leqslant 1.7\times10^{-10}$. Since the $D+{}^3He$ abundance limit turns out to be more constraining than the lithium limit, the limit on $D+{}^3He$ along with that on ^4He give us two constraints with which to determine the two parameters μ_0 and η for a particular value of the neutrino mass. η has an effect on the predicted abundances in a manner familiar from the standard nucleosynthesis plots: ^4He abundance is a slowly increasing function of η whereas $D+{}^3He$ is a sharply decreasing function. On the other hand, increasing μ_0 has the effect of decreasing both ^4He and $D+{}^3He$ abundances as it decreases the energy density in neutrinos. For a given neutrino mass, we attempt to utilize as small an η as possible (to minimize helium production) without overproducing $D+{}^3He$, all the while adjusting μ_0 to get the minimum value necessary to satisfy the abundance constraints. By adjusting both of these parameters, we are able to obtain the minimum value of μ_0 for which both abundance limits are satisfied. The 2σ lower limit of 10.18 min. [9] for the neutron half-life was adopted in the calculation in order to obtain the lower limit of μ_0 consistent with the observations. The values of μ_0 thus obtained are shown in fig. 1. It is important to note that our lower limit on μ_0 is relatively insensitive to the inferred abundance sum of $D+{}^3He$, and is essentially determined by the inferred upper limit on ^4He. This follows since the ^4He abundance is sensitive to the expansion rate (determined by the energy density) and is relatively insensitive to the baryon-to-photon ratio. The ^4He abundance of 0.24 is in fact a 2σ upper limit [9]. Any future inference of a lower abundance for primordial ^4He would only strengthen our limit.

The shaded region of fig. 1 represents the parameter space which is *inconsistent* with the inferred primordial abundances of the light isotopes assuming that the only new physics is the neutrino magnetic moment; the unshaded region above the curve represents the allowed region. In the standard model of electroweak interactions with right-handed neutrinos, the magnetic moment of a Dirac neutrino arises through one-loop graphs and is found to be [10]

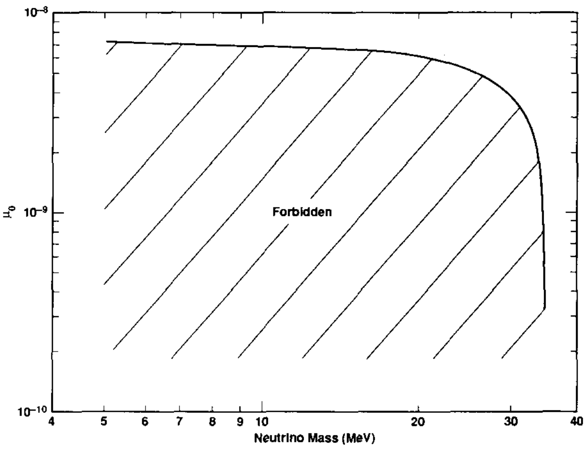

Fig. 1. The minimum value of the ν_τ magnetic moment (as a function of the ν_τ mass) necessary to suppress production of ^4He and $D+{}^3He$ to inferred primordial levels. The magnetic moment is given in units of Bohr magnetons.

$$\mu_0 \sim 3\times 10^{-19}(m_\nu/1\ \mathrm{eV})\ . \tag{14}$$

Clearly the allowed region of fig. 1 requires dipole moments many orders of magnitude larger than that given by eq. (14). Consistency with primordial nucleosynthesis therefore, requires more than just a minimal extension to the standard model. As this analysis has been model independent we do not wish to dwell on the possible mechanism by which a large magnetic moment for the ν_τ is generated. One could imagine models, for instance a two-Higgs doublet model with a large hierarchy of VEVs, where a charged scalar has an anomalously large coupling to the τ-type leptons and gives rise to a magnetic moment for ν_τ that is substantially greater than that from gauge boson exchange alone.

Current experimental mass limits require that a neutrino with a mass in the range 5–35 MeV be the ν_τ. Single photon experiments constrain the magnetic moment of ν_τ to be less than $\mu_0 < 4\times 10^{-6}$ [6,11]. An interesting point is made in ref. [6] where it is observed that a massive ν_τ ($\sim$35 MeV) with $\mu_0 \sim 10^{-6}$ could serve as the dark matter. Finally we note that MeV neutrinos with a magnetic moment near our lower limit must decay in order to avoid overclosing the universe. The effect of these decays on our conclusion is unimportant [5,6].

In conclusion, we have derived a lower limit on the magnetic dipole moment a long-lived Dirac neutrino in the mass range 5–35 MeV must possess in order to circumvent the primordial overproduction of ^{4}He. Although this typically requires $\mu_0 \sim 10^{-8}$, such values are not presently experimentally excluded for ν_τ. These limits on the magnetic moment of MeV mass neutrinos are complimentary to those derived for light neutrinos [12]. This analysis provides a constraint on extentions to the standard electroweak model.

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