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Implication of Helicity Modifications of Primordial Neutrinos on Their Detection

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Primordial neutrinos provide information on the Universe at a very early stage, roughly one second after the big bang. Their detection would have a major impact on our knowledge in cosmology and neutrino physics. The most promising experimental technique for detecting these extremely low energy primordial neutrinos involves their capture on a radioactive tritium target. The capture rate depends on certain yet unknown neutrino properties, including their masses and their Dirac or Majorana nature. We show that the capture rate also depends on the helicity of primordial neutrinos, which evolves as neutrinos propagate through the cosmic gravitational and magnetic fields. We predict the dependence of the capture rate on various properties of primordial neutrinos.

1. Introduction

While the detection of the cosmic microwave background (CMB) has revolutionized the field of cosmology, the predicted cosmic neutrino background (CνB) has not been observed yet. The standard cosmological model predicts the decoupling of primordial neutrinos to occur at about one second after the Big Bang, much earlier than the decoupling time of $\sim 3.8 \times 10^5$ years for the CMB [1]. The observation of the CνB would provide a snapshot of the Universe at a much earlier epoch than is accessible by the CMB.

The predicted CνB density ~ 338 / cm^3, summed over all flavors of active neutrinos and antineutrinos, is comparable to the CMB density ~ 411 / cm^3. The present temperature of the CνB, related to the temperature of the CMB by $T_{C\nu B} = (4/11)^{1/3} T_{CMB}$, is 1.945 K corresponding to an energy of 1.676×10^{-4} eV. Given the current values of $\Delta m^2_{21} = (7.50 + 0.19 - 0.17) \times 10^{-5}$ eV^2 and $|\Delta m^2_{32}| = (2.52 \pm 0.04) \times 10^{-3}$ eV^2 [2] for the mass-squared difference Δm^2_{ij} between neutrino mass states i and j, at least two of the three neutrino mass eigenstates in the CνB are presently non-relativistic. No observation of non-relativistic neutrinos, regardless of their origins, has ever been reported. Nevertheless, serious efforts to detect the CνB via neutrino capture on a radioactive ^{3}H target, a method first suggested in the 1960s [3], are underway as part of the PTOLEMY experiment [4].

A massive neutrino, as a spin-1/2 particle, can be a mixture of positive and negative helicity states. When primordial neutrinos decoupled in the early Universe at a temperature ~ 1 MeV [1], they were highly relativistic and predominantly in helicity eigenstates. As they propagate through the Universe, their helicity is modified by cosmic gravitational and magnetic fields. As a result, the CνB could develop significant mixtures between the two helicity states, as discussed recently in [5, 6] and in this symposium [7]. In this paper, we discuss the implications of the helicity modifications of the CνB on their detection.

2. Neutrino Capture on Tritium Target

Several ingenious ideas have been proposed to search for primordial neutrinos [8]. One concerns coherent neutrino scattering on a large number of nuclei [9]. The de Broglie wavelength of a $\sim 10^{-4}$ eV primordial neutrino is several mm long, implying a coherence over a volume containing $\sim 10^{20}$ nucleons. The force exerted on a target from the coherent neutrino scattering could be greatly enhanced. However, the net force from an isotropic neutrino flux is zero. The small anisotropy of the CνB inferred from the dipole anisotropy observed in CMB implies an extremely tiny acceleration of $\sim 10^{-26}$ cm/s^2 from the "neutrino wind" generated by the CνB on a grain of mm size. Another interesting idea is a search for a net torque exerted on a polarized target, such as magnetized iron, due to the interaction between a polarized electron and the CνB [10]. However, a net torque can only exist if the CνB flux for neutrino and antineutrino is asymmetric. Such an asymmetry requires non-standard cosmological models.

The most promising method for detecting the CνB, proposed by Weinberg in 1962 [3], is the capture of electron neutrinos on a radioactive target such as tritium. Tritium undergoes beta decay (TBD), $^3\mathrm{H} \to ^3 \mathrm{He} + e^- + \bar{\nu}_e$, with a positive Q value, $Q_a = M(^3\mathrm{H}) - M(^3\mathrm{He}) - M(e^-) - M(\bar{\nu}_e) \approx 0.18$ keV. Inverse tritium beta decay (ITBD), the capture of electron neutrino leading to a two-body final state,

$$\nu_e +^3 \mathrm{H} \to^3 \mathrm{He} + e^-, \tag{1}$$

has a positive Q value, $Q_b = M(^3\mathrm{H}) - M(^3\mathrm{He}) - M(e^-) + M(\nu_e)$, and primordial neutrinos with hardly any energy can participate in this reaction.

As a binary reaction, an ITBD initiated by the CνB with essentially zero incident energy would produce electrons with a single energy Q_b. From $M(\nu_e) = M(\bar{\nu}_e)$, as implied by CPT invariance, one obtains $Q_b = Q_a + 2M(\nu_e)$. Hence CνB-initiated ITBD signals would form a peak in the electron energy spectrum situated beyond the TBD end-point energy by twice the neutrino mass. Since there are three neutrino mass eigenstates, the ITBD events would form three peaks with a pattern dictated by the neutrino mass hierarchy. A major experimental challenge is to achieve the excellent energy resolution required for separating the ITBD signals from the TBD background. As the neutrino masses are still unknown, it is impossible to predict the exact locations of the ITBD events in the electron energy spectrum. Nevertheless, observation of the CνB signals in the ITBD reaction would, as an important byproduct, allow a determination of the yet unknown neutrino masses. The ITBD cross section for capturing a neutrino in mass state i and helicity h is [11]

$$\sigma_i^h = \frac{G_F^2}{2\pi v_i}|V_{ud}|^2|U_{ei}|^2 F(Z, E_e)\frac{M(^3\mathrm{He})}{M(^3\mathrm{H})}E_e p_e A_i^h(\bar{f}^2 + 3\bar{g}^2), \tag{2}$$

where V_{ud} is the quark mixing matrix element between u and d quarks, U_{ei} is the mixing matrix element between electron neutrino and mass state i, and $F(Z, E_e)$ is the e–^{3}He Fermi Coulomb correction for an electron of energy E_e and momentum p_e. The $\bar{f}$ and $\bar{g}$ are the nuclear form factors for Fermi and Gamow-Teller transitions. The neutrino helicity-dependent factor A_i^h is

$$A_i^{\pm} = 1 \mp \beta_i, \tag{3}$$

where $\beta_i = v_i/c$, and v_i is the velocity of the incident neutrino ν_i. Equation (3) shows that for relativistic neutrinos ($\beta_i \to 1$), the negative helicity component of the neutrino state dominates the ITBD process. For slowly moving neutrinos ($\beta \to 0$), Eq. (3) implies that the ITBD cross section is independent of the neutrino helicity. The helicity dependence of the ITBD cross section makes it necessary to take the helicities of primordial neutrinos into account in predicting the ITBD rate.

3. Helicity of Primordial Neutrinos

The evolution of the helicities of promordial neutrinos as they propagate through cosmic magnetic fields and gravitational inhomogeneities was investigated recently [5, 6] and presented in this symposium [7]. Here we briefly summarize the findings of these studies.

In the early Universe, neutrinos were produced as chiral eigenstates. When decoupled at a temperature of ~ 1 MeV, they were highly relativistic and the chiral eigenstates essentially coincide with helicity eigenstates. Hence neutrinos decouple in negative helicity states, while antineutrinos decouple in positive helicity states. On their long journey to the Earth, their helicities can potentially be modified by two effects. First, their momentum and spin vectors are both bent by gravitational forces acting transverse to their direction of motion. The rotation angle of the spin vector of a non-zero mass neutrino is less than that of the momentum vector [6, 12]. It follows that a negative-helicity neutrino at the time of decoupling would acquire a non-zero positive helicity component as it propagates through the Universe. Similarly, a positive-helicity antineutrino at decoupling time would accumulate a non-zero negative-helicity component. With the gravitational inhomogeneities of the Universe measured in the Planck experiment as input [13], the root-mean-square bending angles of primordial neutrino momentum $\langle(\Delta\theta_p)^2\rangle^{1/2}$, spin $\langle(\Delta\theta_S)^2\rangle^{1/2}$ and spin relative to momentum $\langle(\Delta\theta)^2\rangle^{1/2}$, have been calculated [6].

Other sources for modifying primordial neutrino helicities are the cosmic and galactic magnetic fields. While the neutrino's momentum is unaffected, its spin would precess in these magnetic fields if it has a nonzero magnetic moment, and modify the neutrino's helicity. The recent observation of an excess of low-energy electron events by XENON1T [14] has prompted the suggestion that solar neutrinos could have a large magnetic moment, of order $\sim 1.4 - 2.9 \times 10^{-11}\mu_B$ [15, 16], which is compatible with the upper limit of $\mu_{\nu_e} < 2.8 \times 10^{-11}\mu_B$ set by the Borexino experiment [17]. Both Majorana and Dirac neutrinos can have transitional magnetic moments, but only Dirac neutrinos can possess a diagonal magnetic moment. The XENON1T data, which does not distinguish diagonal from transitional magnetic moments, can accommodate both neutrino types.

As primordial neutrinos approach the Earth, they encounter the magnetic fields of the Milky Way, B_g of order 10 μG. As the galactic magnetic fields change orientation over a coherence length, Λ_g, of order kpc, the spin orientation of primordial neutrino undergoes a random walk through the galaxy. As shown in Refs. [5, 6], the gravitational bending of a neutrino spin with respect to its momentum is well below that produced by a magnetic moment indicated by the XENON1T data. We also note that the cumulative rotation of a Dirac primordial neutrino from the cosmic magnetic fields is found [5] to be comparable to that from the Milky Way.

4. ITBD Detection Rate

The total ITBD rate is given by $\sigma_i^h v_i$ integrated over the present momentum (p_0) distribution, $f(p_0) = 1/(e^{p_0/T_{C\nu B}} + 1)$, of primordial neutrinos, and summed over mass states i. For Dirac neutrinos with spin rotated by θ_i, both negative and positive helicity states, weighted by $\frac{1}{2}(1 \mp \cos\theta_i)$, contribute and yield the neutrino dependence in the rate,

$$A_{\mathrm{eff,D}} \;=\; \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T = 1 + \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T . \tag{4}$$

The subscript T indicates the average over both the momentum distribution as well as the spin rotation along the neutrino's path.

Majorana neutrinos, as noted, have no diagonal magnetic moments and cannot flip spin in a slowly varying magnetic field, so that $\langle\cos\theta\rangle = 1$. Since the ITBD measures both Majorana neutrinos

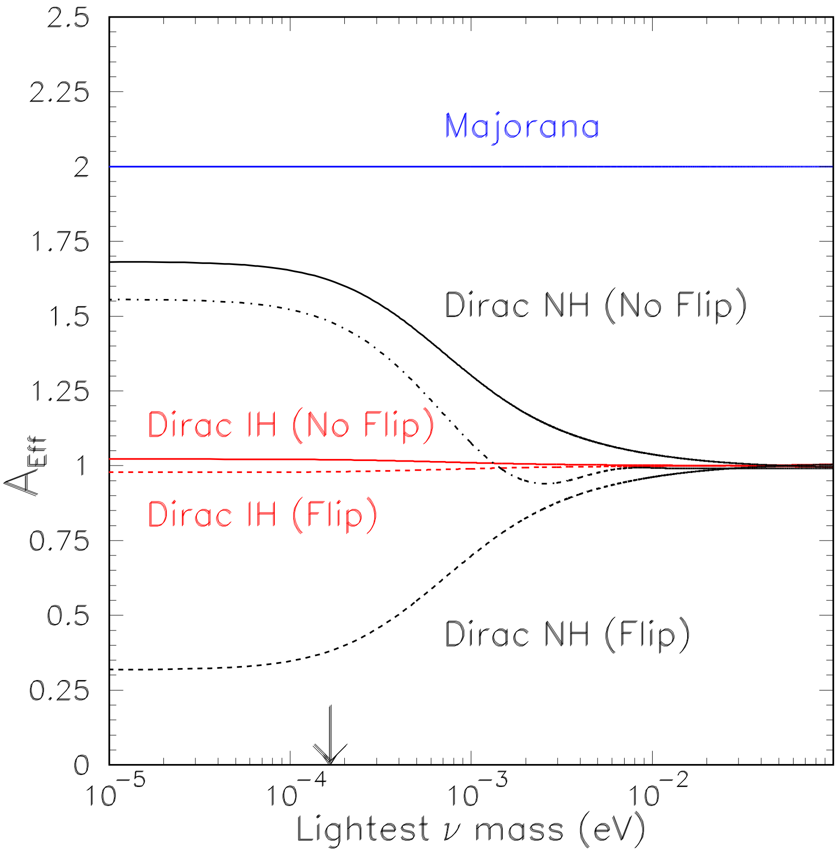

Fig. 1. The coefficient $A_{\rm eff}$ shown as solid curves versus mass of the lightest neutrino for the normal (NH) and inverted (IH) hierarchies for Dirac and Mjoarana neutrinos. The dashed curves show the case of complete helicity flip from left to right handed neutrinos. The dash-dot curve shows the result for Dirac NH neutrinos with $\langle\theta^2\rangle$ given by the Milky Way estimate with $\mu_\nu = 5\times10^{-14}\mu_B$. The present neutrino temperature is marked by the vertical arrow.

and antineutrinos,

$$A_{\rm eff,M} = (1 + \sum_i |U_{ei}|^2\langle\beta_i\rangle_T) + (1 - \sum_i |U_{ei}|^2\langle\beta_i\rangle_T) = 2, \tag{5}$$

independent of the neutrino masses, and spin rotation by cosmic gravitational fluctuations [6].

Figure 1 shows $A_{\rm eff}$ as a function of the mass of the lightest neutrino, for both Dirac and Majorana neutrinos with normal and inverted mass hierarchies. For neutrinos maintaining their original helicity ($\theta_i = 0$), the $A_{\rm eff}$ are the solid curves. As the mass of the lightest neutrino approaches zero, $A_{\rm eff,D}$ approaches $1+|U_{e1}|^2 = 1.6794$ in the normal and $1+|U_{e3}|^2 = 1.0216$ in the inverted hierarchy. When the lightest neutrino mass rises and all neutrinos become nonrelativistic, $A_{\rm eff,D}$ eventually approaches unity independent of the mass hierarchy; $A_{\rm eff}$ is always larger for Majorana than Dirac neutrinos, independent of the mass hierarchy and the mass of the lightest neutrino.

The dashed curves in Fig. 1 show the dependence of $A_{\rm eff,D}$ on the lightest neutrino mass for complete helicity flip, $\theta_i = \pi$. For partial spin rotation, $A_{\rm eff,D}$ lies between the solid and dashed curves. When $\theta_i = \pi/2$, the amplitudes to be left and right handed are equal and $A_{\rm eff,D} = 1$. To illustrate the qualitative dependence of the helicity-flip probability on μ_ν, we show in Fig. 1 $A_{\mathrm{eff,D}}$ for Dirac neutrinos passing through the Milky Way as the dash-dot curve, calculated with $\mu_\nu = 5 \times 10^{-14}\mu_B$, almost three orders of magnitude smaller than the magnetic moment XENON1T would need to explain their event excess. If the magnetic moment of normal hierarchy Dirac neutrinos is of the order suggested by XENON1T, then for the characteristic parameters assumed for cosmic or galactic magnetic fields the neutrino spin rotations would no longer be small; the mean $\cos\theta$ would decrease $A_{\mathrm{eff,D}}$ to unity essentially, with a concomitant decrease in the ITBD detection rate.

While an intense effort is undertaken by the PTOLEMY Collaboration [4] to search for primordial neutrinos using the ITBD reaction, this reaction has never been observed. An observation of the ITBD reaction in parallel with the search for primordial neutrinos would allow both a validation of the theory of ITBD and an evaluation of the performance of the detector for measuring ITBD. A search for sterile neutrinos was recently reported by the BEST collaboration using an intense 3.4 MCi ^{51}Cr source of electron neutrinos [18]. It is conceivable that a source of comparable intensity could be employed for observing the ITBD for the first time [19].

In conclusion, we have investigated the implications of a possibly large neutrino magnetic moment, beyond that in the standard model, on the helicities of relic neutrinos as they propagate through the cosmic and galactic magnetic fields. We find significant helicity modifications even if μ_ν is over two orders of magnitude smaller than that suggested by the XENON1T result. We have also shown how measurements of the rate of relic neutrinos can distinguish Dirac from Majorana neutrinos, with an accuracy that will improve as knowledge of the correct hierarchy as well as the lightest mass come into sharper focus. As the difficulty in resolving the relic neutrino events from the tritium beta decay background increases with decreasing neutrino mass, it is imperative that novel techniques for achieving an energy resolution better than 0.1 eV be developed.

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