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Relic right-handed Dirac neutrinos and implications for detection of cosmic neutrino background

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Abstract

It remains to be determined experimentally if massive neutrinos are Majorana or Dirac particles. In this connection, it has been recently suggested that the detection of cosmic neutrino background of left-handed neutrinos $\nu_{\rm L}$ and right-handed antineutrinos $\bar{\nu}_{\rm R}$ in future experiments of neutrino capture on beta-decaying nuclei (e.g., $\nu_e + {}^3{\rm H} \to {}^3{\rm He} + e^-$ for the PTOLEMY experiment) is likely to distinguish between Majorana and Dirac neutrinos, since the capture rate is twice larger in the former case. In this paper, we investigate the possible impact of right-handed neutrinos on the capture rate, assuming that massive neutrinos are Dirac particles and both right-handed neutrinos $\nu_{\rm R}$ and left-handed antineutrinos $\bar{\nu}_{\rm L}$ can be efficiently produced in the early Universe. It turns out that the capture rate can be enhanced at most by 28% due to the presence of relic $\nu_{\rm R}$ and $\bar{\nu}_{\rm L}$ with a total number density of 95 $\rm cm^{-3}$, which should be compared to the number density 336 $\rm cm^{-3}$ of cosmic neutrino background. The enhancement has actually been limited by the latest cosmological and astrophysical bounds on the effective number of neutrino generations $N_{\rm eff} = 3.14^{+0.44}_{-0.43}$ at the 95% confidence level. For illustration, two possible scenarios have been proposed for thermal production of right-handed neutrinos in the early Universe.

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1. Introduction

Although a number of elegant neutrino oscillation experiments in the past few decades have well established that neutrinos are massive particles, it is still unclear whether massive neutrinos are of Dirac or Majorana nature [1,2]. Thus far, tremendous efforts have been placed on the experimental searches for neutrinoless double-beta ($0\nu\beta\beta$) decays, which take place only if lepton number violation exists and massive neutrinos are Majorana particles [3–6]. The experimental discovery of $0\nu\beta\beta$ decays will provide us with a robust evidence for Majorana neutrinos. However, in case that $0\nu\beta\beta$ decays are not detected in all the future $0\nu\beta\beta$ experiments, it is still possible that neutrinos are Majorana particles, if neutrino mass ordering is normal (i.e., $m_1 < m_2 < m_3$) and an intricate cancellation occurs in the effective neutrino mass relevant for $0\nu\beta\beta$ decays (see, e.g., Ref. [7]). In this case, another independent approach should be utilized to probe the Dirac or Majorana nature of massive neutrinos.

More than fifty years ago, Weinberg pointed out [8] that the cosmic neutrino background (CνB) predicted by the standard Big Bang theory of cosmology can be detected via neutrino capture on beta-decaying nuclei, e.g., $\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$. This possibility has been extensively studied in many recent works [9–14]. In particular, for the future experiment PTOLEMY [15] with 100 grams of tritium, the capture rate $\Gamma(\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-)$ has been found to be [14]

$$\Gamma_\mathrm{M} \approx 8\ \mathrm{yr}^{-1}\ (\text{Majorana})\ ; \qquad \Gamma_\mathrm{D} \approx 4\ \mathrm{yr}^{-1}\ (\text{Dirac})\ . \tag{1}$$

These results have profound implications for cosmology and elementary particle physics. First, a successful detection of CνB is very important to further verify the standard theory of cosmology [16–18], and serves as a unique way to probe our Universe back to the time when it was just one second old. We already have an excellent example that the precise measurements of cosmic microwave background (CMB) have given valuable information on the Universe at the age of 3.8×10^5 years, and greatly improved our knowledge on the cosmology. Second, the relation $\Gamma_\mathrm{M} = 2\Gamma_\mathrm{D}$ between the capture rates in Eq. (1) offers a novel way to distinguish between Dirac and Majorana neutrinos. In this paper, we concentrate on the second point and take it more seriously.

It is worthwhile to emphasize that the contributions from right-handed components of massive Dirac neutrinos are completely neglected in the calculations leading to Eq. (1). See, Ref. [14], for more details. An immediate question is how the right-handed Dirac neutrinos are produced in our Universe, in the standard theories of particle physics and cosmology, and whether their abundance can be safely neglected. The second question is how the right-handed Dirac neutrinos affect the detection of CνB, i.e., the capture rate in Eq. (1), if they are copiously generated in the early Universe and survive today as a cosmic background. In order to answer these two questions, we assume that massive neutrinos are Dirac particles, and investigate carefully their production and evolution in the early Universe, both within and beyond the standard model of particle physics (SM).

The remaining part of the present paper is organized as follows. In Sec. 2, the thermal production of right-handed neutrinos in the minimal extension of the SM with massive Dirac neutrinos is reviewed. The production rate turns out to be extremely small and can be neglected. Then, we investigate the cosmological constraint on the relic density of right-handed neutrinos in Sec. 3, assuming that they can be thermalized in the early Universe in the scenarios beyond the SM. Subsequently, in Sec. 4, two possible scenarios have been presented to show that they can indeed be thermally produced if the primordial magnetic fields or secret interactions among right-handed