PROCEEDINGS OF SCIENCE

Relic Right-handed Dirac Neutrinos and Cosmic Neutrino Background

Shun Zhou[*†]
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
Center for High Energy Physics, Peking University, Beijing 100871, China
E-mail: zhoush@ihep.ac.cn

The PTOLEMY experiment, implementing a 100 g surface-deposited tritium target, is promising to detect cosmic neutrino background via $\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$. In this talk, I consider a thermal production of right-handed Dirac neutrinos in the early Universe, and investigate their impact on the capture rate of cosmic relic neutrinos at PTOLEMY.

Neutrino Oscillation Workshop
4 - 11 September, 2016
Otranto (Lecce, Italy)

*Speaker.

†This work was supported in part by the National Recruitment Program for Young Professionals and by the CAS Center for Excellence in Particle Physics (CCEPP).

PoS(NOW2016)088

1. Introduction

One milestone achievement of the big bang cosmology is the prediction for cosmic microwave background (CMB), which has now been precisely measured and led to a tremendous progress in our understanding of the Universe [1]. As another solid prediction from the big bang theory, cosmic neutrino background (CνB) should exist as well and it must carry useful information about the early Universe when it was just one second old. Therefore, a direct detection of CνB in terrestrial laboratories is of crucial importance to test the standard cosmology on the one hand, and to open a new window on probing intrinsic properties of neutrinos themselves on the other hand.

When the temperature of the Universe dropped down to $T = T_{\rm L} \approx 1$ MeV, the Hubble expansion rate exceeded the weak interaction rate of left-handed neutrinos $\nu_{\rm L}$ and right-handed antineutrinos $\overline{\nu}_{\rm R}$, and thus both $\nu_{\rm L}$ and $\overline{\nu}_{\rm R}$ decoupled from the thermal bath. At this moment, $\nu_{\rm L}$ and $\overline{\nu}_{\rm R}$ were extremely relativistic, given neutrino masses $m_\nu \lesssim 0.1$ eV [2]. Consequently, the number density $n_{\nu_{\rm l}}$ of left-helical neutrinos $\nu_{\rm l}$ was equal to that $n_{\nu_{\rm L}}$ of left-handed neutrinos $\nu_{\rm L}$, while the number density $n_{\nu_{\rm r}}$ of right-helical neutrinos $\nu_{\rm r}$ is vanishing. Hence we have $n_{\nu_{\rm l}} = n_{\nu_{\rm L}}$ and $n_{\nu_{\rm r}} = 0$ for neutrinos, while $n_{\overline{\nu}_{\rm r}} = n_{\overline{\nu}_{\rm R}}$ and $n_{\overline{\nu}_{\rm l}} = 0$ for antineutrinos, at the decoupling temperature $T_{\rm L}$. Since the helicity operator commutes with the free Hamiltonian, neutrino helicities after decoupling are always conserved in the rest frame of CνB. As the Universe is expanding, the neutrino temperature will be red-shifted. Nowadays, the average temperature of CMB photons is $T_\gamma = 2.725$ K, which is related to the neutrino temperature $T_\nu = (4/11)^{1/3} T_\gamma \approx 1.945$ K. The difference between T_γ and T_ν can be traced back to the reheating of photons via $e^+ e^- \to \gamma\gamma$ around $T = 0.5$ MeV. Therefore, we obtain average number densities $\overline{n}_{\nu_{\rm l}} = \overline{n}_{\overline{\nu}_{\rm r}} \approx 56~{\rm cm}^{-3}$ per neutrino flavor in the present Universe.

It is a great challenge to detect such low-energy relic neutrinos, whose average momentum is $\langle p_\nu \rangle \approx 5.28 \times 10^{-4}$ eV. One promising approach is to seize non-relativistic relic neutrinos by radioactive β-decaying nuclei [3], e.g., $\nu_e + {}^3{\rm H} \to {}^3{\rm He} + e^-$, for which there is no energy threshold of ν_e. In this process, the signal is simply a peak located at a distance of $2m_\nu$ from the endpoint of the β spectrum for ${}^3{\rm H} \to {}^3{\rm He} + \overline{\nu}_e + e^-$ [4]. The recently proposed PTOLEMY experiment will implement a 100 g surface-deposited tritium target and could reach an energy resolution of 0.15 eV, which will hopefully discover CνB [5]. See, e.g., Refs. [6, 7], for a review on this topic.

2. Dirac Neutrinos

The simplest extension of the Standard Model (SM) to accommodate tiny neutrino masses is to add three right-handed neutrino singlets and generate Dirac masses for neutrinos in the same way as for quarks and charged leptons. However, the huge hierarchy between neutrino masses $m_\nu \lesssim 0.1$ eV and top-quark mass $m_t = 1.71 \times 10^{12}$ eV needs to be further explained. Since the Yukawa couplings of Dirac neutrinos are extremely small $y_\nu \lesssim 10^{-12}$, the direct production of right-handed neutrinos $\nu_{\rm R}$ and left-handed antineutrinos $\overline{\nu}_{\rm L}$ in the early Universe is highly suppressed [8, 9]. Therefore, we have $n_{\nu_{\rm r}} = n_{\overline{\nu}_{\rm l}} = 0$ at $T = T_{\rm L}$ and today as well.

In Ref. [9], a working example has been given to thermally produce right-handed neutrinos $\nu_{\rm R}$ and left-handed antineutrinos $\overline{\nu}_{\rm L}$. In this scenario, primordial magnetic fields $B_0 \approx 10^{24}$ G within a domain size $L_0 > 10^{-7}$ cm are assumed to be generated during the electroweak phase transition at $T = 100$ GeV. Although the evolution of such magnetic fields in the early Universe is not yet

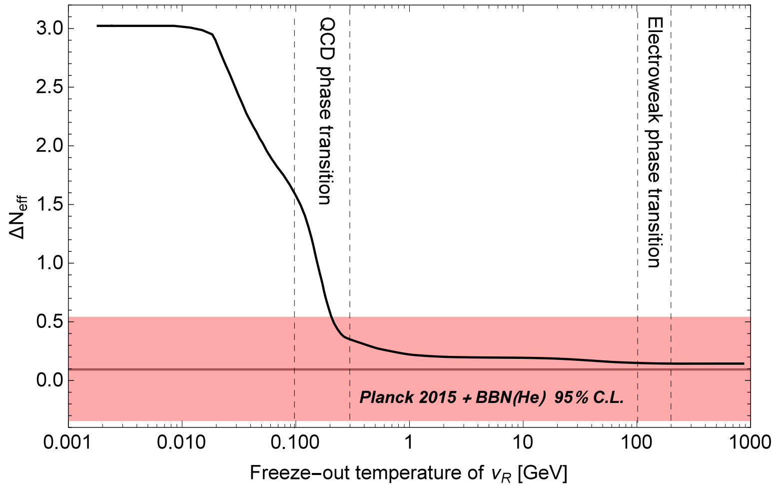

Figure 1: The extra effective number of neutrinos $\Delta N_{\rm eff}$ is shown with respect to the decoupling temperature $T_{\rm R}$ of right-handed neutrinos [9].

quite clear, some phenomenological models are available [10]. It can be shown that massive Dirac neutrinos with a small magnetic dipole moment $\mu_\nu = 3\times 10^{-20}~(m_\nu/0.1~{\rm eV})~\mu_{\rm B}$, where $\mu_{\rm B}$ is the Bohr magneton, can experience spin-flipping conversions $\nu_{\rm L} \to \nu_{\rm R}$ and $\overline{\nu}_{\rm R} \to \overline{\nu}_{\rm L}$ in magnetic fields. For $B_0 \approx 10^{24}$ G and $L_0 > 10^{-7}$ cm, these conversions are sufficiently rapid but become out of equilibrium in the epoch of QCD phase transition around $T \approx 200$ MeV. As these additional thermal relics contribute to the total energy density just like ordinary neutrinos, they are subject to the cosmological upper bound on the extra effective number of neutrinos, namely, $\Delta N_{\rm eff} < 0.53$ at the 95% confidence level. In Fig. 1, one can observe that the decoupling temperature $T_{\rm R}$ of $\nu_{\rm R}$ and $\overline{\nu}_{\rm L}$ above 200 MeV is compatible with the cosmological bound.

We should calculate the number densities of $\nu_{\rm r}$ and $\overline{\nu}_{\rm l}$ at present by assuming that the upper bound $\Delta N_{\rm eff} < 0.53$ is saturated. First, it is straightforward to find the number density at $T_{\rm L}$ [9]

$$\frac{n_{\nu_{\rm r}}(T_{\rm L})}{n_{\nu_{\rm l}}(T_{\rm L})} = \frac{n_{\nu_{\rm r}}(T_{\rm L})}{n_{\nu_{\rm r}}(T_{\rm R})} \cdot \frac{n_{\nu_{\rm l}}(T_{\rm R})}{n_{\nu_{\rm l}}(T_{\rm L})} = \frac{g_{*s}(T_{\rm L})}{g_{*s}(T_{\rm R})} \; , \tag{2.1}$$

where $n_{\nu_{\rm r}}(T_{\rm R}) = n_{\nu_{\rm l}}(T_{\rm R})$ and $n_{\nu_{\rm l}}(T_{\rm R})/n_{\nu_{\rm l}}(T_{\rm L}) = T^3_{\rm R}/T^3_{\rm L}$ hold for neutrinos in thermal equilibrium. For the decoupled $\nu_{\rm R}$ in the adiabatically expanding Universe, the entropy conservation gives rise to $n_{\nu_{\rm r}}(T_{\rm R})/n_{\nu_{\rm r}}(T_{\rm L}) = [g_{*s}(T_{\rm R})T^3_{\rm R}]/[g_{*s}(T_{\rm L})T^3_{\rm L}]$, where g_{*s} denotes the effective number of degrees of freedom contributing to the entropy density. Given $T_{\rm R} \approx 200$ MeV and $T_{\rm L} \approx 1$ MeV, we get $g_{*s}(T_{\rm R}) \approx 38.4$ and $g_{*s}(T_{\rm L}) \approx 10.75$, implying that $n_{\nu_{\rm r}}/n_{\nu_{\rm l}} \approx 28\%$, which remains to be constant until today as both $\nu_{\rm r}$ and $\nu_{\rm l}$ are decoupled below $T_{\rm L}$. Thus, the average number densities are $\overline{n}_{\nu_{\rm r}} = \overline{n}_{\overline{\nu}_{\rm l}} \approx 16~{\rm cm}^{-3}$ per neutrino flavor, which should be compared with $\overline{n}_{\nu_{\rm r}} = \overline{n}_{\overline{\nu}_{\rm l}} \approx 0$ in the case without thermal production of $\nu_{\rm R}$ and $\overline{\nu}_{\rm L}$.

3. Capture Rates

Now that the CνB is made of all four helical neutrino states, namely, $\nu_{\rm l}$ and $\overline{\nu}_{\rm r}$ of an average number density 56 cm^{-3}, and $\nu_{\rm r}$ and $\overline{\nu}_{\rm l}$ of 16 cm^{-3}, their capture rate on the tritium target should be changed. The capture rate for $\nu_e + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$ was first calculated in Ref. [11], and later corrected in Ref. [12]. Considering an unpolarized tritium target and a neutrino mass eigenstate ν_i of spin s_ν (i.e., $+1/2$ or $-1/2$), one can find that the product of the cross section $\sigma_i(s_\nu)$ and the neutrino velocity v_{ν_i} can be written as $\sigma_i(s_\nu)v_{\nu_i} = \mathscr{A}(s_\nu)|U_{ei}|^2\overline{\sigma}$, where $\overline{\sigma} \approx 3.8\times 10^{-45}~\mathrm{cm}^2$, $\mathscr{A}(s_\nu) \equiv 1 - 2s_\nu v_{\nu_i}$ and U is the unitary lepton flavor mixing matrix. For non-relativistic CνB neutrinos with $v_{\nu_i} \to 0$, we have $\mathscr{A}(+1/2) = \mathscr{A}(-1/2) \approx 1$, implying that both left- and right-helical neutrino states can equally be captured [12]. The total capture rate is then given by

$$\Gamma_\mathrm{D} = N_\mathrm{T}\sum_{i=1}^{3}\left[\sigma_i(-1/2)v_{\nu_i}\overline{n}_{\nu_\mathrm{l}} + \sigma_i(+1/2)v_{\nu_i}\overline{n}_{\nu_\mathrm{r}}\right] \approx N_\mathrm{T}\overline{\sigma}\left(\overline{n}_{\nu_\mathrm{l}} + \overline{n}_{\nu_\mathrm{r}}\right) , \tag{3.1}$$

where N_T is the number of tritium nuclei and the unitarity condition $\sum_i |U_{ei}| = 1$ has been used. It is easy to observe that $\Gamma_\mathrm{D} \approx 4~\mathrm{yr}^{-1}$ in the standard case [12] will be increased to $\Gamma_\mathrm{D} \approx 5.1~\mathrm{yr}^{-1}$ in the presence of right-handed neutrinos in the early Universe [9]. As pointed out in Ref. [12], if massive neutrinos are Majorana particles, both ν_l and $\overline{\nu}_\mathrm{r}$ (now should be identified as ν_r) will participate in the capture process, leading to a twice larger rate $\Gamma_\mathrm{M} \approx 8~\mathrm{yr}^{-1}$.

A final remark is about further considerations on CνB. In Ref. [13], a nonthermal production of ν_R and $\overline{\nu}_\mathrm{L}$ from inflaton decays has been proposed for Dirac neutrinos. In this scenario, saturating the bound $\Delta N_\mathrm{eff} < 0.53$, the average number density $\overline{n}_{\nu_\mathrm{r}} \approx 29~\mathrm{cm}^{-3}$ and thus a capture rate of $\Gamma_\mathrm{D} \approx 6.1~\mathrm{yr}^{-1}$ can be reached. Possible discrimination between thermal and nonthermal spectra of right-handed neutrinos may be achieved by observing the annual modulation at PTOLEMY [14].

Acknowledgements

I would like to thank Guo-yuan Huang and Jue Zhang for enjoyable collaboration on cosmic relic neutrinos, and the organisers of NOW 2016 for kind invitation and warm hospitality.

References

[1] S. Weinberg, *Cosmology*, Oxford University Press, 2008, Oxford, United Kingdom.

[2] C. Patrignani et al. (Particle Data Group), Chin. Phys. C **40**, 100001 (2016).

[3] S. Weinberg, Phys. Rev. **128**, 1457 (1962).

[4] J. M. Irvine and R. Humphreys, J. Phys. G **9**, 847 (1983).

[5] S. Betts *et al.*, arXiv:1307.4738.

[6] A. Ringwald, hep-ph/0505024.

[7] P. Vogel, AIP Conf. Proc. **1666**, 140003 (2015).

[8] F. Antonelli, D. Fargion and R. Konoplich, Lett. Nuovo Cim. **32**, 289 (1981).

[9] J. Zhang and S. Zhou, Nucl. Phys. B **903**, 211 (2016) [arXiv:1509.02274].

[10] K. Enqvist, A. I. Rez and V. B. Semikoz, Nucl. Phys. B **436**, 49 (1995) [hep-ph/9408255].

[11] A. G. Cocco, G. Mangano and M. Messina, JCAP **0706**, 015 (2007) [hep-ph/0703075].

[12] A. J. Long, C. Lunardini and E. Sabancilar, JCAP **1408**, 038 (2014) [arXiv:1405.7654].

[13] M. C. Chen, M. Ratz and A. Trautner, Phys. Rev. D **92**, no. 12, 123006 (2015) [arXiv:1509.00481].

[14] G. Y. Huang and S. Zhou, arXiv:1610.01347.