Relic neutrinos: Antineutrinos of primordial nucleosynthesis

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For the first time the antineutrino spectrum formed as a result of neutron and tritium decays during the epoch of primordial nucleosynthesis is calculated. This spectrum is a nonthermal increase in addition to the standard cosmic neutrino background (CνB) whose thermal spectrum was formed before the beginning of primordial nucleosynthesis. For energy larger than 10^{-2} eV the calculated nonthermal antineutrino flux exceeds the CνB spectrum and there are no other comparable sources of antineutrino in this range. The observations of these antineutrinos will allow us to look directly at the very early Universe and nonequilibrium processes taken place before, during, and some time after primordial nucleosynthesis.

I. INTRODUCTION

The observations of the cosmic microwave background (CMB) allow us to see into our Universe when it was about 380 000 years old. Similarly primordial nucleosynthesis provides us with an indirect probe of the early Universe (about a few minutes old) based on the comparison of light element (^{4}He, D, ^{7}Li) observations with corresponding theoretical calculations, which in turn is based on the well-established knowledge of nuclear and particle physics (e.g., [1,2]). We cannot observe the Universe at that epoch directly using electromagnetic radiation due to the opacity of the Universe at early stages right up until primordial recombination. Nevertheless, the direct information about the first seconds of the Universe evolution principally can be obtained by the detection of relic neutrinos, well known as the cosmic neutrino background CνB (note that cosmic neutrino background consists of neutrino as well as antineutrino, so it is more correct to use the following abbreviation Cνν̃B). Like the cosmic microwave background radiation, the CνB was formed with a thermal equilibrium spectrum which for neutrinos ($ν$) and antineutrinos ($\tilde{ν}$) is given by the Fermi-Dirac distribution (with zero neutrino mass):

$$n_{ν,\tilde{ν}}(p)dp = \frac{1}{(2\pi\hbar)^3}\frac{4\pi p^2 dp}{\exp(pc/kT)+1} \qquad (1)$$

Note that we can neglect the neutrino mass at the decoupling period ($T \sim 2$ MeV) because there is the upper limit of $\sum m_ν < 0.23$ eV [3,4] and the ratio $m_ν c^2/kT$ is about 10^{-7} for this period. After neutrino decoupling the spectrum has kept the same form (due to the adiabatic expansion of the Universe) with a

temperature decreasing like $T_ν \propto (1+z)$, where z is the cosmological redshift. It is very important to note that this fact takes place for momentum distribution $n(p)$ whether or not neutrino possesses mass, while the form of energy distribution $n(\varepsilon)$ depends on neutrino mass (see next section). Therefore despite the fact that $m_ν \neq 0$, today ($z = 0$) the momentum distribution $n(p)$ has the form to be the same as Eq. (1) with the current temperature $T_{ν0}$ whose value is related to the current temperature of the relic photons $T_{γ0}$ (the CMB temperature). The theory of primordial nucleosynthesis give us the relation between the relic neutrino and photon temperatures, $T_ν = (4/11)^{1/3}T_γ$, arising from electron-positron annihilation. Given this relation and the current value of $T_{γ0} = 2.725 \pm 0.001$ K [5], we have the present temperature of relic neutrinos to be $T_{ν0} \approx 1.945$ K. However, at the same time the electron-positron annihilation leads to the heating of neutrinos and forms the nonthermal distortion of the neutrino spectrum [6–10], therefore strictly speaking $T_{ν0}$ is not defined.

In addition to the relic neutrinos it should be mentioned that there are other neutrino backgrounds at high energies ($\varepsilon \gtrsim 1$ MeV) which could be called "cosmological" as well: the diffuse supernova neutrino background [11], the active galactic nuclei (AGN) background and cosmogenic (GZK) neutrinos arising from interactions of ultraenergetic protons with the CMB photons (for more details see e.g., [12] and references therein).

In this work we discuss the complementary ability to look at the early Universe and nonequilibrium processes occurred before, during and after primordial nucleosynthesis using spectrum calculations and future possible observations of antineutrinos having arisen from neutron and triton (nucleus of tritium) decays ($n \rightarrow p + e^- + \tilde{ν}$, $t \rightarrow {}^3he + e^- + \tilde{ν}$).

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II. THE SPECTRUM OF ANTINEUTRINO OF PRIMORDIAL NUCLEOSYNTHESIS

During primordial nucleosynthesis as a result of weak and nuclear interactions there is some amount of neutron and tritium (see Fig. 1), whose decays give rise to non-thermal antineutrinos in addition to the thermal relic neutrinos and antineutrinos [Eq. (1)].

The number densities of antineutrinos arising under neutron and tritium decays with momentum between p and $p + dp$ during the time dt is given by

$$dn_\nu(p) = \lambda n_{n,t}(t)f(p)dpdt. \qquad (2)$$

Here λ is neutron or tritium decay rate. It relates with the mean lifetime as $\lambda = 1/\tau$ ($\tau_n = (880.2 \pm 1.0)$ s [14] and $\tau_t = (17.66 \pm 0.03)$ yr [15]), $n_{n,t}(t)$ is the number density of neutron/tritium at the moment t corresponding cosmological epoch with redshift z. It can be expressed as $n_{n,t}(z) = Y_{n,t}(z)n_b(z) = Y_{n,t}(z)n_b^0(1+z)^3$, where $Y_{n,t}(z)$ is the ratio of neutrons or tritium to all baryons n_b, and $n_b^0 = \eta n_\gamma^0 \simeq 2.48 \times 10^{-7}$ cm^{-3} (see, e.g., [16]) is the baryon
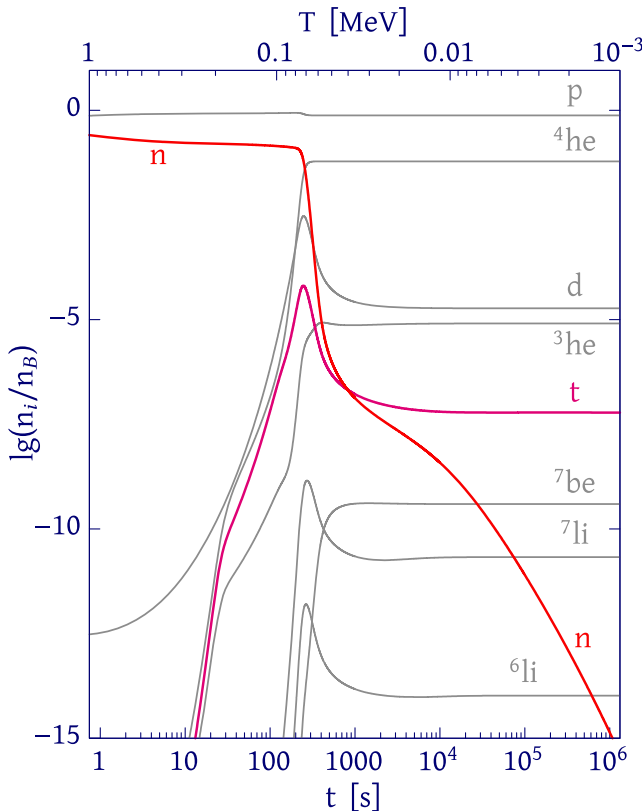

FIG. 1. The time-temperature evolution of the relative abundances $Y_x \equiv n_x/n_b$ of light nuclei produced during primordial nucleosynthesis. Red and crimson lines correspond to neutron and tritium relative abundances. The calculations are done by using our own numerical code of primordial nucleosynthesis [13] (see the text).

number density at the present epoch ($z = 0$). The value $f(p)dp$ is the neutrino fraction with momentum between p and $p + dp$ arising due to neutron/tritium decays

$$f(p)dp = \mathcal{C}\sqrt{(1 - \tilde{p})(1 - \tilde{p} + 2\tilde{m}_e)}(1 - \tilde{p} + \tilde{m}_e)\tilde{p}^2 d\tilde{p} \qquad (3)$$

here, neutrino momentum takes a value $0 \le p \le Q/c$, Q is the value of the energy release of the reaction, $\tilde{p} = pc/Q$ is dimensionless momentum, $0 \le \tilde{p} \le 1$, $\tilde{m}_e = m_e c^2/Q$— dimensionless electron mass, $\mathcal{C}$ is the dimensionless normalization constant determined by

$$\int_0^{Q/c} f(p)dp = 1.$$

Since the spectrum has kept its form under the adiabatic expansion of the Universe and neutrino that has momentum p_0 at the present epoch ($z = 0$) had momentum $p(z) = p_0 \cdot (1 + z)$ at cosmological epoch with redshift z, therefore we can express the modern momentum distribution in the following form:

$$f_0(p_0)dp_0 = f(p_0 \cdot (1 + z))(1 + z)dp_0, \qquad (4)$$

where $f(p_0 \cdot (1 + z))$ is taken from the right-hand side of Eq. (3).

Therefore, the spectrum of the nonthermal antineutrinos formed at the primordial nucleosynthesis era and observed now can be expressed as

$$\frac{dn_\nu(p_0)}{dp_0} = -\frac{1}{\tau}\int_0^{\tilde{z}(p_0)} \frac{n(z)}{(1+z)^3}f(p_0(1+z))(1+z)\frac{dt}{dz}dz, \qquad (5)$$

here the minus sign reflects the fact that redshift decreased as time passed; p_0 takes a value from the range $0 \le p_0 \le Q/c$, for given p_0 the value $p_0(1 + z)$ can not be large than Q/c what gives us the upper limit of integration $\tilde{z}(p_0) = Q/(p_0 c) - 1$, at the same time this value must not be larger than redshift of neutrino decoupling; the factor $1/(1 + z)^3$ in the integral arises from the dilution of neutrons and tritiums due to the Universe expansion. The function dt/dz in Eq. (5) can be derived from the time-temperature-redshift relation (e.g., [1]):

$$t = 1.78 \text{ sec} \cdot \left[\frac{T_{\gamma 0}(1 + z)}{10^{10}\text{K}}\right]^{-2} + \text{Const} \qquad (6)$$

which is valid for this cosmological period, when the early Universe was radiation dominated. To obtain dependences of the relative abundances $n(z)$ of light nuclei on redshift during the period under consideration, we have updated our own previous numerical code of primordial

nucleosynthesis [13] which is based on the historical Wagoner's code [17]. Results obtained by using our code (Fig. 1) are in satisfactory agreement with the results of modern analogous codes [18–21].

The calculated antineutrino spectra, together with the CνB neutrino/antineutrino, the Solar neutrino, and the geologically produced antineutrino spectra are shown in Fig. 2. It should be noted that the calculated antineutrino spectra for both neutrons and tritium have specific features. The neutron spectrum has a sharp step and the tritium spectrum shows a local maximum. These features repeat the existing peculiarities of the time evolution of the neutron and tritium abundances (Fig. 1).

In the case of massless neutrinos with the relativistic energy-momentum relation $\varepsilon = pc$ the neutrino energy distribution function and the neutrino momentum distribution function [Eq. (5)] are the same up to the constant factor $d\varepsilon/dp = c$, while in the case $m_\nu \neq 0$, with the energy-momentum relation $\varepsilon = \sqrt{p^2c^2 + m^2c^4}$, it has led to significant differences of the distributions in the kinetic energy range where $\varepsilon_{kin} \equiv \varepsilon - mc^2 < m_\nu c^2$ (see Fig. 2).

Since a flux of particles is experimentally observable quantity, this is what we show on Fig. 2. Flux of antineutrino can be found by integrating Eq. (5) multiplied by a neutrino velocity $v(\varepsilon) = d\varepsilon(p)/dp$ over hemisphere in the projection on normal to field on which flux is measured:

$$\frac{dF(\varepsilon)}{d\varepsilon} = \frac{1}{4\pi} \int \frac{dn_\nu(\varepsilon)}{d\varepsilon} v(\varepsilon) \cos \Theta d\Omega. \qquad (7)$$

As spatial distribution of antineutrino is isotropic integrating Eq. (7) is reduced to multiplying of Eq. (5) by a factor $v(\varepsilon)/4$. In addition, it is important to note that, in comparing the total fluxes of solar and cosmological neutrinos moving through the surface of an imaginary
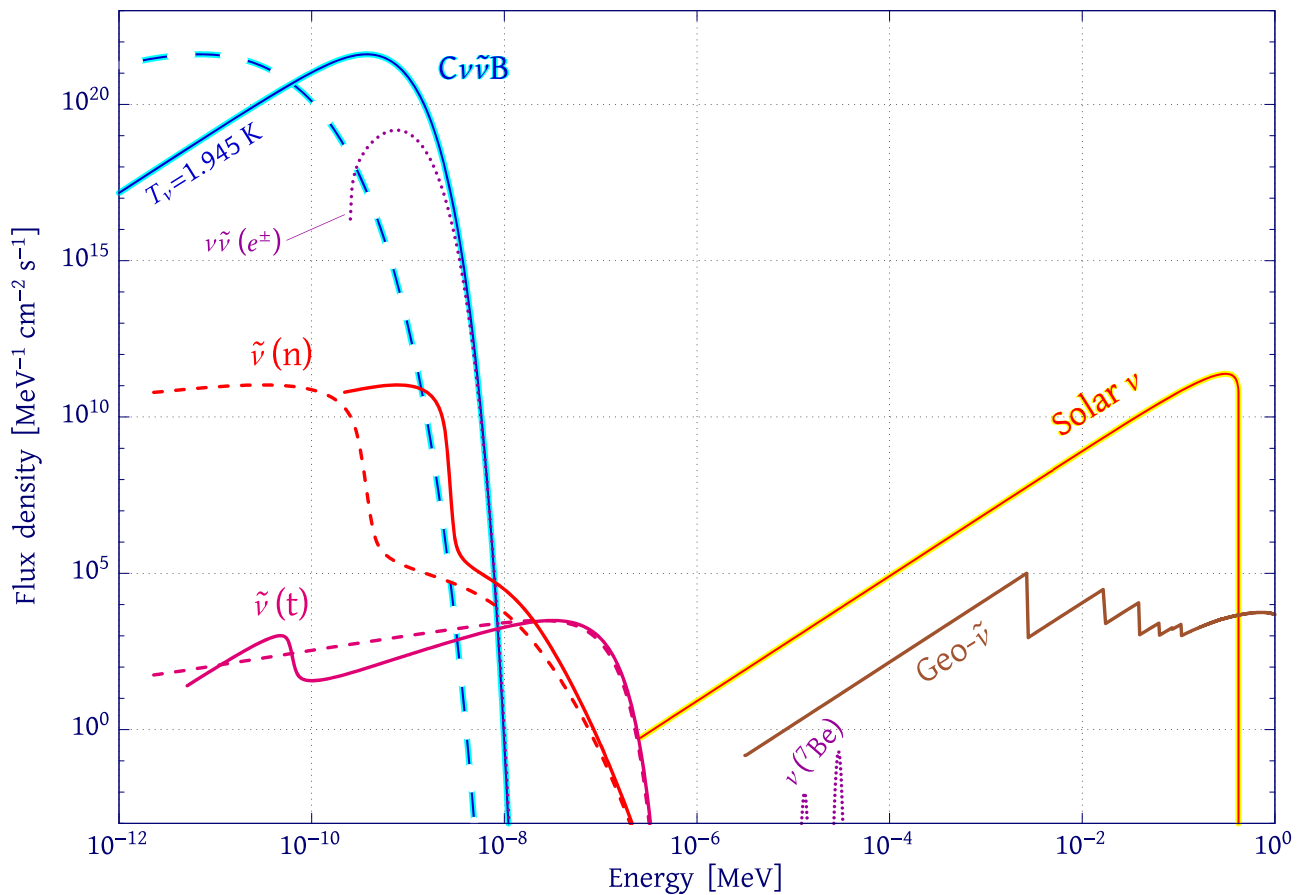

FIG. 2. Neutrino and antineutrino spectra. The relic neutrino and antineutrino equilibrium background C$\nu\tilde\nu$B ($\equiv$CνB) is determined by Eq. (1) (blue-cyan solid curve for $m_\nu = 0$). The solar neutrino spectrum (red-yellow curve) constructed by using data from [22]. The geologically produced antineutrino spectrum (brown curve) [23,24]. The nonthermal spectra. Doublet of narrow cosmological neutrino lines due to decays of ^{7}Be [25] and the nonequilibrium neutrino distortion ($\Delta f \equiv f - f_0$) of the CνB high-energy tail caused by $e^\pm$-annihilation [6,7] (dotted violet curves). The nonthermal antineutrino spectra formed by decays of neutrons $\tilde\nu(n)$ (red curve) and tritons $\tilde\nu(t)$ (crimson curve) which have been calculated in this work. In addition to the spectra mentioned above we present the spectra of CνB and $\tilde\nu(n)$, $\tilde\nu(t)$ calculated under conditions of nonzero neutrino mass (dashed curves; for instance, we take $m_\nu = 0.01$ eV, and the energy for this case denotes $\varepsilon_{kin} \equiv \varepsilon - m_\nu c^2$).

neutrino detector, solar neutrino would penetrate into the detector from only one hemisphere while cosmological neutrino and antineutrino would penetrate into the interior of the detector through both hemispheres.

III. THREE SORTS OF NONTHERMAL RELIC NEUTRINOS

Thus, there are three sorts of nonthermal relic neutrinos related to different physical phenomena of primordial nucleosynthesis:

  (i) The first of these phenomena is the nonequilibrium neutrino distortion of the CνB high-energy tail caused by $e^{\pm}$-annihilation occurred at the beginning of primordial nucleosynthesis at $T \lesssim 1$ MeV (for more details see [6–10]).
 (ii) The second one is narrow neutrino lines from ^{7}Be decay happened after primordial nucleosynthesis and before primordial hydrogen recombination [25]. Note that the authors briefly mentioned about the existence of nonthermal antineutrinos from n and t decays but they did not calculate their spectra.
(iii) Finally, the nonthermal antineutrinos from n and t decays whose spectra were calculated in this work for the first time.

For comparison all three nonthermal relic neutrino spectra are shown in Fig. 2. Unfortunately, the first two mentioned spectra have the very small contrast against the background of the CνB and solar neutrino spectra, while n and t decay antineutrino spectra considerably exceed the CνB and any known antineutrino background for energy larger than 10^{-2} eV.

IV. POSSIBILITY OF THE DIRECT DETECTION OF THE RELIC NEUTRINOS

The existence of CνB has been indirectly proved from the very good agreement between primordial nucleosynthesis predictions and astronomical observations of the light element abundances, ^{4}He, D, ^{7}Li (e.g., [26]).

The ideas of detecting CνB have been discussed since the 1960s. However the direct observations of the relic neutrinos is a great challenge to present experimental techniques due to the very low energy ($\lesssim 10^{-4}$ eV) of relic neutrinos at the present epoch. A principal possibility of the direct detection of the relic neutrino background was first discussed in papers [27,28]. Among several proposals for the direct detection of the relic neutrinos, the most promising ones are relic neutrino capture on radioactive β-decaying nuclei [29] and relic antineutrinos capture on radioactive nuclei decaying via electron capture [30,31]. The descriptions of other ways and current perspectives of the direct detection of the relic neutrinos/antineutrinos see, for instance, the following detailed works [32–37].

V. CONCLUSION

The nonthermal relic neutrinos provide a powerful tool to probe the early Universe. The CMB discovery became definitely an important milestone in cosmology. First, we have learned that the unique physical phenomenon, an echo of early hot stages of the Universe, exists. Second, the study of the CMB distortions gives us information about nonequilibrium processes which have been taking place from primordial recombination up to now, and provides accurate values of several key cosmological parameters [4]. Likewise, the observations of the CνB spectrum and its distortions will become a unique window on the much more early Universe (a few minutes and hours after the big bang).

[1] S. Weinberg, *Cosmology* (Oxford University Press, New York, 2008).

[2] D. S. Gorbunov and V. A. Rubakov, *Introduction to the Theory of the Early Universe: Hot Big Bang Theory* (World Scientific, Singapore, 2011).

[3] S. A. Thomas, F. B. Abdalla, and O. Lahav, Phys. Rev. Lett. **105**, 031301 (2010).

[4] P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett *et al.* (Planck Collaboration), Astron. Astrophys. **594**, A13 (2016).

[5] D. J. Fixsen and J. C. Mather, Astrophys. J. **581**, 817 (2002).

[6] A. D. Dolgov and M. Fukugita, Sov. J. Exp. Theor. Phys. Lett. **56**, 123 (1992).

[7] S. Dodelson and M. S. Turner, Phys. Rev. D **46**, 3372 (1992).

[8] S. Hannestad and J. Madsen, Phys. Rev. D **52**, 1764 (1995).

[9] A. D. Dolgov, Phys. Rep. **370**, 333 (2002).

[10] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, and P. D. Serpico, Nucl. Phys. **B729**, 221 (2005).

[11] J. F. Beacom, Annu. Rev. Nucl. Part. Sci. **60**, 439 (2010).

[12] U. F. Katz and C. Spiering, Prog. Part. Nucl. Phys. **67**, 651 (2012).

[13] A. V. Orlov, A. V. Ivanchik, and D. A. Varshalovich, Astronomical and Astrophysical Transactions **19**, 375 (2000).

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

[15] Y. A. Akulov and B. A. Mamyrin, Phys. Lett. B **610**, 45 (2005).

[16] K. A. Olive (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).

[17] R. V. Wagoner, W. A. Fowler, and F. Hoyle, Astrophys. J. **148**, 3 (1967).

[18] M. S. Smith, L. H. Kawano, and R. A. Malaney, Astrophys. J. Suppl. Ser. **85**, 219 (1993).

[19] A. Arbey, Comput. Phys. Commun. **183**, 1822 (2012).

[20] O. Pisanti, A. Cirillo, S. Esposito, F. Iocco, G. Mangano, G. Miele, and P. D. Serpico, Comput. Phys. Commun. **178**, 956 (2008).

[21] C. Pitrou, A. Coc, J.-P. Uzan, and E. Vangioni, Phys. Rep. **04**, 005 (2018).

[22] J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. **60**, 297 (1988).

[23] S. Enomoto, Earth Moon and Planets **99**, 131 (2006).

[24] S. Enomoto, E. Ohtani, K. Inoue, and A. Suzuki, Earth Planet. Sci. Lett. **258**, 147 (2007).

[25] R. Khatri and R. A. Sunyaev, Astron. Lett. **37**, 367 (2011).

[26] R. H. Cyburt, B. D. Fields, K. A. Olive, and T.-H. Yeh, Rev. Mod. Phys. **88**, 015004 (2016).

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

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

[29] A. G. Cocco, G. Mangano, and M. Messina, J. Cosmol. Astropart. Phys. 06 (2007) 015.

[30] A. G. Cocco, G. Mangano, and M. Messina, Phys. Rev. D **79**, 053009 (2009).

[31] M. Lusignoli and M. Vignati, Phys. Lett. B **697**, 11 (2011).

[32] A. Ringwald, Nucl. Phys. **A827**, 501 (2009).

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

[34] Y.-F. Li, Int. J. Mod. Phys. A **30**, 1530031 (2015).

[35] A. Faessler, R. Hodak, S. Kovalenko, and F. Simkovic, J. Phys. Conf. Ser. **580**, 012040 (2015).

[36] J. Birrell and J. Rafelski, Eur. Phys. J. C **75**, 91 (2015).

[37] Z.-Z. Xing and S. Zhou, *Neutrinos in Particle Physics, Astronomy and Cosmology* (Springer-Verlag, Berlin, Heidelberg, 2011).