Prospectives on Direct Detection of the Cosmic Neutrino Background

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Abstract. The cosmic neutrino background (C$\nu$B) is a fundamental prediction of the hot Big Bang cosmology. Although cosmological observations provide indirect evidence for the existence of the C$\nu$B, we still lack a direct detection in a laboratory. In this work we present the current possible detection methods of the C$\nu$B. The method of C$\nu$B captures on the radioactive decaying nuclei is particularly emphasized in light of the PTOLEMY project. We stress that such direct measurements might not be hopeless in the long term.

1. Hot Big Bang Cosmology
Neutrinos and antineutrinos can form the cosmic neutrino background (C$\nu$B) when they were decoupled from radiation and matter at a temperature of about one MeV and an age of one second after the Big Bang [1]. From the hot Big Bang theory, the temperature and average number density for one species of C$\nu$B is $T_{\nu} \approx 1.945$ and $n_{\nu} \approx 112$ cm$^{-3}$ respectively. As a consequence, one predicts the average three-momentum today for each C$\nu$B species is very small, i.e., $\langle p_{\nu} \rangle \approx 5 \times 10^{-4}$ eV [2].

Although cosmological observations provide indirect evidence for the existence of the C$\nu$B, we still lack a direct detection in a laboratory. From cosmological observations of the Big-Bang Nucleosynthesis and Cosmic Microwave Background, we can obtain the number of neutrinos as $N_{\nu} = 3.15 \pm 0.23$ [3]. Therefore, One would test the theory at $t \approx 1$ sec and $T \approx 1$ MeV, with the direct detection of the C$\nu$B in a laboratory.

2. Possible Detection Methods
There are many different methods [2] for the laboratory detection of the C$\nu$B, which include:

- C$\nu$B captures on the radioactive decaying nuclei [4, 5, 6, 7], where the current target mass for $^3$H is 65 $\mu$g from KATRIN [8], and the PTOLEMY project [9] is planed to use 100 grams for a realistic observation of the C$\nu$B;
- C$\nu$B-induced mechanical effects on the Cavendish-type torsion balance [10, 11], where a sensitivity for the acceleration down to $10^{-28}$ cm/s$^2$ is needed for the C$\nu$B detection, but the current level is $10^{-13}$ cm/s$^2$;
- Z-resonance annihilation of C$\nu$B with the ultra high energy neutrinos (UHE$\nu$s) [12], where the resonant energy of UHE$\nu$s is in the order of $10^{21}$ to $10^{22}$ eV, comparing to the current highest neutrino energy of $10^{15}$ eV;
| Methods                          | Parameters | Requirements | Current levels |
|---------------------------------|------------|--------------|----------------|
| Captures on the $\beta$-decaying nuclei | Target mass          | 100 g        | 65 $\mu$g      |
| Cavendish-type torsion balance | Acceleration    | $10^{-28}$ cm/s$^2$ | $10^{-13}$ cm/s$^2$ |
| $Z$-resonance annihilation of UHE$\nu$s | Neutrino energy | $10^{21}$ eV  | $10^{15}$ eV   |
| Pauli blocking effects      | NA          | NA           | NA             |

Table 1. A summary of current possible detection methods of the $C\nu$B, where the requirements and current levels are also presented.

- Pauli blocking effects of the $C\nu$B in the atomic de-excitation process [13], where the detection prospective has not been explored.

3. $C\nu$B Captures: Weinberg’s trap

For the nuclear $\beta$-decay process with the mass number $A$ and atomic number $Z$ of the parent nucleus,

$$N(A, Z) \to N'(A, Z + 1) + e^- + \bar{\nu}_e,$$

the spectral behavior in the vicinity of the endpoint represents a kinetic measurement of the absolute neutrino masses. On the other hand, the threshold-less neutrino capture process,

$$\nu_e + N(A, Z) \to N'(A, Z + 1) + e^-, $$

is located well beyond the end point of the $\beta$-decay, where the signal is characterized by the monoenergetic kinetic energy of the electron for each mass eigenstate. This capture process is suitable to detect the $C\nu$B, and a measurement of the distance between the decay and capture processes will directly probe the $C\nu$B. The capture rate of this process reads

$$R = [\sigma_\nu \times n_\nu] \times n_T \times N_T, $$

where the cross section times the velocity $\sigma_\nu \times v_\nu$ depends on the nuclear factors and the half life, $n_\nu$ is the $C\nu$B number density and may be enhanced because of the gravitational cluster effects, $N_T$ is the averaged effective target number during the running time. Besides the signal rate, another important factor is the intrinsic background from the corresponding $\beta$-decay, in which good energy resolution is required to suppress the background in the signal region.

Besides the total capture rates, the $C\nu$B detection exhibits interesting properties of flavor effects due to the neutrino mixing [14, 15, 16, 17, 18, 19, 20, 21]. For illustration, we shall discuss the effects of the neutrino mass ordering and absolute neutrino masses.

Fig. 1 shows the capture rate of the $C\nu$B as a function of the kinetic energy $T_e$ of electrons in the standard three-neutrino scheme with normal hierarchical (left panel), inverted hierarchical (middle panel) and quasi-degenerate (right panel) neutrino mass spectra respectively. The gravitational clustering has been neglected for simplicity. $\Delta$ (i.e., $\Delta = 2\sqrt{2\ln 2} \sigma$) denotes the finite energy resolution. As the lightest neutrino mass increases from 0 to 0.1 eV, the neutrino capture signal moves towards the larger $T_e$ region. The distance between the signal peak and the $\beta$-decay background becomes larger for a larger lightest neutrino mass, and therefore the required energy resolution is less stringent. Comparing between the left panel and middle panel, one can observe that it is easier to detect the $C\nu$B in the $\Delta m^2_{31} < 0$ case, where the capture signal is separated more apparently from the $\beta$-decay background. The reason is that the dominant mass eigenstates $\nu_1$ and $\nu_2$ in $\nu_e$ have greater eigenvalues than in the $\Delta m^2_{31} > 0$ case.
masses. We stress that such direct measurements of the CνB would open a new window to the early Universe. In this work, we have discussed the future prospectives for the direct detection of the CνB, with the emphasis on the method of captures on β-decaying nuclei in light of the PTOLEMY project. We calculated the neutrino capture rate against the corresponding β-decay background, and discussed the possible flavor effects including the neutrino mass ordering and absolute neutrino masses. We stress that such direct measurements of the CνB in the laboratory experiments might not be hopeless in the long term.

4. Conclusion

A direct measurement of the CνB would open a new window to the early Universe. In this work, we have discussed the future prospectives for the direct detection of the CνB, with the emphasis on the method of captures on β-decaying nuclei in light of the PTOLEMY project. We calculated the neutrino capture rate against the corresponding β-decay background, and discussed the possible flavor effects including the neutrino mass ordering and absolute neutrino masses. We stress that such direct measurements of the CνB in the laboratory experiments might not be hopeless in the long term.

Figure 1. The relic neutrino capture rate as a function of the kinetic energy of electrons in the standard scheme with normal hierarchical(left panel), inverted hierarchical(middle panel) and quasi-degenerate(right panel) neutrino mass spectra respectively. The gravitational clustering has been neglected for simplicity. We adopt 100 grams of 3H, and best-fit values of the relevant three-neutrino oscillation parameters from Ref. [1].

An exciting development towards a direct detection of CνB is the PTOLEMY project [9], which is designed to employ 100 grams of 3H as the capture target using a combination of a large-area surface-deposition tritium target, the MAC-E filter, the RF tracking, the time-of-flight systems, and the cryogenic calorimetry. Finally, the event rate of PTOLEMY are calculated to reach the observable level of eight events per year for massive Majorana neutrinos [21].

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