A new Direct Detection Strategy for the Cosmic Neutrino Background

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The direct detection of cosmic neutrino background (CNB) has been a longstanding challenge in particle physics, due to its low number density and tiny neutrino masses. In this work, we consider the spectrum of the CNB boosted by cosmic rays via the neutrino self-interaction, and calculate the event rate of the boosted CNB-plasmon scattering in term of the dielectric response, which accounts for in-medium screening effect of a condensed matter target. This can be taken as the new direct detection strategy for the CNB in complementary to the traditional one, which captures the CNB on a β-unstable nucleus. Our result shows that one can either see the event of the CNB for the exposure of per kg·year, or puts a strong constraint on the neutrino self-interaction. We further explore the background induced by the sub-MeV dark matter and the boosted super-light dark matter.

I. INTRODUCTION

The standard cosmological model predicts the existence of the Cosmic Neutrino Background (CNB), which, once discovered, will be a milestone in cosmology and neutrino physics. In the ΛCDM model, the present day temperature of the CNB is about 1.95 K and its average number density is about 56 cm⁻³ for each helicity degree of freedom. As a result, the direct detection of the CNB is extremely difficult when further taking into account its weak interaction with the Standard Model (SM) particles. A traditional strategy for the direct detection of CNB is to capture the CNB on a β-unstable nucleus via the inverse beta decay [1–9], \( n + \nu_e \rightarrow e + p \), which is a threshold-less reaction. The relevant searches have been carried out in KATRIN [10, 11] and PTOLEMY [4] experiments. In those experiments, one needs to pick out the signal of the CNB from the continuous β decay background. However, the two electron energy spectrums are split by the active neutrino mass, i.e. \( \Delta E_e \sim 2m_\nu \). The current best limit on the absolute mass scale of neutrinos comes from the KATRIN experiment, which gives \( m_\beta < 0.8 \text{ eV} \) at the 90% C.L. [10, 11]. Besides, the cosmological structure formation provides strong constraint on the sum of neutrino masses, and the Planck collaboration gives \( \sum m_\nu < 0.12 \text{ eV} \) at the 95% C.L. [12]. Given the tiny neutrino masses, it is technologically challenging to distinguish the signal induced by the CNB from that given by the continuous β-decay, which suggests that this strategy only works in non-standard cosmology with sterile neutrinos or large neutrino masses [3].

It is well-known that the neutrino physics is a new physics beyond the SM, and there might be new neutrino interactions in addition to the electroweak interaction mediated by the Z and W bosons. Furthermore, some typical neutrino self-interactions have been proposed to relieve the Hubble tension problem [13–15], or to avoid the constraint of the X-ray observations on the sterile neutrino dark matter (DM) [16, 17]. In this letter, we first point out that the CNB may be boosted by cosmic rays given a new neutrino interaction. Theoretically, the boosted CNB, that contains large kinetic energy, is possibly to be detected via coherent elastic neutrino-nucleus (or neutrino-electron) scattering in various DM direct detection experiments. However, the Sun is an active neutrino sources in the solar system and countless energetic solar neutrinos pass through the Earth at every second, which will cover up any signal induced by the boosted CNB. Looking into the flux of cosmic neutrinos in the Universe, one can find that the spectrum is not continuous and there is a gap between solar neutrinos and the CNB [18] fluxes, which can be complemented by the flux of the boosted CNB. As a result, the signal induced by the \( O(\text{eV}) \) scale boosted CNB is free from other cosmic neutrino background.

It is indeed very difficult to detect neutrinos of this energy range in any neutrino experiment or in a traditional DM direct detection equipment, which is originally designed to look for heavy DM, and typical signals of which appear as charge, light or heat, induced by elastic or inelastic scattering of DM on the target. Recently, a lot of attentions have been paid to the direct detection of sub-GeV or sub-MeV DM whose kinetic energy is not the largest scale. It catalyzed the development of new direct detection techniques using condensed matter materials, which benefit from both the low energy threshold and the high target density compared to the atomic or molecular detectors. Considering that neutrinos is actually a hot DM, we propose the new strategy for the direct detection of the boosted CNB using condensed matter materials via the neutrino-electron scattering. The scattering rate is given in terms of the dielectric response of
The differential flux of the boosted CNB on the Earth can be written as
\[
\frac{d\Phi_\nu(x)}{dT_\nu} = \int d^3z dT_i \frac{d\Phi_i(z)}{dT_i} \frac{d\sigma_\nu}{dT_\nu} \bigg|_{\theta_E = \theta_E(z - x)/|z - x|^2}
\]
where \(x\) is the position of the Earth and \(z\) is the position where the scattering process takes place, \(n_\nu\) is the local number density of the CNB, \(d\Phi_i/dT_i\) is the differential flux of the cosmic ray, \(\sigma_\nu\) is the scattering cross section of the CNB off the cosmic ray with reduced solid angle integration, \(\theta_E\) is the scattering angle that keeps the boosted CNB towards the Earth.

The minimal incoming energy required to obtain recoil energy \(T_\nu\) for neutrino is \(T_\nu^{\text{min}} = (T_\nu/2 - m_i)(1 + \sqrt{1 + (2T_\nu(m_i + m_\nu)^2)}/(m_\nu(2m_i - T_\nu)^2))\), where the sign \((+)(-)\) implies \(T_\nu > 2m_i(T_\nu < 2m_i)\). If we further assume homogeneous CNB and cosmic ray distributions, the differential flux can be simplified to the conventional one [19],
\[
\frac{d\Phi_\nu}{dT_\nu} = \int \int \int \frac{d\Omega d\ell dT_i}{4\pi} n_\nu \cdot d\sigma_\nu / dT_\nu \frac{d\Phi_i}{dT_i}
\]
where the full line-of-sight integration is performed out to 10 kpc.

We have neglected the neutrino flux attenuation due to propagation by assuming that the mean free path \((d_\nu = 1/n_\nu \sigma_\nu)\) is much larger than \(\ell\).

In the SM, interactions between neutrinos and charged leptons (or neutrinos) are suppressed by heavy gauge bosons. To get a detectable spectrum of the boosted CNB, we assume the existence of new neutrino interactions, which have been proposed to address various cosmological problems. For a local U(1) gauge symmetry with the universal coupling \(g_\nu\) for charged lepton and neutrino interactions, the elastic scattering cross section for the incident CR(electron) [20–23] or solar neutrino [18] colliding with the CNB at rest can be written as,
\[
\frac{d\sigma_{\nu\nu}}{dT_\nu} = \frac{g_\nu^4}{8\pi} \left\{ m_\nu^2(m_\nu - T_\nu) + m_\nu m_\nu(4T_i - 2T_\nu) \right. \\
\left. + m_\nu T_i^2 + m_\nu T_i(T_i - T_\nu)^2 \right\} \\
\times (2m_\nu T_i + T_i^2)^{-1} (2m_\nu T_\nu + m_\nu^2)^{-2}
\]

where we have assumed a universal neutrino mass \(m_\nu\), \(T_i = E_i - m_i\) being the kinetic energy of the incoming particle and \(T_\nu\) is the recoil energy of the CNB. Alternatively, one can derive the spectrum of CNB for a reference cross section \(\bar{\sigma}\), defined as \(\bar{\sigma} \equiv g_\nu^2 m_\nu^2/(\pi(\alpha^2 m_\nu^2 + m_\nu^2)^2)\).

For boosted CNB via neutrino self-interaction, sun-like stars provide main source of cosmic neutrino. One needs to sum up the entire stellar contributions in the Milk Way [24],
\[
\frac{dN_{\nu\text{total}}}{dT_\nu} = \int d^3V n_{\text{star}} \frac{d\Phi_\nu}{dT_\nu}
\]
FIG. 2. The 95% C.L. exclusion limit for cross section ($\sigma$) in boosted CNB and electron scattering excited phonon signal with 1 kg-yr exposure. The colored lines indicate 8 solid state target materials: Al$_2$O$_3$, GaN, GaAs, Ge, Si, SiC, SiO$_2$, ZnS, where solid(dashed) type line indicates the constraint induced by the CR electron (solar neutrino). The ELF of each material is based on the Ref. [25].

where $n_{\text{star}}$ is the distribution function of stellar in the galactic disk.

The Fig. 1 shows neutrino flux as the function of neutrino energy. The blue and orange lines represent the boosted CNB by electron and neutrino cosmic rays respectively, where the solid and dashed lines represent the neutrino flux for a constant $\bar{\sigma} = 5 \times 10^{-43}\text{cm}^2$ (solid lines) and a constant $g_{Z^*} = 2 \times 10^{-5}$ (dashed lines), respectively. Here we set the rest mass of CNB is $m_{\nu} = 10^{-2}$ eV and assume $m_{Z'} \ll \alpha m_e$. The light green and brown solid lines denote the present-day CNB and thermal neutrino from the Sun. The light blue and purple dashed lines represent neutrino fluxes from $\beta$ decays at the Big Bang Nucleosynthesis (BBN) epoch. The red dashed and dotted lines indicate neutrinos from primordial black holes (PBHs) evaporation with the mass $10^{15}$ g and $10^{18}$ g, respectively, in which we have assumed the following fraction of the PBHs: $f_{\text{PBH}} = 1$. One can conclude that the boosted CNB may cover the gap of neutrino flux around $\mathcal{O}(0.1)$ eV. Thus any signal induced by neutrinos in this energy range will be a unique signature of the CNB.

III. EVENT RATE IN CONDENSED MATTER SYSTEM

Recently, the condensed matter system as a new target for the direct detection of sub-GeV DM has been discussed explicitly. The event rate induced by the DM-plasmon scattering are calculated using electronic wave functions with (time-dependent) density functional theory [25–34]. It is rather straightforward that when the deposited energy by the DM is larger than the electron band gap, it can produce free electron excitations. Alternatively, when the kinetic energy from incident particle is below the electron band gap of the target, the deposited energy can only produce collective phenomena in the target, i.e. plasmon, which can provide a much lower threshold for the detection. Previous studies focus on the scattering between the non-relativistic DM and electron or nucleon. In this work, we provide the formula for the relativistic particle scattering off the target electron, and we will mainly consider the neutrino-plasmon scattering signal induced by the low energy boosted CNB. Our result may be applied to the to the direct detection of the boosted DM.

To calculate the event rate of the boosted CNB, we assume that the scattering is mediated by a $Z'$ with universal gauge coupling $g_{Z'}$ to active neutrino and electron. Following the procedures in Refs. [35, 36], the interaction rate for fermion can be written as,

$$\Gamma = \frac{1}{4E} \text{tr} [(\vec{P} + m_\nu) \Sigma^\nu (P)]$$

(6)

where $P = (E, p)$ being the momentum of fermion. $\Sigma^\nu (P)$ is the neutrino’s in-medium cut self-energy given by the following Feynman diagram,

![Feynman Diagram](image)

in which the ellipse represents the electron induced effect in the medium. A straightforward calculation gives

$$\Sigma^\nu (P) = g_{Z'}^2 \int \frac{d^4Q}{(2\pi)^4} \Sigma^\nu_0 (P - Q) \gamma^\nu D^\nu_{\mu\nu}(Q)$$

(7)

where $S^\nu_0 (P - Q)$ is the propagator of neutrino in vacuum, and $D^\nu_{\mu\nu}$ is the cut propagator of $Z'$ in terms of free propagator plus the effect of the in-medium self-energy, that is $D^\nu_{\mu\nu} = D^\nu_{\mu\nu}(Q) - 2(Q^2 - M_{Z'}^2)^{-2} \text{sgn}(Q_0)[1 + f(Q_0)] \text{Im} (\Pi^\nu_{\mu\nu})$. In our calculation, we neglect the $f(Q_0)$ term because the temperature of the medium is negligible. $\Pi^\nu_{\mu\nu}$ can be further decomposed as transverse and longitudinal components, $\Pi^T_{\mu\nu}$ and $\Pi^L_{\mu\nu}$, which are related to the magnetic permeability and the electric permeability [36]. Using the formula $Q^\mu \Pi^\nu_{\mu\nu}(Q) = 0$, implied by the current conservation, one can easily derive the expression of the interaction rate.

Convoluting the boosted CNB flux in Eq. (1) with the transition rate in Eq. (6), the differential event rates per energy and per unit of exposure can be written as

$$\frac{dR}{d\omega} = \frac{g_{Z'}^4}{(2\pi)^2 \rho_T} \int d\Omega_{\nu'} \frac{d\Phi_{\nu'}}{d\Omega_{\nu'}} \int \frac{dq}{E_\nu E_{\nu'}} \times \frac{q^4}{(q^2 + m_{Z'}^2)^2} \delta(E_\nu - E_{\nu'} - \omega) \times \left(\frac{q^2}{2} + 2E_{\nu'}^2 + 2m_\nu^2\right) \text{Im} \left[\frac{-1}{\varepsilon_L(q, \omega)}\right]$$

(8)

where $\rho_T$ is the target mass density, $E_\nu$ is the incident energy of the boosted CNB, $E_{\nu'}$ is the energy of the outgoing neutrino, $\omega$ is the energy deposit in target, $\varepsilon_L(q, \omega)$
be induced by the hypothetical sub-MeV DM scattering in a condensed matter system. Actually, the same signal can be induced by the hypothetical sub-MeV DM scattering rate in a magnetic material will be presented for numerical analysis, we restrict to the following neutrino(DM)-plasmon scattering rate in a magnetic material will be presented in a future work.

For numerical analysis, we restrict to the following neutrino energy range $\mathcal{O}(0.01-0.1)$ eV which merely covers the energy range of a target that can produce collective phenomena. The advantage of searching for the signal of the CNB in this energy range is that it is free from other neutrino backgrounds from celestial bodies, as can be seen from the Fig. 1. Alternatively, this choice only shows a conservative limit on the boosted CNB. The Fig. 2 shows the $(m_\nu - \bar{\sigma})$ exclusion limit from the boosted CNB-plasmon scattering signal with 1 kg-year exposure. The colored lines indicate the following eight solid state target materials: Al$_2$O$_3$, GaN, GaAs, Ge, Si, SiC, SiO$_2$, ZnS, where solid(dashed) type line indicates the constraint induced by the CR electron (solar neutrino). We use the DarkELF package to calculate the plasmon excitations in the boosted CNB - electron scattering [25]. The DarkELF package uses the ELF [29, 30] based on the first principles.

is the longitudinal dielectric function. The last part of the Eq. 8 is also known as the energy loss function (ELF), which is the target dependent object and can be calculated numerically in density functional theory. It should be mentioned that we have restricted ourselves to only consider non-magnetic materials when deriving the Eq. (8). A systematic study of neutrino(DM)-plasmon scattering rate in a magnetic material will be presented in a future work.

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V. CONCLUSION

Direct detections of CNB has been a long standing challenge in the high energy physics. In this letter, we propose a new direct detection strategy of CNB by considering the boosted CNB spectrum induced by new neutrino interactions, which may cover the gap, $(0.01 \text{ eV}, 1\text{ eV})$ in the cosmic neutrino flux spectrum. The boosted CNB may scatter off the electron in condensed matter material and induces detectable collective phenomena. The non-observation of any signal within a given exposure will put constraint on the exotic neutrino interaction. The same strategy is applicable to the direct detection of super-light DM boosted by cosmic rays. It should be mentioned that the model presented here is only a prototype, a further systematic study of neutrino interactions and their direct detection signals is needed.
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