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Looking for cosmic neutrino background

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Since the discovery of neutrino oscillation in atmospheric neutrinos by the Super-Kamiokande experiment in 1998, study of neutrinos has been one of exciting fields in high-energy physics. All the mixing angles were measured. Quests for (1) measurements of the remaining parameters, the lightest neutrino mass, the CP violating phase(s), and the sign of mass splitting between the mass eigenstates m_3 and m_1, and (2) better measurements to determine whether the mixing angle θ_{23} is less than $\pi/4$, are in progress in a well-controlled manner. Determining the nature of neutrinos, whether they are Dirac or Majorana particles is also in progress with continuous improvement. On the other hand, although the ideas of detecting cosmic neutrino background have been discussed since 1960s, there has not been a serious concerted effort to achieve this goal. One of the reasons is that it is extremely difficult to detect such low energy neutrinos from the Big Bang. While there has been tremendous accumulation of information on Cosmic Microwave Background since its discovery in 1965, there is no direct evidence for Cosmic Neutrino Background. The importance of detecting Cosmic Neutrino Background is that, although detailed studies of Big Bang Nucleosynthesis and Cosmic Microwave Background give information of the early Universe at ∼a few minutes old and ∼300 k years old, respectively, observation of Cosmic Neutrino Background allows us to study the early Universe at ∼1 s old. This article reviews progress made in the past 50 years on detection methods of Cosmic Neutrino Background.

Keywords: big-bang cosmology, cosmic neutrino background, cosmic-rays, neutrino elastic-scattering, neutrino capture by beta-decaying nuclei

1. INTRODUCTION

According to the Big Bang theory, neutrinos decoupled from other particles earlier than Cosmic Microwave Background (CMB). Detecting these neutrinos will give direct information of the earliest possible epoch of the Universe we can observe after the Big Bang. This review starts first with a brief summary of Cosmic Neutrino Background (CνB) according to the Big Bang theory with the Standard Model of particle physics except that, as observed, neutrinos are massive rather than massless fundamental particles. There have been ideas on how to detect CνB since 1960s. These proposed detection methods can be classified into two types: direct detection and indirect detection method. The direct detection methods can further be divided into two classes: measurements of energy/momentum transfer from CνB neutrinos to target materials in terms of acceleration of the targets through torsion unbalance or possibly through calorimetry, and measurements of energy of outgoing electrons produced by neutrino capture by β-decaying nuclei. The indirect method basically measures the spectrum of ultra-high energy cosmic rays and identify threshold effects/dips due to interactions between ultra-high energy neutrinos or other cosmic rays from some sources and neutrinos from CνB.

2. THE STANDARD BIG BANG COSMOLOGY AND ITS PREDICTIONS

According to the standard Big Bang cosmology [1–3] the number density of a relativistic particle of type i of momentum $\vec{p}$, the energy E_i and the internal degree of freedom g_i (2 for γ, 1 for ν or $\bar{\nu}$) at temperature T is given by

$$n_i = \frac{g_i}{(2\pi)^3}\int f_i(\vec{p})\mathrm{d}^3p \text{ and } \rho_i = \frac{g_i}{(2\pi)^3}\int E_i(\vec{p})f_i(\vec{p})\mathrm{d}^3p, \quad (1)$$

where $f_i(\vec{p}) = 1/[exp((E_i - \mu_i)/T) \pm 1)]$ with chemical potential μ_i (+ for fermion and − for boson). From Equation (1) for a relativistic boson of type i its number density is $\zeta(3)g_iT^3/\pi^2$ and for a relativistic fermion $(3/4)\zeta(3)g_iT^3/\pi^2$ where ζ is the Riemann zeta function. Also the energy density is $(\pi^2/30)g_iT^4$ for a boson and $(7/8)(\pi^2/30)g_iT^4$ for a fermion [3].

The time dependence of the scale factor $a(t)$ of the Universe, when radiation is dominant, is expressed by $a(t) \sim t^{1/2}$. By definition the Hubble parameter is the ratio $\dot{a}/a$ and thus $H = \dot{a}/a = 1/2t$. From the Friedman equation for radiation-dominant epoch, the Hubble parameter is

$$H^2 = \frac{8\pi G}{3}\rho_R = \frac{8\pi G}{3}\frac{\pi^2}{30}g_{eff}T^4 = 2.76\frac{g_{eff}T^4}{M_{Pl}^2}, \quad (2)$$

where G is the universal gravitational constant, ρ_R is the energy density of radiation, M_{Pl} is the Planck mass, and g_{eff} is the total number of effective degrees of freedom of relativistic particles in thermal equilibrium at temperature T which is given by

$$g_{eff} = \sum_{i=bosons} g_i + \frac{7}{8} \sum_{j=fermions} g_j. \qquad (3)$$

Combining Equations (2, 3), the relation between the time t and the temperature T can be found as

$$t = 0.30 \frac{M_{Pl}}{\sqrt{g_{eff}}T^2} \sim \left(\frac{1\,MeV}{T} \right)^2 \text{sec} \qquad (4)$$

When the interaction rate of neutrino Γ_ν becomes smaller than the expansion rate of the Universe i.e., $H \sim T^2/M_{Pl}$, neutrinos decouple from other particles and stop interacting with them at the decoupling temperature $T_{\nu,dec}$. Γ_ν is $\sigma_\nu v_\nu n_\nu$ where $\sigma_\nu \approx \alpha^2 T^2/m_W^4$ is the typical neutrino cross section with the fine structure constant α, W mass m_W, v_ν neutrino velocity $\sim c = 1$, and the neutrino number density $n_\nu \propto T^3$. Γ_ν is then $\sim \alpha^2 T^5/m_W^4$. When $\Gamma/H \sim \alpha^2 M_{Pl} T^3/m_W^4 = 1$, T corresponds to the neutrino decoupling temperature $T_{\nu,dec} \sim (m_W^4/\alpha^2 M_{Pl})^{1/3} \sim 4\,\text{MeV}$ [3]. More detailed calculations show that $T_{\nu,dec} = 2$–$3\,\text{MeV}$ for ν_e and $3.5\,\text{MeV}$ for $\nu_{\mu,\tau}$. From Equation (4) the neutrino decoupling occurs at ∼0.3–1.0 s after the Big Bang. While CMB provides the information of the Universe at 300,000 years after the Big Bang, the study of nucleosynthesis gives the information of the Universe at ∼200–1000 s after the Big Bang [3, 4]. Observation of CνB, therefore, would provide the information of the earliest observable Universe.

2.1. COSMIC NEUTRINO BACKGROUND

As described in the previous section neutrinos decouple with electrons, positrons and photons at temperature $T \sim$ a few MeV and remain as such until today. Soon after the neutrino decoupling, at about $T = 0.5\,\text{MeV}$, $e^\pm$ pair annihilate into photons and transfer their entropy to these photons. This transfer of entropy to photons effectively slows down the rate of decrease in photon temperature compared with that in neutrino temperature as the Universe expands [3]. Since the entropy of neutrinos is conserved, $T_\nu = (4/11)^{1/3} T_\gamma$ and, since $T_\gamma^{now} = 2.7$ K, $T_\nu^{now} = 1.9$ K $= 1.7 \times 10^{-4}$ eV. Therefore the number density of neutrinos is given by $n_\nu = (3/22) n_\gamma = 56$ cm^{-3} per flavor. In the standard Big Bang model it is assumed that $n_\nu = n_{\bar{\nu}}$ and neutrinos' chemical potentials are zero. However, in this review it is not assumed, in which case it is convenient to introduce an asymmetry parameter for neutrino with flavor α, ν_α: $\eta_\alpha = (n_{\nu_\alpha} - n_{\bar{\nu}_\alpha})/n_\gamma = [\pi^2/12\zeta(3)](\xi_\alpha + \xi_\alpha^3/\pi^2)(T_\nu/T_\gamma)^3$ where $\xi_\alpha = \mu_\alpha/T$ with μ_α being the chemical potential of ν_α [5]. A recent study of the primordial He abundance data and WMAP data finds that the sum of the asymmetries of all neutrino flavors, taking into account the effect of neutrino oscillation with the neutrino mixing angle $sin^2\theta_{13} = 0.04(0.00)$, is $-0.071(-0.064) \leq \eta_\nu \leq 0.054(0.072)$ (90% C.L.) [6]. At the time of neutrino decoupling ($T_{\nu,dec} \sim$ a few MeV), since we know that neutrino masses are much less than a few MeV, all neutrinos are relativistic (for the status of neutrino masses refer to the review by the Particle Data Group) [7]. However, as the current neutrino temperature is 1.9 K (1.7×10^{-4} eV), some of neutrinos may be non-relativistic, in which case whether neutrinos are Dirac or Majorana type is important.

From a recent analysis by the Planck collaboration using the CMB and Baryon Acoustic Oscillation (BAO) data, the effective number of relativistic active neutrinos at the time of decoupling of the CMB N_{eff} is found to be $3.30^{+0.51}_{-0.51}$, consistent with the existence of three active neutrinos [8]. However, according to the analysis using the Planck, WMAP and BICEP2 data by Giusarma et al., N_{eff} is found to be 4.00 ± 0.41 [9].

2.2. CLUSTERING OF CνB

As we know that neutrino has mass, it is possible that CνB can be trapped in gravitational potential well of some structures in the Universe such as large galaxies and clusters of galaxies when CνB has velocity smaller than the escape velocity. For a large galaxy like Milky Way or a large cluster of galaxies the escape velocities are ∼600 or ∼2000 km/s, respectively. From the Maxwell–Boltzmann distribution, the average velocity of non-relativistic neutrino of mass m_ν at temperature T_ν, $< |\beta_\nu| > \; = \sqrt{8kT_\nu/(\pi m_\nu)} = \sqrt{4.3 \times 10^{-4}\text{eV}/m_\nu}$. Therefore $< |v_\nu| >= 19,600(6200)$ km/s for $m_\nu = 0.1(1.0)$ eV [10]. It seems that only a small fraction of neutrinos can be gravitationally trapped in a large cluster of galaxies. However, detailed simulation that takes into account either the current static mass distribution of the Milky Way (MWnow) or an estimated halo mass distribution before the formation of Milky Way through baryonic compression (NFWhalo) reveals that there may be local neutrino overdensity effect at the position of our solar system [11]. The simulation consists of several types of weakly interacting, self-gravitating particles (cold dark matter and neutrinos) modeled as a multi-component collisionless gas with the Vlasov equation and uses the density profile of cold dark matter (CDM) proposed by Navarro, Frank and White (NFWhalo) [12]. The neutrino overdensity $n_\nu/ < n_\nu >$, where $< n_\nu >$ is the average neutrino density predicted by the standard Big Bang model, is with the NFWhalo model, 12 and 1.4 for $m_\nu = 0.6$ and 0.15 eV, respectively, and with the MWnow model, 20 and 1.6 for $m_\nu =$ 0.6 eV and 0.15 eV, respectively. In the both cases (NFWhalo and MWnow) when $m_\nu < 0.1$ eV, there is no overdensity. Overdensity values 20 and 1.4 correspond to values for the neutrino asymmetry parameter η_ν, 2.7 and 0.19, respectively [11].

3. CνB DETECTION METHODS

Several methods to detect CνB have been proposed and these proposed methods can be divided into three categories: (1) direct detection of coherent CνB elastic scattering with target nuclei through momentum transfer, (2) direct detection by neutrino capture by β-decaying nuclei, and (3) indirect method by finding spectral distortion through CνB interaction with ultra-high energy neutrinos or protons/nuclei from unknown sources.

3.1. COHERENT NEUTRINO ELASTIC SCATTERING

In this category, there are two possible methods: use of order G_F effect and of G_F^2 effect where G_F is the Fermi constant.

3.1.1. Order G_F effect

Coherent elastic scattering occurs when the de Broglie wavelength of CνB $h/p_\nu \sim h/4T_\nu \sim 2.4$ mm for relativistic and unclustered neutrinos, or 1.2 mm · 1 eV$/m_\nu$(eV) for clustered non-relativistic neutrinos is much larger than inter-atomic spacing of the target material. When a neutrino with momentum p goes through coherent elastic scattering on the target and emerging with momentum p', a concept of neutrino optics can be introduced with an index of refraction $n = p'/p$ and $n - 1 \sim G_F$ [5]. Uses of neutrino optics were proposed to detect CνB either through refraction [13] or through total reflection [14] as an order G_F effect. However, it was pointed out that the force induced by a linear momentum or energy exchange by neutrinos is canceled out to order G_F when the target is in a uniform neutrino density [15, 16].

The only G_F effect viable for detection of CνB is the method proposed by Stodolsky that uses an energy split of the two spin states of non-relativistic electrons in the target immersed in CνB for which polarized electrons in the target are needed [17]. However, this energy split is proportional to $n_\nu - n_{\bar{\nu}}$ [10, 16]. Following Duda et al. here only their result in an optimistic case of a very large asymmetry favouring ν with $n_\nu - n_{\bar{\nu}} \approx n_\nu$ is presented. Note that for overdensity of 20 ($m_\nu = 0.6\,\text{eV}$) and of 1.4 ($m_\nu = 0.15\,\text{eV}$) as estimated by Ringwald et al., $n_\nu - n_{\bar{\nu}} = 0.95 n_\nu$ and $0.28 n_\nu$, respectively. In this approximation the authors find the energy splits for relativistic (R)/non-relativistic (NR), clustering (C)/non-clustering (NC) and Dirac (D)/Majorana (M) neutrinos: $(\Delta E)^D_R = (\Delta E)^M_R = 2\sqrt{2} g_A G_F |\beta_{Earth}| n_\nu$, where $|\beta_{Earth}| =< |\beta_\nu| >$ is the velocity of the Earth relative to CνB normalized to the speed of light in vacuum c, and g_A is 1/2 for ν_e and $-1/2$ for $\nu_{\mu,\tau}$. According to Ringwald et al. $< \beta_\nu >= 1.4 \times 10^{-3}$ and 2.2×10^{-3} for overdensity of 20 and 1.4, respectively. For non-clustered (NC) non-relativistic neutrinos (NR), $(\Delta E)^M_{NC,NR} = 2(\Delta E)^D_{NC,NR} \simeq 1.7\sqrt{m_\nu/(1.7 \times 10^{-4}\xi\ \text{eV})}(\Delta E)^D_R$, and for clustered (C) neutrino non-relativistic (NR) neutrinos $(\Delta E)^D_{C,NR} = \sqrt{2} g_A G_F |\beta_{Earth}| n_\nu$ and $(\Delta E)^M_{C,NR} \simeq 0$. In the case of Dirac relativistic neutrinos the difference in energy ΔE between the two helicity states of an electron in the direction of CνB induces a torque of magnitude $\Delta E/\pi$. For a target of mass number A, mass M, and linear dimension R with its moment of inertia $I = MR^2/\gamma$ (γ is a geometric factor), the acceleration due to CνB is $a = 10^{-27} f(\gamma/10)(100/A)(1\,\text{cm}/R)(\beta_{Earth}/10^{-3})$ cm/s^2 where f is neutrino overdensity $n_\nu / < n_\nu >$ [10]. The current measurable acceleration using Cavendish type torsion balance mechanism is $\sim 10^{-13}$cm/s^2 [18]. With possible improvements with the current technology a sensitivity down to 10^{-23} cm/s^2 may be achieved [11, 18, 19]. With an optimistic neutrino overdensity of 10, $\gamma = 10$, $A = 100$, and $R = 1$ cm, the expected acceleration is 10^{-26} cm/s^2 to be compared with the most optimistic sensitivity to the smallest detectable acceleration of 10^{-23} cm/s^2. Even in this optimistic situation, the target mass and size would need to be increased by a factor of 1000.

3.1.2. *Order G_F^2 effect*

When the Earth moves through the sea of CνB neutrinos, a target on Earth experiences, by elastic scattering, momentum transfer from neutrinos. In the Earth's rest frame (the laboratory frame) the momentum transfer per scattering is: $< \Delta p >_R \approx \beta_{Earth}(E_\nu/c)$ for relativistic neutrinos, $< \Delta p >_{NC,NR} = \beta_{Earth}(4T_\nu/c) =< \Delta p >_R$ for non-clustering (NC) non-relativistic (NR) neutrinos, and $< \Delta p >_{C,NR} \approx \beta_{Earth} c m_\nu$ for clustered (C) non-relativistic (NR) neutrinos. The acceleration by CνB is given by $a = \Phi_\nu (N_{A\nu}/A)\sigma_{\nu-A} < \Delta p >$ where Φ_ν is the CνB flux, A is the mass number of the target, $N_{A\nu}$ is the Avogadro number, and $\sigma_{\nu-A}$ is the neutrino-nucleus cross section. $\sigma_{\nu-A} = G_F^2 m_\nu^2/\pi \approx 10^{-56}(m_\nu/\text{eV})^2$ cm^2 for NR neutrinos and $= G_F^2 E_\nu^2/\pi \approx 5 \times 10^{-63}(T_\nu/1.9\ \text{K})\,\text{cm}^2$ for R neutrinos. When the target satisfies the aforementioned condition for coherent elastic scattering, the cross section gets a coherent enhancement factor A^2. Then the acceleration is: $a = (N_{A\nu}/A) n_\nu (G_F^2/\pi) A^2 F$ where $F = (4T_\nu)^3 \beta_{Earth}$ for R neutrinos, $F = m_\nu^2 (4T_\nu)\beta_{Earth}$ for NC-NR neutrinos, and $F = m_\nu^3 v_\nu^2$ for C-NR neutrinos [10]. This result includes the nuclear coherent enhancement factor A^2 but does not include another possible coherent enhancement factor N_c due to the larger de Broglie wavelength of CνB than the target size where $N_c = (N_{A\nu}/A)\rho(\lambda_\nu)^3$ with ρ being the density of the target [11, 20, 21]. With this enhancement, Duda et al. found that the acceleration due to CνB $a = 2 \times 10^{-34} f\rho(\text{g cm}^3)$ cm/s^2 for R Dirac/Majorana neutrinos, $3 \times 10^{-28} f(m_\nu(\text{eV}))^2(T_\nu/1.9\,\text{K})^{-2}\rho(\text{g cm}^3)$ cm/s^2 for NC-NR Dirac neutrinos, and $10^{-27} f\rho(\text{g cm}^3)$ cm/s^2 for C-NR Dirac neutrinos. Note that for NR Majorana neutrinos, the corresponding cross sections are reduced by $\beta_\nu^2 \approx 10^{-6}$. Even with an optimistic scenario of $f\rho \sim 100$, $a \approx 10^{-25}$ cm/s^2 is too small compared with the aforementioned smallest detectable acceleration of 10^{-23} cm/s^2.

3.1.3. *Experimental status of coherent elastic neutrino nucleus scattering (CENNS)*

As described above, the methods proposed in this category relies on the big enhancement factor due to CENNS. Although CENNS has been known since the paper by D. Freedman [22], no observation of this reaction has been made. Recently CENNS attracted close attention and several proposals have been made. Wong et al. and Barbeau et al. propose to use antineutrinos from nuclear reactors [23, 24]. The proposal by Akimov et al. plans to use neutrinos from Stopped-pion Spallation Neutron Source (SSNS) at Oakridge National Laboratory, while Brice et al. propose to utilise neutrinos at the Fermilab Booster Neutrino Beam (BNB) [25, 26].

3.2. NEUTRINO CAPTURE BY CνB-DECAYING NUCLEI

The first suggestion to use neutrino capture by β-decaying nuclei (NCB) was by Weinberg in 1962 to detect CνB [27]. Electron (anti)neutrino capture by a nucleus N that naturally undergoes beta (positron) decay to the daughter nucleus N' as $\nu_e/\bar{\nu}_e + N \rightarrow N' + e^+/e^-$ has no energy threshold on the incident (anti)neutrino energy. In β-decay in which the energy conservation requires $M(N) - M(N') = Q_\beta > 0$ where $M(N)$ and $M(N')$ are the masses of nucleus of N and N', respectively, and Q_β is the kinetic energy of electron/positron. For massive neutrino of mass m_ν, the electron kinetic energy in NCB is $E_e = Q_\beta + E_\nu \geq Q_\beta + m_\nu$, while, neglecting the nucleus recoil energy, $E_e \leq Q_\beta - m_\nu$ for electrons from β-decay. Thus there is a gap of $2m_\nu$ around Q_β in electron kinetic energy between β-decay and neutrino capture event. Cocco et al. find that the NCB cross section times neutrino velocity can be written as $\sigma_{NCB} v_\nu = 2\pi^2 ln2/(At_{1/2})$ where A is a function of E_ν only, when the target nucleus characterized by Q_β

and Z is given, and $t_{1/2}$ is the half-life of the target nucleus [28]. As β-decay events are the major background source to the NCB, larger ratio of the NCB to β-decay events $\sim \sigma_{NCB}(v_\nu/c)t_{1/2}$ is preferable. Among β-decaying nuclei isotopes ^{3}H and ^{187}Re have the large ratios 3.0×10^5 and 5.9×10^7, respectively. However, the fact that $\sigma_{NCB}(v_\nu/c)$ for ^{3}H and ^{187}Re are 7.8×10^{-45} cm^2 and 4.3×10^{-52} cm^2, respectively, ^{3}H seems the best choice. Although there is a gap of $2m_\nu$ in the electron kinetic energy between the endpoint of the β-decay and the NCB events, the success of this method depends on the energy resolution whose effect may fill this gap. Cocco et al. estimate the signal (NCB) to the background (β-decay) event ratio R in the outgoing electron kinetic energy region $W_0 - \Delta < E_e < W_0$ where Δ is the energy resolution and W_0 is the endpoint energy. They find that for $R = 3$ and $m_\nu = 0.7(0.3)$ eV the energy resolution should be better than 0.2 (0.1) eV. The event rate per mole per year is calculated to be $2.85 \times 10^{-2}[\sigma_{NCB}(v_\nu/c)/10^{-45}]$cm^2 yr^{-1} mol^{-1}. With 100 g of ^{3}H as the target, the event rate per year is, for $m_\nu = 0.6$ eV, 7.5, 90, and 150 events using the standard Fermi-Dirac (FD) distribution, Navarro-Frank-White profile (NFWhalo), and the present day mass distribution of the Milky Way (MWnow), respectively. For $m_\nu = 0.3$ (0.15) eV, the rate is 7.5 (7.5), 23 (10), and 23 (12), respectively, with FD, NFWhalo and MWnow distribution [11].

A calculation by Faessler et al. [29] finds that the NCB rate per year for the ^{3}H target (50 μg) to be used for the KATRIN experiment [30] is $4.2\times10^{-6}n_\nu/ < n_\nu >$ which is consistent with the result by Cocco et al. above for the FD distribution with $n_\nu/ < n_\nu >= 1$. A similar calculation for 760 g of ^{187}Re to be used for the MARE calorimetric experiment [31] finds the event rate per year $6.7\times10^{-8}n_\nu/ < n_\nu >$, which is too small for a likely value for $n_\nu/ < n_\nu >$.

According to Lazauskas et al. [32], the event rate per year per Mcu (mega-curries = 3.7×10^{16} decays $\sim 2.1 \times 10^{25}$ ^{3}H atoms) for approximately 100 g of ^{3}H is $6.5 \times n_\nu/ < n_\nu >$ yr^{-1} Mcu^{-1}, which is also consistent with the result by Cocco et al. As for the required energy resolution to have a reasonable signal to noise ratio of unity, they conclude that the resolution should be a factor of two or more smaller than the neutrino mass m_ν, which is similar to the conclusion by Cocco et al.

Note that the KATRIN experiment's goal for the energy resolution is 0.93 eV and the mass of the ^{3}H source is only 50 μg [30] and to increase the mass of the ^{3}H source or to improve the energy resolution it is necessary to seek a new way to perform this type of experiment. Toward this goal of improvement the Project 8 experiment has started [33]. This experiment utilizes detection of cyclotron radiation from β-decay electron to achieve an improvement in the energy resolution. Another proposal to improve the neutrino mass resolution is to use cold atomic tritium rather than molecular tritium used for the KATRIN experiment to detect both the electron and ^{3}He in the final state of β-decay [34]. Finally the PTOLEMY experiment (Princeton Tritium Observatory for Light-Early Universe Massive-neutrino Yield) is most ambitious [35]. It is based on relic neutrino capture on tritium. It uses, in addition to MAC-E Filter (Magnetic Adiabatic Collimation combined with an Electrostatic Filter) adopted in the KATRIN experiment, a large surface-deposition tritium target, cryogenic calorimeter, RF tracking similar to the Project 8 experiment, and time-of-flight systems to achieve the required background suppression and enough event rate. PTOLEMY plans to use 100-g of atomic tritium as the target which can provide enough event rate.

3.3. COSMIC RAYS—CνB SCATTERING

It is argued that the Universe is opaque to electrons, nucleons and photons at energies higher than 10^{23} eV [36]. A more careful consideration finds that the interaction between cosmic ray proton and CMB photon $p + \gamma_{CMB} \rightarrow \pi + N$ imposes an energy threshold known as Greisen-Zatsepin-Kuzmin (GZK) cutoff $E_{GZK} \approx 5 \times 10^{19}$ eV, beyond which cosmic ray protons do not survive [37, 38]. However, Weiler argues that the only particle that can survive the GKZ cutoff is neutrinos and interactions of ultra-high energy cosmic ray neutrinos with CνB through the Z resonance $\nu + \bar{\nu} \rightarrow Z \rightarrow p + any$ introduces a dip at certain energy in ultra-high energy neutrino flux. If these neutrinos come from sources with the redshift $z = 3.5$, this dip occurs at 9×10^{19} eV. Depending on the three neutrino masses and the value of redshift parameter z of the sources of these ultra-high energy neutrinos, there may be possibly three dips in energy spectrum of cosmic ray neutrinos if these sources exist. The existence of these neutrino sources can produce cosmic rays beyond the GZK cutoff through the Z resonance (Z-burst). However, although the AGASA experiment claimed that they detected cosmic ray events above the GZK cutoff [39], neither the HiRes Experiment [40] nor the Auger experiment [41] confirmed such events.

As for detailed theoretical analyses on the CνB spectroscopy using ultra-high energy cosmic rays, refer to the papers by Barenboim et al. [42] and by D'Olivo et al. [43]. A detailed theoretical analysis on the Z-burst can be found, for example, in the paper by Fargion et al. [44].

Another interaction of cosmic rays with CνB to detect CνB was proposed by Wigman [45]. He proposes to explain, in terms of inverse β-decay interactions such as $p + \bar{\nu}_e \rightarrow n + e^+$, the changes in the power index of cosmic rays spectrum around $10^{15.3}$ eV (the first knee) observed by the CASA-BLANCA experiment [46] from $n = 2.72 \pm 0.02$ to $n = 2.95 \pm 0.02$, and also at the second knee around $10^{17.5}$ eV from $n = 3.01 \pm 0.06$ to $n = 3.27 \pm 0.02$ observed by the Fly's Eye experiment [47]. In the interaction $p + \bar{\nu}_e \rightarrow n + e^+$ where $\bar{\nu}_e$ is CνB, the center of mass energy $E_{CM} \approx \sqrt{m_p^2 + 2E_p m_\nu}$ should be greater than the sum of proton and neutron masses $m_p + m_n$. This leads to the threshold proton energy for the interaction at $1.695 \times 10^{15}/(m_\nu/(1 \text{ eV}))$ eV. If the energy of the knee is, combining several experimental data, at $(3 \pm 1) \times 10^{15}$ eV and the cause of the first knee is the inverse β-decay interaction by proton, it is consistent with the neutrino mass $m_{\nu_e} = 0.5 \pm 0.2$ eV/c^2.

Although evidence of high energy cosmic ray neutrinos has finally emerged as the IceCube experiment shows [48], there is only one experimental result that suggests that there are cosmic rays beyond the GZK cutoff, which has not been confirmed by the HiRes and Auger experiment. Various mechanisms in addition to the inverse β-decay theory have been proposed to explain the existence of the knees in cosmic ray spectrum [49]. However, it is not clear which explanation is the correct model for the knees.

4. FUTURE PROSPECT AND CONCLUSION

In a half-century history of studies on detection of CνB, interesting proposals have been presented. However, with the current available technology, none of the proposed methods that are described in this review are close to be reality, except for the promising Project 8 and PTOLEMY experiment, unless local neutrino overdensity is much larger than expected. For the method to measure the acceleration due to momentum transfer by CνB using torsion balance, the sensitivity of detector needs to be improved by a factor of 1000, even under optimistic circumstances. In addition the contribution from fake signal from various background sources should be carefully evaluated. Detecting CνB by analyzing cosmic ray spectrum as dips beyond the GZK cutoff needs a much larger cosmic ray detector, even if Nature is kind enough to provide ultra-high energy neutrino sources. The existence of the knee-like structures may be explained by other mechanisms than the inverse β-decay. Among β-decaying nuclei as the target, tritium ^{3}H seems to provide the best chance for an NCB experiment to eventually detect CνB if the ideas of the Project 8 and PTOLEMY experiment work to bring better energy resolution and if $\sim$100-g of ^{3}H source, especially, of atomic tritium can be manufactured. However, this method cannot detect $\nu_{\mu,\tau}$s.

Note added After the submission of this manuscript, a paper by Safdi et al. appeared [50]. This paper describes annual modulation of CνB local density caused by gravitational focusing by the Sun. This modulation can serve as a diagnostic for the signal due to CνB for an experiment based on neutrino capture by β-decaying nuclei.

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