Inverse Tritium Beta Decay with Relic Neutrinos, Solar Neutrinos, and a $^{51}\text{Cr}$ Source

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The inverse tritium beta decay (ITBD) reaction, $\nu_e + ^3\text{H} \rightarrow e^- + ^3\text{He}$, is a promising experimental tool for observing relic neutrinos created in the early Universe. This reaction has been selected by the PTOLEMY experiment for the search of relic neutrinos. Despite its potential, the ITBD reaction induced by any sources of neutrinos has yet to be observed. We show that an intense $^{51}\text{Cr}$ radioactive neutrino source is suitable for observing the ITBD reaction for the first time. As the Sun is another source of intense electron neutrinos, we also examine the ITBD reaction rate from solar neutrinos. Based on our recent studies on the evolution of the helicity of relic neutrinos, we further present the ITBD rate for capturing relic neutrinos as a function of neutrino mass hierarchy, the Dirac versus Majorana nature of neutrino, and the mass of the lightest neutrino.

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I. INTRODUCTION

The standard cosmological model predicts that relic neutrinos decouple at about one second after the Big Bang [1, 2], much earlier than the decoupling time, $\sim 3.8 \times 10^9$ years, of the Cosmic Microwave Background (CMB). While the detection of the CMB has revolutionized cosmology, eventual observation of the predicted Cosmic Neutrino Background (CνB) would, aside from validating the theory of the ITBD reaction, test the performance of detector systems for relic neutrinos. In this paper we propose using an intense $^{51}\text{Cr}$ source of electron neutrinos, from the electron capture reaction $e^- + ^{51}\text{Cr} \rightarrow ^{51}\text{V} + \nu_e$, to observe the ITBD reaction. As the Sun is an intense source of electron neutrinos, we examine as well the expected ITBD reaction rate initiated by solar neutrinos. Solar neutrinos could potentially set an irreducible background for CrB detection in the ITBD reaction analogous to the “neutrino floor” imposed by solar neutrinos for direct dark matter searches [5]. Comparing the ITBD rates from a $^{51}\text{Cr}$ source and solar neutrinos with the expected rates originating from the CrB, we find that while the background for the CrB detection from solar neutrinos is negligible, the $^{51}\text{Cr}$ source could yield the first observation of the ITBD reaction.

The energy release, $Q$, of the ITBD reaction is positive, allowing relic neutrinos with practically zero energy to be detected. Capture of relic neutrinos by ITBD has the distinct signature of mono-energetic electrons separated from the endpoint of the tritium beta decay spectrum by twice the neutrino mass, $m_\nu$. As discussed below, the ITBD cross section depends sensitively on the helicity of the incident neutrino. We recently examined the evolution of the helicity of relic neutrino in cosmic and galactic magnetic fields as well as in cosmic gravitational inhomogeneities, and found a physically significant probability of helicity reversal [6, 7]. We further discuss here the consequences of this helicity evolution of relic neutrinos on the rate of their detection via ITBD.

The predicted CrB density, summed over all flavors of active neutrinos and antineutrinos, is $\sim 383/cm^3$, comparable to the CMB density $\sim 411/cm^3$ [2]. The present temperature of the CrB, related to the temperature of the CMB by $T_{\text{CrB}} = (4/11)^{1/3}T_{\text{CMB}}$, is 1.945 K corresponding to an energy of $1.676 \times 10^{-4}$ eV. Given the current mass-squared differences, $\Delta m_{ij}^2$, between neutrino mass states $i$ and $j$: $\Delta m_{31}^2 = (7.50 \pm 0.12) \times 10^{-5}$ eV$^2$ and $|\Delta m_{32}^2| = (2.52 \pm 0.04) \times 10^{-3}$ eV$^2$ [8], at least two of the three neutrino mass eigenstates in the CrB are presently non-relativistic. Detection of the relic neutrinos poses the special challenge that, regardless of their origin, non-relativistic neutrinos have never been observed.

II. INVERSE TRITIUM BETA DECAY FROM $^{51}\text{Cr}$ SOURCE AND SOLAR NEUTRINOS

The cross section for capturing an electron neutrino with energy $E_\nu$ and helicity $h$ on a tritium atom is [9]

$$
\sigma^h(E_\nu) = \frac{G_F^2}{2\pi\nu} |V_{ud}|^2 F(Z, E_\nu) \frac{m_{\nu_e}}{m_{3H}} E_\nu p_e \times (f_\nu)^2 + (g_A/g_V)^2(g_{G\nu})^2 A^h,
$$

(1)
FIG. 1: The ITBD cross section, Eq. (1), versus incident electron neutrino energy $E_{\nu}$, for massless neutrinos.

where $v$ is the neutrino velocity; $V_{ud}$ is the up-down quark element of the CKM matrix and $F(Z, E_e)$ is the Fermi Coulomb correction for the $e^{-3}\text{He}$ system

$$F(Z, E_e) = \frac{2\pi \eta}{1 - e^{-2\pi \eta}}; \quad \eta = Z\alpha E_e/p_e,$$

(2)

where $Z = 2$ is the atomic number of $^3\text{He}$ and $\alpha$ is the electromagnetic fine structure constant. The nuclear form factors for Fermi and Gamow-Teller transitions are

$$\langle f_F \rangle^2 \approx 0.9987, \quad \langle g_{GT} \rangle^2 \approx 2.788,$$

(3)

with $g_{\nu} = 1$ and $g_A = 1.2695$. The neutrino helicity-dependent factor is

$$A^\pm = 1 \mp \beta,$$

(4)

where $\beta = v/c$. For relativistic neutrinos ($\beta \to 1$), the ITBD reaction is dominantly from neutrinos with negative helicity. For slowly-moving relic neutrinos ($\beta \to 0$), Eq. (4) implies that the ITBD cross section is nearly identical for the two neutrino helicity states. Figure 1 displays the ITBD cross section versus the total electron-neutrino energy $E_{\nu}$, with the neutrino mass neglected, so that $\beta = 1$, $A^+ = 0$ and $A^- = 2$. The pronounced energy dependence of the ITBD cross section in Fig. 1 is largely from the $E_{\nu}p_e$ factor with a minor contribution from the Fermi Coulomb correction.

We consider two possible electron neutrino sources besides relic neutrinos for initiating the ITBD reaction, $^{51}\text{Cr}$ and the Sun. Intense $^{51}\text{Cr}$ sources have been utilized by several neutrino experiments, including GALLEX [10], SAGE [11], and BEST [12]. In particular, a search for a sterile neutrino was recently reported by the BEST Collaboration using a 3.4-MCi $^{51}\text{Cr}$ source [12]. Another intense source of electron neutrinos is the Sun. Below, we first examine the expected ITBD rate utilizing an intense $^{51}\text{Cr}$ source, and then calculate the ITBD rate from solar neutrinos. It is important to evaluate the expected ITBD rate to understand the inevitable “background” events initiated by solar neutrinos.

The energy spectrum of electron neutrinos from a $^{51}\text{Cr}$ source consists of four discrete lines with energies 0.427, 0.432, 0.747, and 0.752 MeV. For $^{51}\text{Cr}$ neutrinos and $^7\text{Be}$ solar neutrinos, the fluxes are in unit of $10^{10}/\text{cm}^2/\text{s}$. For the $pp$ solar neutrinos, the flux is expressed in units of $10^{10}\text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}$ to account for the continuous energy spectrum.

As a specific example of a feasible setup, a compact 3.4-MCi $^{51}\text{Cr}$ source as fabricated for the BEST experiment [12] could be placed at a distance of 50 cm, or less, from the tritium target. This source consists of 26 enriched (97%) metallic $^{50}\text{Cr}$ disks, each with a diameter of 8.4 or 8.8 cm and a thickness of 0.4 cm. After irradiation at the SM-3 reactor at the Research Institute of Atomic

FIG. 2: Flux of various sources of neutrinos versus neutrino energy. The four $^{51}\text{Cr}$ lines are shown in two groups, 0.427 + 0.432 MeV and 0.747 + 0.752 MeV. For $^{51}\text{Cr}$ neutrinos and $^7\text{Be}$ solar neutrinos, the fluxes are in unit of $10^{10}/\text{cm}^2/\text{s}$. For the $pp$ solar neutrinos, the flux is expressed in units of $10^{10}\text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}$ to account for the continuous energy spectrum.
TABLE I: ITBD rate for various sources of electron neutrinos, together with the electron kinetic energies, $T_e$. The relic neutrinos are assumed to be Majorana in the rate calculation.

| Source       | $T_e$ (MeV) | Rate (1/year) |
|--------------|-------------|---------------|
| $^{51}\text{Cr}$ 0.427 + 0.432 MeV $\nu_e$ | 0.447 | 8.8 |
| $^{51}\text{Cr}$ 0.747 + 0.752 MeV $\nu_e$ | 0.767 | 147.0 |
| Solar $pp$ $\nu_e$ | 0.0186 to 0.44 | 0.8 |
| Solar $^7\text{Be}$ $\nu_e$ | 0.881 | 0.23 |
| Relic $\nu_e$/$\bar{\nu}_e$ | 0.018 | 8.2 |

Research with thermal neutrinos for $\sim 100$ days, the disks were placed in a hermetic stainless-steel capsule covered with a shield of 3-cm thick tungsten alloy. The entire assembly of the $^{51}\text{Cr}$ source is 16 cm in diameter and 22.6 cm in height.

We evaluate the ITBD rates on a 100 g tritium target, as proposed by the PTOLEMY collaboration [4]. The total ITBD rate per year for a 3-MCi $^{51}\text{Cr}$ source located 50 cm from the tritium target is shown in Fig. 3, plotted as a function of kinetic energy of the electron emitted in the ITBD reaction. The ITBD rates from various sources of electron neutrinos are listed in Table I.

We turn to solar neutrinos, considering the most dominant components originating from the $p+p \rightarrow d+e^++\nu_e$ reaction ($pp$ neutrinos) and the $^7\text{Be}$ neutrinos at 0.862 MeV from the $e^-+^{12}\text{Be} \rightarrow \nu_e+^7\text{Li}$ reaction. The fluxes of $pp$ and $^7\text{Be}$ solar neutrinos [13] are shown in Fig. 2. The flux reduction of $pp$ solar neutrinos by a factor of 0.55 from neutrino oscillations, as measured by Borexino [14], is taken into account. Similarly, we include a reduction factor 0.53 from neutrino oscillations for the $^7\text{Be}$ neutrinos. As the $pp$ neutrinos have a continuous neutrino energy distribution from 0 to 0.4 MeV, we give the $pp$ solar neutrino flux in units of $10^{10}$cm$^{-2}$s$^{-1}$MeV$^{-1}$.

Figure 2 indicates that the flux of the 0.747 + 0.752 MeV neutrinos from the $^{51}\text{Cr}$ source is more than an order of magnitude higher than the integrated flux of solar $pp$ neutrinos. Together with the higher ITBD cross sections for higher energy neutrinos from the $^{51}\text{Cr}$ source, one expects a significantly larger rate for the ITBD process from the $^{51}\text{Cr}$ source than from solar neutrinos. Figure 3 shows the total ITBD rate per year with a 100 g tritium target, as proposed by the PTOLEMY Collaboration, for neutrinos from $^{51}\text{Cr}$ and the solar $pp$ reaction. The ITBD rate in Fig. 3 is plotted as a function of the kinetic energy of the electron emitted in the ITBD reaction.

III. INVERSE TRITIUM BETA DECAY FROM RELIC NEUTRINOS

The capture rate for a relic neutrino in mass eigenstate $i$ with energy $E_\nu$ and helicity $h$ on a tritium target of mass $M_t$ is

$$\dfrac{d\Gamma^h_i(E_\nu)}{dE_\nu} = |U_{ei}|^2 \dfrac{d\rho(E_\nu)}{dE_\nu} v_i \sigma^h_i(E_\nu) N_t,$$

where $U_{ei}$ is the mixing matrix element between neutrino mass eigenstate $i$ and $\nu_e$; $\rho(E_\nu)$ is the relic neutrino density distribution

$$\dfrac{d^3\rho(E_\nu)}{d^3p_\nu} \propto \dfrac{1}{e^{p_\nu/E_{C\nu B}} + 1},$$

where $p_\nu$ is the relic neutrino momentum; $v_i$ is the velocity of relic neutrino and $\sigma_i^h(E_\nu)$ is the ITBD cross section given in Eq. (1). The number of tritium nuclei in the target is $N_t = M_t/m_{^3\text{H}}$.

The helicity dependence of the ITBD cross section makes it crucial to take the helicities of relic neutrinos into account in predicting the ITBD rate. We recently investigated the evolution of the helicities of relic neutrinos as they propagate through cosmic magnetic fields and gravitational inhomogeneities [6, 7], and briefly summarize our findings.

In the early Universe, neutrinos were in chiral eigenstates. When decoupled at a temperature of $\sim 1$ MeV, they were highly relativistic and the chiral eigenstates essentially coincide with helicity eigenstates. Neutrinos decouple effectively in negative helicity states, while antineutrinos decouple with positive helicity. On their long
journey to Earth, their helicities can be modified by two effects. First, while their momentum and spin vectors are both bent by gravitational forces acting transverse to their direction of motion, the rotation angle of the spin vector of a non-zero mass neutrino is less than that of the momentum vector \([7, 15]\). Thus a neutrino of negative helicity at the time of decoupling would acquire a non-zero negative-helicity amplitude. Reference \([7]\) calculates in detail the root-mean-square bending angles of relic neutrino momentum \(\langle (\Delta \theta_p)^2 \rangle^{1/2}\), spin \(\langle (\Delta \theta_S)^2 \rangle^{1/2}\) and spin relative to momentum \(\langle (\Delta \theta)^2 \rangle^{1/2}\), with the gravitational inhomogeneities of the Universe measured in the Planck experiment as input \([16]\).

Another source for modifying relic neutrino helicities are the cosmic and galactic magnetic fields. While magnetic fields do not affect the neutrino momentum, the spin of a neutrino with a non-zero diagonal magnetic moment, as non-zero mass Dirac neutrinos should have, precesses in magnetic fields, hence modifying the neutrino helicity. Both Majorana and Dirac neutrinos can have transitional magnetic moments, but only Dirac neutrinos can have a diagonal magnetic moment.\(^1\)

As relic neutrinos approach the Earth, they encounter the magnetic fields of the Milky Way, with magnetic field \(B_\odot \sim 10 \mu G\). As the galactic magnetic fields change orientation over a coherence length, \(\Lambda_g\), of order kpc, the spin orientation of relic neutrino undergoes a random walk through the galaxy. As shown in Refs. \([6, 7]\), while the gravitational bending of a neutrino spin with respect to its momentum is well below that produced by a magnetic moment of the magnitude of the Borexino upper limit \([21]\), the cumulative rotation of a Dirac relic neutrino from the cosmic magnetic fields is comparable to that from the Milky Way \([6]\).

The ITBD rate for capturing relic neutrinos is

\[
\Gamma = \int \sum_{i, h} \frac{dA_i^h(E_\nu)}{dE_\nu} dE_\nu,
\]

summed over the mass state \(i\) and helicity states \(h\) for both neutrinos and antineutrinos, and integrated over the energy distribution of the relic neutrinos. The \(i\) and \(h\) dependence of \(A^h_i(E_\nu)\) in Eq. \((5)\) comes from \(|U_{e i}|^2 A^h_i\), cf. Eqs. \((1)\) and \((5)\); we define

\[
\bar{A} = \sum_{i, h} |U_{e i}|^2 A^h_i.
\]

\(^1\) The reported observation (now withdrawn \([17]\)) of an excess of low-energy electron events by XENON1T \([18]\) prompted the suggestion that solar neutrinos could have a large magnetic moment, of order \(\sim 1.4 - 2.9 \times 10^{-11} \mu_B\) \([19, 20]\), which is compatible with the upper limit of \(\mu_{\nu_e} < 2.8 \times 10^{-11} \mu_B\) set by the Borexino experiment \([21]\).

![FIG. 4: Rates of ITBD per year for relic neutrinos on a 100 g tritium target. The rates versus mass of the lightest neutrino are shown as solid curves for the normal (NH) and inverted (IH) mass hierarchies for Dirac and Majorana neutrinos. The dashed curves show the case of complete helicity flip from left to right handed neutrinos. The dot-dashed curve shows the result for Dirac NH neutrinos with the mean square of the relative spin-momentum angle, \(\langle \theta^2 \rangle\), given by the estimate for the Milky Way with neutrino magnetic moment \(\mu_\nu = 5 \times 10^{-14} \mu_B\).](image)

For Majorana neutrinos, both neutrinos and antineutrinos can participate in the ITBD reaction. With a helicity rotation angle \(\theta\), the probability of finding a neutrino in a negative or positive helicity state is \(\cos^2(\theta/2)\) and \(\sin^2(\theta/2)\), respectively. The corresponding probabilities for antineutrinos are \(\sin^2(\theta/2)\) and \(\cos^2(\theta/2)\). From Eqs. \((4)\) and \((8)\), \(\bar{A}\) for Majorana neutrinos becomes

\[
\bar{A}_M = \sum_i |U_{e i}|^2 [\cos^2(\theta/2)(1 + \beta_i) + \sin^2(\theta/2)(1 - \beta_i)] + \cos^2(\theta/2)(1 - \beta_i)\]

\[
= 2 \sum_i |U_{e i}|^2 = 2,
\]

where we use the unitarity relation \(\sum_i |U_{e i}|^2 = 1\). The second line is the antineutrino contribution. Hence, the ITBD rate for Majorana relic neutrinos is independent of the mass and helicity of neutrinos. Dirac antineutrinos, on the other hand, cannot participate in the ITBD reaction. Hence \(\bar{A}\) can only come from neutrinos and is

\[
\bar{A}_D = 1 + \sum_i |U_{e i}|^2 \beta_i \cos \theta_i.
\]

From the expressions of the helicity rotation angle \(\theta\) given in Ref. \([6, 7]\), one can evaluate the ITBD rate for
relic neutrinos on a 100 g tritium target using Eq. (7). Figure 4 shows the ITBD rate for relic neutrinos as a function of the mass of the lightest neutrino, for both Dirac and Majorana neutrinos with normal and inverted mass hierarchies. For Majorana neutrinos, the ITBD rate is 8.2/year independent of the mass hierarchy and the mass of the lightest neutrino. For Dirac neutrinos maintaining their original helicity ($\theta = 0$), the ITBD rates are shown as the black and red curves, respectively, in Fig. 4. As the mass of the lightest neutrino approaches zero, $A_D$ approaches $1 + |U_{e1}|^2 = 1.6794$ in the normal and $1 + |U_{e3}|^2 = 1.0216$ in the inverted hierarchy. When the lightest neutrino mass exceeds 0.1 eV, all neutrinos become nonrelativistic and $A_D$ approaches unity regardless of the mass hierarchy. Since $A_D < A_M$, the ITBD rate for Dirac neutrinos is always smaller than that for Majorana neutrinos.

The dashed curves in Fig. 4 also show the dependence of the ITBD rate on the lightest (Dirac) neutrino mass for complete helicity flip, $\theta = \pi$. For partial spin rotation, the ITBD rate lies between the solid and dashed curves, while for complete randomization of the neutrino helicity, the rate is $\sim 4.1$/year, just half that for Majorana neutrinos. The dot-dashed curve in Fig. 4 corresponds to an ITBD rate for Dirac relic neutrinos passing through the Milky Way with a magnetic moment $\mu_\nu = 5 \times 10^{-14} \mu_B$, almost three orders of magnitude smaller than the magnetic moment XENON1T suggest as a possible explanation of their low energy excess. If the magnetic moment of normal hierarchy Dirac neutrinos is of the order suggested by XENON1T, then the neutrino spin rotations would be very large with a broad distribution and the ITBD rate would approach $\sim 4.1$/year.

In summary, we have examined the prospect of using an intense $^{51}$Cr source for observing the inverse tritium beta decay for the first time. A 3-MCi $^{51}$Cr source placed at a distance of 50 cm from a 100 g tritium target, would give an expected rate $\sim 150$ per year, more than a factor of 10 greater than the expected ITBD rate for relic neutrinos. The electrons from the ITBD with a $^{51}$Cr source will have energies well separated from the end-point energy of tritium beta decay. Thus the requirement on the energy resolution of the spectrometer for separating the $^{51}$Cr ITBD signals from the tritium beta decay background is greatly relaxed, and a tritium target much thicker than the PTOLEMY target could be used for observing $^{51}$Cr ITBD events at a much higher rate. The PTOLEMY tritium target is designed to have a thickness of 1$\mu$g/cm$^2$ in order to achieve sub-eV energy resolution for electron detection. Conceivably an additional tritium target with thickness $\sim 0.1$ g/cm$^2$, a factor 10$^5$ thicker than the currently designed PTOLEMY target, can be utilized for a dedicated measurement of the ITBD signals from the $^{51}$Cr source. This measurement, which only requires an energy resolution $\sim 0.1$ MeV, could lead to the first observation of the ITBD reaction prior to a search for relic neutrinos.

We have also investigated the implications of the relic neutrino helicities on their detection in the ITBD reaction, and note a significant helicity modification even if $\mu_\nu$ is two orders of magnitude smaller than the Borexino upper limit. We emphasize that the ITBD rate for relic neutrinos depends on whether the neutrino is Dirac or Majorana, on the mass hierarchy and the magnetic moment of neutrinos, and on the helicity modifications by cosmic gravitational perturbations. However, it becomes increasingly difficult to resolve the relic neutrino events from the tritium beta decay background for smaller neutrino mass, and extremely fine energy resolution of the detector, on the sub-eV scale, would be required. New detector techniques are needed to fully explore the region of interest shown in Fig. 4.

We also find that the expected ITBD rate from solar neutrinos is a factor of $\sim 5$-10 smaller than that for relic neutrinos. Thus, unlike the “neutrino floors” imposed by the solar neutrinos in the search for dark matter, the search for relic neutrinos via the ITBD reaction is not limited by the presence of the solar neutrinos.

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