Laboratory tests for the cosmic neutrino background using beta-decaying nuclei

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Abstract

We point out that the Pauli blocking of neutrinos by cosmological relic neutrinos can be a significant effect. For zero-energy neutrinos, the standard parameters for the neutrino background temperature and density give a suppression of approximately 1/2. We show the effect this has on three-body beta decays. The size of the effect is of the same order as the recently suggested neutrino capture on beta-decaying nuclei.

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1. Introduction

The last remaining remnant of the big bang, which is composed of a known particle is the Cosmic Neutrino Background (CNB). It decouples from thermal equilibrium at $T \quad 2$ MeV. It gives information about the universe at a time significantly before the decoupling of photons at $T \quad 1$ eV. The processes responsible for their creation and decoupling are well understood nuclear physics.

Today these neutrinos are expected to be extremely cold ($1.952K = 1.68 \quad 10^{4}$ eV). As such, they are extremely difficult to detect due to the fact that weak interaction cross sections scale as $(G_F E)^2$. They have a density of $\quad = 3/22n \quad = 56/cm^3$ per species of neutrino and anti-neutrino, corresponding to a luminosity $L = 1.7 \quad 10^{13}/cm^2 s$ if the neutrinos were massless. [1,2] These numbers rely on a specific cosmological model which could be substantially modified, if neutrinos cluster gravitationally, or if they have nontrivial dynamics after freeze-out. [3] It has also recently been shown that these neutrinos are a quantum liquid, and their fluctuations have the quantum numbers of a graviton, opening the prospect that measurements of relic neutrinos could then be compared with gravitational constants. [4]

Nuclei that undergo β-decay are a precise and specific laboratory to look for the CNB. There exists a vast array of nuclei that can emit or absorb neutrinos at a wide range of energies. A signal seen using β-decaying nuclei constitutes a specific test because they are already known to emit or absorb lepton number in specific ways. All other proposals could not in principle tell if the effect was due to an object with lepton number. [1,2] High-energy neutrinos (e.g. Z-burst) can be absorbed by things which do not carry lepton number, and anomalous forces could have a variety of sources that have nothing to do with lepton number (for instance, a Dark Matter wind). Finally the effects of neutrinos on the CMB cannot be disentangled from other relativistic species that are not be fermionic or do not carry lepton number.

Rates using decaying nuclei are in principle much higher than other proposals such as coherent scattering, because the energy for the observation is coming from nuclear mass differences, and not from the neutrinos themselves. The energy Q in nuclear transitions is O(MeV). Giving the CNB neutrinos this energy in a coherent experiment would require moving with a velocity corresponding to a boost factor $\gamma = Q/T \simeq 10^{10}$. For comparison, γ at the LHC with protons is about 15000, or 5500 with Lead.

There are two ways to see an effect of the neutrino background using a beta-decaying nucleus: add a neutrino to it or remove a neutrino from it. Both were suggested by Weinberg in 1962. [5]

Adding a neutrino to the background is suppressed for momenta which are already occupied by the CNB thermal distribution, due to the fact that neutrinos are fermions and their chemical potential and average energy are similar. This is an $O(1)$ effect, if one can create neutrinos having the correct energy.

Removing a neutrino from the CNB using nuclei is known as neutrino capture (νC). Capture of reactor neutrinos is the original mode used to discover the neutrino. Recently there has been a surge of interest in this mode for detecting the CNB using β-decaying nuclei, which can have zero threshold. [6,7,8]

2. Pauli Blocking by The Cosmic Neutrino Background

The CNB is a thermal distribution in a particular frame u^μ which we assume to be coincident with the dipole from the Cosmic Microwave Background, which points in the direction $(264.85 \pm 0.10), (48.25 \pm 0.04)$ in galactic coordinates, with velocity 368 ± 2 km/s. Its thermal distribution is then

$$F_i(\vec{p}) = \left[e^{(p \cdot u - \mu_i)/kT} + 1 \right]^{-1} \tag{1}$$

for each species of neutrino and anti-neutrino i, having mass m_i and chemical potential μ_i and four-momentum p^μ in the cosmic rest frame $u^\mu = (1, \vec{0})$ and this reduces to the usual non-relativistic Fermi-Dirac distribution. The relativistic chemical potential is the Fermi energy at zero temperature, $\mu_i = E_F = \sqrt{m^2 + p_F^2}$, and the nominal Fermi momentum predicted by the standard cosmological model is $p_F = \sqrt[3]{3\pi^2 n} = \sqrt[3]{3\pi^2 \bar{n}} = 3.6 \times 10^{-5}$ eV, where n is the number density per flavor. We will refer to this as the "standard" chemical potential.

A process which emits neutrinos has a suppression $[1 - F_i(\vec{p})]$ due to Pauli blocking from this thermal distribution. This is independent of whether the neutrinos are described

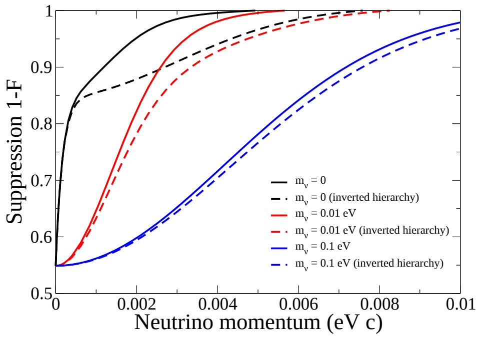

Fig. 1. Sum of suppression factor $1 - F_i(p)$ for three mass eigenstates vs. neutrino momentum for several values of the neutrino mass, assuming a standard chemical potential.

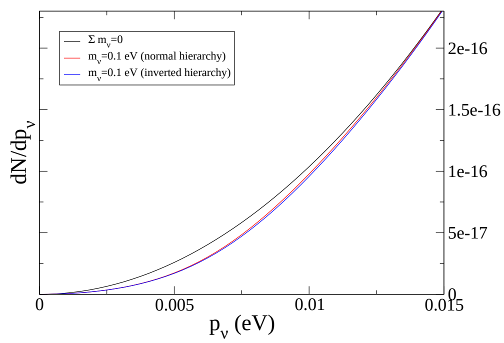

Fig. 2. The differential event rate as a function of neutrino momentum for several choices of neutrino mass and normal/inverted hierarchy, assuming a standard chemical potential and the kinematics of Tritium.

as a localized classical gas having small uncertainty $\Delta x \ll n^{-1/3}$ or a quantum liquid $\Delta x \gg n^{-1/3}$ for number density n. For a beta decay this is

$$d\Gamma = 2\pi \sum_i \int |M_i|^2 U_i^2 [1 - F_i(p)] dPS \tag{2}$$

where dPS is the differential phase space, U_i is the eigenvector component of neutrino mass eigenstate i in the electron neutrino direction, M is the matrix element of the emission of an electron-type neutrino with mass m_i, and one sums over the mass eigenstates since final state emitted particles must be in a mass eigenstate. This suppression factor is experimentally indistinguishable from 1 except in a region in which the emitted neutrino has the same energy as the CNB. We plot the suppression factor, summed over flavors in Fig.1

The Matrix Element for the beta decay is

$$
\begin{aligned}
|M|^2 = \frac{G_F^2}{128\pi^3 M_I^2} & (g_V + g_A)^2 (p_J \cdot p_e)(p_I \cdot p_\nu) \\
& + (g_V - g_A)^2 (p_I \cdot p_e)(p_J \cdot p_\nu) \\
& + (g_V^2 - g_A^2)(p_I \cdot p_J)(p_e \cdot p_\nu)
\end{aligned} \tag{3}
$$

where g_V and g_A are the vector and axial vector weak charges of the atom. For $I =$ neutron, $g_V = g_A = -1/2$. The matrix element also reaches a minimum $|M|^2 = 0$ at $p = 0$, so the event rate at $p = 0$ is zero. Because of this, the minimum in Fig.1 is deceptive. The differential event rate including the matrix element is plotted in Fig.2 for tritium, assuming a standard chemical potential.

To place a neutrino into the background with significant suppression, we need that the invariant $p \cdot u/kT < E_F/kT$. Since our velocity with respect to the cosmic rest frame is small ($\beta = \frac{v}{c} = 1.23 \times 10^{-3}$), one can ignore our velocity and pretend we can do the experiment in the cosmic rest frame.[1]

[1] One must use Special relativity and not Galilean relativity here. The atoms and electron may be non-relativistic, but the neutrino is relativistic.

In a normal β decay an atom I decays to atom J by emitting an electron or positron and an anti-neutrino or neutrino. If one can precisely measure the momenta of I, J, and $e^{\pm}$, one can solve for the neutrino momenta. This requires momentum resolution on each of order $\Delta p < \sqrt{2 m_\nu k T_\nu}$. If the initial state I is at rest, this corresponds to a temperature

$$T = \frac{2 m_\nu}{3 M_I} T_\nu \simeq 1.40 \times 10^{-9} \left(\frac{m_\nu}{\mathrm{eV}}\right) \left(\frac{\mathrm{amu}}{M_I}\right) \mathrm{K}:$$

Stated another way, the de Broglie wavelength of the neutrinos is 1.2 mm. Since the uncertainty on momentum scales with momentum, the initial state must have a similar de Broglie wavelength. Modern atomic Bose-Einstein Condensate and Degenerate Fermi Gas experiments using laser and evaporative cooling routinely reach 10^{-9} K today. Another promising technology to get to these precisions in the initial state is "Crystallized Beams". [9]

The final state of the decay is the atom J almost exactly back-to-back with the electron or positron. Similarly these final state particles must be measured with a precision

$$\frac{\Delta p}{p} \simeq \sqrt{\frac{2 m_\nu k T_\nu}{Q(Q + 2m_e)}} \simeq 1.33 \times 10^{-7} \sqrt{\frac{m_\nu}{\mathrm{eV}}} \sqrt{\frac{18\mathrm{keV}}{Q}}:$$

where in the last term we assume $Q \ll 2m_e$.

One might wonder if the effect shown here can impact experiments such as KATRIN which attempt to measure the neutrino mass using the highest energy electrons in a beta decay. KATRIN attempts to measure mass due to the change in slope and rate suppression near the endpoint, and they do not have the resolution to see the actual endpoint itself. Their resolution is approximately $\Delta E_e \approx 1$ eV. The effects here only effect the highest (electron) energy bin, and reduce the number of events there by $O(10^{-18} N)$ where N is the total decays they see. Existing experiments simply do not have the rate for this effect to be a concern.

3. Acknowledgements

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References

[1] A. Ringwald, arXiv:hep-ph/0505024.
[2] G. B. Gelmini, Phys. Scripta T121 (2005) 131 [arXiv:hep-ph/0412305].
[3] A. Ringwald and Y. Y. Y. Wong, JCAP 0412 (2004) 005 [arXiv:hep-ph/0408241].
[4] B. McElrath, arXiv:0812.2696 [gr-qc].
[5] S. Weinberg, Phys. Rev. 128 (1962) 1457.
[6] A. G. Cocco, G. Mangano and M. Messina, JCAP 0706 (2007) 015 [arXiv:hep-ph/0703075].
[7] R. Lazauskas, P. Vogel and C. Volpe, J. Phys. G 35 (2008) 025001 [arXiv:0710.5312 [astro-ph]].
[8] M. Blennow, arXiv:0803.3762 [astro-ph].
[9] H. Danared, A. Kallberg, K.-G. Rensfelt, and A. Simonsson, Phys. Rev. Lett. 88, 174801 (2002).