Zero Threshold Reactions for Detecting Ultra Low Energy Cosmic Relic Neutrinos

R.S. Raghavan
Institute of Particle, Nuclear and Astronomical Sciences
Virginia Polytechnic Institute and State University, Blacksburg VA 24060

Zero-threshold reactions such as electron capture, $\beta^+ \text{ and } \beta^-$ decay can be induced by ultra low energy cosmic relic neutrinos (CRN). I conclude that the CRN can be detected with a specific reaction signature and quantitatively measured with state of the art nuclear spectroscopic technologies. For current estimates of Pauli-limited number densities of CRN on earth, the detected CRN signals have the sensitivity to discover meV scale neutrino masses for which there are no strategies, much less, technologies at present.

The universal presence of 2K cosmic relic neutrinos (CRN) and the 3K cosmic microwave photon background (CMB) are keystones of modern cosmology. The experimental discovery of the CMB in 1965 and recent results from COBE and WMAP are landmark scientific events that have opened revolutionary perspectives on the structure and dynamics of the Universe. The CRN however, have not yet been discovered despite their basic importance. Because of the ultra low energy and the extremely weak interaction with matter, the detection of CRN poses arguably the ultimate challenge in experimental physics. Current thoughts for detecting CRN hinge on: 1) “Z-bursts” from annihilation of high energy cosmic ray $\nu$’s with CRN at the $Z$ resonance or 2) torques in ultra-sensitive Cavendish torsion balances due to the motion of the earth in the CRN sea. The consensus is that both proposals are far from feasible with current technology.

In this paper I discuss a possible approach for nuclear detection of the CRN that appears feasible with state of the art technology. The underlying principle is CRN-induced zero-threshold (ZTR) nuclear reactions such as electron-capture (EC), $\beta^+$ and $\beta^-$ decays. The measurements would also lead to the mass of the neutrino with sensitivities well beyond any known method including advanced tritium beta decay experiments currently in progress.

The CRN energies are ultra low, $E_\nu \sim 0.17 \text{ meV} \ll 2 \text{ eV}$, the current experimental mass limit. Thus, eV CRN are non-relativistic so that gravitational clustering in galaxies may increase the number density $N_\nu/\text{cc}$ significantly up to the limits due to the Pauli principle. For 1 eV CRN, $N_\nu/\text{cc}$ on the earth is estimated as:

$$N_\nu/\text{cc} = 2 \times 10^3 (m_\nu c^2 / 1 \text{ eV})^3 (v / 10^{-3} c)^3$$

since the earth moves at a speed $v \sim 10^{-3} c$ in our galaxy. The 1 eV CRN flux $\phi$ ($N_\nu \times v$) is:

$$\phi \sim (2 \times 10^3 / \text{cc} \times 3 \times 10^7 \text{ cm/s}) \times 6 \times 10^{10} / \text{cm}^2 \text{ s}$$

This flux is substantial and encourages methods for CRN detection. We set a working basis of $m_\nu c^2 = 1 \text{ eV}$ for our discussion below.

The central idea of a nuclear approach based on zero threshold reaction of CRN was pointed out by Weinberg as early as 1962 (before the advent of Big Bang Cosmology!). He suggested the case of CRN induced $\beta^-$decay and its application to tritium ($^3\text{T}$) decay. Up to now this idea has not borne fruit despite the extraordinary advances in the technology of $^3\text{T}$ $\beta$-ray spectrometry. I show below that the $^3\text{T}$ case is not the optimal choice for CRN detection (in contrast to end point spectral distortions) and suggest how the design of detecting CRN induced $\beta^-$decay can be significantly optimized.

In this work, with the central idea of ZTR as the starting point, I first consider CRN induced radiative EC decay:

$$\bar{\nu}_e + A(Z) + e^- \rightarrow A(Z-1) + \gamma(\text{ZTR})$$

Reaction (2) (the target $A(Z)$ is radioactive) has zero energy threshold.
\[ Q = (M(AZ) - M(AZ-1)) = \Delta M - B_{in} > 0 \quad (4). \]

\( B_{in} \) is the binding energy of the electronic shell from which EC occurs. It can thus be induced by \( \tilde{\nu}_r \) of any energy including ultra-low energy CRN. It is detectable via the mono-energetic \( \gamma \)-ray emitted in the two-body final state of (2) and competes with the normal EC decay of A(Z) (which emits a \( \nu_e \)). More relevant, the background arises from the \( \gamma \) continuum from 3-body radiative EC (internal bremsstrahlung IB).

\[ A(Z)+ e^- \rightarrow A(Z-1) + \nu_e + \gamma (IB) \quad (5). \]

The energy of the \( \gamma \) in (4) is,

\[ q(\gamma ZT) = Q + E(CRN)(\tilde{\nu}_\gamma) + (m_{\nu_e}c^2) - E_R \quad (6) \]

which occurs just beyond the end-point of the IB spectrum from (4). \( E(IB \gamma max) = Q \). \( E_R \) is the recoil energy of the daughter nucleus. Note that in (2), in addition to the vital zero threshold advantage, the final state phase space is provided by \( \gamma (ZT) \approx 1 \text{MeV} \), and not the \( \tilde{\nu}_r \) energy of the CRN, many orders of magnitude smaller.

Spectroscopic detection of \( \gamma(ZTR) \) from the CRN yields not only its flux (from the signal intensity) but the \( \nu m \) mass in two ways. First, the mass explicitly adds linearly to the ZTR signal energy (eq. (6)). Detection of this effect however, imposes very precise (1eV) knowledge of \( Q \) values and makes severe demands on energy resolution for detecting the mass shift in the presence of the background due to the IB (2). But secondly, the ZTR signal rate itself offers a direct probe of the \( \nu \) mass (via (1)) over the whole range of possible values, from “zero” to the current limit of 2 eV. Observation of the ZTR thus vitally bears not only on detecting the presence of CRN (cosmology) but also on the question of sub-eV \( \nu \) mass (particle physics).

We start with the standard formula for radiative reactions \(^9\):\[ \sigma = 4\pi \bar{\lambda}^2 \rho \Gamma (\omega_{\nu} / \omega_{\nu K}) \quad (7) \]

where \( \bar{\lambda} = (\hbar / p_{\nu e}) \) is the deBroglie wavelength of the CRN, \( \Gamma (\text{ev}) = \hbar / \tau \) (mean life) is the width of the EC decay. \( \rho \) is the number density of \( \tilde{\nu}_e \) / unit energy interval in the incident beam that satisfy energy conservation and cause the CRN absorption. For the ZTR, every incident \( \tilde{\nu}_r \) can activate the reaction so that \( \rho = 1 \text{eV} \) for \( \Gamma \) expressed in eV. \( (\omega_{\nu} / \omega_{\nu K}) \) is the radiative fraction given by the probability of normal radiative decay ((5) to K capture, given by: \(^{10}\)

\[ (\omega_{\nu} / \omega_{\nu K}) = (\alpha / 12 \pi) q_{in}^2 \quad (8) \]

where \( \alpha \) is the fine structure constant and \( q_{in} = (q(\gamma ZT)/m_{\nu e}c^2) \) using (4) and (6). We assume that the coupling to CRN-induced radiative decay is identical to that in the normal radiative decay (5).

The momentum \( p_{\nu e} \) is related as: \( p = (1/c)(\nu/c)(m_{\nu e}c^2) \) where \( \nu \) is the earth speed. Thus:

\[ \bar{\lambda}^2 = \hbar^2 c^2 / (m_{\nu_e}c^2)^2 (\nu/c)^2 \quad (9) \]

\[ \sigma = 4\pi \hbar^2 c^2 (\nu_{\nu} / \omega_{\nu K}) / (m_{\nu_e}c^2)^2 (\nu/c)^2 \tau \quad (10) \]

The CRN signal is \( R = \phi = \sigma N_{\nu} \nu = \sigma N_{\nu} (\nu/c)c. \) Using (8) (10) and (1)

\[ R = 4\pi \hbar^2 c^3 / (\nu_{\nu} / \omega_{\nu K}) / (m_{\nu_e}c^2/1\text{eV})/ (\nu/c) \tau \quad (10) \]

The branching ratio of CRN-radiative capture to normal K capture is \( K = R / \omega_{\nu K} = R (f_{\nuK} / t = \tau / \ln 2) \)

\[ K = (2a/3)x10^3 (\hbar c^3 / (\nu/c)) (m_{\nu_e}c^2/1\text{eV}) q_{in}^2 f_{\nu K} \quad (11) \]

The background from the IB of the normal EC in the window \( (\Delta E) \) (in \( m_{\nu_e}c^2/\text{units} \)) below the endpoint \( q_{in} \) is: \(^{12}\)

\[ B_{EC} / \omega_{\nu K} \sim (a / 3\pi) q_{in}^2 (\Delta E / q_{in})^3 \quad (12) \]

Thus the signal/background S/B at the position of the CRN signal measured with an energy resolution \( \Delta E \) is: \( S/B = K / B \). The CRN signal rate with a source of strength C Bq is \( S = CK / s. \)

To illustrate the design interplay, the typical EC decay of \(^{37}\text{Ar}\) with a decay energy of \( \sim (814 - 3) = 811 \text{keV} \), i.e. \( q_{in} = 2.5, f_{\nuK} = (f_{1/2}) / f_{1/2} = 1.3 \times 10^3 s / 35d = 4.2 \times 10^2 \) leads to

\[ K (^{37}\text{Ar}) \approx 1.36 \times 10^{12}, \quad m_{\nu_e}c^2 = 1 \text{eV} \quad (13) \]

If the experimental energy resolution of the CRN signal is \( \Delta E = 1 \text{keV} \), the background at the CRN signal (from (12)) \( 3.5 \times 10^{-12} \) so that the CRN-EC signal can be detected with \( S/B = 0.37 \).

\(^{37}\text{Ar}\) has been made in Mci amounts for calibrating the SAGE solar neutrino detector\(^{11}\). It is useful for CRN-EC spectroscopy since 1) the source production technology is at hand and it has been demonstrated to result in no troublesome impurities and 2) \(^{37}\text{Ar}\) decays by pure EC 100% to the ground state of \(^{37}\text{Cl}\). The only background is that due to the natural IB\(^{12}\).
With 1 Ci \(^{37}\)Ar, \(C = 3.7 \times 10^{11}/s\), this source will yield a CRN signal of \(KC = 0.37 / s\) or \(~1 \times 10^6\) events in one mean life of 50 days of \(^{37}\)Ar if \(m_{\nu} c^2 = 1 \text{eV}\) and the estimate (1) for \(N\), is valid. With a detection efficiency of \(10^{-2}\) and \(\Delta E\sim 1 \text{keV}\) at \(~1 \text{MeV}\) typical for a \(~4 \pi\) envelope of modern Ge detectors, this implies a net signal of \(~15000\) on-line in a small accelerator or in a nuclear reactor since the source can be produced continuously with a short lifetime is not a basic experimental obstacle (122s) and many others. These activities are readily produced in exothermic reactions using small accelerators. Taking the case of \(^{15}\)O with \(f_{1/2} = 4000 \text{s}\) which implies \(f_{\beta} \sim 33\),

\[
K_{\beta^+} (^{15}\text{O}) = 5.5 \times 10^{-8}; \quad (m_{\nu} c^2 = 1 \text{eV}) \quad (16),
\]

a factor \(3 \times 10^4\) more favorable than the CRN-EC effect on \(^{37}\)Ar (eq. 13). The \(\beta^+\) endpoint is \((2.75\text{-}1.02) \text{MeV}\) so that, even with modest energy resolution \(\sim 1 \text{keV}\), \(B_{\beta^+} = (10/1.73)^3 = 2 \times 10^{-10}\) that promises \(S/B \sim 200\). The technology of \(\beta^+\) spectrometry for this effect can be designed similar to KATRIN (e.g. with electrostatic filtration of most of the \(\beta^+\) in the continuum, detectors far away from the source etc), but with much relaxed design constraints. The experimental live time is not limited by the target lifetime as in the case of \(^{37}\)Ar. Clearly, neutrino masses in the range of a few meV can be discovered by the CRN-\(\beta^+\) effect.

We now examine the CRN-\(\beta^+\) effect

\[
\nu_e + A(Z) + \rightarrow A(Z+1) + e^- \quad (17).
\]

In this case the derivations are identical to those for the \(\beta^+\) case. Thus, applying (15) to \(^{3}\)T decay for which \(f_{\beta} = 1100 \text{s}/18 \text{y} = 2 \times 10^{-6}\).

\[
K_{\beta} (^{3}\text{T}) = 3.4 \times 10^{-15} \quad (m_{\nu} c^2 = 1 \text{eV}) \quad (18).
\]

The KATRIN experiment, designed for sub-eV neutrino masses via endpoint measurements, expects an energy resolution of \(~1 \text{eV}\). This implies a background per decay of \(~2 \times 10^{-13}\) for the CRN-\(\beta\) signal of (18). Thus even with such an extraordinary energy resolution, the experiment is likely to yield only an \(S/B \sim 10^{-2}\), i.e. results of marginal significance even with many years of data. The \(^{3}\)T case is thus inappropriate for CRN detection mainly because of the very unfavorable \(f_{\beta}\) factor of the \(^{3}\)T decay.

Short-lived high energy \(\beta\) decays are far more optimal targets as in the case of the CRN-\(\beta^+\) effect above. The arguments are the same. For example, in the case of \(~0.8 \text{sec}\) decay of \(^{4}\)He with \(f_{1/2} \sim 800 \text{s}\) \(f_{\beta} \sim 10^3\) and \(E\beta(\text{max}) = 3.5 \text{MeV}\). For this case,

\[
K_{\beta} (^{4}\text{He}) = 1.7 \times 10^{-6} \quad (m_{\nu} c^2 = 1 \text{eV}) \quad (19)
\]

which can be observed even with \(~10 \text{keV}\) energy resolution with \(S/B \sim 100\). The experiment is thus sensitive to neutrino masses of a few meV. The technology can be based on conventional beta-ray spectrometry, far more modest than KATRIN. \(^{4}\)He can be continuously produced in an accelerator or in a reactor using \(^{7}\)Be (\(n, \alpha\))\(^{4}\)He.

The basic idea of ZTR-CRN that rates of radioactive beta decay in all its modes is affected by the universal presence of the CRN sea. Several reasons combine to open these remarkably sensitive perspectives on the CRN detection: 1) the zero threshold renders these reactions sensitive to the ultra low CRN...
energies; 2) the very large ν deBroglie wavelengths due to the very low neutrino momenta, (the very property that has so far inhibited consideration of nuclear reactions for the purpose), is the crucial factor that leads to the high sensitivities to CRN-induced effects; 3) Given the CRN flux varies as (m)^3 and the CRN effect varies inversely as the square of the momenta, i.e. as 1/(m)^2, the CRN-effect uniquely depends linearly on m, (recall that in the only other methods for m, νββ decay and β-end point studies, the mass effect is ~ (m)^3)

Finally, a specific signature can be devised for the CRN effect in the short lived nuclei ^4He and ^15O. These activities are accelerator produced with non-zero laboratory velocity which adds to the earth velocity v, thus increasing the CRN momentum and decreasing the CRN effect. The maximum effect thus occurs when the nuclides are brought to rest implanted in a matrix. By measuring the effect in flight as a function of the ion velocity, the CRN effect can be varied, thus providing a specific signature. 1 keV ion energy implies ion velocity ~ equal to the earth velocity, which decreases the CRN effect by a factor ~4.

I have described specific experimental scenarios for pursuing all three CNR effects (EC, β' and β) which probe relic neutrinos as well as antineutrinos independently with experimental signatures. Experiments such as KATRIN, even though developed to extraordinary technical perfection, are relatively insensitive to the CRN effect or to meV scale neutrino masses, only because T^1 decay is not the optimal case for these investigations. On the other hand, the CRN effects described here yield the product (N,m) while KATRIN measures m, independently. Thus, up to the sensitivity limits of ~200 meV expected in KATRIN the two measurements can break the coupled result and solve both problems neatly.

In summary, CNR induced weak decays (EC, β' and β) offer eminently practical tools for unambiguously detecting and quantitatively measuring the CNR, indeed with an experimental signature. With the CNR effect depending linearly on the neutrino mass these reactions are also ultra-sharp tools for discovering extremely small (meV scale) neutrino masses. For both these purposes there are few viable strategies, much less, technologies at present. The ZTR methods probe both relic electron neutrinos and antineutrinos independently, testing if the number densities of the two CRN species are equal.

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1 A. A. Penzias & R. W. Wilson, ApJ, 142, 419 (1965)
2 For latest information on WMAP see http://map.gsfc.nasa.gov/index.html
3 For a review of CRN detectability, see G. Gelmini, Phys. Scripta 121 131 (2005)
4 T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982)
5 C. Hagmann astro-ph/9902102 v1 and references therein.
6 The KATRIN home web site is: http://www-ik.fzk.de/~katrin/index.html
7 C. Weinheimer et al, Phys. Lett. B460, 219 (1999); V. Lobashev et al, Phys. Lett. B460, 277 (1999).
8 S. Weinberg, Phys. Rev. 128, 1457 (1962); J. M. Irvine & R. Humphreys, J. Phys. G9, 847 (1983)
9 L. A. Mikaelyan et al, Soviet J. Nucl. Phys. 6, 254 (1968). Eq. 7 follows this work which however was applied to induced EC in a Q >0 reaction e.g. reactor neutrinos incident on a stable target, for which the neutrino energy must exceed the Q value of the reaction. Thus the proper value of ρ at the “resonance energy” = Q must be applied. In our case every neutrino is in “resonance” since Q < 0, thus ρ = 1 for every incident neutrino.
10 W. Bambynek et al Rev. Mod. Phys, 49, 77 (1977).
11 V. Gavrin et al, Phys. Rev. C73, 045805 (2005)
12 V. Gavrin, Private communication
13 A monoenergetic line of 498 keV in the β decay of ^115In (Eβ(max)~498 keV) with a branching K~10^-6 was reported by C. Cattadori et al, Nucl. Phys. A748, 333 (2005) (see talk by V.Tretyak, http://www.nanp.ru/docs/tretyak.pdf). The authors concluded that the observed γ-ray line (not an electron) arose from a very low energy (<2 keV) beta-branching to the first excited state at ~498 keV in the daughter nucleus ^115Sn. Is this line a possible CRN effect? The t_β in this case (from Tretyak) is (t_β/2 = (4×10^11 s/ t_1/2 =10^28s ) = 10^-17, so that K (CRN) (115In) ~ 10^-26 <<<10^-6 observed in this experiment.