Prospects for Observing Cosmic Neutrino Background

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- Properties of the cosmic neutrino background (relic neutrinos)
- Brief review of previous proposed ideas for detection
- Recent development

Expected properties of the (yet unobserved) cosmic neutrino background (CNB) versus the cosmic microwave background (CMB)

	CMB	CNB	Relation
Temperature	2.73K	1.9 K (1.7 x 10^{-4} ev)	$T_\nu/T_\gamma = (4/11)^{1/3}$ $=0.714$
Decouple time	3.8 x 10^5 years	~ 1 sec	
Density	~ 411 / cm^3	~ 56 / cm^3 (per flavor, $n_\nu = n_{\nu\text{-bar}}$)	$n_\nu = (3/22)\, n_\gamma$

- CNB took a snapshot of the Universe at a much earlier epoch than CMB n_ν
- Since $\Delta m_{21}{}^2 = (8.0 \pm 0.3) \times 10^{-5}$ ev^2, and $|\Delta m_{32}{}^2| = (1.9 \rightarrow 3.0) \times 10^{-3}$ ev^2, at least two of the three neutrinos have masses higher than 10^{-2} ev, and these two types of CNB are non-relativistic ($\beta << 1$)

Non-standard cosmic neutrino background

- In inflationary models, CNB density depends on the "reheating temperature" T_R :

  $T_R \geq 8\text{MeV} \Rightarrow n_\nu$ agrees with standard prediction

  $T_R = 5\text{MeV} \Rightarrow n_\nu$ drops to ~90% of the standard prediction

  $T_R = 2\text{MeV} \Rightarrow n_\nu$ drops to ~3% of the standard prediction

- Non-standard models allow

  $n(\nu) \neq n(\overline{\nu})$

- Non-standard models also allow

  $n(\nu_e) \neq n(\nu_\mu) \neq n(\nu_\tau)$ at production

  (flavor oscillation would have removed this asymmetry)

Incomplete list of proposed searches for CNB

1) Coherent ν-nucleus scattering (effect of order G_F^2)

(Zeldovich and Khlpov, 1981; Smith and Lewin, 1983; Duda, Gelmini, Nussinov, 2001)

For CNB, $T_\nu \simeq 10^{-4}$ ev, $\lambda_\nu \simeq 2.4$ mm

$$\sigma(\nu\text{-nucleon}) \sim \mathrm{G}_\mathrm{F}^2 E_\nu^2/\pi \simeq 5\times 10^{-63}\, cm^2 \text{ (Relativistic)}$$

$$\sim \mathrm{G}_\mathrm{F}^2 m_\nu^2/\pi \simeq 10^{-56}\left(\frac{m_\nu}{ev}\right)^2 cm^2 \text{ (Non − Relativistic)}$$

- ν – nucleus coherent scattering ⇒ enhancement factor of $\mathrm{A}^2 \approx 10^4$
- coherence over CNB wavelength ⇒ enhancement factor of $\sim 10^{20}$

(coherence over a volume of $(\lambda_\nu)^3$ containing $\sim 10^{20}$ nuclei)

Isotropic CNB flux ⇒ net force = 0

From COBE dipole anisotropy ⇒ $v_{sun} = 369 \pm 2.5$ km/s (CNB is non-isotropic, just like the dark matter)

⇒ net acceleration due to "neutrino wind" $\sim 10^{-26}$ cm/s^2 on grain of size λ_ν

2) “Neutrino Optics” (effect linear in G_F)

(R. Opher, 1974; R. Lewis, 1980)

Total reflection or refraction of CNB on a flat surface

Index of refraction, $n = p'/p$, and $n - 1 \sim G_F$

Later, Cabibbo and Maiani showed that

$$\vec{F} \sim G_F \int d^3x \rho_A(x) \vec{\nabla} n_\nu(x)$$

Effect is only due to the gradient of $n_\nu(x)$,

and again negligible

3) Torque exerted on a polarized target (effect linear in G_F)

(Stodolsky, 1974)

For a polarized target (magnetized iron),

there is an energy split of the two spin states

of electron in the sea of the CNB

The split is proportional to $n_\nu - n_{\bar{\nu}}$

(no effect for $n_\nu = n_{\bar{\nu}}$)

4) Astrophysical search with ultra-high energy neutrinos (Z-resonance)

(T. Weiler, 1982, 1999)

$\nu + \overline{\nu} \rightarrow Z^0$ resonance formation from interaction of ultra-high energy incident neutrinos with CNB

$$E_\nu^{res} = \frac{m_Z^2}{2m_\nu} = 4.2\times 10^{21}\left(\frac{1\text{ev}}{m_\nu}\right)\text{ev}$$

(Energy depends on the rest masses of neutrinos)

$$\sigma(\nu + \overline{\nu} \rightarrow Z^0) \simeq 4\times 10^{-32}\, cm^2$$

Signatures:

a) Dip in the UHE neutrino energy spectrum at energy $E_\nu \geq 10^{22}$ ev (A possible dip in UHE proton could also come from $p + \overline{\nu}_e \rightarrow e^+ + n$, see W. Hwang and B.Q. Ma, astro-ph/0502377)

b) "Z-burst"

Observation of UHE p, n, γ, and ν from decay of Z^0

However, sources of UHE neutrinos with $E_\nu \geq 10^{22}$ ev might not exist.

5) Capture of CNB on radioactive nuclei

A very old idea: S. Weinberg, 1962

Consider tritium beta-decay:

$$a)\ {}^{3}H \rightarrow {}^{3}He + e^{-} + \overline{\nu}_e$$

This is a 3-body β-decay with Q-value of

$$Q_a = M({}^{3}H) - M({}^{3}He) - M(e^{-}) - M(\overline{\nu}_e)$$

where $M(x)$ refers to mass of particle x

Now consider the CNB capture reaction:

$$b)\ \nu_e + {}^{3}H \rightarrow {}^{3}He + e^{-}$$

This is a 2-body reaction with the Q-value of

$$Q_b = M(\nu_e) + M({}^{3}H) - M({}^{3}He) - M(e^{-})$$

It follows that

$$Q_b = Q_a + 2M(\nu)$$

5) Capture of CNB on radioactive nuclei (continued)

For massless neutrinos, $M(\nu) = 0$, and we have

$$Q_a = Q_b$$

Note that the conventional definition of Q-value for the β-decay, Q_β, assumes $M(\nu) = 0$, hence

$$Q_\beta = Q_a + M(\nu)$$

The maximal energy for electrons from the

$$^3H \to {}^3He + e^- + \bar{\nu}_e$$

β-decay is the end-point energy (ignoring recoil energy)

$$T_a = Q_a = Q_\beta - M(\nu)$$

Electrons from CNB capture reaction are mono-energetic:

$$T_b = Q_b = Q_\beta + M(\nu)$$

(Q_β= 18.6 KeV for tritium β-decay)

It follows that

$$T_b = T_a + 2M(\nu)$$

5) Capture of CNB on radioactive nuclei (continued)

To check the feasibility of separating the CNB capture peak from the end-point, one need to consider

- Neutrino masses
- Experimental energy resolution
- Any local clustering of CNB due to gravity?
- Capture cross section on radioactive nuclei
- Size of the tritium source

Capture rate per tritium atom:

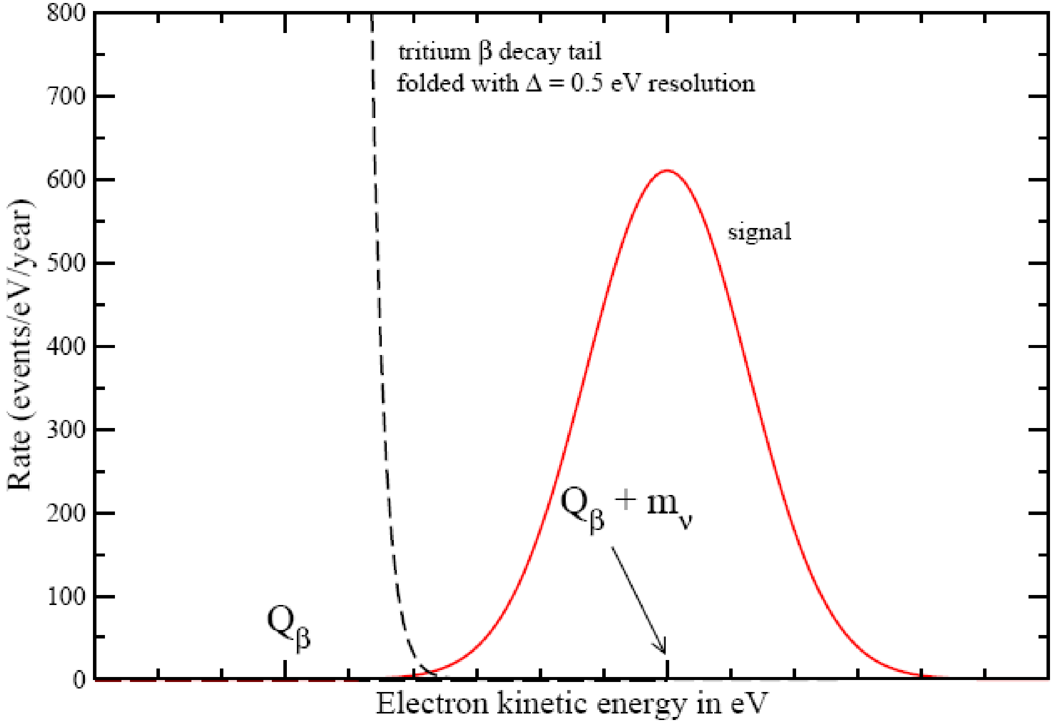
$$R = \sigma \times v_\nu \times n_\nu \simeq 10^{-32} / s$$

Note that for exothermal reaction, $\sigma \times v_\nu$ is constant for small v_ν

$$(\sigma \times v_\nu \simeq 7.6 \times 10^{-45} cm^2 \cdot c)$$

5) Capture of CNB on radioactive nuclei (continued)

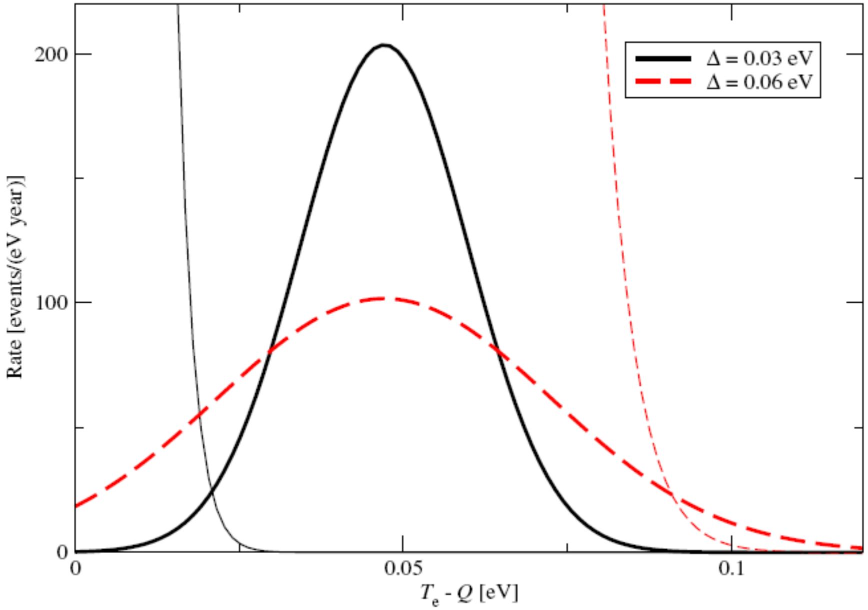
- Neutrino masses: $M(\nu)$=1ev (mass degeneracy of three neutrinos)
- Experimental energy resolution : Δ=0.5ev
- Any local clustering of CNB due to gravity? $n_\nu / < n_\nu >= 50$
- Size of the tritium source: 100 grams



Lazauskas, Vogel, Volpe, J. Phys. G. 35 (2008) 025001

5) Capture of CNB on radioactive nuclei (continued)

- Neutrino masses: $M(\nu)$=0 ev (for the lightest neutrino, assuming inverted mass hierarchy, the other two massive neutrinos are nearly degenerate)
- Experimental energy resolution : Δ=0.03 (0.06) ev
- Any local clustering of CNB due to gravity? $n_\nu / < n_\nu >= 1$
- Size of the tritium source: 100 grams



M. Blennow, Phys. Rev. D 77 (2008) 113014

5) Capture of CNB on radioactive nuclei (continued)

- Is there a way to INCREASE the energy separation between the electrons from the β-decay background and the CNB capture signals?
- How about boosting the momentum of the tritium relative to the sea of CNB? (by accelerating the tritium)?
- Now consider a tritium accelerated to an energy corresponding to $E(^3H)/m(^3H)=\gamma$. It is simple to show that in the center-of-mass frame of $^3H+\nu$, the total energy is equal to $\sqrt{s}=m(^3H)+\gamma\cdot m(\nu)$
- This means that electron emitted from the CNB capture would have an energy larger by $\gamma\cdot m(\nu)$ relative to case when a tritium is at rest.
- On the other hand, electrons from the tritium β-decay would still have the same end-point energy in the tritium rest frame.
- This implies the separation between the energy of CNB capture electron and β-decay end-point is now increased by an amount $\sim\gamma\cdot m(\nu)$.

5) Capture of CNB on radioactive nuclei (continued)

- We need to boost the electrons back to the lab frame, since the detectors will only measure the electron energy in the lab frame.
- It is interesting that one would gain another important factor for electrons emitted along the direction of the tritium momentum. Consider the Lorentz transformation:

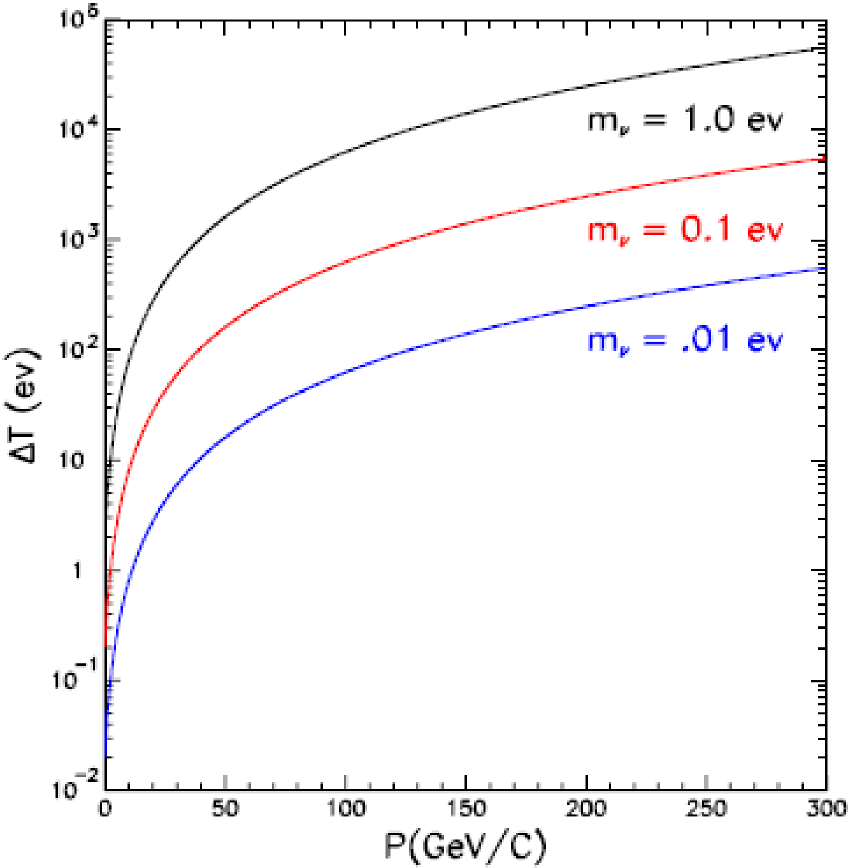
  $E_1' = \gamma E_1 + \beta\gamma P_1; \quad E_2' = \gamma E_2 + \beta\gamma P_2$

  where E and E' are the electron energies in the c.m. frame and the lab frames ,respectively. The subscripts 1 and 2 refer to electrons emitted in the CNB capture and β-decay, rspectively. We have

  $E_1' - E_2' = \gamma(E_1 - E_2) + \beta\gamma(P_1 - P_2) \sim 2\gamma(E_1 - E_2)$ for $\beta \to 1$
- This shows that the energy separation between electrons emitted in the forward angles from the CNB capture and the electrons from the β-decay is further increase by a factor of $\sim 2\gamma$!! This amounts to a separation of $\sim 2(1+\gamma)\gamma m_\nu$ in the relativistic limit.

5) Capture of CNB on radioactive nuclei (continued)

- We have carried out calculations for various neutrino masses over a wide range of tritium momentum:



ΔT is the separation of the kinetic energy for electrons emitted at forward angle from the CNB capture and electrons at end-point from the tritium β-decay.

The figure shows that ΔT becomes very large for high energy tritium beam. Note that P=300 GeV/c can be achieved at the RHIC accelerator.

Summary

- Observation of Cosmic Neutrino Background would have tremendous impact on our knowledge of Universe at the very early stage.
- It would also have important impact on our knowledge on neutrino physics (mass hierarchy, Dirac versus Majorana), as well as developing techniques to detect very low energy neutrinos from other sources (solar, supernova, geo, reactor…).
- Many interesting ideas have been proposed in the past. None of them proved to be viable.
- The recent proposal of "capture on radioactive nuclei" seems promising. More study is required.
- It remains a great challenge to come up with new idea for observing the CNB.

References

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