Detection of the 2 Kelvin Cosmic ν Background

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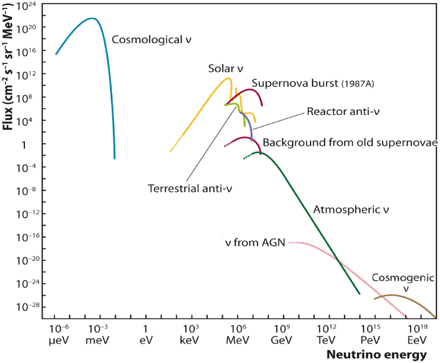


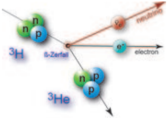
Figure: Flux density at earth's surface due to natural and reactor neutrinos (Eur. Phys. J. H **37**, 515 (2012) ,arXiv:1207.4952 [astro-ph.IM])

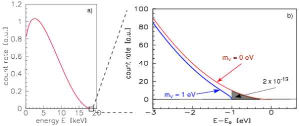
- The CνB is a degenerate Fermi sea of neutrinos that filled the universe **[S. Weinberg, Phys. Rev. 128, 1457 (1962)]**
- Decoupled from photons, baryons, etc. at $t \sim 1s$ ($T^{\nu}_{dec} \sim 1MeV$)
- Current temperature of CνB is about $2K(\sim 0.1meV)$
- Current density (all flavors of ν and $\bar{\nu}$ combined) $n \sim 300cm^{-3}$
- Flavor states decohered $\Longrightarrow$ currently in mass eigenstates

Proposed experiments

β endpoint experiments: Method

β Decay: Used for measuring mass of neutrino (KATRIN, Project 8)

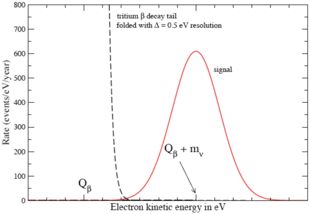




- Non-zero mass of neutrino will distort the β decay tail

Neutrino Capture: Potentially a method to measure the CνB (PTOLEMY)

$$^3H + \nu_e \rightarrow ^3He^+ + e^-$$



- Signal is a mono-energetic electron beyond β decay tail
- Process is exothermic, no threshold energy

β endpoint experiments: PTOLEMY

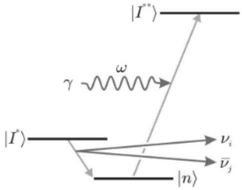
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield (PTOLEMY)

Target: Large active target ~1MCi (100 grams of Tritium)

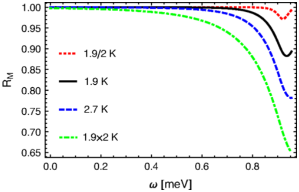
Energy Resolution: High resolution ($\Delta E < m_\nu$) required for signal-background separation. Neutrino mass mixing parameters indicate mass eigenstates at least as massive as 0.05 eV while cosmological bounds < 0.3 eV. Radio-Frequency techniques strive to reach sub-eV energy resolution.

Background: Below microHertz of background rate in signal region (PTOLEMY expected signal rate of approximately 0.3 μHz of neutrino capture events)

Indirect detection by atomic de-excitation



Energy level diagram [Phys. Rev. D 75, 113007]



Spectral distortion caused by Pauli blocking of relic neutrinos assuming the lightest neutrino mass is 5meV, $\epsilon_{eg} = 11$meV and zero chemical potential.

[Phys. Rev. D 91, 063516]

- Radiative emission of neutrino pairs (RENP) can happen as atoms de-excite from a metastable state.
- Use laser to enhance emission probability.
- Compare LH and RH circular polarizations to reject non-parity-violating (non-weak) backgrounds (i.e. photon emission).
- Expected rate for 10^{16} atoms $\sim 1/\text{day}$.
- RENP spectrum is modified in the presence of ambient relic neutrinos by a factor of $(1 - f_i)(1 - \bar{f}_j)$, where f_i $(\bar{f}_j)$ is the momentum distrubution function of mass eigenstate ν_i $(\bar{\nu}_j)$.
- Various caveats such as finding the right atom. No experiment has looked for this process.

Our Ideas

Superconductor experiments

- The binding energy of Cooper pairs in superconductors is $\mathcal{O}(\text{meV})$.
- Held near its transition temperature, depositions of this order of energy create sharp changes in the resistance of the semiconductor.
- Intriguingly, this is the same order of energy as the average neutrino in the $C\nu B$.
- However, even electrons are much more massive than neutrinos that only a tiny fraction of the neutrino energy is transferred in elastic scattering at $C\nu B$ energies, so this idea does not apply well to the question.
- This idea is pursued in the context of light WIMP detection by Hochberg et al. (1504.07237).

Proton-Stimulated Inverse β Decay

What if we invert the energy distribution of a typical Inverse Beta Decay neutrino experiment?
The rate of inverse beta decay in the laboratory frame is

$$\Gamma \sim 10^{-27} \left(\frac{E_p}{GeV} \right)^2 N_{particles} Hz$$

For nominal beam parameters (e.g. the high-luminosity LHC) with $E_p \sim 7$ TeV and $\sim 3 \times 10^{15}$ particles per beam (and two beams),

$$\Gamma \sim 2 \times 10^{-4} Hz$$

which is ~24 events per day along the entire 27 km in circumference.
This comes with significant experimental challenges:

- For 100 events per year, we then only have to instrument ~300 m of beam tube cumulatively
- Background primarily high energy neutrinos; need at least 100 keV resolution to resolve separate cosmic neutrino signal
- We need high (>90%) reconstruction efficiency for coincident neutron-positron pairs

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However...

This experiment would be looking to detect proton Inverse β Decay

$$p + \bar{\nu}_e^{C\nu B} \longrightarrow n + e^+$$

Which is allowed only if the center-of-mass energy is above the threshold

$$\sqrt{s} \geq M_n + m_e - M_p - m_\nu \simeq M_n + m_e - M_p \simeq 1.80 \text{ MeV}$$

For $E_{\nu^{C\nu B}} \simeq m_\nu$ we have $\sqrt{s} = \sqrt{2E_p m_\nu}$ so that a proton beam with energy E_p can only observe this process if

$$m_\nu \geq \frac{(M_n + m_e - M_p)^2}{2E_p} \quad \text{i.e.} \quad m_\nu[\text{eV}] \gtrsim \frac{1.63}{E_p[\text{TeV}]}$$

This means that LHC ($E_p \sim 7 TeV$) can only probe m_ν regions of $m_\nu \gtrsim 0.23$ eV; however, it's close. If next generation of accelerators were to have a beam energy that was higher by a factor of 5 or more, we would be guaranteed to be above threshold for at least one neutrino.

Outtakes: Ideas that didn't quite pan out

Detection of $W^{\pm}$ peak from $e^{-} + \nu_e^{C\nu B}$ scattering: can be performed at e^{-} accelerator. Required beam energy is YeV i.e. 10^{24} eV to achieve $\sqrt{s} \sim 100$ GeV. ν accelerator can look for Z^0 peak with same energy issue, cleaner signature but need ν beam.

Annual modulation of deflection of torsion pendulum: A Cavendish-type torsion balance that measures the "cosmic ν wind" due to the solar system motion through the galaxy. We need 2-3 orders magnitude higher percision than today's technology.

"$1\nu\beta\beta$": Idea is to detect ${}^{A}_{Z}X + \nu_e^{C\nu B} \rightarrow {}^{A}_{Z+2}\, Y + \bar{\nu}_e + 2e^{-}$ at $0\nu\beta\beta$ experiments; hope is to exclude energetic ν because ${}^{A}_{Z}X + \nu_e^{C\nu B} \rightarrow {}^{A}_{Z+1}\, Z + e^{-}$ is above threshold. $\text{Rate}_{1\nu\beta\beta}/\text{Rate}_{2\nu\beta\beta} \sim 10^{-21}$

Ultrarelativistic water Čerenkov detector: Idea is to detect $\nu^{C\nu B}$ by being in a reference frame in which the products of their interactions emit Čerenkov light. Requires a detector to be moving really fast.

Conclusions

Conclusions

- There is increasing interest in a CνB experiment due to advances in low-background and high-resolution detector technology
  - For current technologies, cost and detector mass are the main current limitations
  - The first cosmic neutrino detector will have to be very different from our current neutrino detectors!
- Current proposals include ideas from particle physics, condensed matter and atomic physics
- Many of these ideas may need to wait for significant technological advances
  - If we could generate YeV particle beams, many of the experiments would be immediately feasible with reasonable detector masses
  - Very high energy resolution is a requirement for any cosmic neutrino detector, given the unavoidable background from cosmogenic neutrinos and other low-background processes