Big Bang Relic Neutrinos

Lindley Winslow
October 24, 2012
Sources and their Fluxes....

These are the neutrinos for today!
There are a lot of them!
Why do we know they should be there?

- The same physics that predicts the Cosmic Microwave Background (CMB) predicts the Cosmic Neutrino Background (CNB).

- The helium abundance from Big-Bang Nucleosynthesis (BBN) is sensitive to their coupling to neutron proton.

- They will effect structure formation in the early universe.
When the universe is young and hot...

\[ \nu_i \nu_j \rightarrow \nu_i \nu_j \]
\[ \nu_i \bar{\nu}_j \rightarrow \nu_i \bar{\nu}_j \]
\[ \nu_i e^- \rightarrow \nu_i e^- \]
\[ \nu_i \bar{\nu}_j \rightarrow e^+ e^- \]

CNB

\[ \text{CMB} \]
Knowledge of the Relic Neutrino Spectrum

- After neutrinos decouple, photons can still continue heating.
- Photon/neutrino temperature directly related to each other.

\[
\begin{align*}
\nu_i \nu_j &\to \nu_i \nu_j \\
\nu_i \bar{\nu}_j &\to \nu_i \bar{\nu}_j \\
\nu_i e^- &\to \nu_i e^- \\
\nu_i \bar{\nu}_j &\to e^+ e^- \\
\end{align*}
\]

Decouple at \(\sim 1\ \text{MeV}\).

\[
e^+ e^- \to \gamma\gamma \quad \text{turn off}
\]

\[
T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma
\]

Temperature of neutrinos tied to gamma temperature.
Knowledge of the Relic Photon Spectrum

- The cosmic microwave background illustrates a perfect blackbody spectrum:

$$T_\gamma = 2.725 \pm 0.002 K$$

- Observation of the cosmic microwave background is now a cornerstone of cosmology. Likewise, it is a standard prediction of cosmology and the Standard Model.
Signal Properties

- Cosmological neutrinos (or the CvB) are inherently connected to the photon microwave background. However, there are significant differences between the two.

- Some characteristics:
  
  - The CvB **temperature** is related to the photon temperature (including reheating).
  
  - The CvB is inherently a gas of spin 1/2 particles: obey **Fermi-Dirac statistics** rather than Bose-Einstein).
  
  - The CvB **density** is predicted directly from the photon density.

\[
f_i(p, T) = \frac{1}{e^{\frac{E_i(p) - \mu_i}{T}}}
\]

<table>
<thead>
<tr>
<th>Temperature (Now)</th>
<th>Bose-Einstein ((\gamma)'s)</th>
<th>Fermi-Dirac ((\nu)'s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.725 K</td>
<td>(\frac{3}{\pi^2} g T^3_{\gamma})</td>
<td>(\frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3_{\nu})</td>
</tr>
<tr>
<td></td>
<td>(\frac{1}{30} g T^4_{\gamma})</td>
<td>(\frac{7}{30} \frac{\pi^2}{8} g T^4_{\nu})</td>
</tr>
</tbody>
</table>

From CMB, the neutrino density is \(\sim 110 \, \text{\(\nu\)'s/cm}^3\) per flavor.

(neutrino and anti-neutrino)
Primordial Nucleosynthesis

- Eventually neutrinos also decouple from neutrons and protons (below 1 MeV)

- This governs the production rate of light elements. These include elements such as $^2\text{H}$, $^3\text{He}$, $^4\text{He}$, and $^7\text{Li}$.

\[ \rho_\nu = \rho_\gamma + \rho_\nu = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma \]

- These abundances depend on the baryon density ratio, $\eta_{10}$, and the expansion rate of the universe.

\[ \eta_{10} \equiv 10^{10} \left( \frac{n_B}{n_\gamma} \right) \]

This quantity is unchanged at BBN, recombination, and now
New BBN limits on Physics Beyond the Standard Model from $^4\text{He}$

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University of Minnesota, Minneapolis, MN 55455, USA

Abstract

A recent analysis of the $^4\text{He}$ abundance determined from observations of extragalactic HII regions indicates a significantly greater uncertainty for the $^4\text{He}$ mass fraction. The derived value is now in line with predictions from big bang nucleosynthesis when the baryon density determined by WMAP is assumed. Based on this new analysis of $^4\text{He}$, we derive constraints on a host of particle properties which include: limits on the number of relativistic species at the time of BBN (commonly taken to be the limit on neutrino flavors), limits on the variations of fundamental couplings such as $\alpha_{em}$ and $G_N$, and limits on decaying particles.
Three neutrinos with large errors.
Large Scale Structure

- Neutrinos can also affect the clustering of galaxies (affected both by the number of neutrino species and the mass of the neutrinos)

\[
\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \sum_i \frac{m_{\nu,i} n_{\nu,i}}{\rho_{\text{critical}}}
\]
Why neutrinos can’t be dark matter?

http://cosmicweb.uchicago.edu/filaments.html
\[ \sum m_\nu < 0.58 \text{ eV (95\% CL)} \quad (\text{for } w = -1). \]

As the matter-to-radiation ratio was smaller than one would naively expect, it would accelerate the decay of gravitational potential around the decoupling epoch. This leads to an enhancement in the so-called early integrated Sachs–Wolfe (ISW) effect. The larger \( \sum m_\nu \) is, the larger early ISW becomes, as long as the neutrinos were still relativistic at the decoupling epoch, that is, \( \sum m_\nu \lesssim 1.8 \text{ eV}. \)

The large ISW causes the first peak position to shift to lower multipoles by adding power at \( l \sim 200 \); however, this shift can be absorbed by a reduction in the value of \( H_0. \) This is why \( \sum m_\nu \) and \( H_0 \) are anticorrelated (see Ichikawa et al. 2005, for a further discussion on this subject).

It is the BAO distance that provides a better limit on \( H_0 \), as BAO is an absolute distance indicator. The SN is totally insensitive to \( H_0 \), as their absolute magnitudes have been marginalized over (SN is a relative distance indicator); however, the SN data do help reduce the correlation between \( w \) and \( H_0 \) when \( w \) is allowed to vary. As a result, we have equally tight limits on \( \sum m_\nu \) regardless of \( w \).

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**Fig. 7.** — The WMAP 7-year temperature power spectrum (Larson et al. 2010), along with the temperature power spectra from the ACBAR (Reichardt et al. 2009) and QUaD (Brown et al. 2009) experiments. We show the ACBAR and QUaD data only at \( l \geq 600 \), where the errors in the WMAP power spectrum are dominated by noise. We do not use the power spectrum at \( l > 2000 \) because of a potential contribution from the SZ effect and point sources. The solid line shows the best-fitting 6-parameter flat \( \Lambda \)CDM model to the WMAP data alone (see the 3rd column of Table 1 for the maximum likelihood parameters).
Figure 17. Constraint on the total mass of neutrinos, $\sum m_\nu$ (Section 6.1.3). In all panels, we show the WMAP-only results in blue and WMAP+BAO+SN in red. (Left) Joint two-dimensional marginalized distribution of $H_0$ and $\sum m_\nu$ (68% and 95% CL). The additional distance information from BAO helps reduce the correlation between $H_0$ and $\sum m_\nu$. (Middle) The WMAP data, combined with the distances from BAO and SN, predict the present-day amplitude of matter fluctuations, $\sigma_8$, as a function of $\sum m_\nu$. An independent determination of $\sigma_8$ will help determine $\sum m_\nu$ tremendously. (Right) Joint two-dimensional marginalized distribution of $w$ and $\sum m_\nu$. No significant correlation is observed. Note that we have a prior on $w$, $w > -2.5$, and thus the WMAP-only lower limit on $w$ in this panel cannot be trusted.
\[ N_{\text{eff}} = 3.04 + 7.44 \left( \frac{\Omega_m h^2}{0.1308} \frac{3139}{1 + z_{\text{eq}}} - 1 \right) \]

The way that we use CMB to determine \( N_{\text{eff}} \) is relatively simple. The relativistic particles that stream freely influence CMB in two ways: (1) their energy density changing the matter-radiation equality epoch and (2) their anisotropic stress acting as an additional source for the gravitational potential via Einstein’s equations. Incidentally, the relativistic particles that do not stream freely, but interact with matter frequently, do not have a significant anisotropic stress because they isotropize themselves via interactions with matter; thus, anisotropic stress of photons before the decoupling epoch was very small. Neutrinos, on the other hand, decoupled from matter much earlier (\( \sim 2 \text{ MeV} \)), and thus their anisotropic stress was significant at the decoupling epoch.

The amount of the early ISW effect changes as the equality redshift changes. The earlier the equality epoch is, the more the ISW effect CMB photons receive. This effect can be measured via the height of the third acoustic peak relative to the first peak. Therefore, the equality redshift, \( z_{\text{eq}} \), is one of the fundamental observables that one can extract from the CMB power spectrum.

\[ N_{\text{eff}} = 4.34^{+0.86}_{-0.88} \ (68\% \ CL), \]
More than three neutrinos with large errors...
The Triumph of Cosmology

- The combination of the standard model of particle physics and general relativity allows us to relate events taking place at different epochs together.

- Observation of the cosmological neutrinos would then provide a window into the 1st second of creation.
Why do we know they should be there?

- The same physics that predicts the Cosmic Microwave Background (CMB) predicts the Cosmic Neutrino Background (CNB).

- The helium abundance from Big-Bang Nucleosynthesis (BBN) is sensitive to their coupling to neutron proton.

- They will effect structure formation in the early universe.
Why haven’t we measured them yet?
We have a good track record...

From J. Formaggio

- Neutrinos from reactors.
  - Detected (1950s)

- Neutrinos from supernovae.
  - Detected (1980s)

- Neutrinos from the sun.
  - Detected (1960s)

- Neutrinos from the Earth.
  - Detected (2000s)

- Neutrinos from the atmosphere.
  - Detected (1960s)

- Neutrinos from galactic sources.
  - Not yet (but close!)

- Neutrinos from accelerators.
  - Created & detected (1960s)

- Neutrinos from the Big Bang.
  - Not even close...
1.95K = \sim \text{meV}

Yes that is little m...
Think for a second about thresholds for the standard reactions?
Do they clump?

Yes...but you are only getting a factor of 10 at best.

Figure 4: Neutrino density profiles for the Milky Way\textsuperscript{6}, obtained via $N$-one-body simulations from the MWnow (top curve in each plot) and the NFWHalo run (bottom curve in each plot).
Some Ideas on the Table...

- Various methods proposed:
  
  1. Mechanical force due to coherent scattering.
  2. Neutrino scattering on accelerator beams.
  3. Cosmic ray scattering.
  4. Neutrino capture on beta nuclei.
Coherent Scattering

- Consider the scattering of a macroscopic object against the neutrino wind.

- This wind is actually the motion of the earth with respect to the neutrinos (similar to moving through a dark matter halo).

- Consider the coherent scattering of neutrinos against an object (spheres) and look at the force imposed by the neutrino wind.

\[ \sigma = G_F^2 m^2_{\nu} \frac{k^2}{\pi L} \]  
(scattering)

\[ \frac{d\vec{p}}{dt} = F_{\nu} \sigma \Delta p \]  
(mom. trans.)
Coherent Elastic Scattering

- Effect takes advantage of a macroscopic de Broglie wavelength (for these momenta).
- Equivalent to measuring a small acceleration on a macroscopic object.
- Currently can measure accelerations down to $10^{-13}$ cm/s$^2$. Can push this down to $10^{-23}$ cm/s$^2$ in the future.

$$a_t \approx (10^{-46} - 10^{-54}) \frac{A}{100} \text{ cm s}^{-2}$$
High Energy Scattering : Beams

- Take advantage of cross-section growth with energy, using very high energy isotopes as probes.

- Two possible sources: high energy accelerators & cosmic rays.

- Most parameters necessary for relic neutrino detection beyond scope of conventional machines.

\[
R_\nu = 2 \times 10^{-9} \cdot \frac{m_\nu}{\text{eV}} \frac{A^2}{Z} \frac{E_n}{10\text{TeV}} \frac{L}{\text{km}} \frac{I}{A} \text{[yr}^{-1}]\]
From J. Formaggio

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\]

<table>
<thead>
<tr>
<th>accel.</th>
<th>N</th>
<th>(E_N) [TeV]</th>
<th>(L) [km]</th>
<th>(I) [A]</th>
<th>(\frac{R_\nu A}{m_\nu m_\nu 	ext{eV}}) [yr^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>p</td>
<td>7</td>
<td>26.7</td>
<td>0.6</td>
<td>(2 \times 10^{-8})</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>574</td>
<td>26.7</td>
<td>0.006</td>
<td>(1 \times 10^{-5})</td>
</tr>
<tr>
<td>VLHC</td>
<td>p</td>
<td>87.5</td>
<td>233</td>
<td>0.06</td>
<td>(2 \times 10^{-7})</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>7280</td>
<td>233</td>
<td>0.0006</td>
<td>(1 \times 10^{-4})</td>
</tr>
<tr>
<td>ULHC</td>
<td>p</td>
<td>(10^7)</td>
<td>40000</td>
<td>0.1</td>
<td>10</td>
</tr>
</tbody>
</table>
High Energy Scattering: Cosmic Rays

- Conversely, one can use cosmic rays as the high energy source.

- One can look at absorption of extremely high energy neutrinos near the Z-resonance, or for emission features above the natural GZK cutoff.

\[ E_{\nu}^{\text{res}} = \frac{m_Z^2}{2m_\nu} \]
Neutrino Capture

Instead of beta decay...

\[ ^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \nu_e \]
Neutrino Capture

The process is energetically allowed even at zero momentum.

This threshold-less reaction allows for relic neutrino detection.
Measuring the Endpoint Spectrum

\[
\frac{dN}{dE} = C \times |M|^2 F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}
\]
Detecting the Impossible

- The process is exothermic. There is enough energy for the decay to occur (because beta decay will happen anyway).

- Cross-section falls like the inverse velocity, while flux depends on velocity, so event rate is constant.

\[
\sigma = \sigma_0 \times \left\langle \frac{C}{E_{e}} E_{e} p_{e} F(Z, E_{e}) \right\rangle \frac{2I + 1}{2I + 1}
\]

- Electron energy is almost mono-energetic, after the endpoint energy.

\[
\lambda_{\nu} = \int \sigma_{\nu} \cdot v \cdot f(p_{\nu}) \left( \frac{dp}{2\pi} \right)^3
\]

Neutrino Capture Rate

\[
\sigma_{\nu} \cdot \frac{v}{c} = (7.84 \pm 0.03) \times 10^{-45} \text{ cm}^2
\]

Tritium Cross-Section
Obstacles for a Relic Neutrino Measurement

Target:
What targets are best suited for this technique?

Energy Resolution:
How to best separate the radioactivity from signal?

Backgrounds:
What about other background activities?

From J. Formaggio
Beta Decay: Review

- To determine the rate of a particular reaction, one needs to take into account of a number of factors:

  - The phase space of the decay (i.e. how many different states can occupy a particular momentum).

  - Corrections due to the Coulomb field, or Fermi function.

  - The matrix element related to the initial and final states of the decay.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Δl</th>
<th>Parity change?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superallowed</td>
<td>0, ± 1</td>
<td>No</td>
</tr>
<tr>
<td>Allowed</td>
<td>0, ± 1</td>
<td>No</td>
</tr>
<tr>
<td>1st Forbidden</td>
<td>0, ± 1</td>
<td>Yes</td>
</tr>
<tr>
<td>Unique 1st Forbidden</td>
<td>± 2</td>
<td>Yes</td>
</tr>
<tr>
<td>2nd Forbidden</td>
<td>± 2</td>
<td>No</td>
</tr>
<tr>
<td>3rd Forbidden</td>
<td>± 3</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Spin of states govern type of exchange
E.g.: $0^+ \rightarrow 0^+$ is superallowed

\[
\frac{dN}{dE} = C \times |M|^2 \frac{F(Z,E)\rho_e(E + m_e^2)(E_0 - E)\sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}}{E_0 - E} 
\]

Fermi Function
Matrix Element
Phase space
The Targets

- The half-life of the beta-decay isotope essentially determines the rate at which the neutrino capture reaction occurs.

- Rate (for nominal neutrino density) can therefore be computed.

- Tritium emerges as the one isotope adaptable for relic neutrino detection.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Endpoint (keV)</th>
<th>Half-Life (s)</th>
<th>Cross-Section ((10^{-41} \text{ cm}^2))</th>
<th>Rate ((\text{yr}^{-1} \text{ kg}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^3\text{H})</td>
<td>18.591</td>
<td>(3.89 \times 10^8)</td>
<td>(7.84 \times 10^{-4})</td>
<td>75</td>
</tr>
<tr>
<td>(^{109}\text{Ru})</td>
<td>39.4</td>
<td>(3.23 \times 10^7)</td>
<td>(5.88 \times 10^{-4})</td>
<td>1.6</td>
</tr>
<tr>
<td>(^{187}\text{Re})</td>
<td>2.64</td>
<td>(1.37 \times 10^{18})</td>
<td>(4.32 \times 10^{-11})</td>
<td>(4.7 \times 10^{-11})</td>
</tr>
<tr>
<td>(^{11}\text{C}^\dagger)</td>
<td>960.</td>
<td>(1.27 \times 10^3)</td>
<td>(4.66 \times 10^{-3})</td>
<td>120.8</td>
</tr>
<tr>
<td>(^{15}\text{N}^\dagger)</td>
<td>1199.</td>
<td>(5.99 \times 10^2)</td>
<td>(9.75 \times 10^{-3})</td>
<td>116.2</td>
</tr>
<tr>
<td>(^{15}\text{O}^\dagger)</td>
<td>1732.</td>
<td>(1.22 \times 10^2)</td>
<td>(9.75 \times 10^{-3})</td>
<td>185.3</td>
</tr>
</tbody>
</table>

Bottom Line: 100 g of \(^3\text{H}\) provides \(~10\) events/year
From J. Formaggio

Intense Tritium Sources

KATRIN:

ITER:

Exit Signs:

Intense tritium sources (order ~100 g) are obtainable
The Need for Resolution...

- Resolution is a key ingredient in the tagging of this process.

- As in neutrinoless double beta decay, one must separate the (more abundant) beta decay rate from the (rare) neutrino capture signal.

- The only separation stems from the energy difference (i.e. $2m_\nu$).

- Even if achieved, the background in the signal region must be $<1$ event/year.

R. Lazauskas, P. Vogel, C. Volpe  arXiv:0710.5312
The Connection between Neutrino Mass and Relic Detection

- It is clear that the methods one would employ for a next-generation kinematic neutrino mass measurement would apply equally to neutrino capture.

- Let’s highlight the methods on the table and examine their scalability.

- The KATRIN tritium beta decay experiment
- The MARE bolometric neutrino experiment
- Atomic tritium trap with full kinematic reconstruction
- Decay of radioactive ions in a storage ring
- Detection of RF cyclotron radiation from β orbiting in magnetic field
The KATRIN Experiment

- The KATRIN experiment uses magnetic adiabatic collimation with electrostatic filtering to achieve its energy resolution.

- Target activity is approximately 4.7 Ci. Energy resolution from spectrometer is 0.93 eV.
The MAC-E Filter Technique

Magnetic Adiabatic Collimation:
- Use adiabatic guiding to move $\beta$-particles along B-field lines.
- Field constrained by 2 s.c magnets.

Electrostatic Filter:
- Use retarding potential to remove $\beta$-particle below threshold.
- High pass filter (variable potential)
From J. Formaggio

Limitations of the KATRIN Experiment

- Both the resolution of KATRIN and its activity scale as the area (not the volume).

- KATRIN will certainly be able to probe very low in neutrino mass, but its ability to see relic neutrinos is hampered by the source strength required.

- Some new approach is required.
From J. Formaggio

Direct Neutrino Probes: MARE

- Use bolometers to measure the full energy deposit from beta decay,

- Use $^{187}\text{Re}$ as beta decay isotope ($T_{1/2} = 4.3 \times 10^{10}$ y, $Q = 2.46$ keV)

- All the energy in the final states are measured (good!)

- Scales with volume, not area (good!)

- Cross-section really small for relic detection (not so good...)

Bolometry

$^{187}\text{Re} \rightarrow ^{187}\text{Os} + e^- + \bar{\nu}_e$

1 mm→| ←
Atomic Trapping of Tritium

- Trap atomic tritium by magnetically cooling an atomic beam of tritium. Technique demonstrated on oxygen and hydrogen. Being extended to tritium next.

- Measure both the ion (3He+) and the electron to reconstruct the neutrino mass kinematically.

- This technique avoids the need for measuring the endpoint (rather it reconstructs the mass itself), thus requires less target (good!).

- As a result, they will not have the target mass required for relic detection (not so good...).

Results of fit to simulated data in which $m_\nu = 0.4$ eV

- $m_\nu = 0.473^{+0.152}_{-0.135}$ eV
- $m_\nu = 0.425^{+0.085}_{-0.088}$ eV
- $m_\nu = 0.354^{+0.066}_{-0.050}$ eV

RF Cyclotron Measurements

- Make use of cyclotron emission to measure electron energy in terms of frequency.

- Accuracy of measurement is determined by Nyquist’s limit, or how long you can observe the electron radiating.

- Column density determines maximum time to observe.

- Scaling the volume both improves the accuracy and increases the activity strength (good!).

- Inherently, this is a frequency measurement, something we know how to do really well (good!).

B. Monreal, JAF arXiv:0904:2860
Radioactive Ions in a Storage Ring

- Use kinematics of tritium decay and exploit that decays near/at the endpoint carry all momenta (as two-body decay).

- Count electrons emerging anti-parallel to emerging ion beam.

- Requires:

  (a) Intense ion source ($10^{18}$-$10^{20}$ decays for KATRIN-like sensitivity)

  (b) Extremely narrow momentum beam ($\delta p/p \sim 10^{-5}$)

  (c) Issues with recoil ions and space charge effects from such an intense beam.
Obstacles for a Relic Neutrino Measurement

Target:
Tritium appears still as most favorable isotope. High activity targets (~1 MCi) of tritium necessary. Eventually need to switch to atomic tritium to push resolution.

Energy Resolution:
Need to achieve high resolution ($\Delta < m_\gamma$) for any chance of signal background separation. One order of magnitude desirable.

Backgrounds:
Need to achieve less that few events/year in region of interest. Cosmic rays and other activity will eventually play a role.
This is really a hard measurement!
What do you want to discuss about this topic?

Understanding CMB limits?
New techniques?
Sterile neutrinos and the CMB?
.....