Active-Sterile Neutrino Mixing In Big Bang Nucleosynthesis

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What is a neutrino?

Neutrinos are some of the least well understood particles in the Standard Model. They are nearly massless (≤ 2 eV) and interact only with the weak force and gravity. Given their lack of mass, and the low interaction cross-section of the weak force, they are very hard to detect.

Neutrino mass eigenstates and flavor eigenstates are related by a unitary transformation. Each neutrino is a superposition of flavor eigenstates. Since this superposition is not constant, a neutrino that is predominately a muon neutrino can become primarily an electron neutrino as it propagates through space. This is known as "oscillation" from one neutrino state to another.

There are three types of neutrinos – electron neutrinos (ν_e), muon neutrinos (ν_μ), and tau neutrinos (ν_τ). This corresponds to the three times of leptons – electrons (e), muons (μ) and taus (τ).

Why consider sterile neutrinos?

There are a number of experimental hints that the current three-flavor neutrino model is not sufficient.

Both MiniBooNE and LSND detected an excess of low-energy events that would indicate a higher rate of $\nu_\mu \rightarrow \nu_e$ appearance than expected [1]. Furthermore, several reactor-based experiments (Gosgen, SRP, ILL, Bugey, etc.) have seen fewer than expected antineutrinos [2]. Gallium-based solar neutrino experiments (GALLEX and SAGE) have also seen several percent fewer antineutrino events than expected [3].

Furthermore, all currently known neutrinos are right-handed; no left-handed neutrinos have ever detected, nor any right-handed antineutrinos. It is possible that left-handed neutrinos (and right-handed antineutrinos) are "sterile" – that is, they do not interact with the weak force. Such particles would be nearly undetectable, given the already-low interaction cross-section of active neutrinos. However, such particles could explain the above anomalies.

Neutrinos in the early universe

The neutrino flux during big bang nucleosynthesis (BBN) fixes the proton-to-neutron ratio. BBN occurs when the universe's plasma temperature drops to about 1 MeV. At that point, the universe has cooled enough so that protons and neutrons can enter bound states.

At temperatures above 0.7 MeV, the weak interaction rate is fast in comparison to the universe's expansion rate, and such the forward and reverse reactions of proton-to-neutron conversions are approximately equal.

$$\mathrm{n} + \mathrm{e}^+ \rightarrow \bar{\nu}_\mathrm{e} + \mathrm{p} \qquad (1)$$

$$\mathrm{n} + \nu_\mathrm{e} \rightarrow \mathrm{p} + \mathrm{e}^- \qquad (2)$$

As the universe expands, these reactions slow. The flux of available electron neutrinos determines the neutron-to-proton ratio. By weak freeze-out, the proton-to-neutron ratio is approximately seven-to-one.

These neutron and protons then begin to form into atoms. The vast majority of the neutrons are incorporated into alpha particles (helium nuclei), although about $\frac{1}{10{,}000}$ neutrons are incorporated into deuterium nuclei. Very small amounts of tritium, lithium-6, lithium-7, lithium-8 and beryllium-7 are also produced during BBN.

However, since neutrinos oscillate between flavors, one cannot consider simply electron flux. If sterile neutrinos oscillate into electron neutrinos, they also affect the flux, the neutron-to-proton ratio and ultimately the elemental abundances.

BBN Simulation

We are using the NUC123 code, with default values for model and computation parameters [4]. It is based on the work of Wagoner, Fowler and Hoyle [5]. We compared our D/H and Y_p values to the accepted experimental values ([6], [7])

Models Tested

The best fit for the LSND and MiniBooNE anomalies requires 3 active neutrinos and two steriles[8]. There is no consensus on mixing angles for the two steriles – we simulated both full thermalization (high mixing angles) per Cecilia Lunardini [9] and partial thermalization per Irina Mocioiu [10].

Results

Values outside experimental range have been bolded.

	D/H	Y_p ($* 10^{-5}$)
3+1 thermalized	2.972	0.2582
3+2 thermalized	**3.320**	**0.2691**
3+1, $T_{\nu_s} = 0.4T_\nu$	2.631	**0.2461**
3+2, 1 $T_{\nu_s} = 0.4T_\nu$	2.981	0.2585
3+2, both $T_{\nu_s} = 0.4T_\nu$	2.640	**0.2464**

Conclusions

The 3+2 fully thermalized model is excluded because both D/H and Y_p are outside current measurements.

The 3+1 fully thermalized model results in a D/H value (2.972) very close to the maximum within experimental error (3.03), a less than 1% difference in the D/H ratio. Better measurements of primordial (D/H) may allow us to exclude this model as well.

However, it is also clear there is a great deal of parameter space for sterile neutrinos consistent with BBN. The mixing angles must be small – fully thermalized sterile neutrinos cause deuterium to be over-produced relative to observations.

This data suggests that all sterile neutrinos must decouple earlier than the active neutrinos, before BBN.

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