Symmetry, Cosmology, Nuclear Astrophysics, the Neutrino Mass and Mixing Spectrum, and the Structure of Spacetime

(Is there really any relation between these topics, or this this just **HYPE**?)

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Neutrino Transformation in BBN

(1.) Active-Sterile Only
\[ \nu_{\mu,\tau} \leftrightarrow \nu_s \quad \text{and} \quad \bar{\nu}_{\mu,\tau} \leftrightarrow \bar{\nu}_s \]

c.f., Shi, Schramm, & Fields 1995, 93
Shi 1996

(2.) Active-Active Only
\[ \nu_\alpha \leftrightarrow \nu_\beta \]
\[ \nu_\alpha, \nu_\beta = \nu_e, \nu_\mu, \nu_\tau \]

c.f., Savage, Malaney, & Fuller 1992
\[ \Rightarrow \text{can "hide" an initially large lepton number in neutrinos} \]
\[ \Rightarrow \text{can relax Helium abundance limits on neutrino degeneracy} \]

(3.) Active-Sterile Plus Active-Active

c.f., Foot & Volkas 1997; 1998
Shi & Fuller 1998

(a.) \[ \bar{\nu}_\mu \leftrightarrow \bar{\nu}_s \] creates "large" net mu lepton number
\[ L_{\nu_\mu} > 0 \]

(b.) \[ \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e \] re-distributes lepton number to create
a net electron lepton number \[ L_{\nu_e} > 0 \]

Note that in both steps (a.) and (b.) we could employ tau rather than mu neutrinos (or both)
The Paradox of Neutrino-Heated $r$-Process Nucleosynthesis

- Require neutrino interactions,

$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$\nu_e + n \rightarrow p + e^-$$

to impart energy to baryons, so that baryons can overcome gravitational binding energy near the neutron star, $E_{\text{GR}AV} \sim 100$ MeV per baryon. Since the average energies of neutrinos are $\sim 10$ MeV, we therefore require some $\sim 10$ neutrino and antineutrino captures per nucleon to ensure ejection. If material is ejected by this neutrino heating process, its neutron-to-proton ratio will be set by these reactions.

- However, if we have an intense flux of $\nu_e$'s then there will be a ferocious increase in $Y_e$ (decrease in the number of available neutrons) accompanying the formation of alpha particles at $T \lesssim 0.75$ MeV:

$\Rightarrow$ All protons incorporated into alpha particles, leaving a sea of neutrons.

$\Rightarrow$ Some of these neutrons will be converted to protons via $\nu_e + n \rightarrow p + e^-$. 

This is the "alpha effect,"
Uranium
\[ a + a + n \rightarrow ^{9}Be \]
\[ 2p + 2n \rightarrow ^{4}He \]

r-Process Region

Neutrinos Transform?
(\( \nu_e \) disappearance?)

Hot Proto-Neutron Star

Heating Layer
\[ \frac{\nu_T}{\nu_\mu} \quad \delta m^2_{\mu\tau} \sim 10^{-2} \text{eV}^2 \]

\[ \delta m^2_{\mu e} \sim 6 \text{eV}^2 \quad (0.2 \text{eV}^2 \text{--} 8 \text{eV}^2) \]

\[ \frac{\nu_s}{\nu_e} \quad \delta m^2_{es} \sim 10^{-5} \text{eV}^2 \]

(like old C.Mohapatra scheme for masses)

BBN: OK

SNN: Enables r-Process in neutrino-heated supernova ejecta; removes \( \nu_e \) flux.

SuperK: \( \nu_\mu \leftrightarrow \nu_T \) maximal vacuum mixing

Solar Neutrinos: \( \nu_e \leftrightarrow \nu_s \) matter-enhanced

\( \text{or } \nu_e \sim \nu_s \text{ "just so" } \delta m^2_{\nu} \sim 10^{-3} \text{eV}^2 \)

LSND: \( \nu_\mu \leftrightarrow \nu_e \) vacuum oscillations
\[ \nu_s''? \]
\[ \nu_s' ? \]
\[ \nu_s \quad 100 \text{eV}^2 > \delta m_{es}^2 > 6 \text{eV}^2 \]

\[ \nu_{\tau} \quad \delta m_{\mu\tau}^2 \sim 10^{-2} \text{eV}^2 \]
\[ \nu_{\mu} \quad \delta m_{e\mu}^2 < 10^{-4} \text{eV}^2 \]

?  
BBN: OK, may give interesting CMBR signal  
SNN: Enables r-Process in neutrino-heated ejecta  
"removes" \( \nu_e \) flux  

SuperK: \[ \nu_{\mu} \leftrightarrow \nu_{\tau} \quad \text{maximal vacuum mixing} \]

Solar Neutrinos: \[ \nu_e \leftrightarrow \nu_{\mu,\tau} \quad \text{matter-enhanced or vacuum oscillations} \]

LSND: \[ \nu_{\mu} \rightarrow \nu_s \rightarrow \nu_e \quad \text{Indirect vacuum oscillations} \]

troubled:
Can effective two-\( \nu \) mixing be big enough? Also BBN?
Active-Sterile Neutrino Transformation & BBN

• X. Shi, K. Abazajian, & G.M.F.: First semi-self consistent calculation of the evolution of all neutrino energy distribution functions and nuclear reaction rates through the BBN epoch. Two cases were considered:

• (1) Lepton Number generation via direct $\nu_e \leftrightarrow \nu_s$.

⇒ Find that change in primordial $^4$He relative to SBBN is $\Delta Y \approx -1\%$ to $+9\%$, with the sign depending on sign of Lepton Number.

• (2) Examine Lepton Number Asymmetry in the mu and/or tau sector generated via $\nu_{\mu,\tau} \leftrightarrow \nu_s$ followed by partial transfer of this Lepton Number to the $\nu_e \bar{\nu}_e$-sector via matter-enhanced active-active transformation.

⇒ Find that maximal reduction of $^4$He relative to SBBN is $\sim 2\%$ if the Lepton Number in neutrinos is positive. Otherwise the increase in $Y$ is $\lesssim 5\%$ for $m_{\nu_{\mu,\tau}}^2 - m_{\nu_s}^2 \lesssim 10^4 \text{eV}^2$.

* Overall Conclusion: Change in $^4$He yield induced by neutrino-mixing-generated lepton number asymmetry can be large in the upward direction, but is quite limited in the downward direction (the direction for ameliorating the “Crisis”).
Lepton Number Generation and The Causal Structure of Spacetime

X. Shi & G.M.F
PRL (in press '99)

X. Shi (1996) has shown that the lepton number generation process is chaotic.

It will create domains of lepton number which are bounded by the particle horizon size.

\[
\begin{array}{ccc}
\leq 0 & \geq 0 & \leq 0 \\
\geq 0 & \leq 0 & \leq 0 \\
\end{array}
\]

\(\text{lepton no. generation epoch}\)

\(\text{(some complicated percolation process)}\)

\(\text{(just prior to...)}\)

\(\text{BBN epoch}\)

\(\text{2 gradients drive } \nu_s \text{ production}\)
BBN, CFQ, LSND
and all PDQ

X. Shi, G. M. R., Y. Abarghajian, PRD (submitted)

\[ \delta m_{\mu - \tau}^2 \sim 10^{-2} \text{eV}^2 \]

\[ \nu_\mu \quad \nu_\tau \]

\[ \delta m_{\text{doublets}}^2 \]

\[ \nu_s \quad \nu_e \]

\[ \delta m_{\text{se}}^2 \leq 10^{-5} \text{eV}^2 \]

MSW in \( \odot \)

BBN \( \Rightarrow \)

\[ \sin^2 2\theta_{\text{ms}} \leq 10^{-10} \]

[all active-sterile level crossings at domain boundaries must be nonadiabatic]

BBN \( \Rightarrow \)

\[ \delta m_{\text{e-s}}^2 \sim 10^{-10} \text{eV}^2 \]

"Just so" for \( \odot \)

\[ F = \frac{\sin^2 2\theta_{\text{me}}}{\sin^2 2\theta_{\text{ms}}} \]