Signatures of sterile $\nu$ mixing in high energy cosmic $\nu$ flux

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1. Four flavor $\nu$ oscillation

1.1 Schemes with LSND

(1) (2+2)-scheme

excluded (~4.9 $\sigma$) because it contradicts with $\nu_{\text{atm}}$ or $\nu_{\text{solar}}$

(2) (3+1)-scheme

Strongly disfavored (~3.2 $\sigma$ L) because of the tension between LSND and Bugey+CDHSW (+other negative results)
1.2 (3+1)-scheme without LSND

Constraints by all the negative results give the allowed region

$\theta_{34}$ : could be relatively large
2. Effects of $\nu$ oscillation on high energy cosmic $\nu$

2.1 Flux of high energy cosmic $\nu$

- Active Galactic Nuclei (AGN) & Gamma Ray Burst (GRB) are speculated to produce high energy $\nu$.

- $E > 1$ TeV: small BG from $\nu_{\text{atm}}$. 

![Graph showing the flux of high energy cosmic neutrinos](image)
2.2 Flavor ratio of $\nu$ flux for $N_\nu = 3$

In standard $N_\nu = 3$, when $L \to \infty$

**Oscillation for $L \to \infty$**:

$$P(\nu_\alpha \to \nu_\beta) \cong \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2$$

**Initial flux**:

Just like in $\nu_{\text{atm}}$, the source of $\nu$ is $\pi$ decay

$$F^0(\nu_e): F^0(\nu_\mu): F^0(\nu_\tau) \cong 1:2:0$$

**Observed flux**:

$$F(\nu_e): F(\nu_\mu): F(\nu_\tau) \cong 1:1:1$$

Learned, Pakvasa ‘95
2.3 Triangle representation of flux

Precise normalization is not known

The ratio of different flavors is important quantity to observe

The case for sterile $\nu$

The normalized ratio of active flavors is useful:

$$\tilde{F}(\nu_\alpha) \equiv \frac{F(\nu_\alpha)}{F(\nu_e) + F(\nu_\mu) + F(\nu_\tau)}$$
2.4 Flavor ratio of $\nu$ flux for (3+1)-scheme

(3+1)-scheme w/o LSND gives the prediction which could be distinguished from $N_\nu=3$ case

In principle, (3+1)-scheme could be distinguished from the three flavor case
2.5 Theoretical uncertainties of original ν flux


For illustrations, they discussed ν flux from GRB using Waxman-Bahcall

- Proton energy spectrum
  \[ N_p(E_p) \propto E_p^{-\alpha} \]

- Photon number density
  \[ n_\gamma(\epsilon) \propto \begin{cases} 
  (\epsilon/\epsilon_b)^{-\beta_1} & \text{for } \epsilon \leq \epsilon_b, \\
  (\epsilon/\epsilon_b)^{-\beta_2} & \text{for } \epsilon_b < \epsilon < \epsilon_{\text{max}}, \\
  0 & \text{for } \epsilon \geq \epsilon_{\text{max}}, 
\end{cases} \]

- Muon energy loss due to synchrotron radiation
  \[ \epsilon_\mu = \frac{E_\mu}{E^*} = 8.4 \times 10^4 \left( \frac{\text{Gauss}}{B} \right) \left( \frac{\epsilon_b}{\text{KeV}} \right) \]
  \[ E^* \approx 6.9 \times 10^{13} \left( \frac{\epsilon_b}{\text{KeV}} \right)^{-1} \text{eV} \]

: Proton threshold energy for inelastic interactions with γ

- e:μ=1:2 not necessarily correct
- Energy dependence expected
2.6 e/μ ratio vs μ/τ ratio & energy spectrum for (3+1)-scheme Donini-OY '07

4 curves (energy dependence of p, γ) corresponding to uncertainties by Lipari et al.

μ/τ ratio is less energy dependent (to 1st order in small parameters)

\[ R_{\tau \mu}^{(4-fam)} = c_{34}^2 = c_{34}^2 R_{\tau \mu}^{(3-fam)} \]
Donini-OY ‘07

Energy dependence gives us hint on the uncertainties

μ/τ ratio is less energy dependent

\[ R_{\tau\mu}^{(4-fam)} = C_{34}^2 = C_{34}^2 R_{\tau\mu}^{(3-fam)} \]

(to 1st order in small parameters)
2.7 Statistics of expected events

For a typical galactic source, ten years of running at a km$^3$ water equivalent detector:

e, $\mu$ events $\sim O(100)$

$\tau$ events $\sim O(30)$

$\mu/\tau$ ratio ($N_\nu=3$) = 0.30 $\pm$ 0.06 (theo) $\mp$ 0.03 (stat)

$\mu/\tau$ ratio ($N_\nu=4$) $\sim$ 0.2

Statistics is not sufficient at all!

A possible way out:

● to integrate over all the galactic and extragalactic sources, or
● to sum over many GRB's events of similar intensities
3. Conclusions

- The (3+1)-scheme without LSND constraint predicts flavor ratio of HE cosmic $\nu$ which could be in principle distinguished from standard case.

- The $\mu/\tau$ ratio suffers relatively less from theoretical uncertainties, and plays an important role to look for signatures of sterile $\nu$.

- Information from energy spectrum could be also important to check theoretical uncertainties.

- Statistics from one source is not sufficient to get signatures of sterile $\nu$, but if we sum over data from many sources then we may be able to say something about sterile $\nu$. 