Sterile Neutrinos?
(Discussion Session)

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Compelling Evidences for $\nu-$Oscillations: ν mixing

$$|\nu_l> = \sum_{j=1}^{n} U^*_{lj} \, |\nu_j> , \quad \nu_j : \; m_j \neq 0 ; \quad l = e, \mu, \tau ; \quad n \geq 3 ;$$

$$\nu_{l\mathsf{L}}(x) = \sum_{j=1}^{n} U_{lj} \, \nu_{j\mathsf{L}}(x) , \quad \nu_{j\mathsf{L}}(x) : \; m_j \neq 0 ; \quad l = e, \mu, \tau .$$

B. Pontecorvo, 1957; 1958; 1967;

Z. Maki, M. Nakagawa, S. Sakata, 1962;

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix.

ν_j, $m_j \neq 0$: Dirac or Majorana particles.

Data: at least 3 νs are light: $\nu_{1,2,3}$, $m_{1,2,3} \lesssim 1$ eV.

We can have $n > 3$ ($n = 4$, or $n = 5$, or $n = 6$,...) if, e.g., sterile ν_R, $\tilde{\nu}_L$ exist and they mix with the active flavour neutrinos ν_l ($\tilde{\nu}_l$), $l = e, \mu, \tau$.

Two (extreme) possibilities:

i) $m_{4,5,...} \sim 1$ eV;
in this case $\nu_{e(\mu)} \to \nu_S$ oscillations are possible (hints from LSND and MiniBooNE experiments, re-analises of short baseline (SBL) reactor neutrino oscillation data ("reactor neutrino anomaly", data of radioactive source callibration of the solar neutrino SAGE and GALLEX experiments ("Gallium anomaly");

ii) $M_{4,5,...} \sim (10^2 - 10^3)$ GeV, TeV scale seesaw models;
$M_{4,5,...} \sim (10^{10} - 10^{13})$ GeV, "classical" seesaw models.

We can also have, in principle:

$m_4 \sim 1$ eV ($\nu_{e(\mu)} \to \nu_S$), $m_5 \sim 5$ keV (DM), $M_6 \sim (10 - 10^3)$ GeV or $M_6 \sim (10^{10} - 10^{13})$ GeV (seesaw).

• Data (relativistic ν's): ν_l ($\tilde{\nu}_l$) - predominantly LH (RH). Standard Theory: ν_l, $\tilde{\nu}_l$ - $\nu_{lL}(x)$;

$\nu_{lL}(x)$ form doublets with $l_L(x)$, $l = e\mu, \tau$:

$$\begin{pmatrix} \nu_{lL}(x) \\ \\ l_L(x) \end{pmatrix} \qquad l = e, \mu, \tau \, .$$

• Light, i.e., ~ 1 eV, sterile ν's: relativistic ν's ($\tilde{\nu}$'s) which are predominantly RH (LH): ν_R ($\tilde{\nu}_L$.)
If ν_R, $\tilde{\nu}_L$ exist, must have much weaker interaction than ν_l, $\tilde{\nu}_l$: ν_R, $\tilde{\nu}_L$ - "sterile", "inert".

B. Pontecorvo, 1967

In the formalism of the ST, ν_R and $\tilde{\nu}_L$ - RH ν fields $\nu_R(x)$; can be introduced in the ST as $SU(2)_L$ singlets.

No clear experimental indications exist at present whether the ST should be extended to include $\nu_R(x)$, and if it should, how many $\nu_R(x)$ should be introduced.

$\nu_R(x)$ appear in many extensions of the ST, notably in $SO(10)$ GUT's.

The RH ν's can play crucial role
i) in the generation of $m(\nu) \neq 0$,
ii) in understanding why $m(\nu) \ll m_l, m_q$,
iii) in the generation of the observed matter-antimatter asymmetry of the Universe (via leptogenesis).

The simplest hypothesis is that to each $\nu_{lL}(x)$ there corresponds a $\nu_{lR}(x)$, $l = e, \mu, \tau$.

ST + $m(\nu) = 0$: $L_l = const.$, $l = e, \mu, \tau$;
$L \equiv L_e + L_\mu + L_\tau = const.$

The current "reference scheme": 3-ν mixing

$$|\nu_l> = \sum_{j=1}^{n} U^*_{lj} \, |\nu_j> , \quad \nu_j : \; m_j \neq 0 ; \quad l = e, \mu, \tau ; \quad n = 3 ;$$

$$\nu_{l\mathsf{L}}(x) = \sum_{j=1}^{3} U_{lj} \, \nu_{j\mathsf{L}}(x) , \quad \nu_{j\mathsf{L}}(x) : \; m_j \neq 0 ; \quad l = e, \mu, \tau .$$

The PMNS matrix U - 3×3 unitary to a good approximation (al least: $|U_{l,n}| \lesssim (<<) 0.1$, $l = e, \mu$, $n = 4, 5, ...$).

ν_j, $m_j \neq 0$: Dirac or Majorana particles.

Data: the 3 νs are light: $\nu_{1,2,3}$, $m_{1,2,3} \lesssim 1$ eV.

Sterile Neutrinos - Questions

A. How strong are the evidences for light ($\sim$ 1 eV) sterile neutrinos from the

- 1. LSND and/or MiniBooNE experiments (taking into account the MINOS, ICARUS, OPERA, CDHS etc. constraints)?
- 2. Reactor $\bar{\nu}_e$ anomaly ("new" versus "old" reactor $\bar{\nu}_e$ flux calculation results...)?
- 3. Results of the SAGE and GALLEX calibration experiments (Gallium anomaly)?

B. How strong are the evidences for ν_s with $m_s \sim 7$ keV (possible DM candidate) from the excess of γ's with $E_\gamma \sim 3.5$ keV, claimed to be present in the data of the XMM-Newton experiment?

C. How strong are the eveidences (if any) for light ν_s (number and mass) from the cosmological data?

D. Does theory of massive neutrinos need $\nu_R(x)$?