Probing baryon asymmetry by light right-handed neutrinos

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SM with TWO RH neutrinos

Introduce two RH neutrinos $\nu_{R2}, \nu_{R3}$

$$\delta L = i\bar{\nu}_{RI} \gamma_\mu \nu_{RI} - F_{\alpha I} \bar{L}_\alpha \nu_{RI} \Phi - \frac{M_I}{2} \bar{\nu}_{RI} \nu^c_{RI} + \text{h.c.}$$

$I = 2, 3$

$\alpha = e, \mu, \tau$

- Explain neutrino masses by seesaw mechanism
  - Light (active) neutrinos $\nu_1, \nu_2, \nu_3$
  - Heavy neutrinos $N_2, N_3$

- Explain baryon asymmetry by RH neutrinos
  - Mechanism depends on masses of heavy neutrinos
    - ex) Leptogenesis, Baryogenesis via Neutrino Oscillation
      - Fukugita, Yanagida (86)
      - Akhmedov, Rubakov, Smirnov (98)

- Heavy neutrinos can be tested directly by experiments, if their masses are small enough
In this talk

Consider two quasi-degenerate (RH) heavy neutrinos $N_2, N_3$

- Lighter than charged kaon mass $M_{2,3} < m_K$
  \[ \rightarrow \text{Test by Kaon decays } (K^+ \rightarrow \ell^+ N_i) \text{ is possible} \]
- Quasi-degenerate $M_3 - M_2 = \Delta M \ll 2M_N = M_3 + M_2$
  \[ \rightarrow \text{Baryogenesis via neutrino oscillation is possible} \]

Can we determine all the parameters of the model by experiments and cosmological observations?

- Interactions of heavy neutrinos

\[ \Phi \rightarrow F_{\alpha l} \uparrow \downarrow N_I \quad L_\alpha \]

\[ W \rightarrow g \Theta_{\alpha l} \uparrow \downarrow \ell^+_\alpha \]

\[ Z \rightarrow g_Z \Theta_{\alpha l} \uparrow \downarrow \bar{\nu}_\alpha \]

\[ \nu_{L\alpha} = U_{\alpha i} \nu_i + \Theta_{\alpha l} N^c_I \]

\[ \theta_{\alpha l} = \frac{\langle \Phi \rangle F_{\alpha l}}{M_I} \]

\text{\textbf{F}_{\alpha l} determine the interactions}
Yukawa couplings for $N_{2,3}$

\[ F = U_{\text{PMNS}} \ D_v^{1/2} \ \Omega \ D_N^{1/2} / \langle \Phi \rangle \]

(in IH)

- **Parameters of light (active) neutrinos**
  \[ D_v^{1/2} = \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3} = 0) \quad : \quad \nu \text{ masses} \]
  \[ U_{\text{PMNS}} = \begin{pmatrix}
  c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\
  -c_{23} s_{12} - s_{23} c_{12} s_{13} e^{i\delta} & c_{23} c_{12} - s_{23} s_{12} s_{13} e^{i\delta} & s_{23} c_{13} \\
  s_{23} s_{12} - c_{23} c_{12} s_{13} e^{i\delta} & -s_{23} c_{12} - c_{23} s_{12} s_{13} e^{i\delta} & c_{23} c_{13}
\end{pmatrix} \begin{pmatrix}
  1 \\
  e^{i\eta} \\
  1
\end{pmatrix} \]

- **Parameters of heavy neutrinos**
  \[ D_N^{1/2} = \text{diag}(\sqrt{M_2}, \sqrt{M_3}) \quad : \quad N \text{ masses} \]
  \[ \Omega = \begin{pmatrix}
  \cos \omega & -\sin \omega \\
  \xi \sin \omega & \xi \cos \omega \\
  0 & 0
\end{pmatrix} \quad \text{Complex number } \omega \]
  \[ \text{Sign parameter } \xi = \pm 1 \]

Casas, Ibarra (01)

Dirac phase $\delta$

Majorana phase $\eta$
Parameters of 2RHN model (IH)

- Global analysis
  \[ \sin^2 \theta_{12} = 0.307 \]
  \[ m_2 = 0.0496 \text{ eV} \]
  \[ \sin^2 \theta_{23} = 0.392 \]
  \[ m_1 = 0.0488 \text{ eV} \]
  \[ \sin^2 \theta_{13} = 0.0244 \]
  \[ m_3 = 0 \]

- Unknown parameters
  \[ \delta = [0, 2\pi] \]
  \[ \eta = [0, \pi] \]
  \[ \xi = +1, -1 \]
  \[ M_N \]
  \[ \Delta M \ll M_N \]
  \[ \Re \omega = \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \]
  \[ X_\omega = \exp(\Im \omega) \geq 1 \]

What can we learn from present experiments and cosmological observations?
Direct search experiments

- **PS191 experiment**
  
  **Production** \( \pi^+, K^+ \rightarrow e^+ N, \mu^+ N \)
  
  **Detection** \( N \rightarrow \ell^+ \ell^- \nu, \ell^+ \pi^- \)

- **Upper bounds**

\[
|\Theta_{\alpha l}|^2 \left( a |\Theta_{e l}|^2 + b |\Theta_{\mu l}|^2 + c |\Theta_{\tau l}|^2 \right)
\]

\( a, b, c \): depends on \( M_N \) and search channel

Ruchayski, Ivashko '12

- Majorana (rather than Dirac)
- Not only CC but also NC contributions
- Two quasi-degenerate heavy neutrinos \( (N_2, N_3) \)

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BBN constraint

- Heavy neutrino decays
  \[ N_{\ell} \to 3\nu, \ell^+ \ell^- \nu, \pi^0 \nu, \pi^+ \ell^- \]
  \( \rightarrow N_{\ell} \) is long lived particle
- To keep the success of BBN
  \( \rightarrow \tau_N < 0.1 \text{ sec} \)
  Dolgov, Hansen, Rafflet, Semikoz ('00)

- **Lower bounds**
  \[ a'|\Theta_{eI}|^2 + b'|\Theta_{\mu I}|^2 + c'|\Theta_{\tau I}|^2 \]

*Together with search bounds, we obtain allowed range!*

Gorbunov, Shaposhnikov (07), Ruchayski, Ivashko (12)

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Allowed range of $M_N$

We can obtain allowed range of $X_\omega = \exp(\text{Im}\omega)$

$$\Gamma_N = \tau^{-1}_N \propto \Theta^2 \propto F^2 \text{ and } F \propto X_\omega \text{ for large } \text{Im}\omega$$
Allowed range of $X_\omega$

We find other interesting information in IH case!
Mixing elements of heavy neutrinos

- Since $\Delta M \ll M_N$ and $X_\omega \gg 1$, mixing elements of $N_2$ and $N_3$ are the same

\[ \theta_{\alpha 2} = \theta_{\alpha 3} \quad \text{TA, Eijima, Ishida ('11)} \]

- Mixing elements strongly depend on $\xi \sin \eta$

\[
\begin{align*}
|\Theta_e|^2 &\approx 1.20 \times 10^{-8} \left( \frac{\text{MeV}}{M_N} \right) (1.000 - 0.925 \xi \sin \eta) X_\omega^2, \\
|\Theta_\mu|^2 &\approx 0.76 \times 10^{-8} \left( \frac{\text{MeV}}{M_N} \right) (1.000 + 0.895 \xi \sin \eta - 0.250 \xi \cos \eta \sin \delta + 0.092 \xi \sin \eta \cos \delta) X_\omega^2, \\
|\Theta_\tau|^2 &\approx 0.50 \times 10^{-8} \left( \frac{\text{MeV}}{M_N} \right) (1.000 + 0.860 \xi \sin \eta + 0.380 \xi \cos \eta \sin \delta - 0.140 \xi \sin \eta \cos \delta) X_\omega^2.
\end{align*}
\]

We find allowed range of Majorana phase!
Majorana phase in IH case

\[ \sin \eta \sim 1 \quad \sin \eta \sim 0.3 \quad \text{all } \eta \text{ is allowed} \]

Excluded by BBN +PS191

\[ K^+ \rightarrow e^+ N \]
\[ N \rightarrow e^- \pi^+ + cc \]

Excluded by BBN +PS191

\[ K^+ \rightarrow \mu^+ N \]
\[ N \rightarrow \mu^- \pi^+ + cc \]

Future search experiments by Kaon decays can provide strong information on Majorana phase

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0νββ decays in IH

Effective neutrino mass from light and heavy neutrinos

\[ m_{\text{eff}} = m_i U_{ei}^2 + f_\beta (M_i) M_i \Theta_{ei}^2 = \left[ 1 - f_\beta (M_N) \right] m_\nu^\text{v} \]

\[ m_\nu^\text{v} = \cos^2 \theta_{13} \left( m_1^2 \cos^4 \theta_{12} + m_2^2 \sin^4 \theta_{12} + 2 m_1 m_2 \cos^2 \theta_{12} \sin^2 \theta_{12} \cos 2\eta \right)^{1/2} \]

- Heavy neutrinos give negative contribution to \( m_{\text{eff}} \)
- Constraint on \( \eta \) restricts the predicted range of \( m_{\text{eff}} \)
Oscillation of heavy neutrinos can be a source of BAU

- CPV in oscillation and production generates asymmetries
- Asymmetries are separated into LH and RH leptons
- Asymmetry in LH leptons is converted into BAU

BAU can provide information on $F_{\alpha I}$ since generation of asymmetry is controlled by $F_{\alpha I}$

Especially, CP violating parameters and mass difference

$$T_{osc} \sim (M_0, M_N, \Delta M)^{1/3}$$
**Re$\omega$, $\Delta M$ and BAU (IH)**

$M_N = 250\text{MeV}, \delta = \pi$

- $\eta$ and Re$\omega$ are important for the sign of BAU
- Correct sign of BAU restricts the region of Re$\omega$ depending on $\eta$

- Once $\eta$ is determined, we obtain the relation between Re$\omega$ and $\Delta M$
- Together with measurement of $\delta$ we may probe $\Delta M$ if Re$\omega$ is away from 0 and $\pi/2$

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  m_2 = 0.0496 \text{ eV} \quad m_1 = 0.0488 \text{ eV} \quad m_3 = 0
  \]

- **Free parameters**
  \[
  \delta = [0, 2\pi] \\
  \eta = [0, \pi] \\
  \xi = +1, -1 \\
  M_N \\
  \Delta M \ll M_N \\
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  X_\omega = \exp(\Im \omega) \geq 1
  \]

**Future**
- Oscillation experiments
- Search experiments in K decays (beam dump/peak search) + BBN
- 0v\beta\beta experiments

**Present and future**
- Baryon asymmetry

**Present**
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Summary

- Two right-handed neutrinos offer
  - Seesaw mechanism for neutrino masses
  - Baryogenesis for baryon asymmetry of the universe

- When heavy neutrinos are quasi-degenerate with $M_N \sim 200-400\text{MeV}$, we may have a chance to test directly the origin of neutrino masses and baryon asymmetry by using kaon decays!