Physics of right-handed neutrinos with GeV-scale masses

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Mixing angles and mass squared differences are now measured precisely:

\[
\begin{align*}
\sin^2 \theta_{12} &= 0.308^{+0.013}_{-0.012} \\
\sin^2 \theta_{23} &= 0.440^{+0.023}_{-0.019} \\
\sin^2 \theta_{13} &= 0.02163^{+0.00074}_{-0.00074} \\
\Delta m^2_{21} &= (7.49^{+0.19}_{-0.17}) \times 10^{-5} \text{ eV}^2 \quad \text{(NH case)} \\
\Delta m^2_{31} &= (2.526^{+0.029}_{-0.037}) \times 10^{-3} \text{ eV}^2
\end{align*}
\]

Gonzalez-Garcia, Maltoni and Schwetz (\(\nu\)-fit, August ’16)

Unknown properties:
- Absolute masses of neutrinos (\(m_\nu\) lightest ? Mass ordering ?)
- CP violations (Dirac phase ? Majorana phase(s) ?)
- Dirac or Majorana fermions

\(\Rightarrow\) important to understand the origins of dark matter, baryon asymmetry, ...
Contents

Why are such particles interesting?

- Seesaw mechanism for neutrino masses
- Oscillation mechanism for baryon asymmetry of the universe
- Direct tests by (near) future experiments
Seesaw mechanism by right-handed neutrinos with GeV masses
RH Neutrinos $\nu_R$ and Seesaw Mechanism

\[ \delta L = i \overline{\nu_R} \gamma^\mu \partial_\mu \nu_R - \left( F \overline{L} \nu_R \Phi + \frac{M_M}{2} \overline{\nu_R} \nu_R^c + h.c. \right) \]

- **Seesaw mechanism** ($M_D = F\langle \Phi \rangle \ll M_M$)

\[ -L = \frac{1}{2} \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c. = \frac{1}{2} \begin{pmatrix} M_v & 0 \\ 0 & M_M \end{pmatrix} \begin{pmatrix} \nu^c \\ N \end{pmatrix} + h.c. \]

- **Light active neutrinos** $\nu$

\[ M_\nu = - \frac{M_D^T}{M_M} \times M_D \simeq \text{tiny neutrino masses} \]

→ explain neutrino oscillations

- **Heavy neutrinos** $N$ ($N \simeq \nu_R$)

- Mass $M_M$
- Mixing $\theta = M_D/M_M$

Neutrino mixing

\[ \nu_L = U \nu + \Theta N^c \]
Yukawa coupling and mass of heavy neutrino

\[ m_\nu = \frac{M_D}{M_M} \times M_D = \frac{F^2 \langle \Phi \rangle^2}{M_N} \]

\[ F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle} \]

\[ m_\nu = 5 \times 10^{-11} \text{ GeV} \]

Seesaw does not work!
Yukawa coupling and mass of heavy neutrino

Explain baryon asymmetry of the universe too!

\[ F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle} \]

\[ m_\nu = 5 \times 10^{-11} \text{ GeV} \]

Seesaw does not work!

Leptogenesis (Fukugita, Yanagida ‘86)
Yukawa coupling and mass of heavy neutrino

F = \sqrt{m_\nu M_N} / \langle \Phi \rangle

m_\nu = 5 \times 10^{-11} \text{ GeV}

Explain baryon asymmetry of the universe too!

Seesaw does not work!

Leptogenesis (Fukugita, Yanagida ’86)

Baryogenesis via neutrino oscillation
(Akhmedov, Rubakov, Smirnov ’98, TA, Shaposhnikov ’05)
Mixing and mass of heavy neutrino

\[ |\Theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N} \]

\[ m_\nu = 5 \times 10^{-11} \text{ GeV} \]

Baryogenesis via neutrino oscillation

Leptogenesis
Important parameters of heavy neutrino

- Interactions of heavy neutrino

  **Yukawa interaction**
  \[ N_I \]
  \[ F_{\alpha I} \]
  \[ \Phi \]
  \[ L_\alpha \]

  **gauge interaction through mixing**
  \[ N_I \]
  \[ F_{\alpha I} \]
  \[ \ell_\alpha, \nu_\alpha \]
  \[ W, Z \]

  \[ \therefore g \Theta_{\alpha I} = g \frac{F_{\alpha I} \langle \Phi \rangle}{M_N} \sim \frac{m_w}{M_N} F_{\alpha I} \]

- Key parameters

  **mass** \( M_I \) **and mixing** \( \Theta_{\alpha I} \)

  also Yukawa couplings \( F_{\alpha I} \) (for high temperatures where \( \langle \Phi \rangle = 0 \))
Upper bounds from searches

- Upper bounds on $|\theta_{\mu}|^2$
  from a recent analysis
  Deppisch, Dev, Pilaftsis ‘15
  [arXiv:1502.06541]
  references therein

Lower bound from seesaw

$|\Theta|^2 = \sum_{\alpha,l} |\Theta_{\alpha l}|^2 \geq \frac{\sum m_i}{M_N}$

for the case with quasi-degenerate,
two right-handed neutrinos
Baryogenesis by right-handed neutrinos with GeV masses
Baryon asymmetry of the universe (BAU)

Baryon Number $B = (# \text{ of baryons}) - (# \text{ of antibaryons})$

$$\frac{n_B}{s} = (8.676 \pm 0.054) \times 10^{-11}$$

$n_B$ : baryon number density
$s$ : entropy density

Planck 2015
[arXiv:1502.01589]
Conditions for baryogenesis

- Sakharov (1967)
  - Three conditions must be satisfied for dynamical generation of baryon asymmetry in evolution of the universe
    
    1. Baryon number $B$ is violated
    2. C and CP symmetries are violated
    3. Out of thermal equilibrium

"According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot Universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions."

A.D. Sakharov, JETP Lett 5, 24 (1967)
Baryogenesis conditions

Can GeV-scale RH neutrinos satisfy baryogenesis conditions?

(1) B and L violations
- (B+L) violation due to sphaleron for $T > 100$ GeV
- L violation due to Majorana masses is negligible

(2) C and CP violations
- 1 CP phase in quark sector
- 6 CP phases in lepton sector for three RH neutrinos

(3) Out of equilibrium
- No 1st order EW phase transition as in the SM
- RH neutrinos can be out of equilibrium, if Yukawa couplings are small enough
Baryogenesis via neutrino oscillation

- Oscillation of RH neutrinos can be a source of BAU
  Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)

- Oscillation starts at $T_{osc} \approx (M_0 M_N \Delta M)^{1/3}$

- Asymmetries are generated since evolution rates of $L_\alpha$ and $\bar{L}_\alpha$ are different due to CPV
Evolution of each flavor asymmetry

LH leptons $L_\alpha$

$\Delta L_e$

$\Delta L_{\mu, \tau}$

RH neutrinos $\nu_R$

$\Delta N_{2}$

$\Delta N_{3}$

$T_{osc} = 2.2$ TeV

Figure 5: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{23}^2/M_3^2 = 10^{-6}$, $\xi = +1$, $\sin \theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Figure 6: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{23}^2/M_3^2 = 10^{-6}$, $\xi = +1$, $\sin \theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$. 
Sphaleron converts $\Delta L$ partially into baryon asymmetry

$$B = -\frac{28}{79} \Delta L_{tot} \neq 0$$

$$\frac{n_B}{s} = -2.5 \times 10^{-4} \Delta L_{tot}(T_W)$$

$$\frac{n_B}{s} = (8.676 \pm 0.054) \times 10^{-11}$$

[Planck 2015]
Upper bound on mixing from BAU

- Large mixing region
  - good for search of heavy neutrinos
  - bad for strong washout of BAU

Large mixing means …

$$\Theta_{\alpha I} = \frac{[M_D]_{\alpha I}}{M_I} = \frac{F_{\alpha I} \langle \Phi \rangle}{M_I}$$

→ large Yukawa couplings

→ thermalization of $$\nu_R$$

→ strong washout of BAU

TA, Eijima, Ishida, Minogawa, Yoshii '17 [to appear]
Baryogenesis region

Normal Hierarchy

Upper bound from BAU to avoid strong washout

- From a recent analysis
  TA, Eijima, Ishida, Minogawa, Yoshii ’17 [to appear]

see also

Canetti, Shaposhnikov ’10 [arXiv:1006.0133]

Drewes, Garbrecht, Gueter, Klaric ’16 [arXiv:1609.09069]
Direct tests for right-handed neutrinos with GeV-scale masses
Sensitivity by future searches

Normal Hierarchy

Sensitivity for $|\theta_\mu|^2$

- **LBNE (DUNE)**
  - $N$ decay inside near detector

- **SHiP**
  - beam dump exp.

- **FCC-ee at Z-pole**
  - displaced vertex of $N$ decay
  - Blondel, Graverini, Serra, Shaposhnikov (FCC-ee study team) ‘14 [arXiv:1411.5230]
LNV by heavy Majorana neutrino

- Majorana mass term

\[ \mathcal{L} = -FL_L \Phi \nu_R - \frac{1}{2} M_N \nu_R^c \nu_R + h.c. \]

Majorana mass breaks lepton number by two unit!

- Various LNV processes!
  - Neutrinoless double beta decay \((Z, A) \rightarrow (Z + 2, A) + 2e^-\)
  - Inverse neutrinoless double beta decay \(e^- e^- \rightarrow W^- W^-\)
  - LNV rare decays \((W^- \rightarrow e^- e^- q \bar{q}', K^- \rightarrow e^- e^- \pi^+, ... )\)
  - ...

**Ex.) LNV in B decays**

Ng, Kamal ’78 [PRD18,3412], Abad, Esteve, Pacheco ’84 [PRD30,1488]
Atre, Barger, Han ’05 [hep-ph/0502163]
LNV in B decay

- $B^+ \rightarrow \mu^+ \mu^+ \pi^-$

  - induced by on-shell heavy neutrino $N$

  - Lepton number is violated by two units
    - clear signal for beyond SM!

  Mass region
  
  \[ m_{\mu} + m_{\pi} < M_N < m_B - m_{\mu} \]

References:

- Cvetic, Dib, Kang, Kim ‘10 [hep-ph/1005.4282]
- Canetti, Drewes, Garbrecht ‘14 [1404.7114]
- Milanes, Quintero, Vera ‘16 [1604.03177]
- Cvetic, Kim ‘16 [1606.04140]
- TA, Ishida ‘16 [1609.06113]
Sensitivity by future searches

Normal Hierarchy

Sensitivity for $|\theta_\mu|^2$

$B^+ \rightarrow \mu^+ \mu^+ \pi^-$

- Belle II with $N_B = 5 \times 10^{10}$
- FCC-ee at Z-pole $N_Z = 10^{13}$
  $B^\pm$ are produced in $Z$ decays
  $N_B \approx 6 \times 10^{11}$

TA, Ishida ’16 [1609.06113]
We have considered

**right-handed neutrinos with GeV-scale mass**

- Tiny neutrino masses by seesaw mechanism
- Baryon asymmetry of the universe by oscillation mechanism
- Direct tests by future experiments are possible
  - Direct search at DUNE, SHiP, FCC-ee, …
  - Search for LNV processes to check Majorana property
Backup
Limits on heavy neutrinos

- Limits on the mixing $\theta_{\mu l}$

Deppisch, Dev, Pilaftsis '15
[arXiv:1502.06541]
Sensitivity limits on $|\Theta_\mu|^2$

Sensitivity by using $B^+ \to \mu^+ \mu^+ \pi^-$

Belle II with $N_B = 5 \times 10^{10}$

FCC-ee (B) with $N_Z = 10^{13}$

$(Z \to b \bar{b} \Rightarrow N_B \approx 6 \times 10^{11})$

Cf. Sensitivity by using $W^+ \to \mu^+ \mu^+ \pi^-$

FCC-ee (W) with $N_W = 2 \times 10^8$

Belle, PRD87, 071106 ('13)
LHCb, PRL112, 131802 ('14)

Sensitivity by using $B_c^+ \to \mu^+ \mu^+ \pi^-$

LHCb for LHC run3

Milanes et al, PRD93, 094026 ('16)

TA, Ishida [arXiv:1609.06113]

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LNV in B decay: $B^+ \rightarrow \mu^+\mu^+\pi^-$

- Number of signal events

$$N_{\text{event}} = 2 N_B Br(B^+ \rightarrow \mu^+N) \int dE_N F(E_N) P(E_N)$$

- $N_B$: Number of $B^+$
- Energy distribution of $N$ in $B^+ \rightarrow \mu^+N$ decay

$$F(E_N) = \frac{1}{\Gamma(B^+ \rightarrow \mu^+N)} \frac{d\Gamma(B^+ \rightarrow \mu^+N)}{dE_N}$$

- Probability of signal decay $N \rightarrow \mu^+\pi^-$ inside detector

$$P(E_N) = Br(N \rightarrow \mu^+\pi^-) \left[ 1 - \exp \left( -\frac{L_{\text{det}}}{L_{\text{dec}}} \right) \right]$$  \quad L_{\text{det}}: detector length

Cf. Factor 2 accounts for CC process $B^- \rightarrow \mu^-\mu^-\pi$
Decay length and probability of signal decay

Ex: Search at Belle II

Decay length of $N$: $L_{\text{dec}} = \frac{E_N}{M_N \Gamma_N}$

$M_N = 3 \text{ GeV}$

Probability of signal decay ($N \rightarrow \mu^+ \pi^-$) inside detector (1.5 m)
Energy distribution of $N$ in $B^+ \rightarrow \mu^+ N$ decay

- **At Belle II**
  - $B^+$ moves slowly and $B^+ \rightarrow \mu^+ N$ occurs at rest approximately
  
  \[
  F(E_N) = \delta(E_N - E_*) \quad \text{for} \quad E_* = \frac{m_B^2 + M_N^2 - m_{\mu}^2}{2 m_B}
  \]

- **At FCC-ee ($\sqrt{s} = m_Z$)**
  - We take $E_B \simeq m_Z/2$ approximately
  
  \[
  F(E_N) = \frac{1}{p_{B^+} \beta_f} \quad \text{for} \quad E_N^+ \geq E_N \geq E_N^-
  \]

\[
\begin{align*}
  p_{B^+} &= \sqrt{E_{B^+}^2 - m_B^2} \\
  \beta_f &= \sqrt{1 - \frac{2(M_N^2 + m_{\mu}^2)}{m_{B^\pm}^2} + \frac{(M_N^2 - m_{\mu}^2)^2}{m_{B^\pm}^4}}, \\
  E_N^\pm &= \frac{4(m_{B^\pm}^2 + M_N^2 - m_{\mu}^2)E_{B^+} \pm 4p_{B^+} m_{B^\pm} \beta_f}{8m_{B^\pm}^2}.
\end{align*}
\]
Comparison: upper bounds from BAU

For $M_N = 3$ GeV

\[
|\Theta|^2 < \begin{cases} 
6.6 \times 10^{-7} & [1] \\
2.6 \times 10^{-7} & [2] \\
4.5 \times 10^{-8} & [3] 
\end{cases}
\]

Upper bounds from BAU


Baryogenesis region

Region accounting for observed BAU

Canetti, Shaposhnikov ‘10

TA, Eijima ‘13

\[ M_N > 2.1 \text{ MeV (NH)} \quad M_N > 0.7 \text{ MeV (IH)} \]
Constraints on heavy neutrinos

\[ M_N > 122 \text{ MeV (NH)} \]
\[ M_N > 136 \text{ MeV (IH)} \]