nuMSM and leptogenesis

Takehiko Asaka (Niigata Univ.)

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Introduction
Baryon v.s. antibaryon

Baryon
- proton \((B = +1)\)
- neutron \((B = +1)\)

Antibaryon
- antiproton \((B = -1)\)
- antineutron \((B = -1)\)

- We find baryons mostly, not antibaryons!
  - Existence of antiproton
    - In cosmic rays, \(p + p \rightarrow p + p + p + \bar{p}\)
    - At TEVATRON, \(p + \bar{p} \rightarrow X\)

- Asymmetry between baryons and antibaryons in our Universe

How large ???

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2019/04/10
Baryon Asymmetry of the Universe (BAU)

- Observational value

\[ Y_B = \frac{n_B}{s} = (0.872 \pm 0.004) \times 10^{-10} \]

\( n_B \) : baryon number density, \( s \) : entropy density

Planck 2018 [1807.06209]

CMBR

BBN

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[Strumia 06] [PDG]

2019/04/10
**Baryogenesis**

- Inflation sets baryon number $B = 0$
  $\rightarrow$ non-zero $B$ must be generated after the inflation

**Baryogenesis**

- Conditions for baryogenesis: Sakharov (1967)
  1. Baryon number B is violated
  2. C and CP symmetries are violated
  3. Out of thermal equilibrium
**BAU and lepton number violation**

- **$B$ and $L$ in the Standard Model**
  - $B$ and $L$ are accidental symmetries of SM Lagrangian
  - $B$ and $L$ are broken by non-perturbative effects, but $(B - L)$ is conserved.
  - At high temperatures, $B$ and $L$ violations are very rapid.

- Initial value $(B - L)_0$ is distributed to SM particles for high temperatures

  \[
  B = \frac{28}{79} (B - L)_0
  \]

- Not only $B$ violation, but also $L$ violation can be a source of BAU
Baryogenesis in the Standard Model

- B and L violations
  - Sphaleron for $T > 100 \text{GeV}$

- CP violation
  - 1 CP phase in the quark-mixing (CKM) matrix
    \[
    \text{CPV} \sim \frac{J_{CP}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)}{T_{EW}^{12}} \sim 10^{-19}
    \]
  - too small

- Out of equilibrium [Kajantie, Laine, Rummukainen, Shaposhnikov]
  - Strong first order phase transition if $m_h < 72 \text{ GeV}$
    but $m_h = 125 \text{ GeV}$
  - not satisfied

We have to go beyond the SM!
Right-handed neutrinos

$\nu_R$
BAU and right-handed neutrinos
Neutrino properties

- Mixing angles and mass squared differences are measured very 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 (\(m_{\nu_{\text{lightest}}}\) ? Mass ordering ?)
  - CP violations (Dirac phase ? Majorana phase(s) ?)
  - Dirac or Majorana fermions

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**Extension by RH neutrinos $\nu_R$**

\[
\delta L = i \nu_R \bar{\gamma}_\mu \nu_R - F \bar{L} \nu_R \Phi - \frac{M_M}{2} \nu_R^\dagger \nu_R + \text{h.c.}
\]

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

\[
-L = \frac{1}{2} (\nu_L, \nu_R^\dagger) \begin{pmatrix} 0 & M_D^T \\ M_D & M_M \end{pmatrix} \begin{pmatrix} \nu_L^\dagger \\ \nu_R \end{pmatrix} + \text{h.c.}
\]

\[
-\frac{1}{2} (\nu, N^c) \begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix} \begin{pmatrix} \nu^c \\ N \end{pmatrix} + \text{h.c.}
\]

- **Light active neutrinos $\nu$**
  - Mass $M_\nu = -M_D^T \frac{1}{M_M^2} M_D$ ($M_\nu \ll M_D$)
  - Smallness of neutrino masses is naturally explained

- **Heavy Neutral Leptons (Heavy Neutrinos) $N$** ($N \approx \nu_R$)
  - Mass $M_N = M_M$ and mixing $\Theta = M_D / M_M$
  - Mixing in CC current $\nu_L = U \nu + \Theta N^c$

Minkowski '77
Yanagida '79
Gell-Mann, Ramond, Slansky '79
Glashow '79
Yukawa Coupling and Mass of HNL

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

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

Seesaw does not work!
Mixing and Mass of HNL

\[ |\theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N} \quad m_\nu = 5 \times 10^{-11} \text{ GeV} \]
Range of parameter space

Direct search

Too large neutrino Yukawa couplings

$F^2 > 4\pi$

$M_2 = M_1$

$\mathcal{N} = 2$

Seesaw

Too small neutrino masses

Cosmology (BBN)
Baryogenesis regions

- **Baryogenesis via neutrino oscillation**
  (Akhmedov, Rubakov, Smirnov '98, TA, Shaposhnikov '05)

- **Resonant Leptogenesis**
  (Pilaftsis '97, Pilaftsis, Underwood '05)

- **Leptogenesis**
  (Fukugita, Yanagida '86)

TA, Tsuyuki '15

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Baryogenesis via leptogenesis
Leptogenesis

[Fukugita, Yanagida ’86]

- Attractive idea:
  - Heavy right-handed neutrinos for the seesaw mechanism can provide the mechanism for generating lepton asymmetry.

- Decay of right-handed neutrino $N_1$
  \[
  \varepsilon_{1\alpha} = \frac{\Gamma(N_1 \rightarrow L_{\alpha} + \Phi) - \Gamma(N_1 \rightarrow L_{\alpha} + \Phi)}{\Gamma(N_1 \rightarrow L_{\bar{\alpha}} + \Phi) + \Gamma(N_1 \rightarrow L_{\alpha} + \Phi)}
  \]

- If CP is violated, $\varepsilon_{1\alpha}$ can be non-zero and lepton number can be generated → source of BAU!
BAU via Leptogenesis

\[ \frac{n_B}{s} = \frac{n_{N_1}}{s} \times \epsilon_1 \times 0.35 \times \eta \]

- Number of \( N_1 \sim 10^{-2} \)
- CP asymmetry \( \propto M_1 \)
- Sphaleron conversion

Efficiency factor

\[ M_1 = 10^{10} \text{GeV} \]

\[ \tilde{m}_1 = \frac{F_1^2 v^2}{M_1} \]

[Giudice et al 03]
Lower Bound on Mass $M_1$

\[ \frac{n_B}{s} \propto \epsilon_1 \propto M_1 \]

Lower bound on mass

\[
M_1 > \begin{cases} 
2.4 \times 10^9 \text{ GeV} & \text{if } N_1 \text{ has zero} \\
4.9 \times 10^8 \text{ GeV} & \text{if } N_1 \text{ has thermal initial abundance} \\
1.7 \times 10^7 \text{ GeV} & \text{if } N_1 \text{ has dominant} 
\end{cases}
\]

[Giudice et al ’03]
Resonant leptogenesis

- Resonant production of lepton asymmetry occurs if right-handed neutrinos are quasi-degenerate.

\[
\varepsilon_1 = \frac{\Gamma(N_1 \to L_L + \Phi) - \Gamma(N_1 \to L_L^\ast + \Phi)}{\Gamma(N_1 \to L_L + \Phi) + \Gamma(N_1 \to L_L^\ast + \Phi)}
\]

\[
\Delta M \ll M_N \\
\Delta M = M_2 - M_1 \\
M_N = (M_2 + M_1)/2
\]

\[
\varepsilon_1 \propto \frac{M_N^2}{\Delta M^2} \quad (\text{for } \Delta M^2 > O(M_N \Gamma_N))
\]

- huge enhancement

⇒ Leptogenesis is possible even for \( M_1 \ll 10^9 \text{ GeV} \)

Note that \( M_1 \gtrsim 10^2 \text{ GeV} \) in this case in order to convert lepton asymmetry into baryon asymmetry by EW sphaleron process (\( T \gtrsim 10^2 \text{ GeV} \))
BAU and CPV in neutrino sector

- Neutrino Yukawa couplings

\[ M_\nu = -M_D^T M_{N,\text{diag}}^{-1} M_D \]

Casas, Ibarra (’01)

\[ F = \frac{i}{\langle \Phi \rangle} U M_{\nu,\text{diag}}^{1/2} \Omega M_{N,\text{diag}}^{1/2} \]

In mixing matrix \( U \) of active neutrinos

Dirac phase \( \delta \)

Majorana phase(s) \( \eta (\eta') \)

In mixing matrix \( \Omega \) of RH neutrinos

Phase(s) for \( \nu_R \)

These phases are essential for BAU!
Degenerate right-handed neutrinos with $M_1 = 10^3\text{GeV}$

--- impact on $0\nu\beta\beta$ decay
(See Yoshida-san’s talk.)

TA, Yoshida [arXiv:1812.11323]
Baryogenesis regions

Baryogenesis via neutrino oscillation
(Akhmedov, Rubakov, Smirnov '98, TA, Shaposhnikov '05)

Resonant Leptogenesis
(Pilaftsis '97, Pilaftsis, Underwood '05)

Leptogenesis
(Fukugita, Yanagida '86)
Baryogenesis via Neutrino Oscillation

Akhmedov, Rubakov, Smirnov (’98) / TA, Shaposhnikov (’05)
Shaposhnikov (’08), Canetti, Shaposhnikov (’10)
TA, Ishida (’10), Canetti, Drewes, Shaposhnikov (’12), TA, Eijima, Ishida (’12)
Canetti, Drewes, Shaposhnikov (’12), Canetti, Drewes, Frossard, Shaposhnikov (’12)
...

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

$$V_N = \frac{T^2}{8 k} F^\dagger F$$

- Asymmetries are generated since evolution rates of $L_\alpha$ and $\overline{L_\alpha}$ are different due to CPV

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Baryogenesis Region

Region accounting for $\frac{n_B}{s} = (8.55-9.00) \times 10^{-11}$

Canetti, Shaposhnikov ‘10

$M_N > 2.1$ MeV (NH) $\quad M_N > 0.7$ MeV (IH)

TA, Eijima ‘13
In this section we present our main results, namely, the bounds on the total and individual mixings of HNLs with active neutrinos. We describe how these results were obtained in a separate section.

The value of the BAU can be characterised in different ways. Throughout this work we use the variable \( Y_B = n_B/s \), where \( n_B \) is the baryon number density (particles minus antiparticles) and \( s \) is the entropy density. The observed value is \( Y_{\text{obs}}B = (8.81 \pm 0.28) \times 10^{-11} \). For each set of the model parameters we numerically find the value of \( Y_B \). We are interested in the regions of the parameter space where one can reproduce the observed value \( Y_{\text{obs}}B \).

Our results for the allowed values of \(|U|_2^2\) are shown in figure 1. In order to indicate how large can be the effect of the theoretical uncertainties in BAU computation, discussed in section 6, we show the borders of the regions where one can generate \( 2 \cdot Y_{\text{obs}}B \), and \( Y_{\text{obs}}B/2 \).

Figure 1. Within the white regions it is possible to reproduced the observed value of the BAU (black solid curves). The dashed and dotted curves demonstrate how large the possible theoretical uncertainties could be. Namely, the dashed curves correspond to the condition \( Y_B = 2 \cdot Y_{\text{obs}}B \), whereas the dotted line corresponds to \( Y_B = Y_{\text{obs}}B/2 \) accounting for the factor of 2 uncertainty in the computation of the BAU. The thin grey line shows the see-saw limit, i.e. it is impossible to obtain the correct masses of active neutrinos below this line. The blue line shows the projected sensitivity of the SHiP experiment ref. [62] represented in ref. [63].

Left panel: normal hierarchy, right panel: inverted hierarchy.

The allowed region of the parameter space is larger than it was previously recognized (see also the discussion in section 9, in particular, figure 7). The fact that successful baryogenesis is possible for quite large values of the mixings rises the question about the upper bounds of sensitivity of the direct detection experiments. To illustrate this point, we estimate the lifetime of an HNL using expressions for the decay rates of HNLs from ref. [64]. For instance, let us consider an HNL with the mass \( M = 5 \text{ GeV} \) and mixings close to the...
Dirac phase $\delta$ and baryogenesis via oscillation

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}s_{13}e^{i\delta} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}s_{13} \\ s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & e^{i\phi} \\ e^{i\phi} & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ \cos \omega & -\sin \omega \\ \xi \sin \omega & \xi \cos \omega \end{pmatrix}$$
T2K and NOvA indicate CPV in neutrino sector

T2K, PRL 121, 171802 ('18)

Non-zero Dirac phase

\[ \delta \sim -\frac{\pi}{2} \quad (\text{or} \quad \frac{3\pi}{2}) \]

Important step to understand baryogenesis by RH neutrinos!

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Search for HNL ($\nu_R$)
Production by meson decays

\[ K^+ \rightarrow e^+ N, \ K^+ \rightarrow \mu^+ N, \ldots \]

- **Peak search experiments**
  - Measure \( E_e \) in \( K^+ \rightarrow e^+ N \)
    
    \[ E_e = \frac{m_K^2 - m_e^2 - M_N^2}{2 m_K} \]

- **Beam dump experiments**

\[ K^+ \rightarrow e^+ N \]
\[ N \rightarrow \ell^+ \ell^- \nu + c.c. \]
Search for HNLs at T2K

Production of $N$

$K^+ \rightarrow \ell^+ + N$

Target & horns

$\pi^+, K^+$

Decay volume

Beam dump

ND280

Detection of $N$

$N \rightarrow \ell^- + \ell^+ + \nu$

$K^+ \rightarrow e^+ N \rightarrow e^+ (e^- e^+ \nu_e)$

$K^+ \rightarrow \mu^+ N \rightarrow \mu^+ (e^- e^+ \nu_e)$

$K^+ \rightarrow \mu^+ N \rightarrow \mu^+ (\mu^- e^+ \nu_e)$

$0.86 \times 10^{19}$ POT

PS191

T2K

$10^{21}$ POT

$V = 61.25 \text{m}^3 (9 \text{m}^3)$

$M_N \text{ (GeV)}$

$|\Theta|_e^2$

$|\Theta|_\mu^2$

$|\Theta|_e$

$|\Theta|_\mu$

Takehiko Asaka (Niigata Univ.)
(The T2K Collaboration)

Search for heavy neutrinos with the T2K near detector ND280


FIG. 5. 90% upper limits on the mixing element $U_{e2}^2$ as a function of heavy neutrino mass using the single-channel approach, considering only the contribution from $K^\pm \rightarrow e^\mp N, N \rightarrow e^\pm \pi^\mp$, with the three methods A, B and C. The limits are compared to the ones of PS191 experiment [6, 7].

FIG. 6. 90% upper limits on the mixing elements $U_{e2}^2$ (top), $U_{e3}^2$ (middle), $U_{\mu3}^2$ (bottom) as a function of heavy neutrino mass, obtained with the combined approach. The blue solid lines are obtained after marginalisation over the two other mixing elements. In the top plot, the additional blue dashed line corresponds to the case where profiling is used ($U_{e2}^2 = U_{e3}^2 = 0$). The limits are compared to the ones of other experiments: PS191 [6, 7], E949 [5], CHARM [29].
Limits on mixing of HNL

- Limits on mixing $\Theta_{eI}$

Deppisch, Dev, Pilaftsis ‘15
In this section we present our main results, namely, the bounds on the total and individual mixings of HNLs with active neutrinos. We describe, how these results were obtained in a separate section.

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Summary

Neutrinos may provide the mechanism for generating the matter-antimatter asymmetry of the universe

- Conventional seesaw scenario (M > 10^9 GeV)
  - [Seesaw + Leptogenesis]
  - natural framework of SUSY GUT ...
  - Exp. test for RH neutrinos is impossible

- Connection can be obtained even with M < 10^2 GeV
  - [Seesaw + Baryogenesis via RH neutrino osc.]
  - Such RH neutrinos might be tested!