Probing Origins of Neutrino Masses and Baryon Asymmetry in Kaon Decays

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I. Model with two Right-handed neutrinos N_1, N_2

Lagrangian: $L = L_{SM} + i\overline{N}_I \partial_\mu \gamma^\mu N_I - F_{\alpha I} \overline{L}_\alpha \Phi N_I - \frac{M_I}{2} \overline{N_I}^c N_I + h.c.$

We discuss search for heavy neutrinos with $M_N \leq m_K \simeq 493\mathrm{MeV}$.

1. **Seesaw mechanism** explain the tiny **Neutrino Masses** : $\Delta m^2_{sol} = 7.54 \times 10^{-5} \mathrm{eV}^2 \quad \Delta m^2_{atm} = 2.43\ (2.42) \times 10^{-3} \mathrm{eV}^2$. [G.L.Fogli et al. ('12)]
2. **Baryogenesis via right-handed neutrino oscillation** produces the **BAU** : $Y_B^{Obs} = 8.58 - 9.00 \times 10^{-11}$ from the WMAP data.[WMAP collaboration ('10)]

[Akhemedov, Rubakov, Smirnov('98)]
[Asaka, Shaposhnikov('05)]

$\longrightarrow$ Two heavy neutrinos are required to be quasi-degenerate.

II. Motivation

Neutrino Yukawa matrix : $F_{\alpha I} = i\, U_{PMNS}\, D_\nu^{1/2}\, \Omega\, D_N^{1/2} / \langle \Phi \rangle$ $\quad \alpha = e, \mu, \tau \quad I = 1,2$ (in IH) [Casas,Ibarra('01)]

$D_\nu^{1/2} = \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3} = 0)$

$D_N^{1/2} = \mathrm{diag}(\sqrt{M_1}, \sqrt{M_2}) = \mathrm{diag}\left(\sqrt{M_N - \Delta M/2}\ ,\ \sqrt{M_N + \Delta M/2}\right)$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\eta} & \\ & & 1 \end{pmatrix}$$

$$\Omega = \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} \cos(\mathrm{Re}\,\omega) & -\sin(\mathrm{Re}\,\omega) \\ \xi\sin(\mathrm{Re}\,\omega) & \xi\cos(\mathrm{Re}\,\omega) \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cosh(\mathrm{Im}\,\omega) & -i\sinh(\mathrm{Im}\,\omega) \\ i\sinh(\mathrm{Im}\,\omega) & \cosh(\mathrm{Im}\,\omega) \end{pmatrix}$$

Dirac phase : δ **Majorana phase:** η **Averaged mass:** M_N **Mass difference:** ΔM **Complex parameter:** $\mathrm{Re}\,\omega + i\,\mathrm{Im}\,\omega$ **Sign parameter:** ξ

Can we determine all unknown parameters of this model?

III. Analysis

1. Current status of heavy neutrinos

(i) Constraints from direct search experiments

$\longrightarrow$ Upper bounds on the interaction

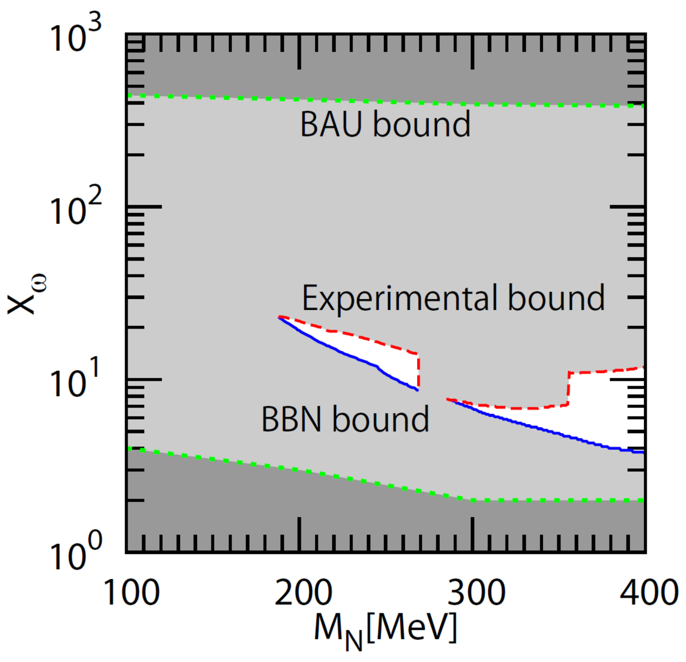
(ii) Constraints from Big-Bang Nucleosynthesis

$\longrightarrow$ Upper bound on the lifetime

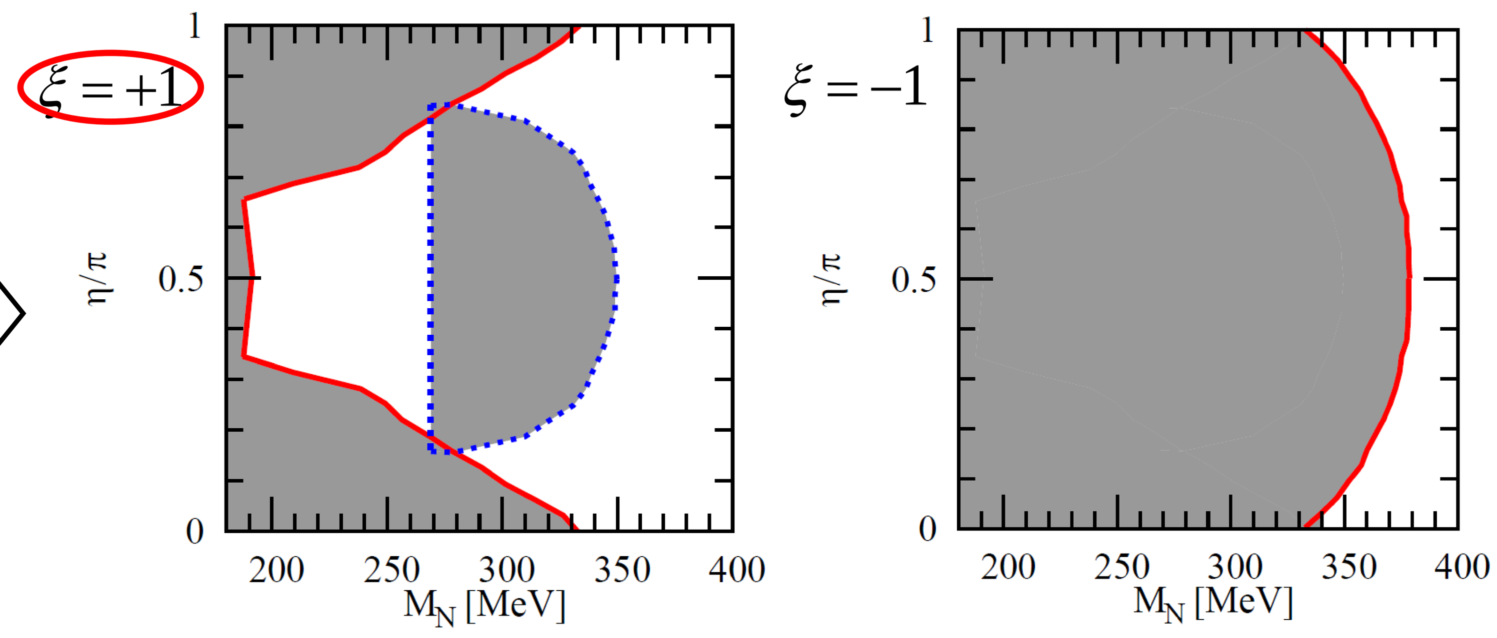
The allowed regions are obtained.

$F \propto \exp(\mathrm{Im}\,\omega) \equiv X_\omega$

Allowed parameter region (IH)



Restricted Majorana phase (IH)



For $M_N \lesssim 350\mathrm{MeV}$, Majorana phase is restricted.

2. Future tests of heavy neutrinos

2-1. Peak search experiment of heavy neutrinos [Shrock('80)]

(i) Averaged mass M_N

Ex) $K^+ \to e^+ + N_I \qquad E_{e^+} = (m_K^2 + m_e^2 - M_N^2)/(2m_K)$

The positron energy E_{e^+} **determines** M_N **.**

(ii) Parameter X_ω

The BR gives the value of X_ω **from** $\mathrm{BR} \propto |F_e|^2 \propto X_\omega^2$ **.**

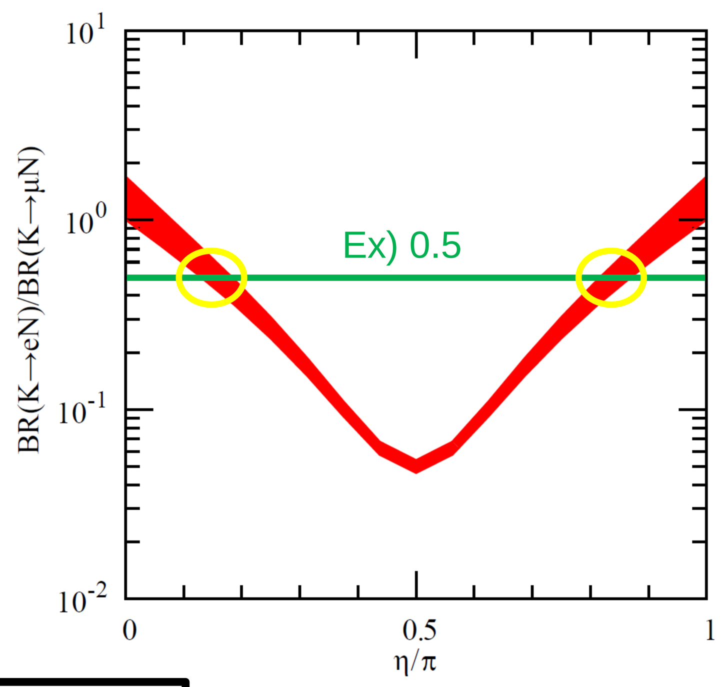
(iii) Sign parameter ξ

For $M_N \lesssim 350\mathrm{MeV}$, $\xi = +1$ **.**

(iv) Majorana phase η

Ratio :

$$R = \frac{\mathrm{BR}(K \to e + N)}{\mathrm{BR}(K \to \mu + N)}$$

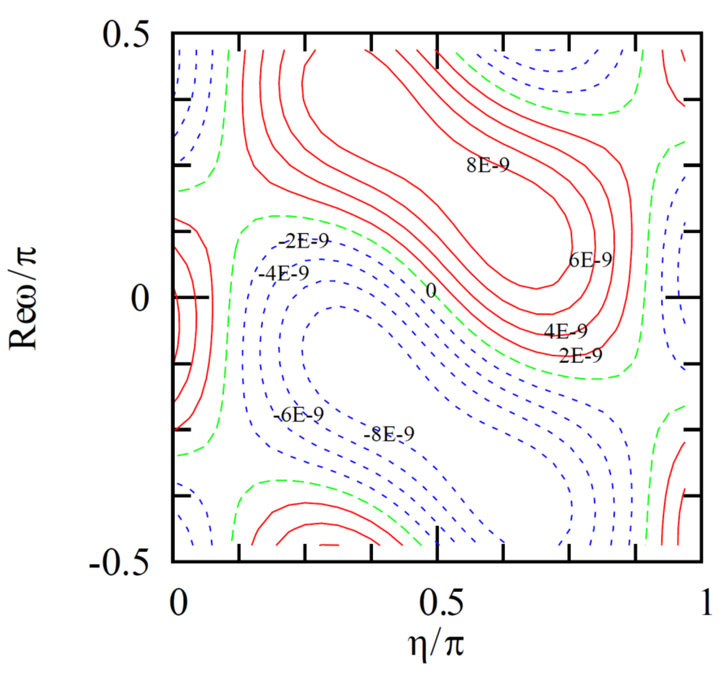


7 unknown parameters

$M_N \quad X_\omega = \exp(\mathrm{Im}\,\omega) \quad \eta \quad \xi \quad \mathrm{Re}\,\omega \quad \Delta M \quad \delta$

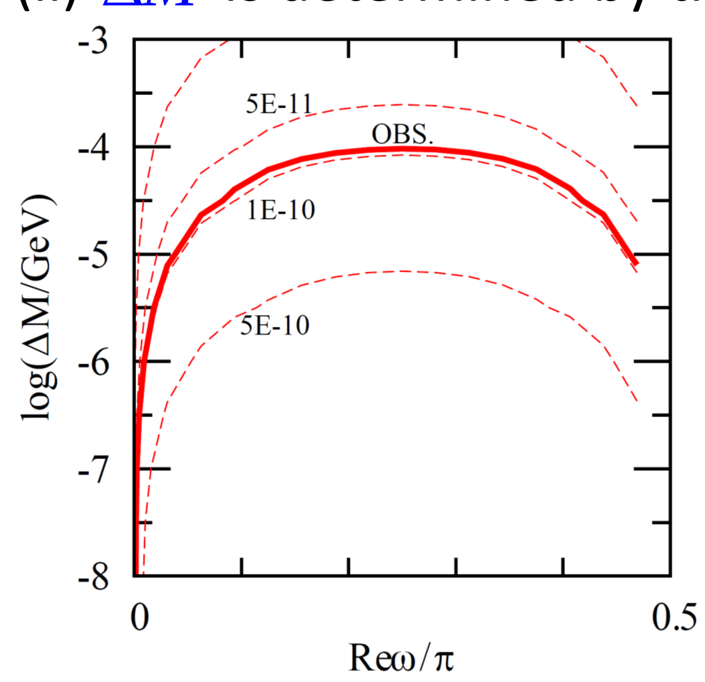
2-2. Realization of the observational value of BAU

(i) η and $\mathrm{Re}\,\omega$ determine the sign of BAU



Correct sign of BAU restricts the region of $\mathrm{Re}\,\omega$ **depending on** η **.**

(ii) ΔM Is determined by the observational value of BAU



$M_N = 250\mathrm{MeV},\ \delta = \pi,\ \eta = \pi/2$

Temperature of osc. Is crucial.

$T_{osc} \sim (M_{pl} M_N \Delta M)^{1/3}$

The order of ΔM **can be determined if** $\mathrm{Re}\,\omega$ **is not around** 0 **or** $\pi/2$ **.**

2-3. Future Osc. Exps.

(i) $\nu - \overline{\nu}$ deference

Dirac phase δ **might be measured.**

(ii) Observation of MSW effect

Neutrino mass hierarchy, NH or IH, might be distinguished.

IV. Conclusion

We found all unknown parameters of two RH neutrinos might be determined by direct search and neutrino oscillation experiments in future, in addition to the requirement of explaining the observational value of BAU. We presented a strategy for probing the origins of Neutrino Masses and Baryon Asymmetry of the Universe.