Bounds on heavy right handed neutrinos and implications for collider searches

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Neutrino Physics, Saturday, 07/07/2018

Based on : 1702.04668 (also see 1207.3734)
INTRODUCTION

Massive or Massless
First evidence of the existence of the solar neutrino: Homestake / Ray-Davis Experiment

SEARCH FOR NEUTRINOS FROM THE SUN*

Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)

A search was made for solar neutrinos with a detector based upon the reaction Cl^{37}(\nu, e^-)Ar^{37}. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was 3 \times 10^{-36} \text{sec}^{-1} per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than 2\times10^6 cm^{-2} \text{sec}^{-1} at the earth, and that less than 9% of the sun’s energy is produced by the carbon-nitrogen cycle.

THE RATE OF THE PROTON-PROTON REACTION*

John N. Bahcall and Robert M. May†
California Institute of Technology, Pasadena
Received January 31, 1968

THE RATE OF THE PROTON-PROTON REACTION AND SOME RELATED REACTIONS

John N. Bahcall* and Robert M. May†
California Institute of Technology, Pasadena, California
Received July 3, 1968
More developments

Super- Kamiokande, Sudbury Neutrino Observatory 1999, Neutrino oscillation between mass and flavor eigenstates

Neutrinos are very special

Nobel Prize in 2015

| Neutrino oscillation data | $\Delta m_{21}^2$ | $|\Delta m_{31}|^2$ | $\sin^2 2\theta_{12}$ | $\sin^2 2\theta_{23}$ | $\sin^2 2\theta_{13}$ |
|--------------------------|------------------|------------------|------------------|------------------|------------------|
| SNO                      | $7.6 \times 10^{-5}\text{eV}^2$ | $2.4 \times 10^{-3}\text{eV}^2$ | 0.87             | 0.999            | 0.084            |
| Super-K                  |                  |                  |                  |                  |                  |
| KamLAND, SNO             |                  |                  |                  |                  |                  |
| T2K                      |                  |                  |                  |                  |                  |
| MINOS                    |                  |                  |                  |                  |                  |
| DayaBay2015              |                  |                  |                  |                  |                  |
| RENO                     |                  |                  |                  |                  |                  |
| DoubleChooz              |                  |                  |                  |                  |                  |

NEWSPAPER HEADLINES AROUND THE WORLD PROCLAIMED THAT NEUTRINOS HAD MASS, BUT...
Neutrinos at Energy) Intensity 8 Cosmic Frontiers

We are looking for $\delta \neq 0$? Can we measure $\rho$ and $\phi$? 

Testing the UNITARITY of $U_{PMNS}$
Neutrino Mass: What Type

Ettore Majorana, (1906-?)

\[ m_\nu \bar{\nu}_L^c \nu_L + \text{H. c.} \]

→ ← ← →

Fermion Number Violating

Paul Dirac, FRS (1902-1984)

\[ m_\nu \bar{\nu}_R \nu_L + \text{H. c.} \]

→ → ← ←

Fermion Number Conserving

Can be tested in neutrinoless double beta decay and collider experiments
Neutrino Mass Hierarchy: Unknown

Can be fixed by the neutrino oscillation experiments?
Birth of (a) new idea/ s : generation of neutrino mass

Weinberg Operator in SM (d=5), PRL 43, 1566(1979)

\[
\overline{\ell}_L H \overline{\ell}_L^T H 
\]

within the Standard Model

The dimension 5 operator can be realized in the following ways

Majorana mass term is generated by the breaking of the lepton numbers by 2 units.
Seesaw Mechanism

\[ \mathcal{L} \supset -Y_D^{\alpha \beta} \ell_L^\alpha H N_R^\beta - \frac{1}{2} m_N^{\alpha \beta} N_R^\alpha C N_R^\beta + H.c. \]

\[ M_D = \frac{Y_D \nu}{\sqrt{2}} \]

\[ M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & m_N \end{pmatrix} \]

Naturally explains the small neutrino mass

\[ m_\nu = -M_D m_N^{-1} M_D^T. \]
Phenomenological Constraints on $\mathcal{N}$

\[ \nu \simeq \mathcal{N} \nu_m + \mathcal{R} N_m \]

\[ \left(1 - \frac{1}{2} \epsilon \right) U_{\text{MNS}} \]

\[ \epsilon = \mathcal{R}^* \mathcal{R}^T \]

\[ m_D m_N^{-1} \]

\[ U_{\text{MNS}}^T m_\nu U_{\text{MNS}} = \text{diag}(m_1, m_2, m_3) \]

In the presence of $\epsilon$, the mixing matrix $\mathcal{N}$ is not unitary, namely $\mathcal{N}^\dagger \mathcal{N} \neq 1$

\[ \mathcal{L}_{CC} = - \frac{g}{\sqrt{2}} W_\mu \bar{\ell}_\alpha \gamma^\mu P_L \left( \mathcal{N}_{\alpha j} \nu_{m_j} + \mathcal{R}_{\alpha j} N_{m_j} \right) + \text{H.c.} \]

\[ \mathcal{L}_{NC} = - \frac{g}{2 \cos \theta_W} Z_\mu \left[ \bar{\nu}_{m_i} \gamma^\mu P_L (\mathcal{N}^\dagger \mathcal{N})_{i j} \nu_{m_j} + \bar{N}_{m_i} \gamma^\mu P_L (\mathcal{R}^\dagger \mathcal{R})_{i j} N_{m_j} \right. \]

\[ \left. + \left\{ \bar{\nu}_{m_i} \gamma^\mu P_L (\mathcal{N}^\dagger \mathcal{R})_{i j} N_{m_j} + \text{H.c.} \right\} \right] \]

Nonunitarity: JHEP 10 (2006) 084
JHEP 12(2007) 061
Fixing the Matrices $\mathcal{N}$ and $\mathcal{R}$

- We consider the two generations of heavy neutrinos

$$U_{\text{MNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \text{diag}(1, e^{i\rho}, 1)$$

- We fix the parameters by the following neutrino oscillation data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.87</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>1.00</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.092</td>
</tr>
<tr>
<td>$\Delta m_{12}^2 = m_2^2 - m_1^2$</td>
<td>$7.6 \times 10^{-5}\text{eV}^2$</td>
</tr>
<tr>
<td>$\Delta m_{23}^2 =</td>
<td>m_3^2 - m_2^2</td>
</tr>
</tbody>
</table>
For the minimal scenario we consider the Normal Hierarchy (NH) and Inverted Hierarchy (IH) cases as

\[ D_{NH} = \text{diag} \left( 0, \sqrt{\Delta m_{12}^2}, \sqrt{\Delta m_{12}^2 + \Delta m_{23}^2} \right) \quad D_{IH} = \text{diag} \left( \sqrt{\Delta m_{23}^2 - \Delta m_{12}^2}, \sqrt{\Delta m_{23}^2}, 0 \right) \]

we assume degenerate case

\[ M_N = m_N^1 = m_N^2 \]

Light neutrino mass matrix can be simplified

\[ m_\nu = \frac{1}{M_N} m_D m_D^T = U_{\text{MNS}}^* D_{NH/\text{IH}} U_{\text{MNS}}^\dagger \quad m_D = \sqrt{M_N} U_{\text{MNS}} \sqrt{D_{NH/\text{IH}}} O \]

\[ \sqrt{D_{NH}} = \begin{pmatrix} 0 & 0 \\ (\Delta m_{12}^2)^{\frac{1}{4}} & 0 \\ 0 & (\Delta m_{23}^2 + \Delta m_{12}^2)^{\frac{1}{4}} \end{pmatrix} \quad \sqrt{D_{IH}} = \begin{pmatrix} (\Delta m_{23}^2 - \Delta m_{12}^2)^{\frac{1}{4}} & 0 \\ 0 & (\Delta m_{23}^2)^{\frac{1}{4}} \end{pmatrix} \]
How can we write $O$?

$$O = \begin{pmatrix} \cos(X + iY) & \sin(X + iY) \\ -\sin(X + iY) & \cos(X + iY) \end{pmatrix} = \begin{pmatrix} \cosh Y & i \sinh Y \\ -i \sinh Y & \cosh Y \end{pmatrix} \begin{pmatrix} \cos X & \sin X \\ -\sin X & \cos X \end{pmatrix}$$

$x$ and $y$ are real parameters.

Due to non-unitarity, the elements of $N$ are highly constrained by the precession experiments of the $W$, $Z$ decays and the LFV processes.

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**Phenomenologies:**
- JHEP 09 (2010) 108
- PRD 84, 013005 (2011)
- JHEP 08 (2012) 125
- JHEP 09 (2013) 023(E)

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**Lee and Shrock:**

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**Branchings:**

<table>
<thead>
<tr>
<th>Process</th>
<th>Branching $\mathcal{B}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \to e\gamma$</td>
<td>$&lt; 4.2 \times 10^{-13}$</td>
<td>EPJ C 76, (2016) no.8, 434</td>
</tr>
<tr>
<td>$\tau \to e\gamma$</td>
<td>$&lt; 4.5 \times 10^{-8}$</td>
<td>PLB 666, (2008)16-22</td>
</tr>
<tr>
<td>$\tau \to \mu\gamma$</td>
<td>$&lt; 12.0 \times 10^{-8}$</td>
<td>PLB 666, (2008)16-22</td>
</tr>
</tbody>
</table>
$$|\mathcal{NN}^\dagger| = \begin{pmatrix} 0.994 \pm 0.00625 & 1.288 \times 10^{-5} & 8.76356 \times 10^{-3} \\ 1.288 \times 10^{-5} & 0.995 \pm 0.00625 & 1.046 \times 10^{-2} \\ 8.76356 \times 10^{-3} & 1.046 \times 10^{-2} & 0.995 \pm 0.00625 \end{pmatrix}$$

$$\mathcal{NN}^\dagger \simeq 1 - \epsilon$$

$$|\epsilon| = \begin{pmatrix} 0.006 \pm 0.00625 & < 1.288 \times 10^{-5} & < 8.76356 \times 10^{-3} \\ < 1.288 \times 10^{-5} & 0.005 \pm 0.00625 & < 1.046 \times 10^{-2} \\ < 8.76356 \times 10^{-3} & < 1.046 \times 10^{-2} & 0.005 \pm 0.00625 \end{pmatrix}$$

$$\epsilon(\delta, \rho, Y) = (\mathcal{R}^\dagger \mathcal{R}^T)_{\text{NH/IH}} = \frac{1}{M_N^2} m_D m_D^T = \frac{1}{m_N} U_{\text{MNS}} \sqrt{D_{\text{NH/IH}}} \mathcal{O} \mathcal{O}^T \sqrt{D_{\text{NH/IH}}} U_{\text{MNS}}^\dagger$$
\[ \varepsilon(\delta, \rho, Y) \text{ is independent of } X \text{ since} \]

\[ O^* O^T = \begin{pmatrix}
\cosh^2 Y + \sinh^2 Y & -2i \cosh Y \sinh Y \\
2i \cosh Y \sinh Y & \cosh^2 Y + \sinh^2 Y
\end{pmatrix} \]

Now we perform a scan for the parameter set \( \{\delta, \rho, Y\} \) and identify an allowed region for which \( \varepsilon(\delta, \rho, Y) \) satisfies the experimental constraints

\[ M_N = 100 \text{ GeV} \]

\(-\pi \leq \delta, \rho \leq \pi \) with the interval of \( \frac{\pi}{20} \) and \( 0 \leq Y \leq 14 \) with the interval of 0.01875
Production of the heavy neutrino at the LHC

Through the Charged Current interaction

\[ q\bar{q}' \rightarrow \ell N_i \quad (u\bar{d} \rightarrow \ell^+_\alpha N_i \text{ and } \bar{u}d \rightarrow \ell^-_\alpha \overline{N_i}) \]

\[ \sigma(q\bar{q}' \rightarrow \ell_\alpha N_i) = \sigma_{LHC}(|R_{\alpha i}|^2) \]

Phenomenological works by Atre, Antusch, Chen, Das et. al., Del-Aguila, Dev et. al., Fischer, Han, Mohapatra et. al., Okada et. al., Savedraa et.al.

Put bounds on the mixing angle to constrain the production cross section

\[ N \rightarrow \ell W, \quad W \rightarrow jj \]

\[ \text{BR}(m_N) \geq 50\% \text{ Leading} \]

Many modes/ many ways to produce the heavy neutrinos at the colliders but (very small) mixings can spoil the game of search, but still we should hope for the best.
Fig. 3 and Fig. 4, respectively. Similarly to the NH case, we have found the constraints which provide us with the upper bound on the cross section. The same results but with respect to heavy neutrino production cross section is proportional to $\sin^2 \theta_{\text{MNS}}$ in Eq. (17). We have found the constraints in the IH case. The allowed region is shaded. The results are shown with respect to the mixing matrix element $\theta_{\text{MNS}}$. Note that as in Eqs. (7) and (8), the allowed region is obtained by solving $|R_{11}|^2 = 0.001$ for $Y$ and identifying an allowed region for $\delta$ and hence the constraints $|R_{12}|^2 < 10^{-15}$. For the NH Case, the corresponding results are shown in Fig. 1. The experimental constraints on the mixing matrix elements are shown in Fig. 2.
FIG. 1: The experimental constraints on the mixing matrix elements \( |R_{21}|^2 \) and \( |R_{22}|^2 \).

In our analysis, we set \( V_{10} \gg V_{21} \) in Eq. (17) provide us with the upper bound on the cross section. The same results but with \( V_{10} \gg V_{21} \) in Eq. (17). We have found similarly to the NH case, we show in Fig. 1 our results on the mixing matrix element \( |R_{21}|^2 \).

FIG. 2: The experimental constraints on the mixing matrix elements \( |R_{21}|^2 \) and \( |R_{22}|^2 \).

As in Eqs. (7) and (8), the result is the same for the IH case, the corresponding results are shown in Fig. 2. For the IH case, the corresponding results are shown in Fig. 1.

The interval of \( Y \) is shown in Fig. 2. In each panel, the shaded region satisfies the experimental constraints.
Here, note that the allowed region is shaded. The results are shown with respect to FIG. 1: The experimental constraints on the mixing matrix elements. The heavy neutrino production cross section is proportional to $|V_{11}|^2$ in Eq. (17). We have found $|V_{ij}|^2 \gg |V_{ij}|^2$ for $i,j = 1, 2, 3$. In our analysis, we set $|V_{ij}|^2 \gg |V_{ij}|^2$ in the NH and IH cases, respectively. For comparison, we list the experimental constraints on $|V_{31}|^2$ and $|V_{32}|^2$ as shown in FIG. 1. Note that as in Eqs. (7) and (8), the results are consistent with the interval of $0 < |R_{31}|^2 < 1$ and $0 < |R_{32}|^2 < 1$.
FIG. 5: The allowed parameter region for a combination of the mixing parameters, three parameters, the Dirac to reproduce all neutrino oscillation data. In this way, the model is controlled by only mental bounds on the mixing between the heavy Majorana neutrinos and the SM neutrinos.

FIG. 4: Same as Fig. 2 but for the IH case.

FIG. 3: Same as Fig. 1 but for the IH case.
FIG. 5: The allowed parameter region for a combination of the mixing parameters, in this way, the model is controlled by only three parameters, the Dirac mass matrix so as to reproduce all neutrino oscillation data.

In summary, we have studied the minimal type-I seesaw scenario and the current experimental bounds on the mixing between the heavy Majorana neutrinos and the SM neutrinos.
FIG. 5: The allowed parameter region for a combination of the mixing parameters, in this way, the model is controlled by only three parameters, the Dirac matrix so as to reproduce all neutrino oscillation data. In Table I the upper bounds on the mixing between the heavy Majorana neutrinos and the SM neutrinos.
FIG. 5: The allowed parameter region for a combination of the mixing parameters, $V_{\nu NH}$. We have also performed parameter scan for the expected upper bounds on the mixing parameters to be tested at the High-Luminosity LHC or at a 100 TeV pp-collider in the future. We have also performed parameter scan for the expected upper bounds on the mixing parameters to be tested at the current LHC experiments. The region for heavy Majorana neutrinos at the current LHC experiments.

<table>
<thead>
<tr>
<th>TABLE I: Upper bounds on the mixing parameters for $V_{\nu NH}$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{12}$</td>
</tr>
<tr>
<td>0.001</td>
</tr>
</tbody>
</table>

FIG. 6: Same as Fig. 5 but for the IH case.
In our case the parameter regions will remain the same even with the higher values of the heavy neutrino mass, e.g., 1 TeV and even high enough, however, the mixing angle squared raises up to $O(10^{-4})$.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Mixing angles</th>
<th>Upper Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>EWPD-\text{e}[62–64]</td>
<td>$</td>
<td>V_{eN}</td>
</tr>
<tr>
<td>EWPD-\text{\mu}[62–64]</td>
<td>$</td>
<td>V_{\mu N}</td>
</tr>
<tr>
<td>EWPD-\text{\tau}[62–64]</td>
<td>$</td>
<td>V_{\tau N}</td>
</tr>
<tr>
<td>L3[65]</td>
<td>$</td>
<td>V_{\ell N}</td>
</tr>
<tr>
<td>Higgs-LHC[66]</td>
<td>$</td>
<td>V_{\ell N}</td>
</tr>
<tr>
<td>LHC-\text{e}(ATLAS, 8 TeV)[67]</td>
<td>$</td>
<td>V_{eN}</td>
</tr>
<tr>
<td>LHC-\text{\mu}(ATLAS, 8 TeV)[67]</td>
<td>$</td>
<td>V_{\mu N}</td>
</tr>
<tr>
<td>LHC-\text{e}(CMS 13 TeV)</td>
<td>$</td>
<td>V_{eN}</td>
</tr>
<tr>
<td>LHC-\text{\mu}(CMS 13 TeV)</td>
<td>$</td>
<td>V_{\mu N}</td>
</tr>
<tr>
<td>LHC-\text{e, \mu}(CMS 13 TeV)</td>
<td>$</td>
<td>V_{eN}V_{\mu N}^*</td>
</tr>
</tbody>
</table>

\text{CMS-trilep-13 TeV:}  
\begin{align*}
|V_{eN}|^2 : & 6.52 \times 10^{-3} \\
|V_{\mu N}|^2 : & 4.32 \times 10^{-3}
\end{align*}
Conclusions

We have studied the minimal type-I seesaw scenario and the current experimental bounds on the mixing between the degenerate heavy Majorana neutrinos and SM neutrinos using the general Dirac Yukawa parameters in the light of Casas-Ibarra conjecture.

To constrain the analysis we use neutrino oscillation data, LFV and LEP results. Hence we obtain indirect limits on the light-heavy mixing angle which are stronger than the current experimental bounds.

We have noticed that the parameter regions of the mixing angles remain unaltered with the change in mass even make it high enough.

Thank You