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Constraining right-handed neutrinos

F. J. Escrihuela* [a], D. V. Forero * [b], O. G. Miranda+ [c], M. A. Tórtola* [d] and J. W. F. Valle* [e]

** AHEP Group, Institut de Física Corpuscular-CSIC/Univ. de València, Parc Científic de Paterna C/Catedràtico José Beltrán, 2 E-46980 Paterna (Valencia) SPAIN*
+ Departamento de Física, Centro de Investigación de Estudios Avanzados del IPN Apdo. Postal 14-740 07000 México, DF, México

Abstract

Several models of neutrino masses predict the existence of neutral heavy leptons. Here, we review current constraints on heavy neutrinos and apply a new formalism separating new physics from Standard Model. We discuss also the indirect effect of extra heavy neutrinos in oscillation experiments.

Keywords: neutrino oscillations, new physics, seesaw models, heavy neutrinos

1. Introduction

In the Standard Model (SM), neutrinos are massless particles contradicting the experimental observation of neutrino oscillations, hence physics beyond the SM is required.

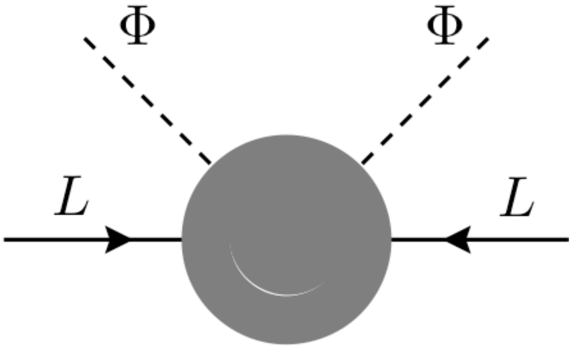

Fig. 1. Dimension five operator responsible for neutrino mass.

five operator $O_5 \, \alpha \, LL\Phi\Phi$ can be added to the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ model in order to introduce neutrino masses [1, 2], where L is one of the three lepton doublets and Φ is the SM scalar doublet.

After electroweak symmetry breaking, Majorana neutrino masses are induced, being proportional to $\langle \Phi \rangle^2$ and implying lepton number violation. Hence, the smallness of neutrino mass, compared to the masses of the SM charged fermions, arises from the smallness of the coefficient in front of the operator O_5 associated with the lepton number violation by two units $(\Delta L = 2)$.

Unfortunately we cannot say too much more about this operator. We do not have any clue about its mechanism, nor its mass scale, nor its flavour structure.

A common possibility is to assume that O_5 is induced, at the tree level, by the exchange of heavy

[a] franesfe@alumni.uv.es
[b] dvanegas@ific.uv.es
[c] omr@fis.cinvestav.mx
[d] mariam@ific.uv.es
[e] valle@ific.uv.es, URL: http://astroparticles.es/

"messenger" particles. In this way, seesaw models postulate neutral heavy states act as "messenger" particles to induce neutrino mass. For instance, a "right-handed" neutrino could be included associated to each of the three isodoublet neutrinos (Type I seesaw) [3, 4]:

$$m_\nu = \lambda_0 \frac{\langle \Phi \rangle^2}{M} \quad (1)$$

The existence of processes with $\Delta L = 2$, such as neutrinoless double beta decay, or lepton flavour violation processes (LFV) as $\mu \to e\gamma$, would give hints on the possible existence of these heavy Majorana neutrino "messengers". Hence we could find signatures of heavy neutrinos and their mixings by studying this kind of processes.

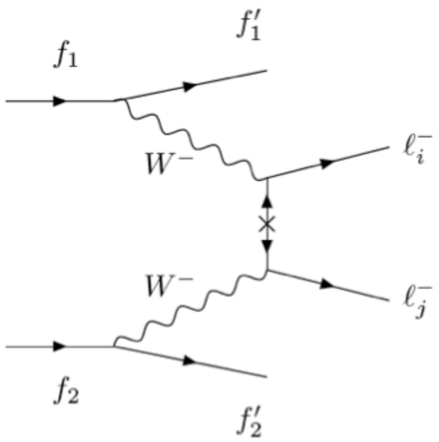

Fig. 2. Diagram of $\Delta L = 2$ process via Majorana neutrino exchange [5]

2. The method

As we said in the previous section, heavy neutrinos are introduced in several extensions of the SM such as linear and inverse seesaw models [6, 7], leading to a rich structure in the lepton mixing matrix. In order to work with this kind of models we will use a symmetric parameterization, consistent with the general formalism [3], neatly separating "new physics (NP)" and "standard model physics (SM)".

For the case of three light neutrinos and n – 3 extra heavy states, we can construct the mixing matrix U as the product of ω_{ij} rotation matrices (Okubo's notation [3, 8]:

$$U^{nxn} = \omega_{n-1n}\, \omega_{n-2n} \cdots \omega_{1n}\; \omega_{n-2n-1}\, \omega_{n-3n-1} \cdots \omega_{23}\, \omega_{13}\, \omega_{12} \quad (2)$$

$$\omega_{ij} = \begin{pmatrix} c_{ij} & 0 & e^{-i\phi_{ij}} s_{ij} \\ 0 & 1 & 0 \\ -e^{i\phi_{ij}} s_{ij} & 0 & c_{ij} \end{pmatrix} \quad (3)$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

The mixing matrix U can be decomposed in a new physics part and its Standard Model part

$$U^{nxn} = R^{NP}\, R^{SM} \quad (4)$$

$$R^{NP} = \omega_{n-1n}\, \omega_{n-2n} \cdots \omega_{1n} \cdots \omega_{34}\, \omega_{24}\, \omega_{14} \quad (5)$$

$$R^{SM} = \omega_{23}\, \omega_{13}\, \omega_{12} \quad (6)$$

and it can be divided in four blocks

$$U^{nxn} = \begin{pmatrix} N & S \\ T & V \end{pmatrix} \quad (7)$$

where N is the block corresponding to the standard three neutrinos, including their mixings between them and the extra neutrinos.

At the same time, the matrix N can be also decomposed as

$$N = N^{NP}\, U^{SM} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{SM} \quad (8)$$

where U^{SM} is the usual mixing matrix of the Standard Model and the matrix N^{NP} includes all the new physics information through the α_{ij} parameters (a more complete discussion will be given in [22])

$$\begin{aligned} \alpha_{11} &= c_{1n}\, c_{1n-1}\, c_{1n-2} \cdots c_{14} \\ \alpha_{22} &= c_{2n}\, c_{2n-1}\, c_{2n-2} \cdots c_{24} \\ \alpha_{33} &= c_{3n}\, c_{3n-1}\, c_{3n-2} \cdots c_{34} \\ \alpha_{21} &= c_{2n}\, c_{2n-1} \ldots c_{25}\, \tilde{s}_{24}\, \bar{s}_{14} \\ &+ c_{2n} \ldots c_{26}\, \tilde{s}_{25}\, \bar{s}_{15}\, c_{14} + \tilde{s}_{2n}\, \bar{s}_{1n}\, c_{1n-1}\, c_{1n-2} \ldots c_{14} \end{aligned} \quad (9)$$

where $\tilde{s}_{ij} = e^{-i\phi_{ij}} \sin\theta_{ij}$ and $\bar{s}_{ij} = -e^{i\phi_{ij}} \sin\theta_{ij}$.

In summary, by choosing a convenient order for the products of the rotation matrices, ω_{ij}, we can obtain a parameterization which puts all the information in a convenient form.

2.1. Simplest extension of SM: 3 +1 neutrinos

The formalism for the simplest extension of the SM includes one extra right handed singlet

$$\psi_L = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix} \quad , \quad N_R \tag{10}$$

with the mixing relations between the gauge and mass eigenstates given as [9]

$$\nu_{kL} = \sum_1^3 W_{k\alpha}\ \nu_{\alpha L} + S_{k4}\ \hat{N}_{4L} \tag{11}$$

The unitary mixing matrix U_{4x4} can be written as

$$U_{4x4} = \begin{pmatrix} N_{3x3} & S_{3x1} \\ T_{1x3} & V_{1x1} \end{pmatrix} = \begin{pmatrix} W_{e1} & W_{e2} & W_{e3} & S_{e4} \\ W_{\mu 1} & W_{\mu 2} & W_{\mu 3} & S_{\mu 4} \\ W_{\tau 1} & W_{\tau 2} & W_{\tau 3} & S_{\tau 4} \\ T_{41} & T_{42} & T_{43} & V \end{pmatrix} \tag{12}$$

where N_{3x3} is again the sub-matrix related with the standard neutrinos and can be decomposed as

$$N_{3x3} = N^{NP}\ U^{SM} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{SM} \tag{13}$$

It's important to notice that N_{3x3} is not unitary whereas U_{4x4} is unitary because includes all neutrinos in the model.

Comparing the terms in N_{3x3} with the terms of U^{SM} we obtain the following expressions for the α factors

$$\begin{aligned} \alpha_{11} &= c_{14} \\ \alpha_{22} &= c_{24} \\ \alpha_{33} &= c_{34} \\ \alpha_{21} &= \tilde{s}_{24}\ \bar{s}_{14} \\ \alpha_{31} &= \tilde{s}_{34}\ c_{24}\ \bar{s}_{14} \\ \alpha_{32} &= \tilde{s}_{34}\ \bar{s}_{24} \end{aligned} \tag{14}$$

2.2. Aplication to 3 +3 model

Usually, more than one extra neutrino is introduced in the theory, as in sequential-type seesaw mechanisms where 3 (Type I) or 6 (Inverse and Linear) extra singlets are included with the $SU(2)_L$ SM doublets.

For such models our parameterization becomes

$$U_{6x6} = \begin{pmatrix} N_{3x3} & S_{3x3} \\ T_{3x3} & V_{3x3} \end{pmatrix} \tag{15}$$

with these expressions for the α parameters

$$\begin{aligned} \alpha_{11} &= c_{16}\, c_{15}\, c_{14} \\ \alpha_{22} &= c_{26}\, c_{25}\, c_{24} \\ \alpha_{33} &= c_{36}\, c_{35}\, c_{34} \\ \alpha_{21} &= \tilde{s}_{26}\ \bar{s}_{16}\ c_{15}\, c_{14} \\ &\quad + c_{26}\ \tilde{s}_{25}\ \bar{s}_{15}\ c_{14}\ + c_{26}\ c_{25}\ \tilde{s}_{24}\ \bar{s}_{14} \\ \alpha_{31} &= c_{36}\ c_{35}\ c_{34}\ c_{24}\ \bar{s}_{14}\ + c_{36}\ \tilde{s}_{35}\ c_{25}\ \bar{s}_{15}\ c_{14} \\ &\quad + \tilde{s}_{36}\ c_{26}\ \bar{s}_{16}\ c_{15}\ c_{14}\ + c_{36}\ \tilde{s}_{35}\ \bar{s}_{25}\ \tilde{s}_{24}\ \bar{s}_{14} \\ &\quad + \tilde{s}_{36}\ \bar{s}_{26}\ c_{25}\ \tilde{s}_{24}\ \bar{s}_{14} + \tilde{s}_{36}\ \bar{s}_{26}\ \tilde{s}_{25}\ \bar{s}_{15} c_{14} \\ \alpha_{32} &= c_{36}\ c_{35}\ \tilde{s}_{34}\ \bar{s}_{24} \\ &\quad + c_{36}\ c_{35}\ \bar{s}_{25}\ c_{24}\ + \tilde{s}_{36}\ \bar{s}_{26}\ c_{25}\ c_{24} \end{aligned} \tag{16}$$

3. Oscillation constraints

The general expression for the survival and conversion neutrino probability is given by [10]

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{k>j} \mathrm{Re}[U^*_{\alpha k}\, U_{\alpha j}\, U_{\beta k}\, U^*_{\beta j}]\sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) + 2\sum_{k>j} \mathrm{Im}[U^*_{\alpha k}\, U_{\alpha j}\, U_{\beta k}\, U^*_{\beta j}]\sin\left(\frac{\Delta m^2_{kj} L}{2E}\right) \tag{17}$$

where $\delta_{\alpha\beta}$ appears due to the unitarity of the mixing matrix. However in a model with extra heavy neutrinos this equation will change a bit because, in this case, the mixing matrix describing the three standard neutrinos (N_{3x3} in our symmetric notation) will not be unitary and the effective probability will not be normalized to 1. In this case, the probability includes the W terms from the truncated matrix N_{3x3}.

$$P_{\alpha\beta} = \sum_{j,k}^{3} W_{\alpha k}^{*} W_{\beta k} W_{\alpha j} w_{\beta j}^{*}$$

$$-4\sum_{k>j} \mathrm{Re}[W_{\alpha k}^{*} W_{\beta k} W_{\alpha j} W_{\beta j}^{*}]\sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right) \quad (18)$$

$$+2\sum_{k>j} \mathrm{Im}[W_{\alpha k}^{*} W_{\beta k} W_{\alpha j} W_{\beta j}^{*}]\sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)$$

For the electron (anti) neutrino survival probability, we get the expression

$$P_{ee} = \sum_{j}^{3} \left|W_{ej}\right|^2 \left|W_{ej}\right|^2$$

$$-4\sum_{k>j} \left|W_{ek}\right|^2 \left|W_{ej}\right|^2 \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right) \quad (19)$$

and using Eq. (11) and Eq. (12) we obtain [22]

$$P_{ee} = \alpha_{11}^4 \left[1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)\right.$$

$$\left. -\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)\right] \quad (20)$$

Note that the effect of the extra neutrinos is totally included in the α_{11}^4 factor illustrating the utility of our symmetric formalism.

Considering now only one extra fourth neutrino, Eq. (19) would change to

$$P_{ee} \approx \cos^4\theta_{14} = \left(1 - \left|S_{e4}\right|^2\right)^2 \quad (21)$$

One could be tempted to study whether the presence of an extra light singlet leptons (sterile neutrinos) could play some role in the reported neutrino anomalies (as MiniBooNE [11]). Unfortunately this is not the case and we stick to the (natural) assumption that the extra states are heavy and do not take part in oscillation effects. In this case one can get a naive constraint from some reported combined analysis [12]

$$\sin^2\theta_{14} = \left|S_{e4}\right|^2 < 0.04 \ (90\%\ C.L.) \quad (22)$$

$$\alpha_{11}^2 = \cos^2\theta_{14} < 0.96 \quad (23)$$

4. Future oscillation experiments

As we can see, from the previous section, it is not possible with current experiments to obtain a very strong constraint on the new physics α parameters so we consider future experimental proposals, such as LENA [13].

LENA is a future neutrino experiment which will use a ^{51}Cr artificial neutrino source with 5 MCi intensity, producing a total of 1.9×10^5 neutrino events. The expected number of neutrino events for an energy recoil of the electron in the range from 200 to 550 keV, in the presence of an extra heavy neutrino would be given by

$$N_i = c_{14}^4 n_e \phi_{Cr} \Delta t \int_{T_i}^{T_{i+1}} \int \frac{d\sigma}{dT} R(T,T')dT'\,dT \quad (24)$$

where c_{14} is the mixing with the heavy neutrino, n_e is the number of electron targets, ϕ_{Cr} is the neutrino flux coming from the source, Δt is 28 days which corresponds to the half-life of the source, and $R(T,T')$ is the resolution function

$$R(T,T') = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(T-T')}{2\sigma^2}\right] \quad (25)$$

where T is the recoil energy, T' is the true energy and $\sigma = 0.075\sqrt{T/MeV}$ is the expected energy resolution.

An estimate of the expected sensitivity as a function of the total percent error of the experiment can be performed in advance, being shown in the Fig. 3

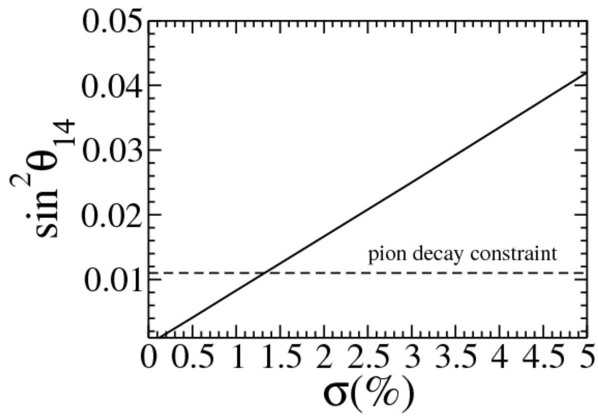

Fig. 3. Estimation of LENA sensitivity.

5. Other constraints

The effects of heavy neutrinos would show up as peaks in the leptonic decays of pions and kaons or from their direct production at higher collider energies [5]. One can perform an analysis of all these data, and combine the corresponding restrictions on heavy neutrinos parameters.

Fig. 4 compiles the bounds on the heavy neutrino mixing with electron neutrinos at 90%CL

6. Conclusions

Extra neutral heavy leptons are motivated in order to introduce neutrino mass but no positive evidence of these particles has been found so far.

Signatures of these heavy neutrinos arising from their mixings with the light ones could be searched at laboratory experiments. The study of these bounds would be useful to shed light upon the mass generation mechanism of neutrinos and probe the scale of new physics.

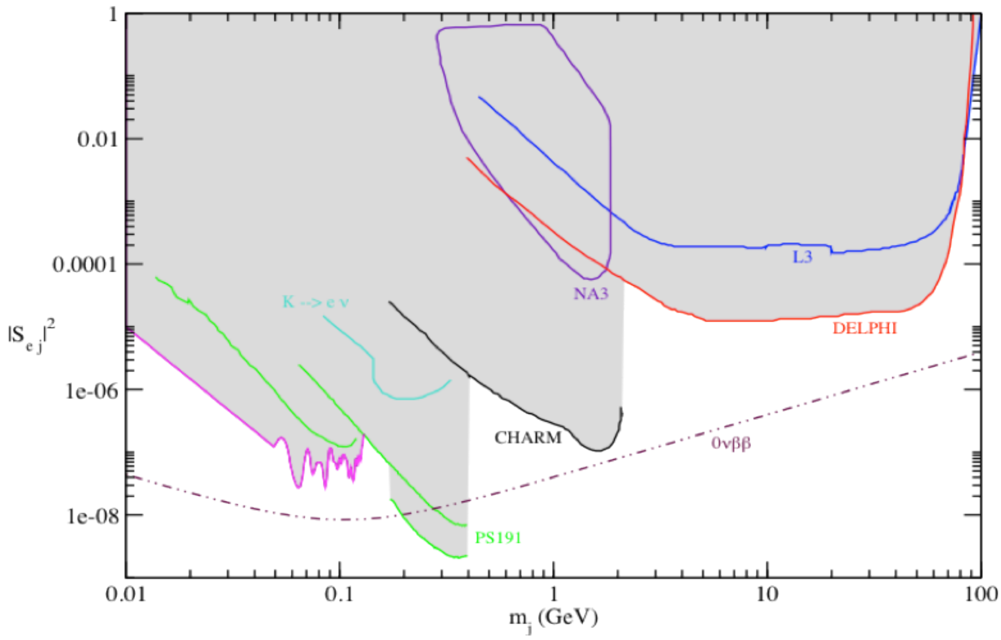

Fig. 4. Bounds on $|S_{ej}|^2$ versus the mass of the extra heavy neutrino m_j. The j in the labels correspond to the number of extra neutrinos (j = 4, 5, 6…)

This plot agglutinates bounds coming from peak searches at lepton decays, as $\pi \to e\nu$ [14] and $K \to e\nu$ [15]; meson decays at PS191 [16], NA3 [17] and CHARM [18] and Z^0 decays at DELPHI [19] and L3 [20]. In Fig. 4 is included also the excluded region from neutrinoless double beta decay experiments [21], valid only if the heavy neutrinos are Majorana particles.

For completeness we show the bounds on the mixing with muon and tau neutrinos in Fig. 5 and Fig. 6 respectively.

From a more complete combined analysis of these data we can get constraints on our new physics parameters α associated to the presence of the heavy neutrinos [22].

Models beyond SM, such as seesaw models, imply a very large number of parameters. The symmetric parameterization of the neutrino mixing matrix describing the charged current provides a very useful way to separate new physics from SM effects, concentrating the information and making easier to work with it. A more detailed account of our work will be described elsewhere.

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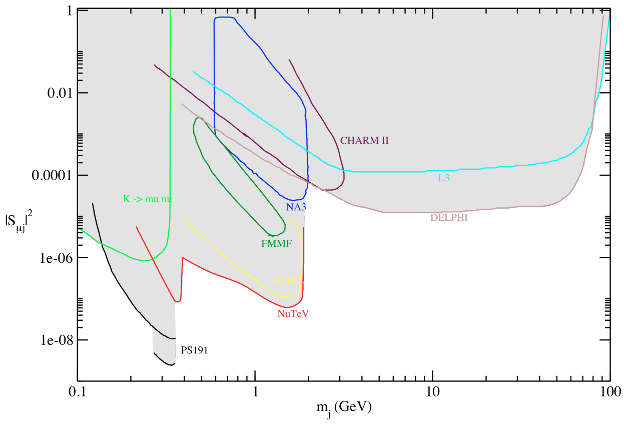

Fig. 6. Bounds on $|S_{\mu j}|^2$ versus m_j

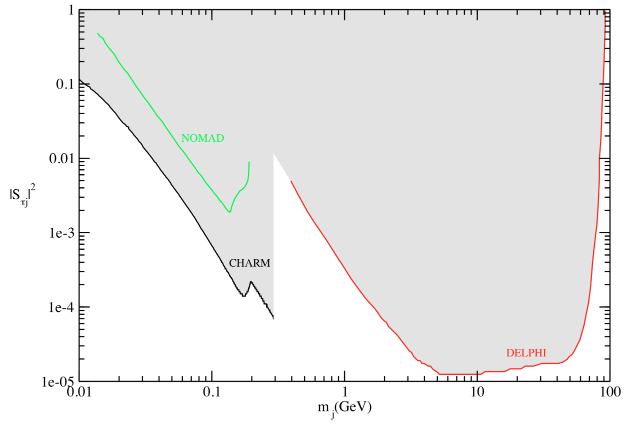

Fig. 6. Bounds on $|S_{\tau j}|^2$ versus m_j

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