Neutrino masses from beta decays after KamLAND and WMAP

(Updated including the NC enhanced SNO data*)

F. R. Joaquim1,†

1Centro de Física das Interacções Fundamentais (CFIF)
Departamento de Física, Instituto Superior Técnico,
Av.Rovisco Pais, 1049-001 Lisboa, Portugal

Abstract

The first data released by the KamLAND collaboration have confirmed the strong evidence in favour of the LMA solution of the solar neutrino problem. Taking into account the ranges for the oscillation parameters allowed by the global analysis of the solar, CHOOZ and KamLAND data, we update the limits on the neutrinoless double beta decay effective neutrino mass parameter and analyze the impact of all the available data from neutrinoless double beta decay experiments on the neutrino mass bounds, in view of the latest WMAP results. For the normal neutrino mass spectrum the range (0.05-0.23) eV is obtained for the lightest neutrino mass if one takes into account the Heidelberg-Moscow evidence for neutrinoless double beta decay and the cosmological bound. It is also shown that under the same conditions the mass of the lightest neutrino may not be bounded from below if the spectrum is of the inverted type. Finally, we discuss how future experiments can improve the present bounds on the lightest neutrino mass set by the Troitsk, Mainz and WMAP results.

PACS numbers: 14.60.Pq, 26.65.+t, 23.40.-s

Keywords: Neutrinoless double beta decay, neutrino masses and mixing

* Addendum in page 17 not included in the published version of this paper.
†Electronic address: filipe@gtae3.ist.utl.pt
I. INTRODUCTION

The first results reported by the Kamioka Liquid scintillator Anti-Neutrino Detector (KAMLAND) experiment [1] have brought new light to the search of the true solution of the solar neutrino problem. Through large distance measurements, the KAMLAND collaboration has measured, for the first time, reactor $\nu_e$ disappearance within the LMA allowed region for the neutrino oscillation parameters. Moreover, the Super-Kamiokande (SK) atmospheric [2] and the KEK to Kamioka (K2K) accelerator [3] neutrino experiments strongly indicate that neutrino flavor oscillations in the $\nu_\mu \rightarrow \nu_\tau$ channel are the most natural explanation for $\nu_\mu$ disappearance. These two evidences have changed our standard picture of particle physics in the sense that neutrino oscillations require neutrinos to be massive. In addition to this, neutrinos behave very differently from the other known elementary particles not only because they are much lighter but also due to the fact that their mixing pattern differs very much from the one observed in the quark sector.

In spite of all the great achievements of oscillation experiments, we are still far from a reasonable understanding of neutrino properties. Among all the unanswered questions in neutrino physics, the most fundamental one concerns the nature of neutrinos. In particular, it is of prior importance to know whether they are Dirac or Majorana particles [4]. While Dirac neutrinos require the existence of highly suppressed Yukawa couplings, which are difficult to accommodate on theoretical grounds, small Majorana neutrino masses naturally arise in the context of minimal extensions of the standard model where the seesaw mechanism [5] operates. Still, our present knowledge of the neutrino sector leaves too much room for speculation about the neutrino mass generation mechanism.

If neutrinos are massive, then the first question which immediately arises is concerned with the value of their absolute mass scale. The direct neutrino mass determination method relies on the detailed analysis of the end-point part of the beta decay spectrum of some nuclei [6]. At present, the most stringent experimental bound on the neutrino mass of comes from the Mainz [7] and Troitsk [8] experiments which have set a maximum value for $m_{\nu_e}$ of 2.2 eV. The KATRIN experiment [9], which is planned to start taking data in 2007, will be able to improve the sensitivity to neutrino masses by approximately one order of magnitude.

The search for positive signs in the neutrinoless double beta $[(\beta\beta)_{0\nu}]$ decay mode of certain even-even nuclei seems to be, at present, the most reliable way to look for the Majorana
nature of neutrinos. The phenomenological consequences of \((\beta \beta)_{0\nu}\) decays in the framework of neutrino oscillations have been widely studied in the literature [10, 11]. The extraction of neutrino mass limits through \((\beta \beta)_{0\nu}\)-decay measurements involves certain subtleties which are related to the fact that this method of probing on the absolute neutrino mass scale strongly depends on the results provided by neutrino oscillation experiments. Therefore, and in spite of not being sensitive to it, neutrino oscillation experiments turn out to be of great importance in the determination of the absolute neutrino mass scale.

All the outstanding developments in experimental neutrino physics were accompanied by an equally remarkable evolution of cosmological experiments. Recently, the results from the Wilkinson Microwave Anisotropy Probe (WMAP) have brought new insights into the measurements of a large set of cosmological parameters with an incredible precision. When combined with the data from the 2 degree Field Galactic Redshift Survey (2dF) [12], the WMAP results severely constrain the neutrino masses. In particular, this simultaneous analysis leads to the following upper bound on the neutrino contribution to the \(\Omega\) cosmological parameter, \(\Omega_\nu h^2 < 0.0076\) where \(h\) is the Hubble constant. This bound, together with the relation \(\sum_i m_i = 91.5 \Omega_\nu h^2 \text{ (eV)} \) [14] implies \(\sum_i m_i < 0.70 \text{ eV}\). Hence, in the framework of three light neutrino species, one obtains

\[
m_i \lesssim 0.23 \text{ eV}
\]

for the mass of each neutrino, indicating that the KATRIN experiment may not have enough sensitivity to measure the electron neutrino mass. Although this is true for \(\beta\)-decay experiments it may not hold for \((\beta \beta)_{0\nu}\)-decay searches which will be sensitive to even lower values of neutrino masses, in the future. This raises the interesting question on how competitive their results can be when compared with the cosmological ones.

Besides the constraints imposed on neutrino masses, the precise cosmological measurements also place important bounds on the number of effective allowed neutrino species \(N_{\nu}^{\text{eff}}\). Furthermore, using the range of the baryon-to-photon ratio \(\eta = 6.5^{+0.4}_{-0.3} \times 10^{-10}\) and the measurements of \(^4\text{He}\) primordial abundances, it has been shown that \(N_{\nu}^{\text{eff}} < 3.4\) [15]. This result turns out to be in serious conflict with the evidence for \(\nu_\mu \rightarrow \nu_e\) oscillations reported by the Liquid Scintillator Neutrino Detector (LSND) collaboration [16]. It is well known that the LSND results require the existence of at least four neutrino species which is incompatible with the bound \(N_{\nu}^{\text{eff}} < 3.4\). Moreover, the neutrino oscillation data indicate that four neutrino oscillation
scenarios are disfavoured when compared with the three neutrino oscillation scheme [17]. The KARMEN experiment [18] already excludes part of the LSND parameter region but a conclusive statement about the validity of the LSND results can only be made by the MiniBooNE experiment [19].

In this paper we update the bounds on the effective Majorana neutrino mass parameter in view of the latest global analysis of all the solar, CHOOZ and KamLAND data. This will be done in the framework of the normal and inverted neutrino mass schemes. Taking into account the WMAP constraint given in (1) and all the presently available neutrino oscillation and \((\beta\beta)_{0\nu}\)-decay data we obtain the neutrino mass bounds for each type of neutrino mass spectrum. Finally, the impact of future \((\beta\beta)_{0\nu}\) decay projects on the determination of neutrino masses is discussed and the consequences of the first Heidelberg-Moscow evidence for \((\beta\beta)_{0\nu}\) decay, when considered simultaneously with the WMAP bound on \(m_i\), are analyzed.

II. NEUTRINO OSCILLATION DATA: PRESENT STATUS

The presently available neutrino oscillation data, not including the results from LSND, can be accommodated in the framework of three mixed massive neutrinos. All the information about neutrino mixing is enclosed in the leptonic mixing matrix \(U\) which relates neutrino flavor and mass eigenstates in the following way

\[
\nu_{L\alpha} = \sum_{i=1}^{3} U_{\alpha j} \nu_{Lj}, \quad \alpha = e, \mu, \tau, \ j = 1, 2, 3.
\]

The mixing matrix \(U\) is a 3 × 3 unitary matrix and its form depends on whether neutrinos are Dirac or Majorana particles. In the framework of three light Majorana neutrinos, the matrix \(U\) can be parametrized as

\[
U = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta}
\end{pmatrix}
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & e^{i\alpha} & 0 \\
    0 & 0 & e^{i\beta}
\end{pmatrix},
\]

where \(s_{ij} \equiv \sin \theta_{ij}\) and \(c_{ij} \equiv \cos \theta_{ij}\). The phase \(\delta\) is the leptonic Dirac \(CP\)-violating phase and \(\alpha\) and \(\beta\) are Majorana phases [20]. The Dirac phase \(\delta\) can induce \(CP\)-violating effects in neutrino oscillations, sizable enough to be measured by very long baseline neutrino oscillation experiments in the future [21]. On the contrary, oscillation experiments are blind to the physical
effects associated to the Majorana phases $\alpha$ and $\beta$. Therefore, the determination of these phases is only viable in experiments sensitive to the Majorana nature of neutrinos like $(\beta\beta)_{0\nu}$-decay experiments. Nevertheless, this seems to be a difficult task to achieve since it requires not only the knowledge of all the neutrino mass and mixing parameters but also the understanding of the physics related with $(\beta\beta)_{0\nu}$ decays. Namely, the uncertainties in the nuclear matrix elements involved in the calculation of the $(\beta\beta)_{0\nu}$-decay rates seem to be the major problem on the possible determination of the Majorana phases [22].

The neutrino oscillation experimental results provide us with information about the neutrino mixing angles $\theta_{ij}$ and mass squared differences $\Delta m^2_{ij} = m_i^2 - m_j^2$. The identification of these parameters with the experimentally measured ones depends on the neutrino mass ordering. In this paper we will always identify $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$ with the ‘solar’, ‘atmospheric’ and the CHOOZ angles, respectively. There are two possible ways of ordering neutrino masses corresponding to the normal ($m_1 < m_2 < m_3$) and inverted ($m_3 < m_1 < m_2$) spectra. In both cases one can express two of the neutrino masses as a function of the remaining one and the $\Delta m^2_{ij}$'s. For the normal neutrino mass spectrum (NNMS)

$$m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}, \quad m_3 = \sqrt{m_1^2 + \Delta m^2_{21} + |\Delta m^2_{32}|}$$  \hspace{1cm} (4)$$

and for the inverted spectrum (INMS)

$$m_2 = \sqrt{m_3^2 + |\Delta m^2_{32}|}, \quad m_1 = \sqrt{m_3^2 + |\Delta m^2_{32}| - \Delta m^2_{21}}.$$  \hspace{1cm} (5)$$

The SK and K2K neutrino data point towards the existence of neutrino oscillations in the $\nu_\mu \rightarrow \nu_\tau$ channel. The results of these two experiments constrain the parameters $\theta_{23}$ and $|\Delta m^2_{32}|$ which, considering the SK only and SK+K2K data, are found to lie in the ranges [23]

$$\text{SK (99 \% C.L.) :} \quad 1.3 \times 10^{-3} \text{ eV}^2 \leq |\Delta m^2_{32}| \leq 5.0 \times 10^{-3} \text{ eV}^2,$$

$$\sin^2 2\theta_{23} > 0.85,$$

SK + K2K (99 \% C.L.) : \quad 1.4 \times 10^{-3} \text{ eV}^2 \leq |\Delta m^2_{32}| \leq 3.8 \times 10^{-3} \text{ eV}^2,$$

$$\sin^2 2\theta_{23} > 0.85,$$  \hspace{1cm} (6)$$

with the best-fit values

$$\text{SK :} \quad |\Delta m^2_{32}| = 2.7 \times 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{23} = 1,$$

SK + K2K : \quad |\Delta m^2_{32}| = 2.6 \times 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{23} = 1.$$  \hspace{1cm} (7)$$
Although the impact of the K2K data is still not very significant, the most important fact to retain is that these results are compatible with the pre-K2K ones.

The presently available data from all solar and reactor neutrino experiments confirm that the solar neutrino problem can be explained through the existence of $\nu_e \rightarrow \nu_{\mu,\tau}$ oscillations. After the release of the first KamLAND results, several global analysis of all the solar, CHOOZ and KamLAND data have been performed [24, 25]. As an example we take the pre-KamLAND and post-KamLAND results obtained in [24] which are summarized in Table I. Besides selecting the LMA region as the solution to the solar neutrino problem, the KamLAND experiment significantly restricts the corresponding oscillation parameter space as can be seen from Table I. The absence of $\nu_e$ disappearance reported by the CHOOZ [26] and Palo Verde [27] experiments imposes severe bounds on the $\theta_{13}$ angle. The global analysis performed in [24] shows that

$$\sin^2 \theta_{13} \lesssim 0.05 \quad (99.73\% \text{C.L.}) ,$$

being the best-fit value

$$(\sin^2 \theta_{13})_{\text{BF}} \lesssim 0.01 .$$

In spite of being insensitive to the absolute neutrino mass scale, neutrino oscillation experiments indicate that neutrinos oscillate with $\Delta m_{21}^2 \ll |\Delta m_{32}^2|$. This allows the classification

\[
\begin{array}{cccc}
\text{2$\nu$ Solar + CHOOZ} & \Delta m_{21}^2 \times 10^{-4} \text{eV}^2 & \sin^2 \theta_{12} & \text{2$\nu$ Solar + CHOOZ + KamLAND} \\
\hline
99\% \text{C.L.} & (0.25 - 4.2) & (0.21 - 0.46) & \text{LMA I} & (0.52 - 1.0) & (0.23 - 0.46) \\
 & & & \text{LMA II} & (1.2 - 2.1) & (0.23 - 0.39) \\
95\% \text{C.L.} & (0.28 - 2.3) & (0.24 - 0.42) & \text{LMA I} & (0.57 - 0.92) & (0.24 - 0.4) \\
 & & & \text{LMA II} & (1.4 - 1.8) & (0.27 - 0.33) \\
90\% \text{C.L.} & (0.3 - 1.9) & (0.24 - 0.4) & & (0.6 - 0.9) & (0.26 - 0.4) \\
\hline
\text{Best-fit} & 0.6 & 0.3 & 0.7 & 0.3 \\
\end{array}
\]
of the neutrino spectrum in hierarchical (HI), inverted hierarchical (IH) and quasi-degenerate (QD). From Eqs. (4) and (5) one has\(^1\)

\[
\begin{align*}
\text{HI} : & \quad m_1 \ll \Delta m_{21}^2 \Rightarrow m_2 \simeq \sqrt{\Delta m_{21}^2}, \quad m_3 \simeq \sqrt{|\Delta m_{32}^2|}, \\
\text{IH} : & \quad m_3 \ll |\Delta m_{32}^2| \Rightarrow m_1 \simeq m_2 \simeq \sqrt{|\Delta m_{32}^2|}, \\
\text{QD} : & \quad m_1 \gg |\Delta m_{32}^2| \Rightarrow m_1 \simeq m_2 \simeq m_3.
\end{align*}
\]

(10)

Although the presently available neutrino data do not discriminate between normal and inverted neutrino mass spectra, such a selection will be possible in future long baseline neutrino experiments; namely, the detailed study of earth matter effects in neutrino oscillations will allow for the determination of the sign of \(\Delta m_{32}^2\) and therefore give us a hint about the mass ordering of neutrino states [29].

### III. \((\beta\beta)_{0\nu}\) DECAYS AND NEUTRINO MASS SPECTRA

The combined analysis of \((\beta\beta)_{0\nu}\)-decay and neutrino oscillation experimental results may be of crucial importance on the clarification of some aspects related with massive neutrinos. In particular, the observation of these processes may not only reveal the Majorana character of neutrinos but also help in the determination of the absolute neutrino mass scale and spectra. If these decays occur due to the exchange of virtual massive Majorana neutrinos, their probability amplitudes are proportional to the so-called effective Majorana mass parameter

\[
m_{ee} = |(\mathcal{M}_\nu)_{11}| = \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|, \tag{11}
\]

where \(\mathcal{M}_\nu\) is the Majorana neutrino mass matrix, \(m_i\) is the mass of the neutrino mass eigenstate \(\nu_i\) and the \(U_{ei}\) are the elements of the first row of the leptonic mixing matrix. The most significant bounds on the value of the effective neutrino mass parameter come from the Heidelberg-Moscow [30] and IGEX [31] \(^{76}\)Ge experiments. Taking into account the uncertainties in the nuclear matrix elements involved in the determination of the \((\beta\beta)_{0\nu}\)-decay amplitudes,

\(^1\) We will not consider here the cases where \(m_1 \simeq m_2 < m_3\) and \(m_3 < m_1 \simeq m_2\) which correspond to the partial and partial inverted mass hierarchy spectra, respectively. The reader is addressed to Ref. [10] for a complete analysis on the subject.
one has

\[
m_{ee} \leq (0.35 - 1.24) \text{ eV} \quad \text{(Heidelberg – Moscow)}, \tag{12}
\]

\[
m_{ee} \leq (0.33 - 1.35) \text{ eV} \quad \text{(IGEX)}. \tag{13}
\]

The reanalysis of the Heidelberg-Moscow data performed in [32] has been interpreted as an evidence of \((\beta\beta)_0\nu\) decay of \(^{76}\text{Ge}\). The deduced range for \(m_{ee}\) was

\[
m_{ee} = (0.11 - 0.56) \text{ eV} \quad 95\% \text{ C.L.}, \tag{14}
\]

which is modified to

\[
m_{ee} = (0.05 - 0.84) \text{ eV} \quad 95\% \text{ C.L.}, \tag{15}
\]

if a \(\pm 50\%\) uncertainty of the nuclear matrix elements is considered. The interval

\[
m_{ee} = (0.4 - 1.3) \text{ eV}, \tag{16}
\]

has been obtained in Ref. [33] using a different set of nuclear matrix elements. After their publication, the results presented in Ref. [32] were criticized\(^2\) by some authors [35]. At the same time, some phenomenological implications of this claimed evidence were explored [36]. In any case, future experiments will have enough sensitivity to clarify this situation, and if confirmed, we will surely be in the presence of the first evidence in favour of the Majorana nature of massive neutrinos.

The definition of the effective Majorana neutrino mass parameter \(m_{ee}\) in terms of the physical parameters \(\theta_{ij}, m_i, \delta, \alpha\) and \(\beta\), is easily obtained from Eq. (11) and the relation

\[
\mathcal{M}_\nu = U^* \text{ diag} (m_1, m_2, m_3) U^\dagger, \tag{17}
\]

which comes from the diagonalization of the \(3 \times 3\) Majorana mass matrix. Parametrizing the mixing matrix \(U\) as done in Eq. (3) one gets

\[
m_{ee} = \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2 \right| = \left| m_1 c_{12}^2 c_{13}^2 + m_2 c_{13}^2 s_{12}^2 e^{-2i\alpha} + m_3 s_{13}^2 e^{-2i\beta} \right|. \tag{18}
\]

This expression can be further written in terms of the lightest neutrino mass \(m_1\) (\(m_3\)) for the NNMS (INMS) and the \(\Delta m^2\)'s, taking into account the mass definitions given in Eqs. (4) and

\(^2\) For a complete discussion on proofs and disproofs the reader is addressed to Ref. [34] and references therein.
from Eqs. (23)-(25) with the appropriate choice of the phases $\alpha$ and $m$ neutrinos with a common mass approximately equal to $m$ for the HI and IH neutrino mass spectra, respectively. In the case of three quasi-degenerate mass spectrum. From Eqs. (19) and (20) and the definitions given in (10) one has

$$m_{ee}^{NS} = \left| m_1 c_{12}^2 c_{13}^2 + \sqrt{m_1^2 + \Delta m_{21}^2} c_{13}^2 s_{12} e^{-2i\alpha} + \sqrt{m_1^2 + \Delta m_{21}^2} |\Delta m_{32}^2| s_{13}^2 e^{-2i\beta} \right|, \quad (19)$$

$$m_{ee}^{IS} = \left| \sqrt{m_3^2 + |\Delta m_{32}^2| - \Delta m_{21}^2} c_{12}^2 c_{13}^2 + \sqrt{m_3^2 + |\Delta m_{32}^2|} c_{13}^2 s_{12} e^{-2i\alpha} + m_3 s_{13}^2 e^{-2i\beta} \right|. \quad (20)$$

Furthermore, since $\Delta m_{21}^2 \ll |\Delta m_{32}^2|$, the following approximations hold

$$m_{ee}^{NS} \approx m_1 \left| c_{12}^2 c_{13}^2 + \sqrt{1 + \frac{\Delta m_{21}^2}{m_1^2}} c_{13}^2 s_{12} e^{-2i\alpha} + \sqrt{1 + \frac{\Delta m_{32}^2}{m_1^2}} s_{13}^2 e^{-2i\beta} \right|, \quad (21)$$

$$m_{ee}^{IS} \approx m_3 \left| \sqrt{1 + \frac{\Delta m_{32}^2}{m_3^2}} c_{12}^2 c_{13}^2 + \sqrt{1 + \frac{\Delta m_{32}^2}{m_3^2}} c_{13}^2 s_{12} e^{-2i\alpha} + s_{13}^2 e^{-2i\beta} \right|. \quad (22)$$

The above equations are valid for any neutrino mass spectrum since the lightest neutrino mass $m_1$ (or $m_3$) is not constrained. With the help of Eqs. (10) one can obtain approximate expressions of the effective neutrino mass parameter $m_{ee}$ depending on the type of neutrino mass spectrum. From Eqs. (19) and (20) and the definitions given in (10) one has

$$m_{ee}^{HI} \approx \sqrt{|\Delta m_{21}^2| s_{12}^2 c_{13}^2 + \sqrt{|\Delta m_{32}^2|} s_{13}^2 e^{-2i(\alpha - \beta)}}, \quad (23)$$

and

$$m_{ee}^{IH} \approx \sqrt{|\Delta m_{32}^2| c_{13}^2 |c_{12}^2 + s_{12}^2 e^{-2i\alpha}|}, \quad (24)$$

for the HI and IH neutrino mass spectra, respectively. In the case of three quasi-degenerate neutrinos with a common mass approximately equal to $m$, Eqs. (19) and (20) reduce to

$$m_{ee}^{QD} \approx m \left| c_{13}^2 (c_{12}^2 + s_{12}^2 e^{-2i\alpha}) + s_{13}^2 e^{-2i\beta} \right|. \quad (25)$$

The allowed ranges for the effective neutrino mass parameter in each case depend not only on the values of the $\Delta m_{ij}^2$'s and mixing angles but also on the Majorana phases $\alpha$ and $\beta$. In fact, depending on whether $CP$ is conserved or violated the value of $m_{ee}$ can drastically change [28]. Here we will only be concerned with the absolute bounds on $m_{ee}$ which can be easily obtained from Eqs. (23)-(25) with the appropriate choice of the phases $\alpha$ and $\beta$, leading to

$$(m_{ee}^{HI})_{\text{low}} \approx \sqrt{|\Delta m_{21}^2| s_{12}^2 c_{13}^2 - \sqrt{|\Delta m_{32}^2|} s_{13}^2}, \quad (m_{ee}^{HI})_{\text{up}} \approx \sqrt{|\Delta m_{21}^2| s_{12}^2 c_{13}^2 + \sqrt{|\Delta m_{32}^2|} s_{13}^2}, \quad (26)$$
TABLE II: Allowed ranges for the effective Majorana mass parameter $m_{ee}$ for each type of neutrino mass spectrum. The values presented here were determined taking into account the SK+K2K data summarized in (6)-(7) and the solar+CHOOZ+KamLAND results given in Table I and in (8) and (9).

| C.L.    | Type   | $m_{ee}^{HI} \times 10^{-3}$ eV | $m_{ee}^{HI} \times 10^{-2}$ eV | $m_{ee}^{QD}/m$ |
|---------|--------|---------------------------------|---------------------------------|-----------------|
| 99%     | LMA I  | $\lesssim 7.5$                 | $(0.3 - 6.2)$                   | $(0.026 - 1)$   |
|         | LMA II | $\lesssim 8.5$                 | $(0.8 - 6.2)$                   | $(0.16 - 1)$    |
| 95%     | LMA I  | $\lesssim 6.5$                 | $(0.7 - 6.2)$                   | $(0.14 - 1)$    |
|         | LMA II | $\lesssim 7.3$                 | $(1.2 - 6.2)$                   | $(0.27 - 1)$    |
| 90%     |        | $\lesssim 6.7$                 | $(0.7 - 6.2)$                   | $(0.14 - 1)$    |
| Best-fit|        | $(2.0 - 3.0)$                  | $(2.0 - 5.0)$                   | $(0.39 - 1)$    |

\[
(m_{ee}^{HI})_{low} \approx \sqrt{|\Delta m_{32}^2|} (1 - s_{13}^2)(1 - 2 s_{12}^2), \quad (m_{ee}^{HI})_{up} \approx \sqrt{|\Delta m_{32}^2|} (1 - s_{13}^2), \quad (27)
\]

\[
(m_{ee}^{QD})_{low} \approx m \left| c_{13}^2 (1 - 2 s_{12}^2) - s_{13}^2 \right|, \quad (m_{ee}^{QD})_{up} \approx m. \quad (28)
\]

The expression $(m_{ee}^{QD})_{up}$ together with the WMAP bound on neutrino masses given in (1) implies $m_{ee} \lesssim 0.23$ eV which can be interpreted has the cosmological bound on the effective Majorana mass parameter. Cancellations in $m_{ee}$ can in principle occur in the HI and QD cases if the following conditions are fulfilled

\[
HI : \quad s_{13}^2 = \frac{\sqrt{|\Delta m_{21}^2|} s_{12}^2}{\sqrt{|\Delta m_{32}^2|} + \sqrt{|\Delta m_{21}^2|} s_{12}^2} \approx (0.03 - 0.15), \quad (29)
\]

\[
QD : \quad s_{13}^2 \approx \frac{\cos 2\theta_{12}}{1 + \cos 2\theta_{12}} \approx (0.07 - 0.35). \quad (30)
\]

Comparing these ranges with the bound given in Eq. (8) one immediately concludes that cancellations cannot occur if neutrinos are almost degenerate. Still, the condition $m_{ee} = 0$ is compatible with a hierarchical neutrino mass spectrum. From Eq. (27) one can see that this can be accomplished in the IH case if $s_{12}^2 = 0.5$, which is already excluded by the data at 99% C.L.. The allowed ranges for the Majorana mass parameter are shown in Table II for each type of neutrino mass spectrum and the dependence of $m_{ee}$ on the lightest neutrino mass for the NNMS (INMS) is shown in Fig. 1a (b) where the shaded regions indicate the possible values
FIG. 1: Dependence of the effective Majorana neutrino mass parameter \( m_{ee} \) on the lightest neutrino mass for the (a) NNMS and (b) INMS. The shaded regions were obtained considering the SK+K2K results and the solar+CHOOZ+KamLAND at 99% C.L. given in (6) and Table I respectively, and the bound (8) on \( s_{13}^2 \). The solid lines correspond to the case where the best-fit values given in (7), (9) and Table I are taken into account.

for \( m_{ee} \) in each case. From Fig. 1 and Table II it becomes evident that the intervals determined for \( m_{ee} \) may overlap when considering the different types of neutrino mass spectra. This fact raises the interesting question on which are the conditions that must be fulfilled in order to get a clear separation of the different types of neutrino mass schemes. The imposition of such constraints can be translated into

\[
(m_{ee}^{\text{HI}})^\text{up} < (m_{ee}^{\text{HI}})^\text{low} , \quad (m_{ee}^{\text{QD}})^\text{up} < (m_{ee}^{\text{QD}})^\text{low} , \quad (m_{ee}^{\text{HI}})^\text{up} < (m_{ee}^{\text{QD}})^\text{low} .
\]  

(31)

Making use of Eqs. (26)-(28) one can show that this is equivalent to

\[
s_{12}^2 < \frac{1 - \tan^2 \theta_{13}}{2 + \sqrt{\Delta m_{21}^2 / |\Delta m_{32}^2|}} , \quad s_{12}^2 < \frac{1}{2} (1 - r_{32} - \tan^2 \theta_{13}) , \quad s_{12}^2 < \frac{1 - \tan^2 \theta_{13} (1 + r_{32})}{2 + r_{21}} , \quad (32)
\]

respectively, with \( r_{32} \equiv \sqrt{\Delta m_{32}^2 / m} \) and \( r_{21} \equiv \sqrt{\Delta m_{21}^2 / m} \). Choosing \( m \gtrsim 0.2 \text{ eV} \) [10] and \( m \lesssim 2.2 \text{ eV} \) (Troitsk+Mainz) one has, considering the 99%C.L. bounds on the oscillation parameters, \( \sqrt{\Delta m_{21}^2 / |\Delta m_{32}^2|} \simeq (0.12 - 0.39) \), \( r_{32} \simeq (0.02 - 0.31) \) and \( r_{21} \simeq (0.3 - 7) \times 10^{-2} \). Together with the inequalities (32) this leads to

\[
s_{12}^2 \lesssim (0.39 - 0.47) , \quad s_{12}^2 \lesssim (0.32 - 0.49) , \quad s_{12}^2 \lesssim (0.45 - 0.50) .
\]  

(33)
Taking into account that the WMAP result implies \( m \simeq 0.23 \text{ eV}, \) the first and third relations above remain practically unchanged whereas the second one is modified to \( s_{12}^2 \lesssim (0.34 - 0.39). \) This discussion shows that discriminating between the HI and IH or HI and QD leads to less restrictive conditions than the one needed for the discrimination between the IH and QD neutrino mass spectra. The possibility of determining the type of neutrino mass spectrum has been studied in detail in Ref. [37] where the uncertainties in the measured value of \( m_{ee} \) due to the imprecise knowledge of the nuclear matrix elements were taken into account. In particular, it has been shown that depending on the uncertainty factor, the above ranges of \( s_{12}^2 \) get modified, being even more restrictive.

At this point one may wonder if the results in favor of \((\beta\beta)_{0
u}\)-decay reported by the Heidelberg-Moscow collaboration may help us in the determination of the neutrino mass spectrum type. Comparing the results plotted in Fig. 1 with the ranges (14)-(16) it becomes obvious that the HI spectrum is ruled out. Requiring \((n_{ee}^{\text{IH}})_{up} \lesssim m_{ee}^{\text{min}} \simeq 0.05, \) one can show that the IH spectrum is excluded if

\[
|\Delta m_{32}^2| \lesssim \left[ \frac{(m_{ee})_{\text{min}}^2}{1 - s_{13}^2} \right]^2 \simeq 2.8 \times 10^{-3} \text{ eV}^2. \tag{34}
\]

Hence, considering the SK+K2K ranges for \(|\Delta m_{32}^2|\) given in (7), one concludes that there is still a small window allowed for the inverted hierarchical neutrino mass spectrum. On the other hand, the bounds presented in (14) and (16) select the QD spectrum as the only possible scenario for neutrino masses since in these cases \((n_{ee}^{\text{IH}})_{up} < m_{ee}^{\text{min}}.\)

### IV. NEUTRINO MASS BOUNDS FROM \((\beta\beta)_{0\nu}\) DECAYS

In this section we analyze the impact of all the available data from \((\beta\beta)_{0\nu}\)-decay experiments on the neutrino mass spectrum, taking into account the present neutrino oscillation results and the cosmological bound on neutrino masses.

Let us suppose that \( m_{ee} \) is found in the range \( m_{ee}^{\text{min}} \leq m_{ee} \leq m_{ee}^{\text{max}}. \) This, together with Eq. (19) leads to

\[
m_{ee}^{\text{max}} \geq m_{ee}^{NS} \geq c_{13}^2 \left| m_1 (1 - 2s_{12}^2) - s_{13}^2 \sqrt{m_1^2 + |\Delta m_{32}^2|} \right|, \tag{35}
\]

and

\[
m_{ee}^{\text{min}} \leq m_{ee}^{NS} \leq m_1 + \left( \sqrt{m_1^2 + |\Delta m_{32}^2|} - m_1 \right) s_{13}^2, \tag{36}
\]
for the NNMS and $m_{ee}^{\text{max}} \gg \sqrt{\Delta m_{21}^2 s_{12}^2}$. The above inequalities allow one to find approximate expressions for the upper and lower bounds of the lightest neutrino mass $m_1$, which we will denote by $m_{\text{up}}$ and $m_{\text{low}}$, respectively. We obtain in this case

$$m_{\text{up}} \approx m_{ee}^{\text{max}} \cos 2\theta_{12} c_{13}^2 + s_{13}^2 \sqrt{(m_{ee}^{\text{max}})^2 + |\Delta m_{32}^2| (\cos^2 2\theta_{12} c_{13}^4 - s_{13}^4)}, \quad (37)$$

$$m_{\text{low}} \approx m_{ee}^{\text{min}} c_{13}^2 - s_{13}^2 \sqrt{(m_{ee}^{\text{min}})^2 + |\Delta m_{32}^2| (1 - 2s_{13}^2)} \quad (38).$$

On the other hand, if $m_{ee}^{\text{min}} \lesssim \sqrt{\Delta m_{21}^2 s_{12}^2}$, the lower bound on $m_1$ does not exist. This can be understood taking into account that this condition is compatible with $m_1 = 0$. In particular, from Eq. (26) one has $(m_{ee}^{\text{HI}})_{\text{low}} \lesssim \sqrt{\Delta m_{21}^2 s_{12}^2}$, which means that for $m_{ee}^{\text{min}} \lesssim \sqrt{\Delta m_{21}^2 s_{12}^2} \approx 0.0025 \text{ eV}$ the value of $m_1$ is not bounded from below. The expressions for $m_{\text{up}}$ and $m_{\text{low}}$ can be further simplified if the terms proportional to $|\Delta m_{32}^2|$ are negligible or more specifically if

$$(m_{ee}^{\text{max}})^2 \gg |\Delta m_{32}^2| (\cos^2 2\theta_{12} c_{13}^4 - s_{13}^4), \quad (m_{ee}^{\text{min}})^2 \gg |\Delta m_{32}^2| (1 - 2s_{13}^2). \quad (39)$$

If this is the case, one gets

$$m_{\text{up}} \approx m_{ee}^{\text{max}} \cos 2\theta_{12} c_{13}^2 \quad (40)$$

and

$$m_{\text{low}} \approx m_{ee}^{\text{min}}, \quad (41)$$

which show that $m_{\text{up}}$ strongly depends on the $\theta_{12}$ angle while $m_{\text{low}}$ is only affected by the value of $m_{ee}^{\text{min}}$. Equivalent expressions can be found for the INMS considering that

$$m_{ee}^{\text{max}} \geq m_{ee}^{\text{IS}} \geq \left| c_{13}^2 (1 - 2s_{12}^2) \sqrt{m_3^2 + |\Delta m_{32}^2|} - m_3 s_{13}^2 \right|, \quad (42)$$

$$m_{ee}^{\text{min}} \leq m_{ee}^{\text{IS}} \leq \sqrt{m_3^2 + |\Delta m_{32}^2|}, \quad (43)$$

for $m_{ee}^{\text{max}} \gg \sqrt{\Delta m_{21}^2 s_{12}^2}$. These inequalities imply

$$m_{\text{up}} \approx m_{ee}^{\text{max}} s_{13}^2 + \cos 2\theta_{12} c_{13}^2 \sqrt{(m_{ee}^{\text{max}})^2 - |\Delta m_{32}^2| (\cos^2 2\theta_{12} c_{13}^4 - s_{13}^4)} \quad (44)$$

$$m_{\text{low}} \approx \sqrt{(m_{ee}^{\text{min}})^2 - |\Delta m_{32}^2|}, \quad (45)$$
FIG. 2: (a) Allowed region for the upper bound on the lightest neutrino mass for both the NNMS and INMS when the Heidelberg-Moscow result $m_{ee} \lesssim (0.35 - 1.24)$ eV is taken into account. The horizontal dash-dotted line indicates the bound on $m^{\text{up}}$ set by the Troitsk and Mainz experiments. The vertical dashed lines delimit the $s_{12}^2$ ranges given in Table I, and the vertical dotted line corresponds to the best-fit value $(s_{12}^2)_{BF} = 0.3$. The limit on $m^{\text{up}}$ imposed by the WMAP+2dF results is also shown. (b) Values of $(s_{12}^2)_{\text{max}}$ under which the bounds $m^{\text{up}} = 2.2$ eV (Troitsk+Mainz) and $m^{\text{up}} = 0.23$ eV (WMAP+2dF) can be improved for a given $m_{ee}^{\text{max}}$. The horizontal dash-dotted lines delimit the presently allowed regions for $s_{12}^2$ at 99% C.L. and the vertical dotted lines correspond to the sensitivities of future $(\beta\beta)_{0\nu}$-decay experiments.

which reduce to the expressions given in Eq. (40) in the limit where the terms proportional to $|\Delta m_{32}^2|$ can be neglected. It can easily be seen from the above expression that for $m_{ee}^{\text{min}} \lesssim \sqrt{|\Delta m_{32}^2|_{\text{max}}} \simeq 0.06$ eV there is no lower bound on $m_3$ in the INMS case.

Let us now discuss the implications of the Heidelberg-Moscow experimental result given in (12) on the values of neutrino masses. In this case $m_{ee} \lesssim (0.35 - 1.24)$ eV and therefore only an upper bound on the neutrino masses can be set. In order to compute it we can use the first expression in (40) for both NNMS and INMS since for this range of $m_{ee}^{\text{max}}$ the first inequality in Eq. (39) is verified. Therefore, we will denote both $m^{\text{up}}_{\text{NS}}$ and $m^{\text{up}}_{IS}$ just by $m^{\text{up}}$. In Fig. 2a we show the allowed region for $m^{\text{up}}$ as a function of $s_{12}^2$, obtained for $s_{13}^2 = 0.05$. Taking into account the Troitsk and Mainz bound on $m^{\text{up}}$ and the 99% C.L. allowed range for $s_{12}^2$ one can conclude that $m_{ee}^{\text{max}} \lesssim 1$ eV. This can be seen putting $s_{13}^2 = 0.05$ and $m^{\text{up}}_{\text{NS}} = 2.2$ eV in Eq. (40).
Using the best-fit value \( s_{12}^2 = 0.3 \) and the bound (9) one gets \( m_{ee}^{\text{max}} \lesssim 0.9 \text{ eV} \). Considering \( m_{ee} \lesssim 0.35 \text{ eV} \) one can see that the value of \( m_{\text{up}}^{\text{max}} \) extracted from \((\beta\beta)_{0\nu}\) decay is smaller than the Troitsk and Mainz bound for \( s_{12}^2 \lesssim 0.4 \). Alternatively, with \( s_{12}^2 = 0.3 \) and \( s_{13}^2 = 0.01 \) we get \( m_{\text{up}}^{\text{max}} \simeq 0.9 \text{ eV} \) for \( m_{ee}^{\text{max}} = 0.35 \text{ eV} \). From Fig. 2a we can also see that the bounds on \( m_{\text{up}} \) are always more conservative than the WMAP bound.

The sensitivity to \( m_{ee} \) is expected to be improved by several future experiments like the NEMO3 experiment [38], which has started to take data last year, and the CUORICINO project [39] to be operative this year. Other experimental setups are being planned or under construction with the goal of reaching sensitivities of \( m_{ee} \simeq 0.01 \text{ eV} \) [40]. Taking this into consideration, it is interesting to analyze how these upcoming experiments can improve the present bounds on \( m_{\text{up}} \). It can be shown that in order for this to happen the following condition has to be verified

\[
s_{12}^2 \gtrsim \frac{1}{2} \left( 1 - \frac{m_{ee}^{\text{max}}}{m_{\text{up}}} \left( 1 - s_{13}^2 \right) \right) \cong \frac{1}{2} \left( 1 - \frac{m_{ee}^{\text{max}}/m_{\text{up}} + s_{13}^2}{(1 - s_{13}^2)} \right) \equiv (s_{12}^2)_{\text{max}}, \quad (46)
\]

where the last expression corresponds to the limit \( m_{\text{up}} \gg \sqrt{\Delta m_{32}^2} \). In Fig 2b we show the dependence of \( (s_{12}^2)_{\text{max}} \) on the values of \( m_{ee}^{\text{max}} \) for \( m_{\text{up}} = 2.2 \text{ eV} \) (Troitsk+Mainz) and \( m_{\text{up}} = 0.23 \text{ eV} \) (WMAP+2dF). The vertical dotted lines indicate the sensitivities of some future \((\beta\beta)_{0\nu}\)-decay experiments.

Turning now our attention to the evidence for \((\beta\beta)_{0\nu}\) decay reported by the Heidelberg-Moscow collaboration and taking into account the \( m_{ee} \) ranges given in (14)-(16), we can use Eqs. (35) and (36) to compute the values of \( m_{\text{NS}}^{\text{up}} \) and \( m_{\text{NS}}^{\text{low}} \) which are shown in Fig. 3. The horizontal lines correspond to the values of \( m_{\text{NS}}^{\text{low}} \) for \( m_{ee}^{\text{min}} = 0.05, 0.11, 0.4 \text{ eV} \). We can see that the lower bounds on the lightest neutrino mass in each case obey the relation \( m_{\text{NS}}^{\text{low}} \simeq m_{ee}^{\text{min}} \), as already shown in Eq. (41). Consequently, the lower bound of \( m_{ee} \) given in (16) is in conflict with the WMAP result. Considering the results (14) and (15), together with the cosmological bound on neutrino masses, one has for the NNMS

\[
0.05 \text{ eV} \lesssim m_1 \lesssim 0.23 \text{ eV}.
\]

(47)

Regarding the inverted neutrino mass spectrum, we note that the above results obtained for \( m_{\text{up}}^{\text{NS}} \) remain valid, as already discussed before. However, the situation changes for \( m_{\text{IS}}^{\text{low}} \) in the sense that now the lower bound on the lightest neutrino mass may not exist. Considering \( m_{ee}^{\text{min}} = 0.1, 0.4 \text{ eV} \) we obtain \( m_{\text{IS}}^{\text{low}} \simeq 0.1, 0.4 \text{ eV} \) since for these values of \( m_{ee}^{\text{min}} \) we can neglect
FIG. 3: Allowed ranges for the lightest neutrino mass $m_1$ in the NS case, when the latest results of the Heidelberg-Moscow experiment are considered. The shaded region corresponds to the interval of $m_{ee}$ given in (14) and the dash-dotted and solid lines to the ranges (15) and (16), respectively.

$|\Delta m^2_{32}|$ in Eq. (45). On the other hand, from Eq. (45) and the SK+K2K allowed ranges for $\Delta m^2_{32}$ given in (6) one has $m_{1\text{IS}}^\text{low} \lesssim 1.1 \times 10^{-3}$ eV for $m_{ee}^{\text{min}} = 0.05$.

V. CONCLUSIONS

In this paper we have focused on the implications of the available data from $(\beta\beta)_{0\nu}$-decay experiments in the light of the latest neutrino oscillation and WMAP results. We have briefly commented on the possible occurrence of cancellations in the effective Majorana neutrino mass parameter taking into account the allowed ranges for the neutrino oscillation parameters at 99% C.L. given in Refs. [23] and [24]. We conclude that cancellations are only possible for the HI neutrino mass spectrum. However, this is no longer true if one relies on the best-fit values given in (7), (9) and Table I since in this case the condition $m_{ee} \simeq 0$ cannot be fulfilled for any of the neutrino mass schemes considered here. As for the extraction of neutrino mass bounds from the presently available $(\beta\beta)_{0\nu}$-decay data we have seen that, while the establishment of an upper bound on the mass of the lightest neutrino strongly depends on the value of $s^2_{12}$, the lower bound is only sensitive to $m_{ee}^{\text{min}}$, for the NNMS. In particular, the range $0.05 \text{ eV} \lesssim m_1 \lesssim 0.23 \text{ eV}$ is obtained if one considers the intervals for $m_{ee}$ given in (14)-(16) together with the WMAP bound. In the INMS case, the knowledge of $|\Delta m^2_{32}|$ may be relevant
for the lower bound on the lightest neutrino mass since in this case the lower bound on $m_3$ may not exist if a $\pm 50\%$ uncertainty in the nuclear matrix elements is taken into account. We have also discussed how the upcoming $(\beta\beta)_{0\nu}$-decay experiments may improve the WMAP result and concluded that, again, the key point relies on the measurement of $s_{12}^2$ which is expected to be improved by the future KamLAND and BOREXINO [41] data. Nevertheless, a sensitivity of $m_{ee} \simeq 0.09$ eV is required if the best-fit value $s_{12}^2 = 0.3$ is considered. Finally, we would like to remark that the cosmological bound on the absolute neutrino mass scale has important consequences for the future prospects in the study of $(\beta\beta)_{0\nu}$-decay searches. On the other hand, the bound $m_i < 0.23$ eV is not encouraging for the KATRIN experiment which will be sensitive to $m_i \gtrsim 0.35$ eV. In any case, one should remember that the kind of analysis presented here is based on the assumption that $(\beta\beta)_{0\nu}$ decays are mediated by the exchange of massive Majorana neutrinos. However, other mechanisms can give rise to these processes [42]. This possibility opens a new challenging question, namely how one can identify the physics behind $(\beta\beta)_{0\nu}$ decays.

VI. ADDENDUM: UPDATE WITH THE NC ENHANCED SNO DATA

Recently, the SNO collaboration has released the first data from the salt enhanced NC measurements [43]. Global analysis of all the solar neutrino and KamLAND data [44–49] show that, after including the new SNO data, the high-$\Delta m^2$ region ($\Delta m^2 > 10^{-4}$ eV$^2$) of the neutrino oscillation parameter space is now only accepted at the 3$\sigma$ level. Moreover, maximal mixing in the 1-2 neutrino sector is ruled out at more than 5$\sigma$.

In this addendum we update the allowed ranges for $m_{ee}$ obtained in the published version of this paper, taking into account the new ranges for the neutrino oscillation parameters (see also Refs. [50]). We consider the following results obtained in Ref. [46] at the 2$\sigma$ (3$\sigma$) levels

\begin{align*}
6 \ (5.4) \times 10^{-5} \text{ eV}^2 &< \Delta m_{21}^2 < 8.4 \ (9.5) \times 10^{-5} \text{ eV}^2, \quad 0.25 \ (0.23) < s_{12}^2 < 0.36 \ (0.39) \\
1.8 \ (3.3) \times 10^{-3} \text{ eV}^2 &< \Delta m_{32}^2 < 1.4 \ (3.7) \times 10^{-3} \text{ eV}^2, \\
\quad s_{13}^2 &\leq 0.035 \ (0.054). \quad (48)
\end{align*}

For the best-fit values of the above parameters one has [46]

\begin{align*}
\Delta m_{21}^2 = 6.9 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{32}^2 = 2.6 \times 10^{-3} \text{ eV}^2, \quad s_{12}^2 = 0.30, \quad s_{13}^2 = 0.006. \quad (49)
\end{align*}
In Fig. 4 we show the updated plots for the allowed ranges of \( m_{ee} \) as a function of the lightest neutrino mass, using the 3\( \sigma \), 2\( \sigma \) and best-fit results given in (48) and (49). From the plots and Eqs. (26)-(28), we get the following ranges for \( m_{ee} \)

\[
3\sigma \text{ (2}\sigma \text{) [Best fit]} : \ 0 \ (0) [2.2] \times 10^{-3} \lesssim m_{ee}^{\text{HI}} \lesssim 6.9 \ (5.2) [2.8] \times 10^{-3} \text{ eV} , \quad (50)
\]

\[
3\sigma \text{ (2}\sigma \text{) [Best fit]} : \ 0.7 \ (1.1) [2.0] \times 10^{-2} \text{ eV} \lesssim m_{ee}^{\text{HH}} \lesssim 6.1 \ (5.7) [5.0] \times 10^{-2} \text{ eV} , \quad (51)
\]

\[
3\sigma \text{ (2}\sigma \text{) [Best fit]} : \ m_{ee}^{\text{QD}} \gtrsim 0.035 \ (0.05) [0.09] \text{ for } m = 0.23 \text{ eV} . \quad (52)
\]

One can therefore see that the new SNO results reduce the allowed ranges for the effective Majorana mass parameter \( m_{ee} \). Nevertheless, the main conclusions taken in the previous version of this paper remain practically unchanged. Significant deviations from these results still require further improvements on the determination of the neutrino oscillation and \( (\beta\beta)_{0\nu} \) parameters.

Acknowledgements

The author thanks G.C. Branco and R. González Felipe for the careful reading of the manuscript and valuable suggestions. This work was supported by Fundação para a Ciência e a Tecnologia (FCT, Portugal) under the grant PRAXISXXI/BD/18219/98.

[1] K. Eguchi et al. [KamLAND Collaboration], Phys. Rev. Lett. 90, 021802 (2003) [arXiv:hep-ex/0212021].
[2] Y. Fukuda et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 81, 1562 (1998) [arXiv:hep-ex/9807003].
[3] M. H. Ahn et al. [K2K Collaboration], Phys. Rev. Lett. 90, 041801 (2003) [arXiv:hep-ex/0212007].
[4] The possibilities of distinguishing Dirac from Majorana neutrinos have been discussed in M. Zralek, Acta Phys. Polon. B 28, 2225 (1997) [arXiv:hep-ph/9711506].
[5] M. Gell-Mann, P. Ramond and R. Slansky, in Supergravity, ed. by P. van Nieuwenhuizen and D. Z. Freedman (North Holland, Amsterdam, 1979), p.315; S. L. Glashow, in Quarks and Leptons, Cargèse, 1979, edited by M. Levy et al. (Plenum, New York, 1980); T. Yanagida, in Proc. of the Workshop on the Unified Theory and Baryon Number in the Universe, ed. by O. Sawada and A. Sugamoto (KEK report 79-18, 1979), p.95, Tsukuba, Japan; 912; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980).
[6] For a complete review on the status and prospects for measuring neutrino masses see e.g. S. M. Bilenky, C. Giunti, J. A. Grifols and E. Masso, Phys. Rept. 379, 69 (2003) [arXiv:hep-ph/0211462].
[7] J. Bonn et al., Prog. Part. Nucl. Phys. 48, 133 (2002).
[8] V. M. Lobashev et al., Nucl. Phys. Proc. Suppl. 91, 280 (2001).
[9] A. Osipowicz et al. [KATRIN Collaboration], arXiv:hep-ex/0109033.
[10] For a review on several aspects related with $(\beta\beta)_0\nu$ decay see e.g. S. M. Bilenky, S. Pascoli and S. T. Petcov, Phys. Rev. D 64, 053010 (2001) [arXiv:hep-ph/0102265], and references therein.
[11] J. Schechter and J. W. Valle, Phys. Rev. D 25, 2951 (1982). S. T. Petcov and A. Y. Smirnov, Phys. Lett. B 322, 109 (1994) [arXiv:hep-ph/9311204]; M. Hirsch, H. V. Klapdor-Kleingrothaus and S. G. Kovalenko, Phys. Rev. D 53, 1329 (1996) [arXiv:hep-ph/9502385]; R. N. Mohapatra, arXiv:hep-ph/9507234. S. M. Bilenky, A. Bottino, C. Giunti and C. W. Kim, Phys. Rev. D 54, 1881 (1996) [arXiv:hep-ph/9602216]; F. Vissani, JHEP 9906, 022 (1999) [arXiv:hep-ph/9906525]; H. V. Klapdor-Kleingrothaus, H. Pas and A. Y. Smirnov, Phys. Rev. D 63, 073005 (2001) [arXiv:hep-ph/0003219]; K. Matsuda, T. Kikuchi, T. Fukuyama and H. Nishiura, Mod. Phys. Lett. A 17, 2597 (2002) [arXiv:hep-ph/0204254]; H. Minakata and H. Sugiyama, arXiv:hep-ph/0212240; G. C. Branco, R. Gonzalez Felipe, F. R. Joaquim and T. Yanagida, Phys. Lett. B 562, 265 (2003) [arXiv:hep-ph/0212341]; G. Bhattacharyya, H. Pas, L. g. Song and T. J. Weiler, arXiv:hep-ph/0302191; K. Matsuda, T. Fukuyama and H. Nishiura, arXiv:hep-ph/0302254; K. Cheung, Phys. Lett. B 562, 97 (2003) [arXiv:hep-ph/0302265]; H. V. Klapdor-
Kleingrothaus and U. Sarkar, arXiv:hep-ph/0304032; A. Abada and G. Bhattacharyya, arXiv:hep-ph/0304159.

[12] O. Elgaroy et al., Phys. Rev. Lett. 89, 061301 (2002) [arXiv:astro-ph/0204152].

[13] C. L. Bennett et al., arXiv:astro-ph/0302207; D. N. Spergel et al., arXiv:astro-ph/0302209.

[14] E. W. Kolb and M. S. Turner, “The Early Universe”, Addison-Wesley (1990).

[15] A. Pierce and H. Murayama, arXiv:hep-ph/0302131.

[16] A. Aguilar et al. [LSND Collaboration], Phys. Rev. D 64, 112007 (2001) [arXiv:hep-ex/0104049].

[17] M. Maltoni, T. Schwetz, M. A. Tortola and J. W. Valle, Nucl. Phys. Proc. Suppl. 114, 203 (2003) [arXiv:hep-ph/0209368].

[18] W. Kretschmer [KARMEN Collaboration], Acta Phys. Polon. B 33, 1775 (2002).

[19] I. Stancu et al. [MiniBooNE collaboration], FERMILAB-TM-2207

[20] S. M. Bilenky, J. Hosek and S. T. Petcov, Phys. Lett. B 94 (1980) 495; I. Y. Kobzarev, B. V. Martemyanov, L. B. Okun and M. G. Shchepkin, Sov. J. Nucl. Phys. 32 (1980) 823 [Yad. Fiz. 32 (1980) 1590]; M. Doi, T. Kotani, H. Nishiura, K. Okuda and E. Takasugi, Phys. Lett. B 102 (1981) 323; L. Wolfenstein, Phys. Lett. B 107 (1981) 77; B. Kayser and A. S. Goldhaber, Phys. Rev. D 28 (1983) 2341.

[21] See e.g. M. Lindner, arXiv:hep-ph/0209083, and references therein.

[22] W. Rodejohann, arXiv:hep-ph/0203214; V. Barger, S. L. Glashow, P. Langacker and D. Marfatia, Phys. Lett. B 540, 247 (2002) [arXiv:hep-ph/0205290]; S. Pascoli, S. T. Petcov and W. Rodejohann, [arXiv:hep-ph/0209059].

[23] G. L. Fogli, E. Lisi, A. Marrone and D. Montanino, Phys. Rev. D 67, 093006 (2003) [arXiv:hep-ph/0303064].

[24] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo and A. M. Rotunno, Phys. Rev. D 67, 073002 (2003) [arXiv:hep-ph/0212127].

[25] M. Maltoni, T. Schwetz and J. W. Valle, Phys. Rev. D 67, 093003 (2003) [arXiv:hep-ph/0212129]; J. N. Bahcall, M. C. Gonzalez-Garcia and C. Peña-Garay, JHEP 0302, 009 (2003) [arXiv:hep-ph/0212147]; P. C. de Holanda and A. Y. Smirnov, JCAP 0302, 001 (2003) [arXiv:hep-ph/0212270]; A. B. Balantekin and H. Yüksel, J. Phys. G 29, 665 (2003) [arXiv:hep-ph/0301072].

[26] M. Apollonio et al. [CHOOZ Collaboration], Phys. Lett. B 466, 415 (1999) [arXiv:hep-ex/9907037].

[27] F. Boehm et al., Phys. Rev. Lett. 84, 3764 (2000) [arXiv:hep-ex/9912050].
[28] S. Pascoli, S. T. Petcov and L. Wolfenstein, Phys. Lett. B 524, 319 (2002) [arXiv:hep-ph/0110287].
[29] P. Lipari, Phys. Rev. D 61, 113004 (2000) [arXiv:hep-ph/9903481].
[30] H. V. Klapdor-Kleingrothaus, Nucl. Phys. Proc. Suppl. 100, 309 (2001) [arXiv:hep-ph/0102276].
[31] C. E. Aalseth et al., Phys. Atom. Nucl. 63, 1268 (2000) [Yad. Fiz. 63, 1341 (2000)].
[32] H. V. Klapdor-Kleingrothaus, A. Dietz, H. L. Harney and I. V. Krivosheina, Mod. Phys. Lett. A 16, 2409 (2001) [arXiv:hep-ph/0201231].
[33] P. Vogel, “Limits From Neutrinoless Double-Beta Decay (Rev.),” in Particle Data Group (K. Hagiwara et al.), Phys. Rev. D 66, 010001 (2002).
[34] H. V. Klapdor-Kleingrothaus, arXiv:hep-ph/0302237; H. V. Klapdor-Kleingrothaus [Heidelberg-Moscow Collaboration], arXiv:hep-ph/0303217.
[35] F. Feruglio, A. Strumia and F. Vissani, Nucl. Phys. B 637, 345 (2002) [arXiv:hep-ph/0201291]; C. E. Aalseth et al., Mod. Phys. Lett. A 17, 1475 (2002) [arXiv:hep-ex/0202018]; Y. G. Zdesenko, F. A. Danevich and V. I. Tretyak, Phys. Lett. B 546, 206 (2002).
[36] H. V. Klapdor-Kleingrothaus and U. Sarkar, Mod. Phys. Lett. A 16, 2469 (2001) [arXiv:hep-ph/0201224]; E. Ma, Mod. Phys. Lett. A 17, 289 (2002) [arXiv:hep-ph/0201225]; V. Barger, S. L. Glashow, D. Marfatia and K. Whisnant, Phys. Lett. B 532, 15 (2002) [arXiv:hep-ph/0201262]; H. Minakata and H. Sugiyama, Phys. Lett. B 532, 275 (2002) [arXiv:hep-ph/0202003]; G. C. Branco, R. González Felipe, F. R. Joaquim and M. N. Rebelo, Nucl. Phys. B 640, 202 (2002) [arXiv:hep-ph/0202030]; Z. Z. Xing, Phys. Rev. D 65, 077302 (2002) [arXiv:hep-ph/0202034]; S. Pakvasa and P. Roy, Phys. Lett. B 535, 181 (2002) [arXiv:hep-ph/0203188]; G. Barenboim, J. F. Beacom, L. Borissov and B. Kayser, Phys. Lett. B 537, 227 (2002) [arXiv:hep-ph/0203261]; M. Frigerio and A. Y. Smirnov, Nucl. Phys. B 640, 233 (2002) [arXiv:hep-ph/0202247].
[37] S. Pascoli, S. T. Petcov and W. Rodejohann, Phys. Lett. B 558, 141 (2003) [arXiv:hep-ph/0212113].
[38] C. Marquet [NEMO Collaboration], Nucl. Phys. Proc. Suppl. 87, 298 (2000).
[39] E. Fiorini, Phys. Rept. 307, 309 (1998).
[40] H. V. Klapdor-Kleingrothaus, J. Hellmig and M. Hirsch, J. Phys. G 24, 483 (1998); H. Ejiri, J. Engel, R. Hazama, P. Krastev, N. Kudomi and R. G. Robertson, Phys. Rev. Lett. 85, 2917 (2000) [arXiv:nucl-ex/9911008]; G. Bellini et al., Eur. Phys. J. C 19, 43 (2001) [arXiv:nucl-ex/0007012]; K. Zuber, Phys. Lett. B 519, 1 (2001) [arXiv:nucl-ex/0105018]; C. E. Aalseth et al. [Majorana
Collaboration], arXiv:hep-ex/0201021; Y. G. Zdesenko, O. A. Ponkratenko and V. I. Tretyak, J. Phys. G 27, 2129 (2001) [arXiv:nucl-ex/0106021]; K. Wamba [EXO Collaboration], arXiv:hep-ph/0210186.

[41] T. Shutt [Borexino Collaboration], Nucl. Phys. Proc. Suppl. 110, 323 (2002).

[42] For a review see e.g J. D. Vergados, Phys. Rept. 361, 1 (2002) [arXiv:hep-ph/0209347], and references therein.

[43] S. N. Ahmed et al. [SNO Collaboration], arXiv:nucl-ex/0309004.

[44] A. B. Balantekin and H. Yuksel, arXiv:hep-ph/0309079.

[45] G. L. Fogli, E. Lisi, A. Marrone and A. Palazzo, arXiv:hep-ph/0309100.

[46] M. Maltoni, T. Schwetz, M. A. Tortola and J. W. Valle, arXiv:hep-ph/0309130.

[47] P. Aliani, V. Antonelli, M. Picariello and E. Torrente-Lujan, arXiv:hep-ph/0309156.

[48] P. Creminelli, G. Signorelli and A. Strumia, JHEP 0105 (2001) 052 [arXiv:hep-ph/0102234 v5].

[49] P. C. de Holanda and A. Y. Smirnov, arXiv:hep-ph/0309299.

[50] H. Murayama and C. Pena-Garay, arXiv:hep-ph/0309114; S. Pascoli and S. T. Petcov, arXiv:hep-ph/0310003.