CONSTRATNRS ON NEUTRINOLESS DOUBLE 
BETA DECAY FROM NEUTRINO OSCILLATION 
EXPERIMENTS 

S.M. Bilenky 
Joint Institute for Nuclear Research, Dubna, Russia, and 
Technion, Physics Department, 32000 Haifa, Israel, 

C. Giunti 
INFN, Sezione di Torino, and Dipartimento di Fisica Teorica, Università di Torino, 
Via P. Giuria 1, I–10125 Torino, Italy, 

and 

M. Monteno 
INFN, Sezione di Torino, and Dipartimento di Fisica Sperimentale, Università di Torino, 
Via P. Giuria 1, I–10125 Torino, Italy. 

Abstract 

We show that, in the framework of a general model with mixing of three 
Majorana neutrinos and a neutrino mass hierarchy, the results of the 
Bugey and Krasnoyarsk reactor neutrino oscillation experiments imply 
strong limitations for the effective Majorana mass $|\langle m \rangle|$ that character- 
izes the amplitude of neutrinoless double beta decay. We obtain further 
limitations on $|\langle m \rangle|$ from the data of the atmospheric neutrino experi- 
ments. We discuss the possible implications of the results of the future 
long baseline neutrino oscillation experiments for neutrinoless double-β 
decay.
1 Introduction

The investigation of the fundamental properties of neutrinos (neutrino masses, neutrino mixing, the nature of neutrinos (Dirac or Majorana?)), is the most important problem of today’s neutrino physics. This investigation is one of the major directions of search for physics beyond the Standard Model.

At present there are several experimental indications in favor of neutrino oscillations. The first indication was found in solar neutrino experiments (Homestake, Kamiokande, GALLEX and SAGE [1]). The second indication was found in the Kamiokande [2], IMB and Soudan [3] atmospheric neutrino experiments. A third indication in favor of neutrino oscillations was claimed recently by the LSND collaboration [4]. On the other hand, in many experiments with neutrinos from reactors and accelerators no indication in favor of neutrino oscillations was found (see the reviews in Refs.[5]).

The neutrino oscillation experiments do not allow to answer to the question: what type of particles are massive neutrinos, Dirac or Majorana? (see Ref.[6]). The answer to this question, that has a fundamental importance for the theory, could be obtained in experiments on the search for processes in which the total lepton number $L = L_e + L_\mu + L_\tau$ is not conserved. The classical process of this type is neutrinoless double-$\beta$ decay ($\beta\beta_{0\nu}$):

$$(A, Z) \rightarrow (A, Z + 2) + e^- + e^-,$$

The observation of this process would be an unambiguous proof that neutrinos are massive Majorana particles.

At present, the neutrinoless double-$\beta$ decay of several nuclei is searched for in more than 40 experiments (see, for example, Ref.[7]). No positive indication in favor of this process was found up to now. The most stringent limits on the half-lives for ($\beta\beta_{0\nu}$) decay were found in $^{76}\text{Ge}$ and $^{136}\text{Xe}$ experiments. In the $^{76}\text{Ge}$ experiments of the Heidelberg-Moscow and IGEX collaborations [8] it was found that

$T_{1/2}^{(76}\text{Ge}) > 7.4 \times 10^{24}\text{y} \quad (90\% \text{ CL}) \quad \text{Heidelberg-Moscow}, \quad (2)$

$T_{1/2}^{(76}\text{Ge}) > 4.2 \times 10^{24}\text{y} \quad (90\% \text{ CL}) \quad \text{IGEX}. \quad (3)$

In the $^{136}\text{Xe}$ experiment of the Caltech-Neuchatel-PSI collaboration [9] it was found that

$T_{1/2}^{(136}\text{Xe}) > 4.2 \times 10^{23}\text{y} \quad (90\% \text{ CL}) \quad (4)$

There are different mechanisms of violation of the lepton number that can be responsible for ($\beta\beta_{0\nu}$) decay (see, for example, Ref.[10]). We will consider here the contribution to the amplitude of the ($\beta\beta_{0\nu}$) process due to the usual mechanism of Majorana neutrino mixing. This mechanism is based on the assumption that the left-handed flavor neutrino fields $\nu_{iL}$ that enter in the standard CC weak interaction Hamiltonian

$$\mathcal{H}_I = \frac{G_F}{\sqrt{2}} \sum_{\ell=e,\mu,\tau} \bar{\ell}_L \gamma^\alpha \nu_{iL} j_{\alpha}^{\text{CC}} + \text{h.c.} \quad (5)$$
(here $G_F$ is the Fermi constant, $j_{\alpha}^{CC}$ is the standard CC hadronic current) are superpositions of the left-handed components $\nu_{iL}$ of massive Majorana neutrino fields:

$$\nu_{\ell L} = \sum_i U_{\ell i} \nu_{iL} \quad (\ell = e, \mu, \tau). \quad (6)$$

Here $\nu_i = \nu_i^c \equiv C\nu_i^T$ is the field of a Majorana neutrino with mass $m_i$ ($C$ is the charge conjugation matrix) and $U$ is the unitary mixing matrix.

In the framework of Majorana neutrino mixing, $(\beta\beta)_{0\nu}$ decay is a process of the second order in the weak interaction, with a virtual neutrino. In the case of small neutrino masses ($\lesssim 1$ MeV), the contribution to the matrix element of $(\beta\beta)_{0\nu}$ decay of the left-handed weak interaction is proportional to the effective mass (see, for example, Ref.\[11\])

$$\langle m \rangle = \sum_i U_{ei}^2 m_i. \quad (7)$$

The negative results of the experiments on the search for $(\beta\beta)_{0\nu}$ decay imply upper bounds for the the parameter $|\langle m \rangle|$. The numerical values of the upper bounds depend on the model that is used for the calculations of the nuclear matrix elements. From the results of the $^{76}\text{Ge}$ and $^{136}\text{Xe}$ experiments the following upper bounds were obtained:

$$|\langle m \rangle| < (0.6 - 1.6) \text{ eV} \quad (^{76}\text{Ge} \quad \text{[8, 12]}),$$

$$|\langle m \rangle| < (2.3 - 2.7) \text{ eV} \quad (^{136}\text{Xe} \quad \text{[9]}). \quad (8) (9)$$

A large progress of the experiments on the search for neutrinoless double-$\beta$ decay is expected in the future. Several collaborations plan to reach a sensitivity of $0.1 - 0.3$ eV for $|\langle m \rangle|$ \textit{[8, 13]}.

In the present paper we will obtain limits on the effective Majorana mass $|\langle m \rangle|$ from the existing results of neutrino oscillation experiments under the assumption that neutrinos with definite masses are Majorana particles. Implications of the results of solar and reactor neutrino experiments for neutrinoless double-$\beta$ decay were discussed in Refs.\[14, 15\]. Here we will extend these considerations and we will enlarge considerably the range of possible values of the heaviest neutrino mass. We will show that rather strong limitations on the parameter $|\langle m \rangle|$ can be obtained from the results of the reactor neutrino experiments. We will also take into account the atmospheric neutrino anomaly and we will discuss the possible implications for $(\beta\beta)_{0\nu}$ decay of the results of the new data-taking long baseline reactor neutrino experiments CHOOZ and Palo Verde \[16\].

2 Mixing of three neutrinos with a mass hierarchy

The results of the LEP experiments on the measurement of the invisible width of the $Z$ boson imply that only three flavor neutrinos exist in nature (see Ref.\[17\]). The number of
massive Majorana neutrinos that corresponds to three neutrino flavors is equal to three in the case of a left-handed Majorana mass term and can be more than three in the general case of a Dirac and Majorana mass term (see, for example, Ref. [11]).

We will consider the case of three light Majorana neutrinos. As it is well known, a characteristic feature of the mass spectra of leptons, up and down quarks is the hierarchy of the masses of the particles of different generations. What about neutrinos? Different possibilities for the mass spectrum of three neutrinos were considered recently in the literature [18, 19]. We will assume here that the neutrino masses $m_1, m_2, m_3$, like the masses of quarks and leptons, satisfy a hierarchy relation:

$$m_1 \ll m_2 \ll m_3.$$  

(10)

This scheme corresponds to the standard see-saw mechanism of neutrino mass generation, which is based on the assumption that the total lepton number is violated at a very large energy scale and is the only known mechanism that explains naturally the smallness of the neutrino masses with respect to the lepton masses. We will not assume, however, any specific see-saw relation between neutrino masses. We will use only the results of the neutrino oscillation experiments in the general framework of a hierarchy of neutrino masses.

In all four solar neutrino experiments (Homestake, Kamiokande, GALLEX and SAGE [1]) the detected event rates are significantly smaller than the event rates predicted by the Standard Solar Model (SSM) [20]. Moreover, a phenomenological analysis of the data of the different solar neutrino experiments, in which the predictions of the SSM are not used, strongly suggest that the solar neutrino problem is real [21]. In order to take into account the results of solar neutrino experiments in the framework of a hierarchy of neutrino masses, we have to assume that $\Delta m^2_{21} \equiv m^2_2 - m^2_1$ is relevant for the suppression of the flux of solar $\nu_e$'s.

If the disappearance of solar $\nu_e$'s is due to neutrino mixing, the results of the solar neutrino experiments and the predictions of the SSM can be reconciled with

$$\Delta m^2_{21} \sim (0.3 - 1.2) \times 10^{-5} \text{eV}^2 \quad \text{or} \quad \Delta m^2_{21} \sim 10^{-10} \text{eV}^2,$$

(11)

in the case of MSW resonant transitions [22] and just-so vacuum oscillations [23], respectively.

Under the assumption of a neutrino mass hierarchy, for the effective Majorana mass $|\langle m \rangle|$ that characterizes the amplitude of $(\beta\beta)_{0\nu}$ decay we have

$$|\langle m \rangle| \simeq |U_{e3}|^2 m_3 \simeq |U_{e3}|^2 \sqrt{\Delta m^2},$$

(12)

with $\Delta m^2 \equiv m^2_3 - m^2_1$. 

3
3 Reactor and solar neutrinos

In order to obtain information on the effective Majorana mass \(|\langle m \rangle|\) from the results of neutrino oscillation experiments, we will use the method developed in Ref.\[15\] (see also Ref.\[14\]).

In the case of a small \(\Delta m_{21}^2\) and a neutrino mass hierarchy, the modulus of the amplitude \(A_{\nu_\ell \to \nu_{\ell'}}\) of the transitions \(\nu_\ell \to \nu_{\ell'}\) of terrestrial neutrinos is given by

\[
|A_{\nu_\ell \to \nu_{\ell'}}| = \left| \delta_{\ell' \ell} + U_{\ell 3}^* \left( e^{-i \frac{\Delta m_{21}^2 L}{2p}} - 1 \right) \right|. \tag{13}
\]

Here \(L\) is the distance between the neutrino source and the detector and \(p\) is the neutrino momentum. In Eq.(13) we took into account the fact that for the distances and energies of terrestrial neutrino oscillation experiments we have

\[
\frac{\Delta m_{21}^2 L}{2p} \ll 1. \tag{14}
\]

For the \(\nu_\ell (\bar{\nu}_\ell)\) survival probability, from Eq.(13) we have (see Ref.[14])

\[
P_{\nu_\ell \to \nu_\ell} = P_{\bar{\nu}_\ell \to \bar{\nu}_\ell} = 1 - \frac{1}{2} B_{\ell,\ell} \left( 1 - \cos \frac{\Delta m_{21}^2 L}{2p} \right), \tag{15}
\]

where the oscillation amplitudes \(B_{\ell,\ell}\) are given by

\[
B_{\ell,\ell} = 4 |U_{\ell 3}|^2 \left( 1 - |U_{\ell 3}|^2 \right), \tag{16}
\]

with \(|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1\), because of the unitarity of the mixing matrix.

Several oscillation experiments with reactor \(\overline{\nu}_e\)'s have been performed in the latest years (see the review in Ref.[3]). No indication in favor of neutrino oscillations were found in these experiments. In our analysis we will use the data of the recent Krasnoyarsk and Bugey \[24\] experiments, which give the most stringent limits for the neutrino oscillation parameters.

We will consider the square of the largest neutrino mass \(m_3^2 \simeq \Delta m^2\) as an unknown parameter. Taking into account the limits for the neutrino mass obtained by the \(^3\text{H}\) \(\beta\)-decay experiments (see Ref.[17]), we will consider the region \(\Delta m^2 \leq 10^2\ \text{eV}^2\). The negative results of the reactor neutrino oscillation experiments allow to obtain an upper bound for the effective Majorana mass \(|\langle m \rangle|\) in the wide interval

\[
10^{-2}\ \text{eV}^2 \leq \Delta m^2 \leq 10^2\ \text{eV}^2. \tag{17}
\]

At any fixed value of \(\Delta m^2\) we have an upper limit for the amplitude \(B_{e,e}\) of \(\overline{\nu}_e \to \overline{\nu}_e\) transitions

\[
B_{e,e}^0 \leq B_{e,e}. \tag{18}
\]
The quantity $B_{ee}$ can be obtained from the exclusion plots found from the data of reactor experiments. From Eqs. (16) and (18) it follows that $|U_{e3}|^2$ must satisfy one of the two inequalities:

$$|U_{e3}|^2 \leq a_e^0,$$  

or

$$|U_{e3}|^2 \geq 1 - a_e^0,$$  

where

$$a_e^0 \equiv \frac{1}{2} \left( 1 - \sqrt{1 - B_{ee}^0} \right).$$  

In Fig. 4 we have plotted the values of the parameter $a_e^0$ obtained from the 90% CL exclusion plots of the Bugey and Krasnoyarsk experiments, for $\Delta m^2$ in the range (17). Figure 4 shows that $a_e^0$ is small in the considered range of $\Delta m^2$. Thus, from the results of the reactor oscillation experiments it follows that $|U_{e3}|^2$ can only be small or large (close to one).

The results of the solar neutrino experiments exclude this last possibility. In fact, the averaged probability $P_{\nu_e \to \nu_e}(E)$ of solar $\nu_e$‘s to survive, in the case of a neutrino mass hierarchy with $\Delta m^2_{21}$ relevant for the oscillations of solar neutrinos, is given by (see Ref. [25])

$$P_{\nu_e \to \nu_e}(E) = \left(1 - |U_{e3}|^2\right)^2 P_{\nu_e \to \nu_e}^{(1,2)}(E) + |U_{e3}|^4,$$  

where $P_{\nu_e \to \nu_e}^{(1,2)}(E)$ is the $\nu_e$ survival probability due to the mixing between the first and the second generations and $E$ is the neutrino energy. If $|U_{e3}|^2$ satisfies the inequality (20), we have $P_{\nu_e \to \nu_e}(E) \geq (1 - a_e^0)^2 \equiv P_{\nu_e \to \nu_e}^{\text{min}}$. In Fig. 4 we have plotted the values of $P_{\nu_e \to \nu_e}^{\text{min}}$ obtained from the results of the Bugey and Krasnoyarsk experiments, for $\Delta m^2$ in the interval (17). It can be seen that $P_{\nu_e \to \nu_e}(E) > 0.65$ for all the considered values of $\Delta m^2$ and $P_{\nu_e \to \nu_e}(E) > 0.91$ for $3 \times 10^{-2} \text{ eV}^2 \leq \Delta m^2 \leq 10^2 \text{ eV}^2$. Furthermore, Eq. (22) implies that the maximal variation of $P_{\nu_e \to \nu_e}(E)$ as a function of neutrino energy is given by $(1 - |U_{e3}|^2)^2$. If $|U_{e3}|^2$ satisfies the inequality (20), we have $(1 - |U_{e3}|^2)^2 \leq (a_e^0)^2$, which is a very small quantity (from Fig. 4 one can see that $(1 - |U_{e3}|^2)^2 \leq 4 \times 10^{-2}$ for $\Delta m^2$ in the interval (17)). Thus, in this case $P_{\nu_e \to \nu_e}$ as a function of neutrino energy is practically constant. The large lower bound for the survival probability $P_{\nu_e \to \nu_e}$ and its practical independence from the neutrino energy are not compatible with the data of the solar neutrino experiments (see Ref. [26]). Thus, from the results of the solar and reactor neutrino experiments we come to the conclusion that $|U_{e3}|^2$ is small and satisfies the inequality (19).

The limit (19) for $|U_{e3}|^2$ implies the following upper bound for the effective Majorana mass $|\langle m \rangle|$:

$$|\langle m \rangle| \leq a_e^0 \sqrt{\Delta m^2}.$$  

(23)
The upper bounds obtained with Eq. (23) from the 90% CL exclusion plots of the Bugey and
Krasnoyarsk reactor neutrino oscillation experiments are presented in Fig. 3. With the thick
solid line we have drawn the unitarity upper bound $|\langle m \rangle| \leq \sqrt{\Delta m^2}$.

As it is seen from Fig. 3, from the results of the reactor neutrino experiments it follows
that for $\Delta m^2 \lesssim 10 \text{eV}^2$ the effective Majorana mass $|\langle m \rangle|$ cannot be larger than $10^{-1} \text{eV}$. Let us stress that the sensitivity to $|\langle m \rangle| \simeq 10^{-1} \text{eV}$ is the goal of future experiments on
the search for $(\beta \beta)_{0\nu}$ decay [8, 13].

In the region $10 \text{eV}^2 \lesssim \Delta m^2 \lesssim 10^2 \text{eV}^2$ the upper bound for the parameter $|\langle m \rangle|$ grows
with $\Delta m^2$ and reaches the value of $4 \times 10^{-1} \text{eV}$ at $\Delta m^2 \simeq 10^2 \text{eV}^2$. The region of relatively
large values of $\Delta m^2 (10 - 10^2 \text{eV}^2)$ is very important for the dark matter problem. Two
experiments at CERN (CHORUS and NOMAD [27]) are searching for $\nu_\mu \rightarrow \nu_\tau$ oscillations
in this range of $\Delta m^2$.

In Fig. 3 we have also presented the upper bound for $|\langle m \rangle|$ that corresponds to the
projected sensitivity of the reactor long baseline neutrino oscillation experiments CHOOZ
and Palo Verde [16]. These experiments will allow to obtain new limits for the effective
Majorana mass $|\langle m \rangle|$ in the region of small $\Delta m^2$. If their sensitivity limit will be reached
without detecting neutrino oscillations, in the region $\Delta m^2 \lesssim 2 \text{eV}^2$ the upper bound for
$|\langle m \rangle|$ will be less than about $3 \times 10^{-2} \text{eV}$.

4 Atmospheric neutrinos

Up to now we have taken into account only the results of solar and reactor neutrino experi-
ments and we considered the heaviest neutrino mass $m_3 \simeq \sqrt{\Delta m^2}$ as an unknown parameter. Let us take now into account also the results of the atmospheric neutrino experiments.

The Kamiokande collaboration found [2] that the detected ratio of muon and electron atm-
spheric neutrino events is significantly smaller than the expected one. For the double ratio
$R = (\mu/e)_{\text{data}}/(\mu/e)_{\text{MC}}$ ($\langle \mu/e \rangle_{\text{MC}}$ is the Monte-Carlo calculated ratio of muon and electron
events under the assumption that neutrinos do not oscillate), the Kamiokande collaboration
found

$$R_{\text{sub-GeV}}^{\text{Kamiokande}} = 0.60^{+0.06}_{-0.05} \pm 0.05 \, , \quad R_{\text{multi-GeV}}^{\text{Kamiokande}} = 0.57^{+0.08}_{-0.07} \pm 0.07 \, .$$ (24)

The atmospheric neutrino anomaly was observed also in the IMB and Soudan [3] experiments:

$$R_{\text{IMB}} = 0.54 \pm 0.05 \pm 0.12 \, , \quad R_{\text{Soudan}} = 0.75 \pm 0.16 \pm 0.10 \, .$$ (25)

On the other hand, the double ratio $R$ measured in the Frejus and NUSEX [28] experiments
is compatible with one:

$$R_{\text{Frejus}} = 0.99 \pm 0.13 \pm 0.08 \, , \quad R_{\text{NUSEX}} = 1.04 \pm 0.25 \, .$$ (26)
The results of the Kamiokande experiment can be explained \[2\] by two flavor neutrino oscillations $\nu_\mu \leftrightarrow \nu_\tau$ or $\nu_\mu \leftrightarrow \nu_e$. with the following allowed ranges for the oscillation parameters:

\[
5 \times 10^{-3} \lesssim \Delta m^2 \lesssim 3 \times 10^{-2}\text{eV}^2 \quad 0.7 \lesssim \sin^2 2\theta \lesssim 1 \quad (\nu_\mu \leftrightarrow \nu_\tau), \tag{27}
\]

\[
7 \times 10^{-3} \lesssim \Delta m^2 \lesssim 8 \times 10^{-2}\text{eV}^2 \quad 0.6 \lesssim \sin^2 2\theta \lesssim 1 \quad (\nu_\mu \leftrightarrow \nu_e). \tag{28}
\]

We have analyzed the Kamiokande atmospheric neutrino data \[4\] in the framework of the model under consideration with mixing of three neutrinos and a neutrino mass hierarchy. The oscillation probabilities of atmospheric neutrinos depend on three parameters: $\Delta m^2$, $|U_{e3}|^2$, and $|U_{\mu 3}|^2$. The matter effect for the atmospheric neutrinos reaching the Kamiokande detector from below has been taken into account. The presence of matter is important because it modifies the phases of neutrino oscillations \[29\] and its effect is to enlarge the allowed region towards low values of $\Delta m^2$. The best fit of the Kamiokande data is obtained for

\[
\Delta m^2 = 2.3 \times 10^{-2}\text{eV}^2, \quad |U_{e3}|^2 = 0.26, \quad |U_{\mu 3}|^2 = 0.49, \tag{29}
\]

with $\chi^2 = 6.7$ for 9 degrees of freedom, corresponding to a CL of 67%. The range allowed at 90% CL in the plane of the parameters $\Delta m^2$, $|\langle m \rangle|$ is shown in Fig.3 as the region enclosed by the dash-dotted curve. The best fit of the Kamiokande data corresponds to $|\langle m \rangle| = 3.9 \times 10^{-2}\text{eV}$ (the triangle in Fig.3). From Fig.3 it can be seen that the results of Kamiokande experiment imply that

\[
|\langle m \rangle| \lesssim 10^{-1}\text{eV}. \tag{30}
\]

If we take into account also the limit obtained from the reactor neutrino oscillation experiments, for upper bound of the effective Majorana mass we have

\[
|\langle m \rangle| \lesssim 7 \times 10^{-2}\text{eV}. \tag{31}
\]

It is interesting to investigate how the region in the plane of the parameters $\Delta m^2$, $|\langle m \rangle|$ allowed by the Kamiokande data is modified by the inclusion in the fit of the data obtained in the Frejus experiment. The best fit of Kamiokande and Frejus data is obtained for

\[
\Delta m^2 = 1.7 \times 10^{-2}\text{eV}^2, \quad |U_{e3}|^2 = 0.17, \quad |U_{\mu 3}|^2 = 0.29, \tag{32}
\]

with $\chi^2 = 28$ for 19 degrees of freedom corresponding to a CL of 8% (the best fit value of $|\langle m \rangle|$ is $2.2 \times 10^{-2}\text{eV}$, depicted as a square in Fig.3). The corresponding allowed region (at 90% CL) is shown in Fig.3 as the region enclosed by the dash-dot-dotted curve. The figure shows that the region allowed by the combined Kamiokande and Frejus data is not very
different from the region allowed by the Kamiokande data alone. If we take into account the limit obtained from the results of the Bugey and Krasnoyarsk reactor experiments, we have

$$|\langle m \rangle| \lesssim 4 \times 10^{-2} \text{eV}.$$  \hfill (33)

The limits on the effective Majorana mass $|\langle m \rangle|$ obtained above could decrease substantially after the fulfillment of the program of neutrino oscillation experiments of the next generation, that will explore the region of neutrino mixing parameters allowed by the data of the atmospheric neutrino experiments. We are referring to the Super-Kamiokande [30] and long baseline accelerator (KEK–Super-Kamiokande [30], MINOS and ICARUS [31]) and reactor (CHOOZ and Palo Verde [16]) experiments.

If, for example, $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\Delta m^2 \sim 10^{-2} \text{eV}^2$ will be found in the accelerator long baseline experiments and the reactor long baseline experiments will reach their projected sensitivity, the region of allowed values of the parameters $|\langle m \rangle|$, $\Delta m^2$ will be very small (see Fig.3), with the upper bound

$$|\langle m \rangle| \lesssim 10^{-2} \text{eV}.$$  \hfill (34)

For the $(\beta\beta)^{0\nu}$ decay experiments the sensitivity to $|\langle m \rangle| \simeq 10^{-2} \text{eV}$ is a challenging problem [32].

On the other hand, if the atmospheric neutrino anomaly will be confirmed in the $\nu_\mu \leftrightarrow \nu_e$ channel by reactor long baseline neutrino oscillation experiments, it will mean that the value of $|\langle m \rangle|$ lies within the interval $10^{-3} - 10^{-1} \text{eV}$. In this case, from a determination of $|U_{e3}|^2$ and $\Delta m^2$ in reactor experiments, through Eq.(12) it will be possible to infer the value of $|\langle m \rangle|$.

5 Conclusions

We have shown that, in the framework of a general model with mixing of three Majorana neutrinos and a neutrino mass hierarchy, from the results of the reactor, solar and atmospheric neutrino experiments it is possible to obtain rather strict limits on the value of the effective Majorana mass $|\langle m \rangle|$, that characterizes the amplitude of neutrinoless double beta decay.

We have shown that the results of the Bugey and Krasnoyarsk reactor neutrino oscillation experiments imply that $|\langle m \rangle| \lesssim 10^{-1} \text{eV}$ if $\Delta m^2$ is less than about $10 \text{eV}^2$. If $\Delta m^2$ has a value in the interval $10 - 100 \text{eV}^2$, we have $|\langle m \rangle| \lesssim 4 \times 10^{-1} \text{eV}$.

We have also shown that the Kamiokande atmospheric neutrino data imply that $|\langle m \rangle| \lesssim 7 \times 10^{-2} \text{eV}$. Future long baseline reactor and accelerator neutrino experiments could decrease the upper bound for the effective Majorana mass $|\langle m \rangle|$ to the level of about $10^{-2} \text{eV}$.

The constraints on the value of the effective Majorana mass $|\langle m \rangle|$ that follow from neutrino oscillation experiments must be taken into account in the interpretation of the
data of \((\beta\beta)_0\nu\) decay experiments. The observation in the future experiments of neutrinoless double-\(\beta\) decay with a half-life that corresponds to a value of the effective mass \(|\langle m \rangle|\) that is significantly larger than \(10^{-1}\) eV could imply that the mass \(m_3\) of the heaviest neutrino is larger than \(2 - 3\) eV, or that the neutrino masses do not have a hierarchy pattern\(^1\) and are not generated by the standard see-saw mechanism. Other possibilities are that a new non-standard interaction is responsible for neutrinoless double-\(\beta\) decay (right-handed currents, \ldots, for a review see Ref.\([10]\)), or that four or more massive Majorana neutrinos exist in nature\(^2\).

**Acknowledgments**

This work was done while one of authors (S.B) was Lady Davis visiting professor at the Technion. The author would like to thank the Physics Department of Technion for its hospitality and A. Dar and D. Wyler for useful discussions.

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\(^1\) Another possibility for the spectrum of three neutrinos that can accommodate the data of solar neutrino experiments is the inverted mass hierarchy \(m_1 \ll m_2 \approx m_3\). In this case the reactor data do not imply any limitations on the effective Majorana mass \(|\langle m \rangle|\) \([19]\).

\(^2\) The schemes with four massive neutrinos allow to accommodate all existing indications in favor of neutrino mixing \([9, 19, 24]\), including the indications obtained recently in the LSND experiment \([4]\). The connection between \((\beta\beta)_0\nu\) decay and neutrino oscillations in the framework of schemes with four massive neutrinos was discussed in Refs.\([14, 19, 24]\). Let us notice that the LSND indications in favor of \(\nu_\mu \leftrightarrow \nu_e\) oscillations will be tested in two years by the KARMEN experiment \([28]\).
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Figure Captions

Figure 1. The quantity $a_0^\nu$ (see Eq.(21)) obtained from the 90% CL exclusion plots of the Bugey and Krasnoyarsk [24] reactor neutrino oscillation experiments.

Figure 2. The 90% CL lower bound for the probability of solar $\nu_e$'s to survive in the case of a large value of the parameter $|U_{e3}|^2 \geq 1 - a_0^\nu$.

Figure 3. The 90% CL upper bound for the effective Majorana mass $|\langle m \rangle|$ obtained from the results of the Bugey (solid line) and Krasnoyarsk (dotted line) neutrino reactor experiments. The regions enclosed by dash-dotted (dash-dot-dotted) lines are allowed by the data of the Kamiokande (Kamiokande and Frejus) atmospheric neutrino experiments. The upper bound for $|\langle m \rangle|$ that corresponds to the projected sensitivity of the long baseline CHOOZ (short-dashed line) and Palo Verde (long-dashed line) reactor neutrino oscillation experiments are also shown.
Figure 1
Figure 2
\[ \Delta m^2 (\text{eV}^2) \]

\[ |\langle m \rangle| (\text{eV}) \]

\[ \sqrt{\Delta m^2} \]

Figure 3