



Possibilities of Future Double Beta Decay Experiments to Investigate Inverted and Normal Ordering Region of Neutrino Mass

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An overview of modern experiments on the search for neutrinoless double decay is presented. The obtained limits on the effective mass of the Majorana neutrino $\langle m_\nu \rangle$ are discussed taking into account the uncertainties in the value of the nuclear matrix elements (NMEs) and the value of the axial-vector constant g_A . Predictions for the values of $\langle m_\nu \rangle$ from the results of oscillation experiments and modern cosmological data are presented. The possibilities of the next generation experiments with sensitivity to $\langle m_\nu \rangle$ at the level of $\sim 10\text{--}50$ meV (studying mainly the inverted ordering (IO) region) are discussed. The prospects for studying the normal ordering (NO) region are discussed too. It is shown that the possibilities of studying the NO depend on the mass of the lightest neutrino m_0 . In the limiting case of small mass ($m_0 \leq 0.1$ meV), the values of $\langle m_\nu \rangle \approx 1\text{--}4$ meV are predicted, which makes the study of this region inaccessible by the next generation experiments. But there is an allowed region of m_0 (7–30 meV) in the framework of NO, where the predicted values for $\langle m_\nu \rangle$ could be $\sim 10\text{--}30$ meV and that is quite achievable for the next generation experiments. The possibility to rich in the future sensitivity to $\langle m_\nu \rangle$ at the level of $\sim 1\text{--}10$ meV is also discussed.

Keywords: neutrino mass, Majorana neutrino, double beta decay, neutrino mass ordering, low background experiments

1. INTRODUCTION

The interest in neutrinoless double decay increased significantly after the discovery of neutrino oscillations in experiments with atmospheric, solar, reactor, and accelerator neutrinos (see, for example, discussions in [1–3]). This is due to the fact that the very existence of neutrino oscillations indicates that the neutrino has a non-zero mass. However, oscillation experiments are not sensitive to the nature of the neutrino mass (Dirac or Majorana) and do not provide information on the absolute scale of neutrino masses. Registration of neutrinoless double beta decay will clarify many fundamental aspects of neutrino physics (see, for example, discussions in [4–6]):

- (i) lepton number non-conservation;
- (ii) neutrino nature: whether the neutrino is a Dirac or a Majorana particle;
- (iii) absolute neutrino mass scale;
- (iv) the type of neutrino mass ordering (normal or inverted);
- (v) CP violation in the lepton sector (measurement of the Majorana CP-violating phases).

This process assumes a simple form, namely

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-. \quad (1)$$

The discovery of this process is of fundamental interest, since it is practically the only way to establish the Majorana nature of neutrino. The Majorana nature of the neutrino would have interesting implications in many extensions of the Standard Model. For example the seesaw mechanism requires the existence of a Majorana neutrino to explain the lightness of neutrino masses [7–10]. A Majorana neutrino would also provide a natural explanation for the lepton number violation, and for the leptogenesis process which may explain the observed matter-antimatter asymmetry of the Universe [11].

The standard underlying mechanism behind neutrinoless double-beta decay is the exchange of a light Majorana neutrino. In this case, the half-life time of the decay can be presented as

$$[T_{1/2}(0\nu)]^{-1} = G_{0\nu} g_A^4 |M_{0\nu}|^2 \left| \frac{\langle m_\nu \rangle}{m_e} \right|^2, \quad (2)$$

where $G_{0\nu}$ is the phase space factor, which contains the kinematic information about the final state particles, and is exactly calculable to the precision of the input parameters [12, 13], g_A is the axial-vector coupling constant¹, $|M_{0\nu}|$ is the nuclear matrix element, m_e is the mass of the electron, and $\langle m_\nu \rangle$ is the effective Majorana mass of the electron neutrino, which is defined as $\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_i \right|$ where m_i are the neutrino mass eigenstates and U_{ei} are the elements of the neutrino mixing Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

In contrast to two-neutrino decay (this decay has been detected—see review [18], for example), neutrinoless double beta decay has not yet been observed. The best limits on $\langle m_\nu \rangle$ are obtained for ^{136}Xe , ^{76}Ge , ^{130}Te , ^{100}Mo , and ^{82}Se (see section 3). The assemblage of sensitive experiments for different nuclei permits one to increase the reliability of the limit on $\langle m_\nu \rangle$. Present conservative limit can be set as 0.23 eV at 90% C.L. (using conservative value from the KamLAND-Zen experiment). But one has to take into account that, in fact, this value could be in ~ 1.5 – 2 times greater because of the possible quenching of g_A (see recent discussions in [17]).

The main goal of next generation experiments is to investigate the IO region of neutrino mass ($\langle m_\nu \rangle \approx (14\text{--}50)$ meV). If one will not see the decay in this region then it will be necessary to investigate region with $\langle m_\nu \rangle < 14$ meV.

2. PREDICTIONS ON $\langle M_\nu \rangle$ FROM NEUTRINO OSCILLATION AND COSMOLOGICAL DATA

Using the data of oscillatory experiments, one can obtain predictions for possible values of $\langle m_\nu \rangle$. Usually a so-called

¹Usually the value $g_A = 1.27$ is used (the free neutron decay value). In nuclear matter, however, the value of g_A could be quenched. In 2ν decay case effect of quenching could be quite strong [6, 14–17]. In case of 0ν decay it can be a factor of ~ 1.2 – 1.5 (see discussion in [17]). This question is still under discussion and there is no final answer up to now.

“lobster” (“crab”) plot is constructed, which shows the possible values of $\langle m_\nu \rangle$, depending on the type of ordering and the mass of the lightest neutrino m_0 , which is unknown (see, for example, recent papers [6, 19, 20]). The cosmological constraints on Σm_ν are used to limit the possible values of m_0 . In **Figure 1**, predictions on the effective Majorana neutrino mass are plotted as function of the lightest neutrino mass m_0 . The 2σ and 3σ values of neutrino oscillation parameters are taken into account [21]. The PLANCK collaboration in a recent publication gives a limit of $\Sigma m_\nu < 0.12$ eV [22], using the new CMB data with different large scale structure observations. This leads to a limitation on $m_0 < 30$ and < 16 meV for normal and inverted ordering, respectively. Taking into account PLANCK’s limit, different regions of possible values of $\langle m_\nu \rangle$ are obtained depending on the type of ordering:

- 1) $\langle m_\nu \rangle \approx 14\text{--}50$ meV for all values of m_0 in the IO case.
- 2) In the NO case the situation is more complicated. The $\langle m_\nu \rangle$ can take values from practically 0 to 30 meV. And it has to be stressed that there is an allowed region of $m_0 = 7\text{--}30$ meV, where the $\langle m_\nu \rangle$ could be $\sim 10\text{--}30$ meV and that is quite achievable for the next generation experiments. At $m_0 = 10\text{--}30$ meV, the NO and IO regions partially overlap and it will be difficult to uniquely determine the type of ordering. And only at $m_0 < 10$ meV it will be possible to reliably distinguish between the NO and IO. At $m_0 = 1\text{--}10$ meV, a strong decrease in the values of $\langle m_\nu \rangle$ is possible for certain values of the Majorana phases (nevertheless, the probability of almost total nullification $\langle m_\nu \rangle$ is sufficiently small [20]). At values of $m_0 \leq 0.1$ meV the $\langle m_\nu \rangle \approx 1\text{--}4$ meV (the so-called “limiting” case).

A global analysis of all available data was carried out in de Salas et al. [20] and it was shown that the NO is more preferable (at 3.5σ level). It was also demonstrated that $\Sigma m_\nu \geq 0.06$ eV for

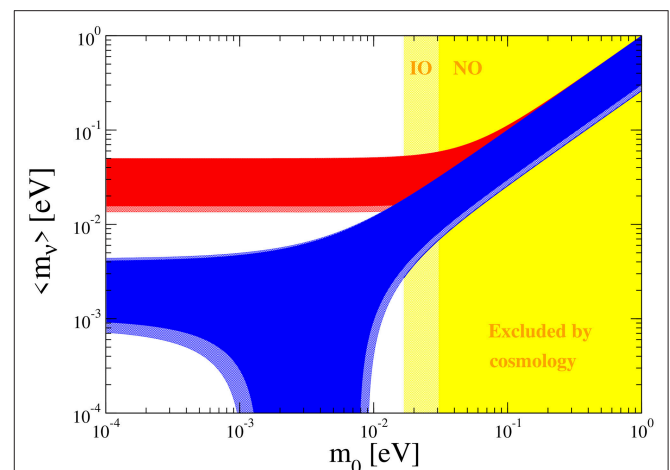


FIGURE 1 | Predictions on $\langle m_\nu \rangle$ from neutrino oscillations vs. the lightest neutrino mass m_0 in the two cases of normal (the blue region) and inverted (the red region) spectra. The 2σ and 3σ values of neutrino oscillation parameters are considered [21]. The excluded region by cosmological data ($\Sigma m_\nu < 0.12$ eV) m_0 is presented in yellow (> 30 meV for the NO and > 16 meV for the IO).

the NO case, and $\Sigma m_\nu \geq 0.1$ eV for the IO. Nevertheless, the question of the order of the neutrino masses is not yet fully clarified and experiments on a double beta decay can contribute to its solution. A limit on $\langle m_\nu \rangle$ below 14 meV could be used to rule out the IO scheme, assuming that neutrinos are Majorana fermion. On the other hand a positive detection of $0\nu\beta\beta$ decay in the range that corresponds to $\langle m_\nu \rangle > 14$ meV would not give sufficient information to determine the mass ordering without an independent determination of m_0 . Finally, in the context of three neutrino mixing, neutrinoless double beta decay experiments alone will be able to determine the neutrino mass ordering only ruling out the inverted scheme, that is to say if the ordering is normal and $m_0 \leq 10$ meV.

It is hoped that in a few years the value of Σm_ν could be determined from cosmology (see, for example, discussions in [20, 23]). This will help make a reliable conclusion about the type of ordering (for example, if the measured value will be less than 0.1 eV, it will mean that the NO is realized) and obtain information on the value of m_0 . And this, in turn, will improve the predictions for a possible range of $\langle m_\nu \rangle$. For example, in Penedo and Petcov [19] it was demonstrated that if the sum of neutrino masses is found to satisfy $\Sigma m_\nu > 0.10$ eV, then for NO case $\langle m_\nu \rangle > 5$ meV for any values of the Majorana phases.

3. PRESENT STATUS AND CURRENT EXPERIMENTS

Table 1 shows the best results for today on search for $0\nu\beta\beta$ decay for the most interesting nucleus-candidates for this process. Limits on the values of $T_{1/2}$ and $\langle m_\nu \rangle$ are given. To calculate $\langle m_\nu \rangle$ the NMEs from recent works [14, 33–43] and the value $g_A = 1.27$ have been used. One can see that the best modern experiments have reached a sensitivity of $\sim 10^{25}$ – 10^{26} years for the half-life and ~ 0.1 – 0.3 eV for the $\langle m_\nu \rangle$. The spread in the values of the

neutrino mass in each case is related to the currently existing uncertainties in the calculations of NMEs. Uncertainty in the values of NMEs is a factor of ~ 2 – 3 . As already noted, quenching of g_A in the nucleus is possible and, as a result, the limits on the neutrino mass could be ~ 1.5 – 2 times weaker. **Table 1** shows that the most stringent limits on the effective mass of Majorana neutrino are obtained in experiments with ^{136}Xe , ^{76}Ge , ^{130}Te , ^{100}Mo , and ^{82}Se . For some nuclei, **Table 1** lists two limit values for $T_{1/2}$ and $\langle m_\nu \rangle$. This is due to the fact that in some cases (^{136}Xe , ^{130}Te , and ^{76}Ge) a large background fluctuation leads to too “optimistic” limits, substantially exceeding the “sensitivity” of the experiments. Therefore, the values of the “sensitivity” of the experiments are also given in the **Table 1**. I believe that these values are although more conservative, but the most reliable. With this in mind, the conservative limit on $\langle m_\nu \rangle$ from modern double beta decay experiments is 0.23 eV (90% C.L.).

Table 2 shows the best current and planned to start in 2018–2019 modern experiments that will determine the situation in the neutrinoless double beta decay in the coming years. It is seen that in the best of these experiments sensitivity to the $\langle m_\nu \rangle \sim 0.04$ – 0.2 eV will be achieved, which, apparently, will not be enough for verification of the IO region (because to observe the effect, it is necessary to see the signal at least at 3σ level; therefore, even the most sensitive experiments with the most favorable values of NMEs will not be able to register the decay).

4. POSSIBILITIES OF FUTURE DOUBLE BETA DECAY EXPERIMENTS TO INVESTIGATE IO REGION OF NEUTRINO MASS

Table 3 shows the most promising planned experiments, which will be realized in ~ 5 – 15 years. To test the IO region of

TABLE 1 | Best present limits on $0\nu\beta\beta$ decay (at 90% C.L.).

Isotope	$Q_{2\beta}$, keV	$T_{1/2}$, yr	$\langle m_\nu \rangle$, eV	Experiment	References
^{48}Ca	4267.98	$> 5.8 \times 10^{22}$	$< 3.1 - 15.4$	CANDLES	[24]
^{76}Ge	2039.00	$> 5.8 \times 10^{25}$ ($> 8 \times 10^{25}$)	$< 0.14 - 0.37$ ($< 0.12 - 0.31$)	GERDA-I+GERDA-II	[25]
^{82}Se	2997.9	$> 2.4 \times 10^{24}$	$< 0.4 - 0.9$	CUPID-0/Se	[26]
^{96}Zr	3355.85	$> 9.2 \times 10^{21}$	$< 3.6 - 10.4$	NEMO-3	[27]
^{100}Mo	3034.40	$> 1.1 \times 10^{24}$	$< 0.33 - 0.62$	NEMO-3	[28]
^{116}Cd	2813.50	$> 2.2 \times 10^{23}$	$< 1 - 1.7$	AURORA	[29]
^{128}Te	866.6	$> 1.5 \times 10^{24}$	$2.3 - 4.6$	Geochem. exp.	(see [18])
^{130}Te	2527.52	$> 7 \times 10^{24}$ ($> 1.5 \times 10^{25}$)	$< 0.19 - 0.74$ ($< 0.13 - 0.50$)	CUORICINO + CUORE0 + CUORE	[30]
^{136}Xe	2457.83	$> 5.6 \times 10^{25}$ ($> 1.07 \times 10^{26}$)	$< 0.08 - 0.23$ ($< 0.06 - 0.16$)	KamLAND-Zen	[31]
^{150}Nd	3371.38	$> 2 \times 10^{22}$	$< 1.6 - 5.3$	NEMO-3	[32]

To calculate $\langle m_\nu \rangle$ the NME from Barea et al. [14], Hyvarinen and Suhonen [33], Simkovic et al. [34], Rath et al. [35], Rodriguez and Martinez-Pinedo [36], Menendez et al. [37], Neacsu and Horoi [38], Mustonen and Engel [39], and Song et al. [40], phase-space factors from Kotila and Iachello [12] and Mirea et al. [13] and $g_A = 1.27$ have been used. In case of ^{150}Nd NME from Terasaki [41] and Fang et al. [42] and in case of ^{48}Ca from Iwata et al. [43] were used in addition. The bold type denotes the so-called “sensitivity” values (see text).

TABLE 2 | Best current and planned to start in 2018–2019 modern experiments.

Experiment	Isotope	M, kg	Sensitivity $T_{1/2}$, yr	Sensitivity $\langle m_\nu \rangle$, meV	Status	References
CUORE	^{130}Te	200	9.5×10^{25}	53–200	current	[30]
GERDA-II	^{76}Ge	35	1.5×10^{26}	90–230	current	[25]
Majorana-D	^{76}Ge	30	1.5×10^{26}	90–230	current	[44]
EXO-200	^{136}Xe	200	5.7×10^{25}	85–225	current	[45]
CUPID-0/Se	^{82}Se	5	6×10^{24}	250–590	current	[26]
KamLAND-Zen	^{136}Xe	750	2×10^{26}	45–120	start in 2018	[46]
SNO+-I	^{130}Te	1,300	2×10^{26}	36–140	start in 2019	[47, 48]
NEXT	^{136}Xe	100	6×10^{25}	83–220	start in 2019	[49]
CUPID-0/Mo	^{100}Mo	4	1.5×10^{25}	90–170	start in 2019	[50]
AMoRE-I	^{100}Mo	2.5	$\sim 10^{25}$	110–210	start in 2019	[51, 52]
SuperNEMO-D	^{82}Se	7	6.5×10^{24}	240–560	start in 2019	[53, 54]

Sensitivity at 90% C.L. for three (GERDA-II, Majorana Demonstrator, SuperNEMO Demonstrator, and KamLAND-Zen) and five (for other experiments) years of measurements is presented. M is mass of the isotope.

TABLE 3 | Main most developed and promising projects for next generation experiments.

Experiment	Isotope	M, kg	Sensitivity $T_{1/2}$, yr	Sensitivity $\langle m_\nu \rangle$, meV	Status	References
LEGEND	^{76}Ge	200	$\sim 10^{27}$	34–90	in progress	[55]
		1,000	$\sim 10^{28}$	11–28	R&D	
nEXO	^{136}Xe	5000	9×10^{27}	8–22	R&D	[56]
CUPID	^{130}Te , ^{100}Mo ^{82}Se , ^{116}Cd	~ 200 –500	$(2 - 5) \times 10^{27}$	6–17	R&D	[57, 58]
KamLAND2-Zen	^{136}Xe	1,000	6×10^{26}	25–70	R&D	[46]
SNO+-II	^{130}Te	8,000	7×10^{26}	20–70	R&D	[47]
AMoRE-II	^{100}Mo	100	5×10^{26}	15–30	R&D	[52]
SuperNEMO	^{82}Se	100–140	$(1 - 1.5) \times 10^{26}$	50–140	R&D	[53, 54]
PandaX-III	^{136}Xe	200	$\sim 10^{26}$	65–170	R&D	[59]
		1,000	$\sim 10^{27}$	20–55	R&D	

Sensitivity at 90% C.L. for five (KamLAND2-Zen, SNO+-II, AMoRE-II, SuperNEMO, PandaX-III, LEGEND-200) and 10 (LEGEND-1000, nEXO, and CUPID) years of measurements is presented. M is mass of the isotope.

neutrino masses, it is necessary to achieve sensitivity to $\langle m_\nu \rangle$ at the level of ~ 14 –50 meV. Practically all experiments listed in **Table 3** have a chance to register a $0\nu\beta\beta$ decay, but only CUPID, nEXO, and LEGEND-1000 overlap quite well the range of $\langle m_\nu \rangle$ associated with the IO. Thus, if the IO is actually realized in nature and the neutrino is Majorana particle, then it is likely that the neutrinoless double beta decay will be registered in the experiment in ~ 5 –15 years. And the CUPID, nEXO, and LEGEND-1000 experiments have the greatest chances to see the effect. But even these, the most sensitive experiments, do not guarantee the observation of the effect. At unfavorable values of NMEs and g_A , the sensitivity of these experiments will be insufficient to completely cover the entire range of possible values of $\langle m_\nu \rangle$ for the IO. And one has to remember that in order to observe the effect it is necessary to have at least 3σ confidence level [in **Table 3**, the sensitivity is indicated at 90% C.L. (1.6σ)].

5. POSSIBILITIES OF FUTURE DOUBLE BETA DECAY EXPERIMENTS TO INVESTIGATE NO REGION OF NEUTRINO MASS

In the NO case, the following possible ranges of $\langle m_\nu \rangle$ can be distinguished:

- 1) 10–30 meV. In this case, $0\nu\beta\beta$ decay could be detected in the next generation experiments (see **Table 3**). But, for this area of mass, it will be difficult to distinguish the NO from IO. In this case additional information about m_0 is required.
- 2) 3–10 meV. In this case, detectors containing ~ 1 –10 tons of $\beta\beta$ isotope are required. And it is possible (in principle) to investigate this region of $\langle m_\nu \rangle$ in the future (sensitivity to $T_{1/2}$ on the level of $\sim 10^{28}$ – 10^{29} yr will be needed).

- 3) 1–3 meV. In this case, detectors containing ~ 10 –100 tons of $\beta\beta$ isotope are required. It will be very difficult (if possible) to investigate this region of $\langle m_\nu \rangle$ in the future (sensitivity to $T_{1/2}$ on the level of $\sim 10^{29} - 10^{30}$ yr will be needed).
- 4) < 1 meV. This area is not available for observation in foreseeable future.

The possibility of studying $0\nu\beta\beta$ decay with sensitivity to neutrino mass on the level of ~ 1 –5 meV has been analyzed in Barabash [60]. It was shown that the 3–5 meV region can be studied by detectors containing ~ 10 tons of $\beta\beta$ isotope. Moreover, the detectors should have a sufficiently high efficiency ($\sim 100\%$), good energy resolution (FWHM < 1 –2%), and low level of background in the investigated region ($\sim 10^{-6} - 10^{-7}$ c/keV \times kg \times yr). In addition, the cost of an isotope becomes important and can seriously limit the feasibility of such experiments [60]. It was noted in Barabash [60] that ^{136}Xe , ^{130}Te , ^{82}Se , ^{100}Mo , and ^{76}Ge are most promising isotopes, and the most suitable experimental techniques are low-temperature scintillation bolometers, gas Xe TPC, and HPGe semiconductor detectors.

Summarizing all of the above, one can conclude that if we are dealing with the NO and $\langle m_\nu \rangle = 10$ –30 meV, then $0\nu\beta\beta$ decay could be registered in next-generation experiments (~ 5 –15 years from now). To study the range of $\langle m_\nu \rangle < 10$ meV, new, more sensitive experiments with the mass of the investigated isotope ~ 1 –10 tons ($\langle m_\nu \rangle = 3$ –10 meV) or ~ 10 –100 tons ($\langle m_\nu \rangle = 1$ –3 meV) are required. In more detail, such possible experiments are discussed in Barabash [60].

6. CONCLUSION

Thus, we can conclude that the present conservative limit on $\langle m_\nu \rangle$ from double beta decay experiments is 0.23 eV (90% C.L.). Within the next 3–5 years, the sensitivity of modern experiments

will be brought to ~ 0.04 –0.2 eV. To study the IO region (0.014–0.05 eV), new generation experiments will be realized, which will achieve the required sensitivity in ~ 5 –15 years. If we are dealing with NO, then everything depends on the value of $\langle m_\nu \rangle$ that is realized in nature. If $\langle m_\nu \rangle = 10$ –30 meV, then this lies in the sensitivity region of the next generation experiments and $0\nu\beta\beta$ decay could be registered. If $\langle m_\nu \rangle = 3$ –10 meV, new, more sensitive experiments with ~ 1 –10 tons of $\beta\beta$ isotope are required (and it seems possible). For $\langle m_\nu \rangle = 1$ –3 meV experiments with of ~ 10 –100 tons of the isotope are required and it will be very difficult (if possible) to reach needed sensitivity in this case. If, however, $\langle m_\nu \rangle \leq 1$ meV, then apparently $0\nu\beta\beta$ decay will not be registered in the foreseeable future².

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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²In this article, we proceed from the assumption that we are dealing with an $0\nu\beta\beta$ decay, going through the exchange of light Majorana neutrinos. This mechanism is the most popular at the moment. Nevertheless, it should be emphasized that, in principle, other mechanisms are possible (right-handed currents, supersymmetry, heavy neutrinos, doubly charged Higgs bosons, etc.)—see, for example, discussions in Vergados et al. [6], Engel et al. [61], and Avignone et al. [62]. Therefore, if the $0\nu\beta\beta$ decay will be detected, then, first of all, it will be necessary to verify that we are dealing with a mechanism associated with a light neutrino. And only after that it will be possible to make a reliable conclusion about the value of $\langle m_\nu \rangle$. It is not excluded that several mechanisms will contribute to the $0\nu\beta\beta$ transition at the same time. In this case, it will be difficult to determine the true value of $\langle m_\nu \rangle$. On the other hand, the presence of other decay mechanisms allows us to hope for the registration of $0\nu\beta\beta$ decay even at very low value of $\langle m_\nu \rangle$.

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