Double beta decay experiments: present and future

A S Barabash
National Research Center "Kurchatov Institute", Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117218 Moscow, Russia
E-mail: barabash@itep.ru

Abstract. Last experimental achievements in double beta decay are presented. Possible progress in this field in the near and far future is discussed. The possibilities to investigate IO (inverted ordering) and NO (normal ordering) region of neutrino mass are considered.

1. Introduction
The investigation of neutrinoless double-beta ($0\nu\beta\beta$) decay may help to clarify the following problems of neutrino physics (see, for example, [1, 2, 3]): (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 hierarchy (normal or inverted), (v) CP violation in the lepton sector.

This process can be written as

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

(1)

The standard mechanism for 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

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

(2)

where $G_{0\nu}$ is the phase space factor, which is calculable with high precision [4, 5], $g_A$ is the axial-vector coupling constant, $| M_{0\nu} |$ 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 $\langle m_\nu \rangle = \sum_i | U_{ei}^2 m_i |$, where $m_i$ are the neutrino mass eigenstates and $U_{ei}$ are the elements of the neutrino mixing Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

$g_A = 1.27$ is usually used (the free neutron decay value). But the value of $g_A$ could be quenched in nuclear matter. In case of $2\nu$ decay effect of quenching could be quite strong [3, 6, 7, 8, 9]. In the case of $0\nu$ decay, the effect is probably not as strong, but it can be on the level of $\sim 1.2-1.5$ (see discussion in [9]). The "$g_A$ problem" is still under discussion.

In contrast to two-neutrino decay (this decay has been detected in 11 nuclei - see, for example, [10]), 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). Present conservative limit on $\langle m_\nu \rangle$ can be set as 0.23 eV (90% C.L.). But, in principle, this value could be $\sim 1.5$-2 times greater because of the possible quenching of $g_A$ (see [9]).
The goal of next generation experiments is to investigate the IO region of neutrino mass \((\langle m_\nu \rangle \approx (14-50) \text{ meV})\). At the same time part of NO region will be investigated too. If the decay will not be registered in this region then it will be necessary to investigate the region with \(\langle m_\nu \rangle < 14 \text{ meV}\).

2. Predictions on \(\langle m_\nu \rangle\)

Using the oscillation data, one can obtain predictions for possible values of \(\langle m_\nu \rangle\). Usually a so-called ”lobster” plot is constructed, which shows the possible values of \(\langle m_\nu \rangle\), depending on the mass of the lightest neutrino \(m_0\) and the type of ordering. The cosmological constraint on \(\Sigma m_\nu\) is used to limit the possible values of \(m_0\). Predictions on the effective Majorana neutrino mass as function of the lightest neutrino mass \(m_0\) are plotted in figure 1. The \(2\sigma\) and \(3\sigma\) values of neutrino oscillation parameters from [11] are taken into account. Recent limit from the PLANCK Collaboration \(\Sigma m_\nu < 0.12 \text{ eV}\) [12] is used. This leads to a limitation on \(m_0 < 30 \text{ meV}\) and \(m_0 < 16 \text{ meV}\) for the NO and IO, respectively. As a result, different regions of possible values of \(\langle m_\nu \rangle\) could be established depending on the type of ordering:

1) IO case. \(\langle m_\nu \rangle \approx 14-50 \text{ meV}\) for all allowed values of \(m_0\).

2) NO case. The \(\langle m_\nu \rangle\) depends on \(m_0\) and can take values from 0 to 30 meV. At \(m_0 = 1-10 \text{ meV}\), a strong decrease in the values of \(\langle m_\nu \rangle\) is possible for certain values of the Majorana phases (nevertheless, the probability of a complete cancellation of \(\langle m_\nu \rangle\) is quite small [13]). At values of \(m_0 \leq 0.1 \text{ meV}\) the \(\langle m_\nu \rangle \approx 1-4 \text{ meV}\) (the ”limiting” case).

A global analysis of all available data was carried out in [13] and it was demonstrated that the NO is more preferable (at \(3.5\sigma\) level). It was also shown that \(\Sigma m_\nu \geq 0.06 \text{ eV}\) for the NO case, and \(\Sigma m_\nu \geq 0.1 \text{ eV}\) for the IO. However, 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 inverted ordering scheme, assuming that neutrinos are Majorana particles.

3. Present status

The best modern results on search for 0\(\nu\beta\beta\) decay are shown in table 1. Limits on the values of \(T_{1/2}\) and \(\langle m_\nu \rangle\) are given. To calculate \(\langle m_\nu \rangle\) the NMEs from [6, 14, 15, 16, 17, 18, 19, 20, 21] and the value \(g_A = 1.27\) have been used. Table 1 shows that the best modern experiments have reached a sensitivity of \(\sim 10^{25-26} \text{ yr}\) for the half-life and \(\sim 0.1-0.3 \text{ eV}\) for the \(\langle m_\nu \rangle\). The spread in the values of the neutrino mass is related to the existing uncertainties in the calculations of NMEs. For some nuclei, one can see in table 1 two limit values for \(T_{1/2}\) (and, accordingly, for \(\langle m_\nu \rangle\)). This is due to the fact that in these cases 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 table 1. Author believe that these values are, of course, more conservative, but the most reliable. With this in mind, the conservative limit on \(\langle m_\nu \rangle\) from double beta decay experiments is 0.23 eV (90\% C.L.).

The best modern (and planned to start in 2018-2019) experiments that will determine the situation in the neutrinoless double beta decay in the coming years are shown in table 2. It’s clear that in these experiments the sensitivity to the \(\langle m_\nu \rangle\) on the level of \(\sim 0.04-0.2 \text{ eV}\) will be achieved. And, apparently, it will be not enough for verification of the IO region (especially, taking into account the fact that the observation of the effect requires at least \(3\sigma\) C.L. It means that ”discovery sensitivity” is in \(\sim 1.9\) times worse than that presented in table 2).

4. Possibilities of future double beta decay experiments (IO region)

The most promising planned experiments are presented in table 3. These experiments are planned to be realized in \(\sim 5-15\) years from now. To test the IO region, it is necessary to achieve sensitivity to \(\langle m_\nu \rangle\) at the level of \(\sim 14-50 \text{ meV}\). Most of experiments listed in table 3
**Figure 1.** Predictions on $\langle m_\nu \rangle$ from neutrino oscillations versus the lightest neutrino mass $m_0$ in cases of NO (the blue region) and IO (the red region). The 2$\sigma$ and 3$\sigma$ values of neutrino oscillation parameters are considered [11]. The excluded region by cosmological data $m_0$ is presented in yellow ($> 30$ meV for the NO and $> 16$ meV for the IO). The value of $\Sigma m_\nu < 0.12$ eV has been used [12].

**Table 1.** Best present limits on $0\nu\beta\beta$ decay (at 90% C.L.). To calculate $\langle m_\nu \rangle$ the NME from [6, 14, 15, 16, 17, 18, 19, 20, 21], phase-space factors from [4, 5] and $g_A = 1.27$ have been used. The bold type denotes the so-called “sensitivity” values (see text).

| Isotope | $Q_{2\beta}$, keV | $T_{1/2}$, yr | $\langle m_\nu \rangle$, eV | Experiment | References |
|---------|-------------------|----------------|-----------------------------|------------|------------|
| $^{136}$Xe | 2457.83 | $> 5.6 \times 10^{25}$ | $< 0.08 - 0.23$ | KamLAND-Zen | [22] |
| | | ($> 1.07 \times 10^{26}$) | ($< 0.06 - 0.16$) | | |
| $^{76}$Ge | 2039.00 | $> 5.8 \times 10^{25}$ | $< 0.14 - 0.37$ | GERDA-I+GERDA-II | [23] |
| | | ($> 8 \times 10^{25}$) | ($< 0.12 - 0.31$) | | |
| $^{130}$Te | 2527.52 | $> 7 \times 10^{24}$ | $< 0.19 - 0.74$ | CUORICINO + | |
| | | ($> 1.5 \times 10^{25}$) | ($< 0.13 - 0.50$) | CUORE0 + CUORE | [24] |
| $^{100}$Mo | 3034.40 | $> 1.1 \times 10^{24}$ | $< 0.33 - 0.62$ | NEMO- 3 | [25] |
| $^{82}$Se | 2997.9 | $> 2.4 \times 10^{24}$ | $< 0.4 - 0.9$ | CUPID-0/Se | [26] |

have a chance to register a $0\nu\beta\beta$ decay, but only CUOID, nEXO and LEGEND-1000 overlap quite well the range of $\langle m_\nu \rangle$ associated with the IO. Thus, it is likely that in $\sim 5$-15 years the neutrinoless double beta decay will be registered in the experiment if the IO is actually realized in nature and the neutrino is a Majorana particle. And the CUPID, nEXO and LEGEND-1000 experiments have the greatest chances to observe the effect. But even these, the most sensitive experiments, do not guarantee the registration 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 $3\sigma$ confidence level. But in table 3, the sensitivity is indicated at 90% C.L. ($1.6\sigma$).
Table 2. Best current and planned to start in 2018-2019 experiments on $0\nu\beta\beta$ decay. 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 indicated. M denotes the mass of the isotope.

| Experiment     | Isotope | M, kg | Sensitivity $T_{1/2}$, yr | Sensitivity $\langle m_{\nu}\rangle$, meV | Status       | References |
|----------------|---------|-------|---------------------------|------------------------------------------|--------------|------------|
| CUORE          | $^{130}$Te | 200   | $9.5 \times 10^{25}$     | 53–200                                   | current      | [24]       |
| GERDA-II       | $^{76}$Ge | 35    | $1.5 \times 10^{26}$     | 90–230                                   | current      | [23]       |
| Majorana-D     | $^{76}$Ge | 30    | $1.5 \times 10^{26}$     | 90–230                                   | current      | [27]       |
| EXO-200        | $^{136}$Xe | 200   | $5.7 \times 10^{25}$     | 85–225                                   | current      | [28]       |
| CUPID-0/Se     | $^{82}$Se | 5     | $6 \times 10^{24}$       | 250–590                                   | current      | [26]       |
| KamLAND-Zen    | $^{136}$Xe | 750   | $2 \times 10^{26}$       | 45–120                                   | start in 2018| [29]       |
| SNO+-I         | $^{130}$Te | 1300  | $2 \times 10^{26}$       | 36–140                                   | start in 2019| [30, 31]  |
| NEXT           | $^{136}$Xe | 100   | $6 \times 10^{25}$       | 83–220                                   | start in 2019| [32]       |
| CUPID-0/Mo     | $^{100}$Mo | 4     | $1.5 \times 10^{25}$     | 90–170                                   | start in 2019| [33]       |
| AMoRE-I        | $^{100}$Mo | 2.5   | $\sim 10^{25}$          | 110–210                                  | start in 2019| [34, 35]  |
| SuperNEMO-D    | $^{82}$Se | 7     | $6.5 \times 10^{24}$     | 240–560                                  | start in 2019| [36, 37]  |

Table 3. Main most developed and promising projects for next-generation experiments. Sensitivity at 90% C.L. for five (KamLAND2-Zen, SNO+-II, AMoRE-II, SuperNEMO, PandaX-III, LEGEND-200) and ten (LEGEND-1000, nEXO and CUPID) years of measurements is presented. M denotes the mass of the isotope.

| Experiment          | Isotope | M, kg | Sensitivity $T_{1/2}$, yr | Sensitivity $\langle m_{\nu}\rangle$, meV | Status          | References |
|---------------------|---------|-------|---------------------------|------------------------------------------|-----------------|------------|
| LEGEND [38]         | $^{76}$Ge | 200   | $\sim 10^{27}$           | 34–90                                    | in progress     |             |
| nEXO [39]           | $^{136}$Xe | 5000  | $9 \times 10^{27}$       | 8–22                                     | R&D             |             |
| CUPID [40, 41]      | $^{130}$Te, $^{100}$Mo | 200-500 | $(2 - 5) \times 10^{27}$ | 6-17                                  | R&D             |             |
| KamLAND2-Zen [29]  | $^{136}$Xe | 1000  | $6 \times 10^{26}$       | 25-70                                    | R&D             |             |
| SNO+-II [30]        | $^{130}$Te | 8000  | $7 \times 10^{26}$       | 20-70                                    | R&D             |             |
| AMoRE-II [35]       | $^{100}$Mo | 100   | $5 \times 10^{26}$       | 15-30                                    | R&D             |             |
| SuperNEMO [36, 37]  | $^{82}$Se, $^{116}$Cd | 100–140 | $(1 - 1.5) \times 10^{26}$ | 50–140                               | R&D             |             |
| PandaX-III [42]     | $^{136}$Xe | 200   | $\sim 10^{26}$          | 65–170                                   | R&D             |             |

5. Possibilities of future double beta decay experiments (NO region)
In the NO case, the following possible ranges of $\langle m_{\nu}\rangle$ could be defined:

1) $\langle m_{\nu}\rangle = 10-30$ meV. In this case, there is a high probability that $0\nu\beta\beta$ decay will be detected in the next generation experiments (see table 3). But, for this region of $\langle m_{\nu}\rangle$, it will be difficult to distinguish the NO from IO (additional information about $m_0$ is required).

2) $\langle m_{\nu}\rangle = 3-10$ meV. In this case, detectors with $\sim 1-10$ tons of $\beta\beta$ isotope have to be used. And it is possible to investigate this region of $\langle m_{\nu}\rangle$ ($T_{1/2} \sim 10^{26} - 10^{29}$ yr).

3) $\langle m_{\nu}\rangle = 1-3$ meV. In this case, detectors with $\sim 10-100$ tons of $\beta\beta$ isotope have to be used.
It will be very difficult (if possible) to investigate this region of \( \langle m_\nu \rangle \) \((T_{1/2} \sim 10^{29} - 10^{30} \text{ yr})\).

4) \( \langle m_\nu \rangle < 1 \text{ meV} \). These values of \( \langle m_\nu \rangle \) is not available for observation in foreseeable future.

In [43] the possibility to investigate \( 0\nu\beta\beta \) decay with sensitivity to neutrino mass on the level of \( \sim 1-5 \text{ meV} \) has been analysed. It was demonstrated that the 3-5 meV region can be studied by detectors with \( \sim 10 \text{ tons of } \beta\beta \) isotope. In this case, the detectors should have a good energy resolution (FWHM <1-2%), sufficiently high efficiency (\( \sim 100\% \)) and low level of background in the investigated region (\( \sim 10^{-6} - 10^{-7} \text{ c/kev} \times \text{kg} \times \text{yr} \)). Besides, the cost of an isotope becomes important and can seriously limit the feasibility of such experiments [43]. It was noted in [43] that \(^{136}\text{Xe}, ^{130}\text{Te}, ^{82}\text{Se}, ^{100}\text{Mo} \) and \(^{76}\text{Ge} \) are most promising isotopes (the cheapest isotopes are \(^{136}\text{Xe} \) and \(^{130}\text{Te} \)), and the most suitable experimental techniques are low-temperature scintillation bolometers, gas Xe TPC and HPGe semiconductor detectors. This is discussed in more detail in [43].

6. Conclusion

Thus, the present conservative limit on \( \langle m_\nu \rangle \) from double beta decay experiments is 0.23 eV (90\% C.L.). The sensitivity of modern experiments will be brought to \( \sim 0.04-0.2 \text{ eV} \) (90\% C.L.) within the next 3-5 years. To study the IO region (0.014-0.05 eV), new generation experiments will be realised, which will achieve the required sensitivity in \( \sim 5-15 \text{ years} \). In case of the NO everything depends on the value of \( \langle m_\nu \rangle \) that is realized in nature. If \( \langle m_\nu \rangle = 10-30 \text{ meV} \), then this lies in the sensitivity region of the next generation experiments and \( 0\nu\beta\beta \) decay could be detected. If \( \langle m_\nu \rangle = 3-10 \text{ meV} \), new, more sensitive experiments with \( \sim 1-10 \text{ tons of } \beta\beta \) isotope will be needed (and it seems possible). For \( \langle m_\nu \rangle = 1-3 \text{ meV} \) experiments with \( \sim 10-100 \text{ tons of } \beta\beta \) isotope will be needed and it will be very difficult (if possible) to reach needed sensitivity in this case. If \( \langle m_\nu \rangle \leq 1 \text{ meV} \), then \( 0\nu\beta\beta \) decay will not be registered in the foreseeable future.

In this article we consider the \( 0\nu\beta\beta \) decay in framework of light Majorana neutrinos exchange mechanism. Nevertheless, it should be emphasized that other mechanisms are possible too (right-handed currents, supersymmetry, heavy neutrinos, doubly charged Higgs bosons, etc.). Therefore, if the \( 0\nu\beta\beta \) decay will be detected, then 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 should be noted, that 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 \( \langle m_\nu \rangle \).

Acknowledgments

This work was supported by Russian Science Foundation (grant No. 18-02-00003). The author thanks to Prof. F. Simkovic and V. Umatov for help in preparing the figure.

References

[1] Pascoli S, Petcov S T and Schwetz T 2006 Nucl. Phys. B 734 24
[2] Bilenky S M and Giunti C 2015 Int. J. Mod. Phys. A 30 1530001
[3] Vergados J D, Ejiri H and Simkovic F 2016 Int. J. Mod. Phys. E 25 163007
[4] Kotila J and Iachello F 2012 Phys. Rev. C 85 034316
[5] Mirea M, Palomii T and Stoica S 2015 Rom. Rep. Phys. 67 872-889
[6] Barea J, Kotila J and Iachello F 2015 Phys. Rev. C 91 034304
[7] Pirinen P and Suhonen J 2015 Phys. Rev. C 91 054309
[8] Kostensalo J, Haaranen M and Suhonen J 2017 Phys. Rev. C 95 044313
[9] Suhonen J 2017 Phys. Rev. C 96 055501
[10] Barabash A S 2015 Nucl. Phys. A 935 52
[11] Capozzi F et al. 2017 Phys. Rev. D 95 096014
[12] Planck Collaboration: Aghanim N et al. 2018 Planck 2018 results. VI. Cosmological parameters Preprint astro-ph.CO/1807.06290
[13] de Salas P F et al. 2018 Neutrino mass ordering from oscillations and beyond: 2018 status and future prospects Preprint hep-ph/1806.11051
[14] Hyvarinen J and Suhonen J 2015 Phys. Rev. C 91 024613
[15] Simkovic F, Rodin V, Faessler A and Vogel P 2013 Phys. Rev. C 87 045501
[16] Rath P K et al. 2013 Phys. Rev. C 88 064322
[17] Rodriguez T R and Martinez-Pinedo G 2010 Phys. Rev. Lett. 105 252503
[18] Menendez J, Poves A, Caurier E and Nowacki F 2009 Nucl. Phys. A 818 139
[19] Neacsu A and Horoi M 2015 Phys. Rev. C 91 024309
[20] Mustonen M and Engel J 2013 Phys. Rev. C 87 064302
[21] Song L S et al. 2017 Phys. Rev. C 95 024305
[22] Gando A et al. 2016 Phys. Rev. Lett. 117 082503
[23] Agostini M et al. 2018 Phys. Rev. Lett. 120 132503
[24] Alduino C et al. 2018 Phys. Rev. Lett. 120 132501
[25] Arnold R et al. 2015 Phys. Rev. D 92 072011
[26] Azzolini O et al. 2018 Phys. Rev. Lett. 120 232502
[27] Aalseth C E et al. 2018 Phys. Rev. Lett. 120 132502
[28] Albert J B et al. 2018 Phys. Rev. Lett. 120 072701
[29] Shirai J 2018 In Proceedings of XVII International Workshop on Neutrino Telescopes (Neutel2017), 13-17 March 2017, Venezia, Italy, Pros. Science 027
[30] Andringa S et al. 2016 Adv. High Energy Phys. 2016 6194250
[31] Fischer V 2018 Search for neutrinoless double-beta decay with SNO+ Preprint physics.ins-det/1809.05986
[32] Martin-Albo J et al. 2016 JHEP 05 159
[33] Poda D V 2017 AIP Conf. Proc. 1894 020017
[34] Yoon Y S 2018 PoS (ICRC2017) 1056
[35] Kim S C 2018 In: Proc. Neutrino 2018 – XXVIII Int. Conf. Physics and Astrophysics
[36] Barabash A S et al. 2017 Nucl. Instrum. Methods A 868 98
[37] Cascella M et al. 2016 Nucl. Instrum. Methods A 824 507
[38] Abgrall N et al. 2017 AIP Conf. Proc. 1894 02027
[39] Albert J B et al. 2018 Phys. Rev. C 97 065503
[40] Wang G et al. 2015 CUPID CUORE (Cryogenic underground observatory for rare events) upgrade with particle identification Preprint physics.ins-det/1504.03599
[41] Wang G et al. 2015 R&D towards CUPID (CUORE Upgrade with particle identification) Preprint physics.ins-det/1504.03612
[42] Chen X et al. 2017 Sci. China Phys. Mech. Astron. 60 061011
[43] Barabash A S 2018 Int. J. Mod. Phys. A 33 1843001