Brief review of double beta decay experiments

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Abstract. Best present experimental achievements in double beta decay are presented. Possible progress in this field in the near and far future is discussed.

1. Introduction
The detection and study of $0\nu\beta\beta$ decay may clarify the following problems of neutrino physics (see recent review [1], for example): (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, inverted, or quasidegenerate), (v) CP violation in the lepton sector (measurement of the Majorana CP-violating phases).

Usually, three main modes of the $2\beta$ decay are considered:

$$ (A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}, \quad (1) $$

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

$$ (A, Z) \rightarrow (A, Z + 2) + 2e^- + \chi^0(+\chi^0), \quad (3) $$

where $A$ is the atomic number, $Z$ is the charge of the nucleus, $e^-$ is the electron, $\bar{\nu}$ is an antineutrino, and $\chi^0$ is the Majoron.

Best present achievements for mentioned above processes are presented in tables 1-3.

2. Best recent results
In 2016 new (record) limits for existence of neutrinoless double beta decay in experiments with $^{136}$Xe (KamLAND-Zen) and $^{76}$Ge (GERDA-II) have been obtained.

2.1. $^{136}$Xe (KamLAND-Zen) [24]
KamLAND-Zen experiment phase-2 (383 kg of the enriched xenon) has been finished in May 2016. Limit of $9.2 \cdot 10^{25}$ yr (90% C.L.) for 534.5 days of measurements has been established. Combining this limit with result of a phase-1 [32] authors obtained limit of $1.07 \cdot 10^{26}$ yr (90% C.L.), which corresponds to limit $\langle m_\nu \rangle < 0.06 - 0.16$ eV. It must be emphasized that sensitivity of the experiment is $5 \cdot 10^{25}$ yr ($\langle m_\nu \rangle \sim 0.09 - 0.24$ eV), and more strong limit is obtained thanks to big "negative" fluctuation of a background. To be conservative I recommend to use exactly
The best limit on this last value as most reliable and correct limit by this moment. Nevertheless for today this is Table 2. Best present results on $0\nu\beta\beta$ decay (limits at 90% C.L.). To calculate $\langle m_{\nu}\rangle$ the NME from $[3, 4, 5, 6, 7, 8, 9, 10, 11]$, phase-space factors from $[12, 13]$ and $g_A = 1.27$ have been used. In case of $^{150}$Nd NME from $[14, 15]$ and in case of $^{48}$Ca from $[10]$ were used in addition.

### Table 1. Average and recommended $T_{1/2}(2\nu)$ values (from $[2]$).

| Isotope | $T_{1/2}(2\nu)$, yr |
|---------|---------------------|
| $^{48}$Ca | $4.4^{+0.6}_{-0.5} \cdot 10^{19}$ |
| $^{76}$Ge | $1.65^{+0.14}_{-0.12} \cdot 10^{21}$ |
| $^{82}$Se | $(0.92 \pm 0.07) \cdot 10^{20}$ |
| $^{96}$Zr | $(2.3 \pm 0.2) \cdot 10^{19}$ |
| $^{100}$Mo | $(7.1 \pm 0.4) \cdot 10^{18}$ |
| $^{100}$Mo-$^{106}$Ru($0^+_1$) | $6.7^{+0.5}_{-0.4} \cdot 10^{20}$ |
| $^{116}$Cd | $(2.87 \pm 0.13) \cdot 10^{19}$ |
| $^{128}$Te | $(2.0 \pm 0.3) \cdot 10^{24}$ |
| $^{130}$Te | $(6.9 \pm 1.3) \cdot 10^{20}$ |
| $^{136}$Xe | $(2.19 \pm 0.06) \cdot 10^{21}$ |
| $^{150}$Nd | $(8.2 \pm 0.9) \cdot 10^{18}$ |
| $^{150}$Nd-$^{150}$Sm($0^+_1$) | $1.2^{+0.3}_{-0.2} \cdot 10^{20}$ |
| $^{238}$U | $(2.0 \pm 0.6) \cdot 10^{21}$ |

### Table 2. Best present results on $0\nu\beta\beta$ decay (limits at 90% C.L.). To calculate $\langle m_{\nu}\rangle$ the NME from $[3, 4, 5, 6, 7, 8, 9, 10, 11]$, phase-space factors from $[12, 13]$ and $g_A = 1.27$ have been used. In case of $^{150}$Nd NME from $[14, 15]$ and in case of $^{48}$Ca from $[10]$ were used in addition.

| Isotope  | $Q_{2\beta}$, keV | $T_{1/2}$, y | $\langle m_{\nu}\rangle$, eV | Experiment |
|----------|-------------------|-------------|-------------------|------------|
| $^{48}$Ca | 4267.98           | $< 5.8 \cdot 10^{22}$ | $< 3.1 - 15.4$ | CANDLES $[17]$ |
| $^{76}$Ge | 2039.00           | $> 3.5 \cdot 10^{25}$ | $< 0.18 - 0.48$ | GERDA-I+GERDA-II $[18]$ |
| $^{82}$Se | 2997.9            | $< 3.6 \cdot 10^{23}$ | $< 1 - 2.4$ | NEMO- 3 $[19]$ |
| $^{96}$Zr | 3355.85           | $> 9.2 \cdot 10^{21}$ | $< 3.6 - 10.4$ | NEMO-3 $[20]$ |
| $^{100}$Mo | 3034.40          | $> 1.1 \cdot 10^{24}$ | $< 0.33 - 0.62$ | NEMO- 3 $[21]$ |
| $^{116}$Cd | 2813.50      | $> 1.9 \cdot 10^{23}$ | $< 1 - 1.8$ | AURORA $[22]$ |
| $^{128}$Te | 866.6            | $> 1.5 \cdot 10^{24}$ | $2.3 - 4.6$ | Geochem. exp. (see $[2]$) |
| $^{130}$Te | 2527.52          | $< 4 \cdot 10^{24}$ | $< 0.26 - 0.97$ | CUORICINO + CUORE0 $[23]$ |
| $^{136}$Xe | 2457.83          | $> 0.5 \cdot 10^{26}$ | $< 0.09 - 0.24$ | KamLAND-Zen $[24]$ |
| $^{150}$Nd | 3371.38          | $< 2 \cdot 10^{22}$ | $< 1.6 - 5.3$ | NEMO-3 $[25]$ |

this last value as most reliable and correct limit by this moment. Nevertheless for today this is the best limit on $\langle m_{\nu}\rangle$ among all experiments. Now there is a preparation of measurements with 750 kg of the enriched xenon and a new (pure) internal balloon and sensitivity of the experiment will be increased up to $\sim 2 \cdot 10^{26}$ yr.

2.2. $^{76}$Ge ($GERDA-II$)
At the Neutrino-2016 Conference GERDA Collaboration reported the first results of GERDA-II experiment with 35.8 kg of HPGe detectors manufactured of the enriched germanium. 10.8 kg-yr
of statistics has been obtained during May 2015 – December 2016. The main achievement is the reduction of background in the double beta decay region to 10^{-3} c/keV-kg-yr (an order of magnitude below the background level obtained in GERDA-I [33]). As a result, there was no recorded events in neutrinoless double beta decay region. Combining the results of GERDA-I and GERDA-II a new limit on T_{1/2}(0\nu) for 76\text{Ge} has been obtained. Using two different methods the following results were obtained with a 90\% confidence level:

1) T_{1/2}(0\nu) > 5.2 \cdot 10^{25}\text{ yr} (sensitivity is 4 \cdot 10^{25}\text{ yr}) (frequentist test statistics).

2) T_{1/2}(0\nu) > 3.5 \cdot 10^{25}\text{ yr} (sensitivity is 3 \cdot 10^{25}\text{ yr}) (Bayesian method).

It seems that the second method provides more reliable and correct result. Set statistics in GERDA-II experiment continues. The planned experiment sensitivity for 3 years of measurements is 10^{26}\text{ yr}.

### 3. Prospects for the future experiments

Seven of the most developed and promising experiments which can be realized within the next ~30 years are presented in table 4. The estimation of the sensitivity to \langle m_\nu \rangle is done using NMEs from [3,4,5,6,7,8,9,10,11] and phase-space factor values from [12,13]. Actually the experiments specified in Table 4 don’t settle all variety of the offered experimental approaches to 2\beta decay search. There is a set of other propositions (see reviews [41,42,43], for example). The part of them already is at a stage of development of prototypes with a mass of the studied isotope 1-10 kg (NEXT [44], CANDLESS [45], LUCIFER [46], AMORE [47], LUMINEU/LUCINEU [48,49]).

In this Section I will try to predict the Future. In Section 3.1 the results which (I hope) will be obtained in 2017-2019 are presented. And in Sec. 3.2. possible dates for the start of data taking for a few large scale experiments are given.

#### 3.1. Near future (2017-2019)

I believe that to the end of this period we will have the following results:

1. Xe: T_{1/2}(0\nu) > 2 \cdot 10^{26}\text{ yr} (\langle m_\nu \rangle < 0.045 \text{ - } 0.120 \text{ eV}).

   This result will be obtained by new KamLAND-Zen experiment with 750 kg of 136\text{Xe} and with new (more pure) internal balloon.

#### Table 3. Best present limits on 0\nu 0\beta 0\beta decay (ordinary Majoron) at 90\% C.L. To calculate \langle g_{ee} \rangle the NME from [3,4,5,6,7,8,9,10,11], phase-space factors from [26] and g_A = 1.27 have been used. In case of 150\text{Nd} NME from [14,15] and in case of 48\text{Ca} from [10] were used in addition.

| Isotope | T_{1/2}, y | \langle g_{ee} \rangle, \times 10^{-3} | Experiment |
|---------|------------|---------------------------------|------------|
| 48\text{Ca} | > 4.6 \cdot 10^{21} | < 8.6 - 43.1 | NEMO-3 [27] |
| 76\text{Ge} | > 4.2 \cdot 10^{23} | < 2.4 - 6.3 | GERDA-I [28] |
| 82\text{Se} | > 1.5 \cdot 10^{22} | < 5.0 - 12.2 | NEMO-3 [29] |
| 96\text{Zr} | > 1.9 \cdot 10^{21} | 7.4 - 21.3 | NEMO-3 [30] |
| 100\text{Mo} | > 4.4 \cdot 10^{22} | < 1.7 - 3.1 | NEMO-3 [31] |
| 116\text{Cd} | > 1.1 \cdot 10^{22} | 4.5 - 8.0 | AURORA [32] |
| 128\text{Te} | > 1.5 \cdot 10^{24} | 6.3 - 12.3 | Geochem. exp. (see [2]) |
| 130\text{Te} | > 1.6 \cdot 10^{22} | < 4.6 - 17.4 | NEMO-3 [30] |
| 136\text{Xe} | > 2.6 \cdot 10^{24} | < 0.45 - 1.2 | KamLAND-Zen [31] |
| 150\text{Nd} | > 3 \cdot 10^{21} | < 3.7 - 11.9 | NEMO-3 [25] |
Table 4. Seven most developed and promising projects. Sensitivity at 90% C.L. for three (1-st step of GERDA and MAJORANA, first step of SuperNEMO, CUORE-0 and KamLAND-Zen) five (EXO-200, SuperNEMO, SNO+ and CUORE) and ten (EXO, full-scale GERDA and MAJORANA) years of measurements is presented. M - mass of isotopes.

| Experiment | Isotope | M, kg | Sensitivity $T_{1/2}$, yr | Sensitivity $\langle m_\nu \rangle$, meV | Status |
|------------|---------|-------|---------------------------|---------------------------------|--------|
| CUORE [34] | $^{130}$Te | 200 | $9.5 \times 10^{25}$ | 53–200 | in progress |
| GERDA [35] | $^{76}$Ge | 35 | $1 \times 10^{26}$ | 110–280 | current |
| | | 1000 | $6 \times 10^{27}$ | 14–37 | R&D |
| MAJORANA | $^{76}$Ge | 30 | $1 \times 10^{26}$ | 110–280 | current |
| | | 1000 | $6 \times 10^{27}$ | 14–37 | R&D |
| EXO [37] | $^{136}$Xe | 200 | $4 \times 10^{25}$ | 100–270 | current |
| | | 5000 | $10^{27} - 10^{28}$ | 6–53 | R&D |
| SuperNEMO | $^{82}$Se | 7 | $6.5 \times 10^{24}$ | 240–570 | in progress |
| | | 100–200 | $(1-2) \times 10^{26}$ | 40–140 | R&D |
| KamLAND-Zen | $^{136}$Xe | 750 | $2 \times 10^{26}$ | 45–120 | in progress |
| | | 1000 | $6 \times 10^{26}$ | 26–69 | R&D |
| SNO+ [40] | $^{130}$Te | 800 | $9 \times 10^{25}$ | 55–205 | in progress |
| | | 8000 | $7 \times 10^{26}$ | 20–73 | R&D |

2. $^{76}$Ge: $T_{1/2}(0\nu) > 1.5 \cdot 10^{26}$ yr ($\langle m_\nu \rangle < 0.09 - 0.23$ eV).
   This result will be obtained combining GERDA-II ($\sim 10^{26}$ yr) and MAJORANA-DEMONSTRATOR ($\sim 10^{26}$ yr) results.

3. $^{130}$Te: $T_{1/2}(0\nu) > 1 \cdot 10^{26}$ yr ($\langle m_\nu \rangle < 0.05 - 0.19$ eV).
   This result will be obtained combining CUORE ($\sim 0.7 \cdot 10^{26}$ yr) and SNO+ ($\sim 0.7 \cdot 10^{26}$ yr) results.

   Of course, during this period some other new results will be obtained (EXO, SuperNEMO-Demonstrator, NEXT, LUCIFER, LUCINEU, AMORE,...), but it will be not competitive with mentioned above results (in the sense of sensitivity to $\langle m_\nu \rangle$).

3.2. Far future (2020-2030)
It is quite complicated to predict far future. This is why I will try just to predict dates when the most prospect experiments will start to take data. One can find these predictions in table 5.

Table 5. Start of data taking for some large scale experiments (prediction).

| Experiment | Start of data taking, yr |
|------------|--------------------------|
| KamLAND2-Zen ($1000$ kg of $^{136}$Xe) | $\sim 2020 - 2022$ |
| SNO+ ($8000$ kg of $^{nat}Te$) | $\sim 2020 - 2022$ |
| CUPID ($^{100}$Mo, $^{82}$Se, $^{116}$Cd,...) | $\sim 2022$ |
| LEGEND-I ($200$ kg of $^{76}$Ge) | $\sim 2022 - 2025$ |
| LEGEND ($1000$ kg of $^{76}$Ge) | $\sim 2025 - 2030$ |
| nEXO ($5000$ kg of $^{130}$Xe) | $\sim 2025 - 2030$ |
4. Conclusion

Thus, at present, the $2\nu\beta\beta$ decay of 11 nuclei ($^{48}\text{Ca}$, $^{76}\text{Ge}$, $^{82}\text{Se}$, $^{96}\text{Zr}$, $^{100}\text{Mo}$, $^{116}\text{Cd}$, $^{128}\text{Te}$, $^{130}\text{Te}$, $^{136}\text{Xe}$, $^{150}\text{Nd}$ and $^{238}\text{U}$) has been registered. Moreover, the $2\nu\beta\beta$ decay of $^{100}\text{Mo}$ and $^{150}\text{Nd}$ to $0^+_1$ excited states of daughter nuclei and the ECEC($2\nu$) process in $^{130}\text{Ba}$ (geochemical experiments) have been detected too.

The $0\nu\beta\beta$ decay has not been observed yet, and the best limits on $\langle m_\nu \rangle$ have been obtained in experiments with $^{136}\text{Xe}$, $^{76}\text{Ge}$, $^{100}\text{Mo}$, and $^{130}\text{Te}$. Using most reliable NME calculations it is possible to set the present conservative limit as $\langle m_\nu \rangle < 0.24$ eV. Conservative present limit on decay with Majoron emission has been obtained as $\langle g_{ee} \rangle < 1.2 \cdot 10^{-5}$ (ordinary Majoron with $n = 1$).

Sensitivity to $\langle m_\nu \rangle$ on the level $\sim 0.05-0.20$ eV will be reached by next generation experiments in a few years from now and on the level $\sim 0.02-0.05$ eV (inverted hierarchy region) after 2022. I do not discuss here effect of possible quenching of axial-vector coupling constant $g_A$ (see discussions in [3, 50], for example). If the quenching of $g_A$ really exist it will decrease our sensitivity to $\langle m_\nu \rangle$.

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