75 years of double beta decay: yesterday, today and tomorrow

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Abstract. In this report I will briefly review the motivation and history of double beta decay search since the first consideration of two neutrino process $2\beta(2\nu)$ by Maria Goeppert-Mayer in 1935. The first experiments on search for double beta decay in the late of 1940s and beginning of 1950s are considered. It is underlined that for the first time the $2\beta(2\nu)$ decay has been registered in geochemical experiment with $^{130}$Te in 1950. In direct (counter) experiment this type of decay for the first time has been registered in $^{82}$Se by Michael Moe’s group in 1987. Now two neutrino double beta decay has been recorded for 10 nuclei ($^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{90}$Zr, $^{100}$Mo, $^{116}$Cd, $^{128}$Te, $^{130}$Te, $^{150}$Nd, $^{238}$U). In addition, the $2\beta(2\nu)$ decay of $^{100}$Mo and $^{150}$Nd to the $0^+_1$ excited state of the daughter nucleus has been observed and the ECEC($2\nu$) process in $^{130}$Ba was observed too. As to neutrinoless double beta decay ($2\beta(0\nu)$) this process has not yet been registered. In the review results of the most sensitive experiments (Heidelberg-Moscow, IGEX, CUORICINO, NEMO-3) are discussed and conservative upper limits on effective Majorana neutrino mass and the coupling constant of the Majoron to the neutrino are established as $\langle m_\nu \rangle < 0.75$ eV and $\langle g_{ee} \rangle < 1.9 \times 10^{-4}$, respectively. The next-generation experiments, where the mass of the isotopes being studied will be as grand as 100 to 1000 kg, are discussed. These experiments will have started within a few years. In all probability, they will make it possible to reach the sensitivity to the neutrino mass at a level of 0.01 to 0.1 eV.

1. Introduction
The current interest in neutrinoless double beta decay is that the existence of this process is closely related to the following fundamental aspects of particle physics [1, 2, 3]: (i) lepton-number non-conservation, (ii) the presence of a neutrino mass and its origin, (iii) the existence of right-handed currents in electroweak interactions, (iv) the existence of the Majoron, (v) the structure of the Higgs sector, (vi) supersymmetry, (vii) the existence of leptoquarks, (viii) the existence of a heavy sterile neutrino, and (ix) the existence of a composite neutrino.

All of these issues are beyond the standard model of electroweak interaction, therefore the detection of $0\nu\beta\beta$ decay would imply the discovery of new physics. Of course, now interest in this process is caused primarily by the problem of a neutrino mass. If $0\nu\beta\beta$ decay is discovered, then according to current thinking, this will automatically mean that the rest mass of at least one neutrino flavor is nonzero and is of Majorana origin.

Interest in neutrinoless double-beta decay has seen a significant renewal in recent years after evidence for neutrino oscillations was obtained from the results of atmospheric, solar, reactor and accelerator neutrino experiments (see, for example, the discussions in [4, 5, 6]). These results are impressive proof that neutrinos have a non-zero mass. However, the experiments studying...
neutrino oscillations are not sensitive to the nature of the neutrino mass (Dirac or Majorana) and provide no information on the absolute scale of the neutrino masses, since such experiments are sensitive only to the difference of the masses, $\Delta m^2$. The detection and study of $0\nu\beta\beta$ decay may clarify the following problems of neutrino physics (see discussions in [7, 8, 9]): (i) lepton number non-conservation, (ii) neutrino nature: whether the neutrino is a Dirac or a Majorana particle, (iii) absolute neutrino mass scale (a measurement or a limit on $m_1$), (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).

2. Yesterday

The double beta decay problem arose practically immediately after the appearance of W. Pauli's neutrino hypothesis in 1930 and the development of $\beta$-decay theory by E. Fermi in 1933. In 1935 M. Goeppert-Mayer identified for the first time the possibility of two neutrino double beta decay, in which there is a transformation of an $(A, Z)$ nucleus to an $(A, Z+2)$ nucleus that is accompanied by the emission of two electrons and two anti-neutrinos [10]:

$$\begin{equation}
(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}
\end{equation}$$

It was demonstrated theoretically by E. Majorana in 1937 [11] that if one allows the existence of only one type of neutrino, which has no antiparticle (i.e. $\nu \equiv \bar{\nu}$), then the conclusions of $\beta$-decay theory are not changed. In this case one deals with a Majorana neutrino. In 1939 W. Furry introduced a scheme of neutrinoless double beta decay through the virtual state of intermediate nucleus [12]:

$$\begin{equation}
(A, Z) \rightarrow (A, Z+2) + 2e^-
\end{equation}$$

The first experiment to search for $2\beta$-decay was done in 1948 using Geiger counters. In this experiment a half-life limit for $^{124}\text{Sn}$ was established, $T_{1/2} > 3 \cdot 10^{15}$ y [13]. During the period from 1948 to 1965 ~ 20 experiments were carried out with a sensitivity to the half-life on the level of $\sim 10^{16} - 10^{19}$ y (see reviews [14, 15]). The $2\beta$-decay was thought to have been "discovered" a few times, but each time it was not confirmed by new (more sensitive) measurements. The exception was the geochemical experiment, in which two neutrino double beta decay of $^{130}\text{Te}$ was really detected in 1950 [16].

At the end of the 1960s and beginning of 1970s significant progress in the sensitivity of double beta decay experiments was realized. E. Fiorini et al. carried out experiments with Ge(Li) detectors and established a limit on neutrinoless double beta decay of $^{76}\text{Ge}$, $T_{1/2} > 5 \cdot 10^{21}$ y [17]. Experiments with $^{48}\text{Ca}$ and $^{82}\text{Se}$ using streamer chamber with a magnetic field and plastic scintillators were done by C. Wu’s group and led to impressive limits of $> 2 \cdot 10^{21}$ y [18] and $> 3.1 \cdot 10^{21}$ y [19] respectively. During these years many sensitive geochemical experiments were done and $2\nu\beta\beta$ decay of $^{130}\text{Te}$, $^{128}\text{Te}$ and $^{82}\text{Se}$ was detected (see reviews [20, 15, 21]).

In 1981 a new type of neutrinoless decay with Majoron emission was introduced [22]:

$$\begin{equation}
(A, Z) \rightarrow (A, Z+2) + 2e^- + \chi^0
\end{equation}$$

The important achievements in the 1980s were connected with the first evidence of two neutrino double beta decay in direct counting experiments. This was done by M. Moe’s group for $^{82}\text{Se}$ using a TPC ($T_{1/2} = 1.1_{-0.3}^{+0.8} \cdot 10^{20}$ y) [23]. There was also the first use of semiconductor detectors made of enriched Ge in the ITEP-ErPI experiment [24].

During the 1990s the two neutrino decay process was detected in many experiments for different nuclei (see [25, 26]), two neutrino decay to an excited state of the daughter nucleus was also detected [27]. In addition, the sensitivity to $0\nu\beta\beta$ decay in experiments with $^{76}\text{Ge}$ (Hidelberg-Moscow [28] and IGEX [29]) was increased up to $\sim 10^{25}$ y.
Since 2002 the progress in double beta decay searches has been connected mainly with the two experiments, NEMO-3 [30, 31, 32, 33, 34, 35, 36] and CUORICINO [37, 38, 39]. The basic historical marks of 75 years study of this process are presented in Tables 1 and 2 (from [40]).

3. Today

3.1. Two neutrino double beta decay
As discussed above this decay was first recorded in 1950 in a geochemical experiment with $^{130}$Te [16]. In 1967, it was also found for $^{82}$Se [43]. Attempts to observe this decay in a direct measurement employing counters were unsuccessful for a long time. Only in 1987 could M. Moe, who used a time-projection chamber (TPC), observe $2\beta(2\nu)$ decay in $^{82}$Se for the first time [23]. Within the next few years, experiments employing counters were able to detect $2\beta(2\nu)$ decay in many nuclei. In $^{100}$Mo [27, 68, 69], and $^{150}$Nd [70] $2\beta(2\nu)$ decay to the $0^+$ excited state of the daughter nucleus was also recorded. The $2\beta(2\nu)$ decay of $^{238}$U was detected in a radiochemical experiment [71], and in a geochemical experiment for the first time the ECEC process was detected in $^{130}$Ba [60]. Table 3 displays the present-day averaged and recommended values of $T_{1/2}(2\nu)$ from [26]. At present, experiments devoted to detecting $2\nu\beta\beta$ decay are approaching a level where it is insufficient just to record the decay. It is necessary to measure numerous parameters of this process to a high precision (half-life value, energy sum spectrum, single electron energy spectrum and angular distribution). Tracking detectors that are able to record both the energy of each electron and the angle at which they diverge are the most appropriate instruments for solving this problem. Current tracking NEMO-3 experiment is measuring all parameters of double beta decay for seven different nuclei ($^{48}$Ca, $^{82}$Se, $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, $^{130}$Te, and $^{150}$Nd) [30, 31, 32, 33, 34, 35, 36].

3.2. Neutrinoless double beta decay
In contrast to two-neutrino decay, neutrinoless double-beta decay has not yet been observed\footnote{The possible exception is the result with $^{76}$Ge, published by a fraction of the Heidelberg-Moscow Collaboration (see Table 4). First time the "positive" result was mentioned in [74]. The Moscow part of the Collaboration does not agree with this conclusion [75] and there are others who are critical of this result [76, 78, 77]. Thus, at the present time, this "positive" result is not accepted by the "$2\beta$ decay community" and it has to be checked.} although it is easier to detect it. In this case, one seeks, in the experimental spectrum, a peak of energy equal to the double beta transition energy and of width determined by the detector’s resolution.

The constraints on the existence of $0\nu\beta\beta$ decay are presented in Table 4 for the nuclei for which the best sensitivity has been reached. In calculating constraints on $\langle m_\nu \rangle$, the nuclear matrix elements from [61, 62, 63, 65, 67] were used (3-d column). It is advisable to employ the calculations from these studies, because the calculations are the most thorough and take into account the most recent theoretical achievements. In the papers [61, 62, 63] $g_{pp}$ values ($g_{pp}$ is parameter of the QRPA theory) were fixed using experimental half-life values for $2\nu$ decay and then NME($0\nu$) were calculated. In column four, limits on $\langle m_\nu \rangle$, which were obtained using the NMEs from a recent Shell Model (SM) calculations [64], are presented (for $^{116}$Cd NME from [65] is used).

From Table 4 using NME values from [61, 62, 63, 64, 66, 67], the limits on $\langle m_\nu \rangle$ for $^{130}$Te are comparable with the $^{76}$Ge results. Now one cannot select any experiment as the best one. 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 0.75 eV.

3.3. Neutrinoless double beta decay with Majoron emission
Table 5 displays the best present-day constraints for an "ordinary" Majoron (n = 1). The "nonstandard" models of the Majoron were experimentally tested in [82] for $^{76}$Ge and in [83].
for $^{100}$Mo, $^{116}$Cd, $^{82}$Se, and $^{96}$Zr. Constraints on the decay modes involving the emission of two Majorons were also obtained for $^{100}$Mo $^{34}$, $^{116}$Cd $^{30}$, and $^{130}$Te $^{35}$. In a recent NEMO Collaboration papers $^{32}$ $^{34}$ $^{35}$, new results for these processes in $^{100}$Mo, $^{82}$Se, $^{150}$Nd and $^{96}$Zr were obtained with the NEMO-3 detector. Table 6 gives the best experimental constraints on decays accompanied by the emission of one or two Majorons (for $n = 2$, $3$, and $7$). Hence at the present time only limits on double beta decay with Majoron emission have been obtained (see table 5 and 6). A conservative present limit on the coupling constant of ordinary Majoron to the neutrino is $\langle g_{ee} \rangle < 1.9 \cdot 10^{-4}$.

4. Tomorrow
There are more than 20 different propositions for future double beta decay experiments. Here seven of the most developed and promising experiments which can be realized within the next few years are presented (see Table 7). The estimation of the sensitivity in the experiments is made using NMEs from $^{61}$ $^{62}$ $^{63}$ $^{64}$ $^{66}$ $^{67}$. In all probability, they will make it possible to reach the sensitivity for the neutrino mass at a level of 0.01 to 0.1 eV.

First phase of GERDA (18 kg of $^{76}$Ge), EXO-200 (200 kg of $^{136}$Xe), CUORE-0 ($\sim$ 40 kg of natural Te) and KamLAND-Xe (400 kg of $^{136}$Xe) plan to start data-taking in 2011. For this reason I expect occurrence of new, very interesting results in 2011-2012.

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Table 1. Main "milestones" in double beta decay search.

| Date   | Event                                                                 | Remarks                                                                 |
|--------|------------------------------------------------------------------------|-------------------------------------------------------------------------|
| 1935   | The idea of $2\beta^2(\nu)$ decay has been formulated                 | M. Goeppert-Mayer [10]                                                  |
| 1939   | The idea of $2\beta^0(\nu)$ decay has been formulated                 | W.H. Furry [12]                                                         |
| 1948   | The first $2\beta$ decay experiment has been realized                 | E.L. Fireman [13]; (Geiger counters and 25 g of enriched $^{124}$Sn were used) |
| 1950   | **The first observation of $2\beta^2(\nu)$ decay has been done**      | M.G. Inghram, and J.H. Reynolds [16] (geochem. experiment with $^{130}$Te); $T_{1/2} \approx 1.4 \cdot 10^{21}$ y |
| 1950   |                                                                         |                                                                         |
| 1966   | The first counter experiment with sensitivity higher than $10^{20}$ y has been realized | E. Mateosian, and M. Goldhaber [41] ("detector=source", 11.4 g of enriched $^{48}$Ca); $T_{1/2}(0\nu) > 2 \cdot 10^{20}$ y |
| 1967   | The first experiment with semiconductor Ge detector has been realized  | E. Fiorini et al. [42] (17 cm$^3$ Ge(Li) detector on see level); $T_{1/2}(0\nu) > 3 \cdot 10^{20}$ y |
| 1967   | The observation of $2\beta(2\nu)$ decay of $^{82}$Se has been done    | T. Kirsten et al. [43] (geochemical experiment); $T_{1/2} \approx 0.6 \cdot 10^{20}$ y |
| 1967-  | The first counter experiment with sensitivity higher than $10^{21}$ y has been realized | R.K. Bardin, P.J. Gollon, J.D. Ullman, and C.S. Wu [44, 48] (strimmer chamber+scintillation counters); $T_{1/2}(0\nu;^{48}$Ca) $> 2 \cdot 10^{21}$ y, $T_{1/2}(2\nu;^{48}$Ca) $> 3.6 \cdot 10^{19}$ y |
| 1973   | The sensitive counter experiment with $^{76}$Ge has been realized      | E. Fiorini et al. [47] (68 cm$^3$ Ge(Li) detector at 4200 m w.e. depth); $T_{1/2}(2\nu) > 5 \cdot 10^{21}$ y |
| 1975   | The sensitive counter experiment with $^{82}$Se has been realized      | B.T. Cleveland et al. [19] (streamer chamber + scint. counters); $T_{1/2}(0\nu;^{82}$Se) $> 3.1 \cdot 10^{21}$ y |
| 1980-  | The idea of $2\beta$ decay with Majoron emission has been formulated   | Singlet [45], doublet [47] and triplet [46, 22] Majoron has been introduced |
| 1981   |                                                                        |                                                                         |
| 1982   | J. Schechter and J.W.F. Valle theorem is formulated                    | J. Schechter, and J.W.F. Valle [48] (the occurrence of $2\beta(0\nu)$ decay implies that neutrinos are Majorana particles with nonzero mass) |
| 1984   | The program to develop low temperature detectors for double beta decay search has been formulated | E. Fiorini, and T.O. Niinikoski [49] |
| 1985   | The fundamental theoretical investigation of double beta decay has been done | M. Doi, T. Kotani, and E. Takasugi [50] (the main formulas for probability of decay, energy and angular electron spectra have been obtained) |
| Date   | Event                                                                 | Remarks                                                                                   |
|--------|----------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| 1986   | The $g_{pp}$ parameter (characterize the particle-particle interaction in nuclei) of QRPA model has been introduced | P. Vogel, and M.R. Zirnbauer [51] (within frameworks of QRPA models the satisfactory agreement between theoretical and experimental $T_{1/2}(2\nu)$ values for the first time has been observed) |
| 1987   | **The first observation of $2\nu$ decay in counter experiment has been done** | M. Moe et al. [23] (TPC with $^{82}$Se; $T_{1/2}(2\nu) = 1.1^{+0.8}_{-0.3} \times 10^{20}$ y) |
| 1987-  | The first counter experiment with sensitivity higher than $10^{24}$ y has been done | D.O. Caldwell et al. [52] (8 detectors from natural Ge with full weight 7.2 kg; $T_{1/2}(0\nu) > 1.2 \times 10^{24}$ y) |
| 1987-  | The first semiconductor detector made of enriched germanium (86% of $^{76}$Ge) has been started to work. | ITEP-ErPI Collaboration [63, 21] (2 detectors from enriched Ge with full weight $\sim 1.1$ kg). |
| 1991   | The first observation of $2\nu$ decay to the excited state of daughter nucleus has been done | A.S. Barabash et al. [27] (low background HPGe detector, 1 kg of $^{100}$Mo, $^{100}$Mo-$^{100}$Ru($0_1^+;1130$ keV) transition; $T_{1/2} = 6.1^{+1.8}_{-1.1} \times 10^{20}$ y) |
| 1990-  | The experiments with ELEGANT-V detector                              | H. Ejiri et al. [54, 55]. $2\beta(2\nu)$ decay observation in $^{100}$Mo and $^{116}$Cd |
| 1991-  | The experiments with NEMO-2 detector                                  | NEMO-2 Collaboration [56, 57, 58, 59]. Study of $2\beta(2\nu)$ decay ($^{100}$Mo, $^{116}$Cd, $^{82}$Se and $^{96}$Zr) with registration of all parameters of the decay |
| 1991-  | The IGEX experiment                                                   | Measurements with 6.5 kg of enriched $^{76}$Ge; $T_{1/2}(0\nu) > 1.57 \times 10^{25}$ y [29] |
| 1990-  | The Heidelberg-Moscow experiment                                      | Measurements with 11 kg of enriched $^{76}$Ge [28]; $T_{1/2}(0\nu) > 1.9 \times 10^{25}$ y, $T_{1/2}(2\nu) = 1.74 \pm 0.01(stat) ^{+0.18}_{-0.16}(syst) \times 10^{21}$ y |
| 2001   | First observation of ECEC($2\nu$)                                     | Geochemical experiment with $^{130}$Ba, $T_{1/2} = (2.2 \pm 0.5) \times 10^{21}$ y [60] |
| 2002-  | NEMO-3 experiment                                                     | NEMO-3 Collaboration [30, 31, 32, 33, 34, 35, 36]; $T_{1/2}(0\nu;^{100}$Mo$) > 1.1 \times 10^{24}$ y. Observation and precise investigation of $2\beta(2\nu)$ decay for 7 isotopes ($^{48}$Ca, $^{82}$Se, $^{96}$Zr, $^{100}$Mo, $^{116}$Cd, $^{130}$Te, $^{150}$Nd) |
| 2003-  | CUORICINO experiment                                                 | CUORICINO Collaboration [37, 38, 39]; $T_{1/2}(0\nu;^{130}$Te$) > 2.8 \times 10^{24}$ y |
### Table 3. Average and recommended $T_{1/2}(2\nu)$ values (from \[26\]).

| Isotope     | $T_{1/2}(2\nu)$             |
|-------------|----------------------------|
| $^{48}$Ca   | $\langle m_{\nu} \rangle$, eV |
| $^{76}$Ge   | $\langle m_{\nu} \rangle$, eV |
| $^{82}$Se   | $\langle m_{\nu} \rangle$, eV |
| $^{90}$Zr   | $\langle m_{\nu} \rangle$, eV |
| $^{100}$Mo  | $\langle m_{\nu} \rangle$, eV |
| $^{100}$Mo$^{100}$Ru$(0^+_1)$ | $\langle m_{\nu} \rangle$, eV |
| $^{116}$Cd  | $\langle m_{\nu} \rangle$, eV |
| $^{128}$Te  | $\langle m_{\nu} \rangle$, eV |
| $^{130}$Te  | $\langle m_{\nu} \rangle$, eV |
| $^{150}$Nd  | $\langle m_{\nu} \rangle$, eV |
| $^{238}$U   | $\langle m_{\nu} \rangle$, eV |
| $^{130}$Ba; ECEC($2\nu$) | $\langle m_{\nu} \rangle$, eV |

### Table 4. Best present results on $2\beta(0\nu)$ decay (limits at 90% C.L.). *) See footnote 1; **) NME from \[65\] is used; *** conservative limit from \[79\] is presented.

| Isotope     | $T_{1/2}$, y  | $\langle m_{\nu} \rangle$, eV | Experiment |
|-------------|---------------|-------------------------------|------------|
| $^{76}$Ge   | $> 1.9 \cdot 10^{25}$ | $< 0.22 - 0.41$ | \[28\] HM |
|             | $\simeq 1.2 \cdot 10^{25}$ | $< 0.28 - 0.52$ | \[72\] Part of HM |
|             | $\simeq 2.2 \cdot 10^{25}$ | $< 0.21 - 0.38$ | \[73\] Part of HM |
|             | $> 1.6 \cdot 10^{25}$ | $< 0.24 - 0.44$ | \[29\] IGEX |
| $^{130}$Te  | $> 2.8 \cdot 10^{24}$ | $< 0.35 - 0.59$ | \[30\] NEMO- 3 |
| $^{100}$Mo  | $> 1.1 \cdot 10^{24}$ | $< 0.45 - 0.93$ | \[30\] NEMO- 3 |
| $^{136}$Xe | $> 4.5 \cdot 10^{23}$ | $< 1.41 - 2.67$ | \[79\] DAMA |
| $^{82}$Se   | $> 3.6 \cdot 10^{23}$ | $< 1.89 - 1.61$ | \[36\] NEMO-3 |
| $^{116}$Cd  | $> 1.7 \cdot 10^{23}$ | $< 1.45 - 2.76$ | \[80\] SOLOTVINO |

### Table 5. Best present limits on $0\nu\chi^0\beta\beta$ decay (ordinary Majoron) at 90% C.L. The NME from the following works were used, 3-d column: \[61\] \[62\] \[63\] \[66\] \[67\], 4-th column: \[64\]. *) Conservative limit from \[79\] is presented; **) NME from \[65\] is used.

| Isotope     | $E_{2\beta}$, keV | $T_{1/2}$, y  | $\langle g_{ee} \rangle$, eV |
|-------------|-------------------|---------------|----------------------------|
| $^{76}$Ge (2039) | $> 6.4 \cdot 10^{22}$ | $< (0.54 - 1.44) \cdot 10^{-4}$ | \[28\] |
| $^{82}$Se (2995) | $> 1.5 \cdot 10^{22}$ | $< (0.58 - 1.19) \cdot 10^{-4}$ | \[32\] |
| $^{100}$Mo (3034) | $> 2.7 \cdot 10^{22}$ | $< (0.35 - 0.85) \cdot 10^{-4}$ | \[32\] |
| $^{116}$Cd (2805) | $> 8 \cdot 10^{21}$ | $< (0.79 - 2.56) \cdot 10^{-4}$ | \[80\] |
| $^{128}$Te (867) | $> 1.5 \cdot 10^{24}$ | $< (0.63 - 1) \cdot 10^{-4}$ | \[81\] \[26\] |
| $^{136}$Xe (2458) | $> 1.6 \cdot 10^{22}$ | $< (1.51 - 3.54) \cdot 10^{-4}$ | \[79\] |
Table 6. Best present limits on $T_{1/2}$ for decay with one and two Majorons at 90% C.L. for modes with spectral index $n = 2$, $n = 3$ and $n = 7$.

| Isotope ($E_{2/3}$, keV) | $n = 2$ | $n = 3$ | $n = 7$ |
|-------------------------|---------|---------|---------|
| $^{76}$Ge (2039)        | -       | > 5.8 $\cdot 10^{21}$ | $^{82}$ |
| $^{82}$Se (2995)        | > 6 $\cdot 10^{21}$ | > 3.1 $\cdot 10^{21}$ | $^{32}$ |
| $^{96}$Zr (3350)        | > 9.9 $\cdot 10^{20}$ | > 5.8 $\cdot 10^{20}$ | $^{35}$ |
| $^{100}$Mo (3034)       | > 1.7 $\cdot 10^{22}$ | > 1 $\cdot 10^{22}$ | $^{32}$ |
| $^{116}$Cd (2805)       | > 1.7 $\cdot 10^{21}$ | > 8 $\cdot 10^{20}$ | $^{80}$ |
| $^{130}$Te (2527)       | -       | > 9 $\cdot 10^{20}$ | $^{85}$ |
| $^{128}$Te (867) (geochem) | > 1.5 $\cdot 10^{24}$ | > 1.5 $\cdot 10^{24}$ | $^{81}$, $^{26}$ |
| $^{150}$Nd (3371)       | > 5.4 $\cdot 10^{20}$ | > 2.2 $\cdot 10^{20}$ | $^{34}$ |

Table 7. Seven most developed and promising projects. Sensitivity at 90% C.L. for three (1-st steps of GERDA and MAJORANA, KamLAND, SNO+) five (EXO, SuperNEMO and CUORE) and ten (full-scale GERDA and MAJORANA) years of measurements is presented. * For the background $0.001$ keV$^{-1} \cdot$ kg$^{-1} \cdot$ y$^{-1}$; ** for the background $0.01$ keV$^{-1} \cdot$ kg$^{-1} \cdot$ y$^{-1}$.

| Experiment | Isotope | Mass of isotope, kg | Sensitivity $T_{1/2}$, y | Sensitivity $\langle m_\nu \rangle$, meV | Status | Start of data-tacking |
|------------|---------|---------------------|--------------------------|----------------------------------------|--------|-----------------------|
| CUORE      | $^{130}$Te | 200                 | 6.5 $\cdot 10^{26}$*      | 20-50                                  | in progress | $\sim$ 2013            |
|            | $^{86}$ | $^{87}$ Ge         | -                        | 2.1 $\cdot 10^{26}$**         | 40-90                  |                      |
| GERDA      | $^{76}$Ge | 40                  | 2 $\cdot 10^{26}$        | 70-200                                | in progress | $\sim$ 2012            |
|            | -       | 1000                | 6 $\cdot 10^{27}$        | 10-40                                 | R&D        | $\sim$ 2015            |
| MAJORANA   | $^{76}$Ge | 30-60               | (1 - 2) $\cdot 10^{26}$  | 70-200                                | in progress | $\sim$ 2013            |
| EXO        | $^{136}$Xe | 200                 | 6.4 $\cdot 10^{25}$      | 100-200                               | in progress | $\sim$ 2011            |
|            | -       | 1000                | 8 $\cdot 10^{26}$        | 30-60                                 | R&D        | $\sim$ 2015            |
| SuperNEMO  | $^{82}$Se | 100-200             | (1 - 2) $\cdot 10^{26}$  | 40-100                                | R&D        | $\sim$ 2013-2015       |
| KamLAND    | $^{136}$Xe | 400                | 4 $\cdot 10^{26}$        | 40-80                                 | in progress | $\sim$ 2011            |
|            | -       | 1000                | 10$^{27}$                | 25-50                                 | R&D        | $\sim$ 2013-2015       |
| SNO+       | $^{150}$Nd | 56                  | 4.5 $\cdot 10^{24}$      | 100-300                               | in progress | $\sim$ 2012            |
|            | -       | 500                 | 3 $\cdot 10^{25}$        | 40-120                                | R&D        | $\sim$ 2015            |