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Double beta decay experiments: current status and prospects

A S Barabash

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Contents

Abstract. **Double beta decay experiments are reviewed and the results of the most sensitive of them are examined. Current half-life values for two-neutrino double beta decay are presented together with the best available limits on neutrinoless double beta decay and decay with a Majoron emission. The most promising next-generation experiments with a Majorana-neutrino mass sensitivity of 0.01–0.1 eV are described.**

1. Introduction

The present interest in neutrinoless double beta-decay ($2\beta(0\nu)$) originates in the fact that the actual existence of this process is closely related to the following fundamental aspects of elementary particle physics:

— lepton number nonconservation;
— the existence of a neutrino mass and its nature
— the existence of right-handed currents in the electroweak interaction;
— the existence of the majoron;
— the structure of the higgs sector;
— supersymmetry;
— the existence of leptoquarks;
— the existence of a heavy sterile neutrino;
— the existence of a composite neutrino.

All these issues lie beyond the framework of the Standard Model of electroweak interaction; therefore, registration of the $2\beta(0\nu)$-decay will signify the discovery of 'new physics'. The main interest in this process is naturally related to the problem of neutrino mass: if the $2\beta(0\nu)$ decay is discovered, then, according to present-day notions, this will automatically mean that the rest mass of at least one neutrino differs from zero and is a Majorana-type mass. Moreover, this will signify violation of lepton number conservation.

Interest in the $2\beta(0\nu)$-decay recently underwent significant growth, when the analysis of results with atmospheric, solar, reactor, and accelerator neutrinos led to the conclusion that neutrino oscillations do exist. This means that the neutrino has mass. However, oscillation experiments are not sensitive to the nature (Majorana or Dirac) of the neutrino mass and provide no information on the absolute scale of neutrino masses (because Δm^2 is actually measured). Registration and investigation of the $2\beta(0\nu)$ decay can clarify the following problems of neutrino physics:

(1) Is the neutrino mass a Dirac or a Majorana type?

(2) The absolute neutrino mass scale (measuring or establishing a bound for m_1).

(3) The hierarchy type (normal, inverse, or quasidegenerate).

(4) *CP* violation in the lepton sector (measurement of the Majorana *CP*-violating phase).

Usually, three main modes of the 2β decay are considered:

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

$$(A, Z) \to (A, Z+2) + 2e^-\,, \tag{2}$$

$$(A, Z) \to (A, Z+2) + 2e^- + \chi^0\,, \tag{3}$$

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

The **$2\beta(2\nu)$ decay** (process (1)) is a second-order process in weak interaction, and it is not forbidden by any conservation laws. At present, this process has been registered for 11 nuclei (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U). Moreover, the $2\beta(2\nu)$ decay has been registered for ^{100}Mo and ^{150}Nd to 0^+_1-excited states of daughter nuclei and the ECEC(2ν)-process (double electron capture with the

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A S Barabash Alikhanov Institute for Theoretical and Experimental Physics,
ul. B Cheremushkinskaya 25, 117218 Moscow, Russian Federation
E-mail: barabash@itep.ru

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Table 1. Modern $T_{1/2}(2\nu)$ values. (From Ref. [1].)

Isotope	$T_{1/2}(2\nu)$, year
^{48}Ca	$4.4^{+0.6}_{-0.5} \times 10^{19}$
^{76}Ge	$1.60^{+0.13}_{-0.1} \times 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$
$^{100}\text{Mo} - {}^{100}\text{Ru}(0^+_1)$	$6.2^{+0.7}_{-0.5} \times 10^{20}$
^{116}Cd	$(2.85 \pm 0.15) \times 10^{19}$
^{128}Te	$(2.0 \pm 0.3) \times 10^{24}$
^{130}Te	$(6.9 \pm 1.3) \times 10^{20}$
^{136}Xe	$(2.20 \pm 0.06) \times 10^{21}$
^{150}Nd	$(8.2 \pm 0.9) \times 10^{18}$
$^{150}\text{Nd} - {}^{150}\text{Sm}(0^+_1)$	$1.33^{+0.45}_{-0.26} \times 10^{20}$
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$
^{130}Ba, ECEC(2ν)	$\sim 10^{21}$

emission of two neutrinos) has been registered in ^{130}Ba. Table 1 presents the average and recommended modern values of the half-life $T_{1/2}(2\nu)$ from Ref. [1].

The **2β(0ν) decay** (process (2)) involves violation of the lepton number conservation law ($\Delta L = 2$) and requires the Majorana neutrino rest mass to differ from zero or the existence of an admixture of right-handed currents in the electroweak interaction. The same process also occurs some supersymmetric models, where the 2β(0ν) decay is initiated by the exchange of supersymmetric particles. Moreover, this decay arises in models with the extension of the Higgs sector in the framework of the electroweak interaction theory and in certain other cases.

The **2β(0νχ^0) decay** (process (3)) requires the existence of a Majoron χ^0, a massless Goldstone boson produced in the global violation of $B-L$ symmetry, where B is the baryon and L is the lepton quantum number. If the Majoron does exist, it may play an important role in the history of the early Universe and in the evolution of stars.

No neutrinoless 2β decay has been registered, yet; however, experimental data permit imposing constraints on the Majorana neutrino mass $(\langle m_\nu \rangle)$, on parameters of the admixture of right-handed currents in electroweak interactions $(\langle \eta \rangle$ and $\langle \lambda \rangle)$, on the Majoron–neutrino coupling constant $(\langle g_{ee} \rangle)$, etc. The reliability and accuracy of these constraints depend to a significant extent on the quality of calculations of nuclear matrix elements (NME(0ν)). At present, the accuracy of such calculations is insufficient, and the values of NME(0ν) differ by factors of 1.5–2 in calculations by different authors. Nevertheless, using the most conservative estimates of NME(0ν), it is possible to obtain quite reliable restrictions for all the aforementioned parameters. Tables 2 and 3 present the best present-day results of searches for the 2β(0ν) and 2β(0νχ^0) decays. In calculating the restrictions on $\langle m_\nu \rangle$ and $\langle g_{ee} \rangle$, the calculated NME values from Refs [9–15] were used. We use precisely the results of these calculations, which are the most thoroughly performed ones and which take the recent theoretical achievements into account.

Table 2. Best results of searches for the 2β(0ν) decay. All bounds are imposed at a confidence level of 90%.

Isotope	$E_{2\beta}$, keV	$T_{1/2}$, tear	$\langle m_\nu \rangle$, eV
^{136}Xe	2458.7	$> 1.9 \times 10^{25}$ [2]	$< 0.13-0.35$
^{76}Ge	2039.0	$> 2.1 \times 10^{25}$ [3]	$< 0.19-0.66$
^{100}Mo	3034.4	$> 1.1 \times 10^{24}$ [4]	$< 0.29-0.70$
^{130}Te	2527.5	$> 2.8 \times 10^{24}$ [5]	$< 0.28-0.81$

Table 3. Best results of searches for 2β(0νχ^0)-decay (ordinary Majoron). All bounds are imposed at a confidence level of 90%.

Isotope	$T_{1/2}$, year	$\langle g_{ee} \rangle$
^{136}Xe	$> 2.6 \times 10^{24}$ [6]	$< (0.8-1.6) \times 10^{-5}$
^{100}Mo	$> 2.7 \times 10^{22}$ [7]	$< (0.41-0.84) \times 10^{-4}$
^{82}Se	$> 1.5 \times 10^{22}$ [7]	$< (0.64-1.7) \times 10^{-4}$
^{76}Ge	$> 6.4 \times 10^{22}$ [8]	$< (0.79-2.3) \times 10^{-4}$

2. Present-day experiments

The number of possible 2β-decay candidates is quite large and involves 35 nuclei. But because the 2β-decay probability depends strongly on the transition energy, nuclei exhibiting 2β-transition energies $E_{2\beta} > 2$ MeV are the most interesting ones. In this section, we discuss the most sensitive modern experiments.

2.1 EXO-200 experiment

The EXO-200 (Enriched Xenon Observatory) experiment is carried out in the WIPP (Waste Isolation Pilot Plant) underground laboratory in the USA (a depth of 1585 meters of water equivalent (m.w.e)). The detector is a time-projection chamber (TPC) filled with liquid xenon, surrounded by layers of passive and active shielding. The energy of electrons from a double beta-decay is determined with the aid of simultaneous registration of the ionization and scintillation signals: in this case, the energy resolution amounts to 4% of the full width at half maximum (FWHM) at an energy of 2.46 MeV. The TPC is filled with enriched xenon (the ^{136}Xe content is 80.6%). The fiducial volume contains 98.5 kg of xenon, i.e., 79.4 kg of ^{136}Xe (3.52×10^{26} atoms). In 2011, the 2β(2ν) decay of ^{136}Xe was registered for the first time in this experiment [16], and later a very precise value was obtained for the half-life [17]:

$$T_{1/2}(2\nu, {}^{136}\text{Xe}) = \big(2.172 \pm 0.017\,(\text{stat}) \pm 0.060\,(\text{syst})\big) \times 10^{21}\ \text{years}. \qquad (4)$$

The background index in the 0ν-decay region amounted to 1.5×10^{-3} counts per keV per year (Fig. 1). As a result, the bound obtained over 2896.6 h of measurements (the total statistic being 32.5 kg × year) was [18]

$$T_{1/2}(0\nu, {}^{136}\text{Xe}) > 1.6 \times 10^{25}\ \text{years}\ (90\%\ \text{c.l.})\,. \qquad (5)$$

This permitted establishing the limit $\langle m_\nu \rangle < 0.14-0.38$ eV. Data taking in the EXO-200 experiment continues. The background level achieved in five years of measurements permits obtaining sensitivity at a level of $\sim 4 \times 10^{25}$ years $(\langle m_\nu \rangle < 0.09-0.24$ eV).

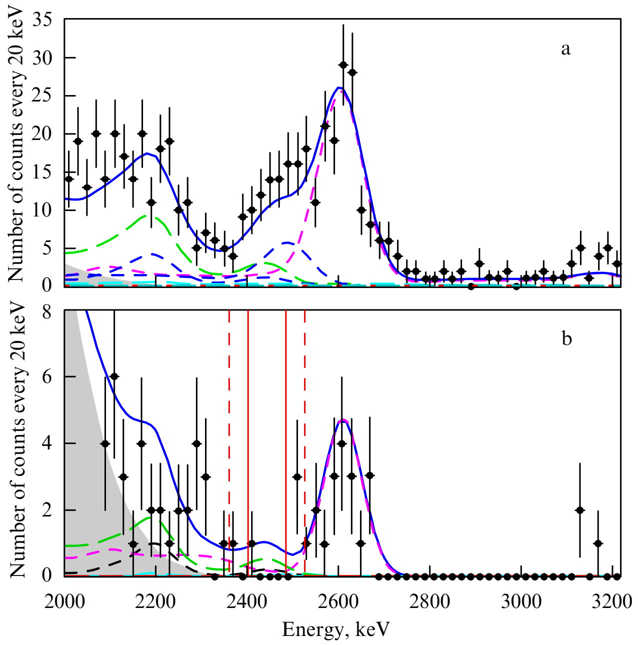

Figure 1. Energy distribution of events in the ^{136}Xe 2β(0ν)-decay region for (a) multiple and (b) single events [18]. The 1(2)σ regions close to the 2β-transition energy value $Q_{\beta\beta}$ are indicated by solid (dashed) vertical straight lines. The solid curve is the result of fitting, the dashed curves represent the contributions of different background sources. The dark regions show the contribution of the ^{136}Xe 2β(2ν)-decay.

EXO-200 is a prototype of the planned 5-ton experiment, at the second stage of which registration is also intended of the ^{136}Ba ion, which will permit suppressing all sorts of backgrounds, except the contribution from 2β decay (see Section 3.4).

2.2 KamLAND-Zen experiment

The KamLAND-Zen experiment (KamLAND Zero-Nu) involves the KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector) detector (Fig. 2). The detector is a sphere 13 m in diameter (the outer 'balloon') made of a transparent material 125 microns thick and surrounded by water shielding (3200 t). The detector contains 1000 t of liquid scintillator (LS), which is viewed by photomultiplier tubes (PMTs): 1325 PMTs 17 inches in diameter and 554 PMTs with photocathodes 20 inches in diameter. An additional inner balloon 3.08 m in diameter containing 14 t of LS is situated at the center of the detector. This scintillator has 320 kg of enriched xenon (the ^{136}Xe content is 90.93%) dissolved in it. The sensitive volume (2.7 m in diameter) contains 179 kg of ^{136}Xe. The scintillation light is registered by PMTs. The energy resolution amounts to $\sigma = (6.6 \pm 0.3)\,\%/\sqrt{E\,[\text{MeV}]}$, while the spatial resolution is $\sigma = 15\ \text{cm}/\sqrt{E\,[\text{MeV}]}$.

The energy spectrum of events, corresponding to an exposure of 89.5 kg × year, is shown in Fig. 3. Data taking was initiated in the autumn of 2011. The background level turned out to be about 100 times higher than expected. This was due to contamination of the surface of the inner balloon with radioactive isotopes that gradually penetrate the scintillator. The authors of the experiment consider this background to be a consequence of the accident at the Fukushima nuclear power plant. Nevertheless, the 2β(2ν) decay was registered even in such unfavorable conditions [6, 19], and rigorous bounds were imposed on the decays of ^{136}Xe 2β(0ν) [2] and 2β(0νχ^0) [6]:

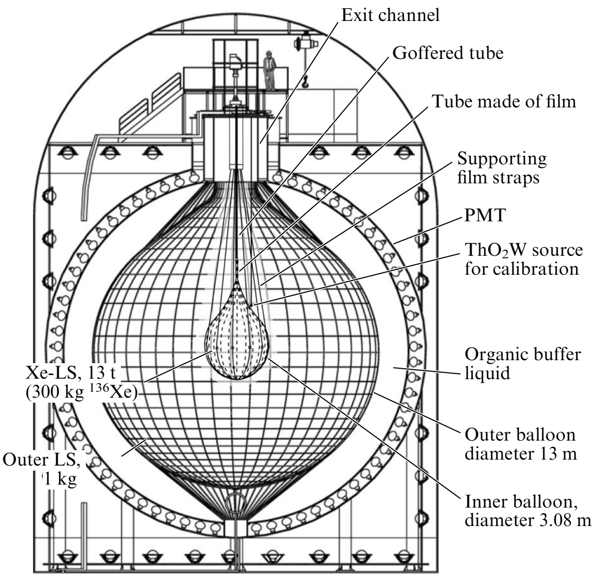

Figure 2. Layout of KamLAND-Zen [19].

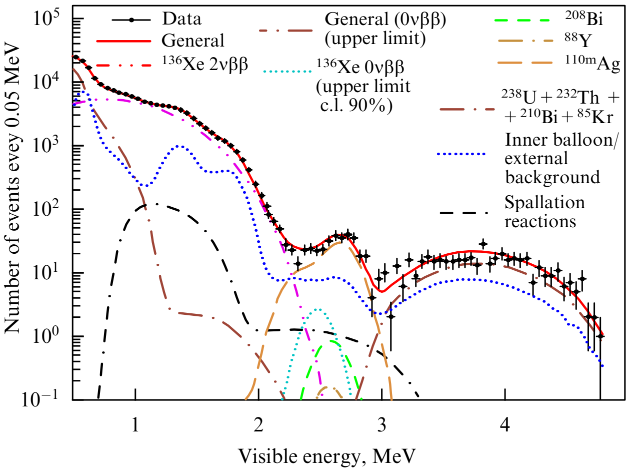

Figure 3. (Color online.) Spectrum of candidate events together with the fitting results for the background and 2β(2ν) decay [2]. The fitting region is 0.5–4.8 MeV.

$$T_{1/2}(2\nu, {}^{136}\text{Xe}) = \left[2.30 \pm 0.02\,(\text{stat}) \pm 0.12\,(\text{syst})\right] \times \times 10^{21}\ \text{years}\,, \tag{6}$$

$$T_{1/2}(0\nu, {}^{136}\text{Xe}) > 1.9 \times 10^{25}\ \text{years}\ (\text{c.l. } 90\%)\,, \tag{7}$$

$$T_{1/2}(0\nu\chi^0, {}^{136}\text{Xe}) > 2.6 \times 10^{24}\ \text{years}\ (\text{c.l. } 90\%)\,. \tag{8}$$

The result for the 2β(2ν) decay is in good agreement with results of the EXO experiment [16, 17], and the results for the bounds imposed on the 2β(0ν) and 2β(0νχ^0) decays led to the most stringent modern restrictions on $\langle m_\nu \rangle$ and $\langle g_{ee} \rangle$: $\langle m_\nu \rangle < 0.13-0.35$ eV, $\langle g_{ee} \rangle < (0.8-1.6) \times 10^{-5}$.

At present, the KamLaND–Zen collaboration is attempting to decrease the background level by cleaning the scintillator of radioactive admixtures. Replacing the inner balloon can be a cardinal measure. In principle, the background can be reduced by a factor of 100. If this goal is successfully achieved, the sensitivity of the experiment will amount to $\sim 2 \times 10^{26}$ years in three years of measurements,

Figure 4. Layout of the GERDA-I installation [20].

which corresponds to the sensitivity to the effective Majorana neutrino mass $\langle m_\nu \rangle < 0.04-0.11$ eV. Subsequently, a second phase of the experiment is planned with the use of 1000 kg of ^{136}Xe (see Section 3.5).

2.3 GERDA-I experiment

The GERDA-I (GERmanium Detector Array I) experiment is a low-background experiment searching for the $2\beta(0\nu)$ decay of ^{76}Ge with the use of HPGe (High Purity Germanium) detectors, made of enriched germanium-76 [3]. In this experiment, a new approach is applied to the organization of passive and active protection. First, serious efforts were taken to minimize the amount of structural material around the HPGe detectors. Second, to reduce the background level, the germanium crystals were placed in a vessel with liquid argon, which was inside an enormous tank of water (10 m in diameter and height) (Fig. 4). The liquid argon and water were subjected to a special cleaning from radioactive admixtures. The total weight of HPGe detectors at the first stage was about 15 kg. The energy resolution of the detectors is $\approx 4-5$ keV in the energy range of the 2β decay of ^{76}Ge (2.039 MeV).

It is interesting to note that mainly the HPGe detectors are used in the experiment; these detectors were previously used in Heidelberg–Moscow experiments and in the IGEX (International Germanium EXperiment). The whole installation is situated in the Gran Sasso underground laboratory (Italy) at a depth of 3500 m.w.e. The GERDA-I experiment started taking data in November 2011 and concluded in May 2013. Measurement data were collected for 21.6 kg × year. The spectra are shown in Fig. 5 [3]. As a result, the ^{76}Ge half-life was determined for the 2ν channel [20]:

$$T_{1/2}(2\nu, {}^{76}\text{Ge}) = 1.84^{+0.14}_{-0.1} \times 10^{21} \text{ years}. \qquad (9)$$

This result is consistent with those of preceding experiments.

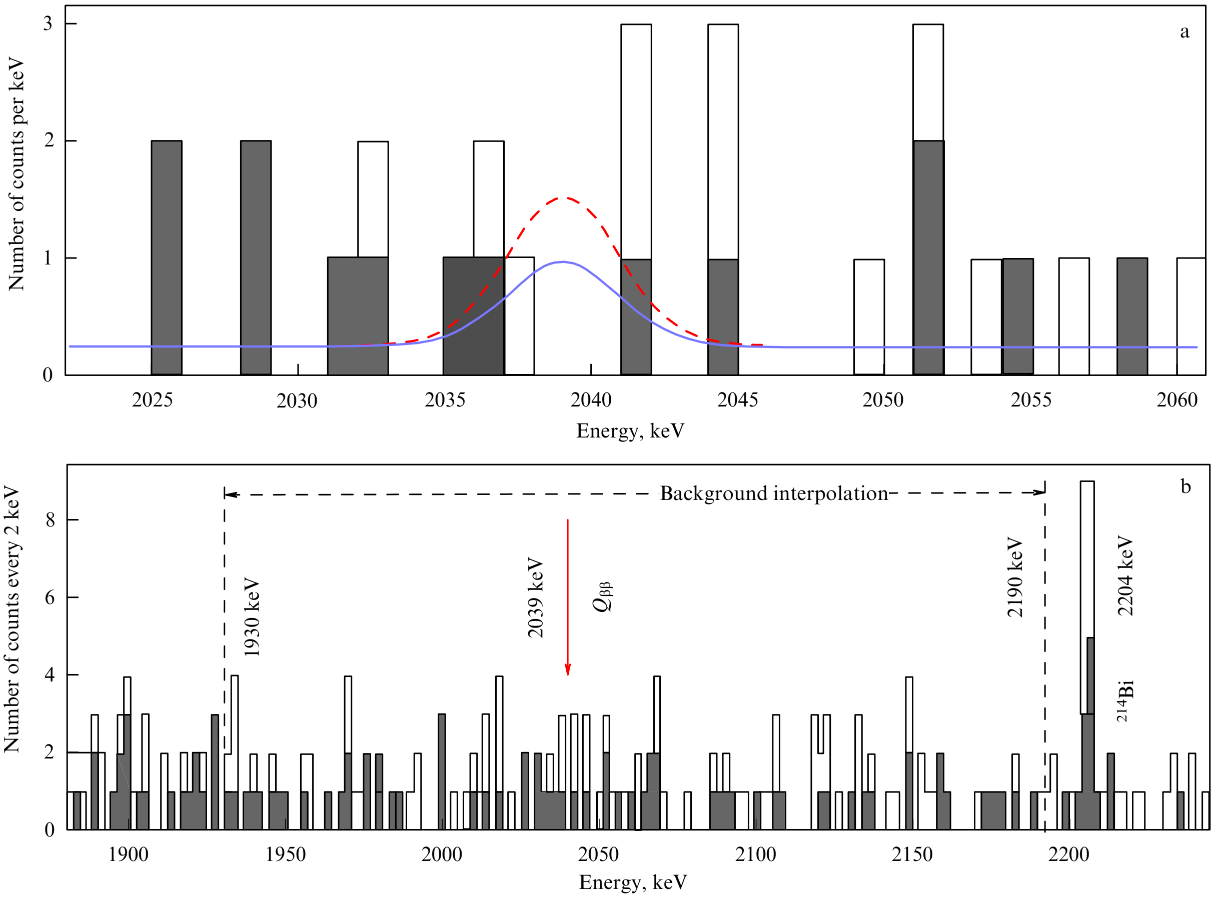

Figure 5. (a) Total spectrum for all detectors in the GERDA-I experiment [3] for the entire range under investigation; shown are the signals expected for $T_{1/2} = 2.1 \times 10^{25}$ years (solid curve) and $T_{1/2} = 1.2 \times 10^{25}$ years (dashed curve). (b) The part of the spectrum used in estimating the mean background in the region under investigation. The dark color indicates events left after completing the analysis by the shape of the pulse.

In studying the 0ν mode, a 'blind' analysis was applied, in which the experimental data in the region of the 0ν decay remained unknown until the very last moment. The data were revealed in June 2013. After application of all selection methods (including selection by the shape of the pulse), the background in the investigated region amounted to ~ 0.1 count per keV a year. The number of events expected from the background being 2.5, 3 real events were registered (Fig. 5). As a result, the limit $T_{1/2} > 2.1 \times 10^{25}$ years $\left(\langle m_\nu \rangle < 0.2\text{–}0.4 \text{ eV}\right)$ was established at a 90% confidence level.

The GERDA-I experiment turned out to be a new step in the development of the experimental technique applied in searching for the ββ0ν decay of ^{76}Ge. The proposed technique demonstrated its operational integrity and efficiency, while the achieved background level was an order of magnitude lower than the one achieved in preceding experiments, Heidelberg–Moscow and IGEX. Plans include performing the next stage of the experiment, GERDA-II, in which the mass of ^{76}Ge is to be increased and the background level is to be essentially reduced (see Section 3.2).

3. Planned experiments

At present, there are about 30 proposals for searching for 2β(0ν) decay. However, most likely, not all of them will be realized. Many projects only exist on paper, and many are still at the initial stage of research. Table 4 presents the parameters of the seven most advanced experiments, which will, with a high probability, be carried out in the nearest future. As can be seen from Table 4, the masses of isotopes in these experiments can be several hundred kilograms or even several tons. If this program is implemented, then, in the case of four isotopes, the sensitivity to the parameter $\langle m_\nu \rangle$ will amount to the level of $10^{-2} - 10^{-1}$ eV, which will permit testing the scheme involving the inverse neutrino mass hierarchy.

3.1 CUORE experiment

The CUORE (Cryogenic Underground Observatory for Rare Events) experiment is under way at the Gran Sasso underground laboratory (Italy, 3500 m.w.e.). The intention is to investigate 760 kg of natural TeO$_2$, i.e., about 200 kg of ^{130}Te. One thousand low-temperature ($T \approx 8$ mK) detectors weighing 760 g each will be constructed and placed in 19 towers. A major problem is to decrease the background level by a factor of approximately 20 compared with the background level achieved with the 62-crystal detector Cuoricino. If the background level of 0.01 count per kg × keV × year is achieved, the sensitivity of the experiment to the 0ν decay of ^{130}Te will be $\sim 10^{26}$ years $\left(\langle m_\nu \rangle \sim 0.05\text{–}0.13 \text{ eV}\right)$. The experiment has received financial support and will be realized. Data taking is currently under way at Gran Sasso with the CUORE-0 detector — one of the towers of the CUORE detector. The main goal is to verify the possibility of decreasing the background in the CUORE experiment to the required level.

The CUORE experiment is to start taking data in 2015.

3.2 GERDA experiment

GERDA is one of the two planned experiments with ^{76}Ge (the other — Majorana — is described in Section 3.3). The experiment is carried out in the Gran Sasso underground laboratory. The main idea is to put practically 'naked' HPGe detectors in very clean liquid argon and use it as passive and active (from scintillation light) protection. In turn, the Dewar flask with liquid argon is placed in a tank with ultrapure water, which also plays the role of passive and active (Cherenkov radiation) protection.

The experiment comprises three stages. The first, GERDA-I, has already been completed (see Section 2.3). At the second stage, about 40 kg of enriched germanium is to be investigated (about 20 kg of new HPGe detectors with 'point contacts' will be added to the detectors already in operation). At the second stage, the background level in the region of the 0ν decay is planned to be reduced to $\sim 10^{-3}$ counts per keV a year. In this case, the sensitivity in three years of measurements will be $T_{1/2} \sim 2 \times 10^{26}$ years $\left(\langle m_\nu \rangle < 0.06\text{–}0.2 \text{ eV}\right)$. Data taking will start in 2014. At the third stage (which will probably be a joint GERDA–

Table 4. Most promising experiments planned for studying 2β decay

Experiment	Isotope experiment	Isotope mass, kg	Sensitivity*, $T_{1/2}$, year	Sensitivity*, $\langle m_\nu \rangle$, eV	State of the experiment
CUORE [21]	^{130}Te	200	10^{26}	0.05 – 0.13	Under construction
GERDA [22]	^{76}Ge	40 1000	2×10^{26} 6×10^{27}	0.06 – 0.20 0.01 – 0.04	Ongoing R&D**
Majorana [23]	^{76}Ge	30 1000	10^{26} 6×10^{27}	0.09 – 0.30 0.01 – 0.04	Under construction R&D**
EXO [24]	^{136}Xe	200 5000	4×10^{25} 2×10^{27}	0.09 – 0.24 0.02 – 0.04	Ongoing R&D**
KamLAND-Zen [25]	^{136}Xe	320 1000	2×10^{26} 6×10^{26}	0.04 – 0.11 0.02 – 0.06	Ongoing Under construction
SuperNEMO [26]	^{86}Se	100 – 200	$(1-2) \times 10^{26}$	0.04 – 0.10	R&D**, Under construction
SNO+ [27]	^{130}Te	800 8000	10^{26} 10^{27}	0.05 – 0.13 0.015 – 0.045	Under construction

* Sensitivity is shown at a 90% confidence level of probability for three years (the first stages of the GERDA, Majorana, KamLAND-Zen experiments), five years (CUORE, SuperNEMO (Super Neutrino Ettore Majorana Observatory), KamLAND-Zen-2, EXO, SNO+), and ten years (full-scale experiments GERDA and Majorana) of measurements.

** Research and development.

Majorana experiment), 1 t of ^{76}Ge is planned to be investigated. The sensitivity will be brought up to $T_{1/2} \sim 6 \times 10^{27}$ years $\left(\langle m_\nu \rangle < 0.01-0.04 \text{ eV}\right)$, which will permit testing the scheme involving the inverse neutrino mass hierarchy.

3.3 Majorana experiment

The Majorana installation will contain about 1000 HPGe detectors based on enriched germanium (enrichment superior to 87%). The total mass of ^{76}Ge to be investigated will be 1000 kg. The shielding to be used, unlike the protection scheme in the GERDA experiment, will be a 'classical' passive shielding consisting of layers of superpure copper, lead, and polyethylene. The entire apparatus will be situated in an underground laboratory. The use of HPGe detectors (with a high energy resolution), the analysis of a signal by its shape and by anticoincidences, and the use of low-background construction materials will permit reducing the background level in the region of the 0ν decay to 2.5×10^{-4} counts per kg × keV × year. This will allow achieving the sensitivity $T_{1/2} \sim 6 \times 10^{27}$ years $\left(\langle m_\nu \rangle < 0.01-0.04 \text{ eV}\right)$. The sensitivity for the 0ν decay of ^{76}Ge to the 0_1^+ excited state of ^{76}Se will be $T_{1/2} \sim 10^{27}$ years.

At the first stage, 40 kg of HPGe detectors (30 kg of enriched germanium and 10 kg of natural germanium) will be investigated. For this, the Majorana Demonstrator installation, consisting of two cryostats surrounded by passive and active shielding, is under construction. The installation is situated in the SURF (Stanford Underground Research Facility) underground laboratory (USA). The sensitivity to be achieved in the experiment in three years of measurements will be $T_{1/2} \sim 10^{26}$ years $\left(\langle m_\nu \rangle < 0.09-0.30 \text{ eV}\right)$. Data taking will start in 2014.

The GERDA and Majorana collaborations joined efforts in developing a full-scale experiment with 1 t of ^{76}Ge. The final layout of this experiment will be determined after completion of the Majorana Demonstrator and GERDA-II experiments.

3.4 EXO experiment

Both ionization electrons and Ba$^+$ ions produced in the 2β decay $^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}^{++} + 2\text{e}^-$ are to be registered in the EXO experiment. In Ref. [24], the proposal was made to investigate one tonne of ^{136}Xe. At present, the authors of the experiment are discussing a 5-ton experiment (project nEXO). At the first stage, the ^{136}Ba ions will not be registered (this will done during further development of the EXO-200 experiment). To avoid background problems from the 2ν decay, the energy resolution must be not less than 3.5% (FWHM) at an energy of 2.5 MeV. If the research work on the registration of barium ions is successfully concluded, the version involving registration of barium ions will be realized (which will lead to an essentially lower background level).

That registration of single barium ions is theoretically possible was already demonstrated a long time ago. However, the main problem consists in achieving a high registration efficiency in a real experiment. To realize this idea, the registration efficiency must be not less than 70% (such an efficiency has not yet been achieved).

The experiment is planned to be carried out in the SNO (Sudbury Neutrino Observatory, 6000 m.w.e.) underground laboratory in Canada. Data taking will start after 2016.

3.5 KamLAND-Zen-2 experiment

The KamLAND-Zen-2 experiment is a continuation of the KamLAND-Zen experiment presently under way (see Section 2.2). At the new stage, 1000 kg of ^{136}Xe is proposed to be investigated. For this purpose, an inner 'balloon' of larger dimensions (≈ 4 m) with a liquid scintillator, in which the enriched xenon will be dissolved, will be used. To improve the energy resolution, the number of PMTs is to be doubled and a scintillator with a large specific light yield is to be used in the inner balloon. The sensitivity of the experiment planned to be achieved in five years of measurements will be $T_{1/2} \sim 6 \times 10^{26}$ years $\left(\langle m_\nu \rangle < 0.02-0.06 \text{ eV}\right)$. Data taking will apparently start in 2016.

3.6 SNO + experiment

The SNO detector (Canada), used for the registration of solar neutrinos, is being modernized for the SNO + experiment. To search for double beta-decay, the detector is to be filled with a liquid scintillator with the isotope to be investigated incorporated into it. First, ^{150}Nd was proposed to be investigated. However, at the beginning of 2013, the collaboration abandoned neodymium and decided to investigate ^{130}Te. Such a change was due to the possibility of incorporating tellurium readily and in large quantities (0.3–3%) into the scintillator; in its natural mixture, tellurium has a high concentration (34.5%) of ^{130}Te and a low decay rate in the 2ν channel (which significantly lowers the unavoidable background from the two-neutrino decay).

Filling the detector with a liquid scintillator is planned for 2014. At the first stage, 0.3% of tellurium (800 kg of ^{130}Te) will be incorporated into the scintillator, and at the second stage, 3% of tellurium (8000 kg of ^{130}Te) will be used. The sensitivity $T_{1/2} \sim 10^{26}$ years is planned for the first stage and $T_{1/2} \sim 10^{27}$ years for the second. Thus, SNO + is capable of serious competition with the CUORE experiment.

3.7 SuperNEMO experiment

The NEMO (Neutrino Ettore Majorana Observatory) collaboration is considering the possibility of performing an experiment with 100–200 kg of ^{82}Se in order to achieve a sensitivity to the 0ν decay of this isotope at a level of $\sim (1-2) \times 10^{26}$ years in five years of measurements (which corresponds to a sensitivity to the neutrino mass of ∼ 0.04–0.1 eV). In order to reach this goal, the same experimental technique as in NEMO-3 [28] is proposed to be used. However, the new detector will have a planar geometry and consist of 20 identical sections. At the center of the sections, an ^{82}Se source 40 mg cm^{-2} thick with an extremely low content of radioactive impurities (7 kg of ^{82}Se in each section) will be placed. The detector will record all characteristics of double beta decay: the electron energy will be registered by counters based on plastic scintillators ($\Delta E/E \approx 8\%$ at $E = 1$ MeV), while tracks will be reconstructed with the aid of information from Geiger counters.

The same apparatus can also be used for investigating other isotopes (^{150}Nd, ^{48}Ca, ^{100}Mo, ^{116}Cd, and ^{130}Te). An attractive feature of this experiment is the use of an experimental technique that has already been tested. The apparatus is to be situated in a new hall at the underground Fréjus laboratory (depth: 4800 m.w.e.) in France.

The first module (the Demonstrator device) containing 7 kg of ^{82}Se will be commissioned at the first stage. At present, assembly of the apparatus has started, and production of individual elements of the detector is under way. The Demonstrator is housed in an existing hall of the Fréjus laboratory. The device is to be put into operation in 2015.

4. Conclusion

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

Neutrinoless 2β decay has not yet been registered, and the best restrictions on the effective Majorana neutrino mass have been obtained in experiments with ^{136}Xe, ^{76}Ge, ^{100}Mo, and ^{130}Te. Taking the uncertainties in the NME values into account, it is possible to impose the conservative bound $\langle m_\nu \rangle < 0.35$ eV.

One can hope that in the nearest few years, the sensitivity to the neutrino mass in EXO-200, KamLAND-Zen, GERDA-II, Majorana Demonstrator, and CUORE-0 will be enhanced to values of the order of 0.1–0.3 eV. These experiments will determine the level of research in the field of 2β decay for the next several years.

Experiments of the next generation, with masses of the investigated isotopes $\sim 100-5000$ kg, to be commissioned in approximately 3–5 years, will permit achieving a sensitivity to $\langle m_\nu \rangle$ at a level of $10^{-1}-10^{-2}$ eV, which will make it possible to test the validity of the scheme with the inverse neutrino mass hierarchy. To test the scheme with the normal hierarchy $\big(\langle m_\nu \rangle \sim 0.003$ eV$\big)$, devices involving masses of the investigated isotopes not less than 10 t and an extremely low background level [29] are required.

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