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DOUBLE-BETA DECAY AND RARE PROCESSES

CAMEO Project and Discovery Potential of the Future 2β-Decay Experiments*

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Abstract—The demands on the future supersensitivity 2β-decay experiments (aiming to observe neutrinoless 2β decay or to advance restrictions on the neutrino mass to $m_\nu \leq 0.01$ eV) are considered and requirements for their discovery potential are formulated. The most realistic 2β projects are reviewed and the conclusion is obtained that only several of them with high energy resolution would completely satisfy these severe demands and requirements. At the same time, most of the recent projects (CAMEO, CUORE, DCBA, EXO, etc.) could certainly advance the limit on the neutrino mass up to $m_\nu \leq 0.05$ eV.

Recent observations of neutrino oscillations [1–4], demonstrating that neutrinos have nonzero mass (m_ν), provide important motivation for the double-beta (2β) decay experiments [5–7]. The neutrinoless (0ν) double-β decay, being forbidden in the Standard Model (SM) of electroweak theory since it violates lepton number (L) conservation, requires neutrinos to be massive Majorana particles [8]. At the same time, many extensions of the SM incorporate L-violating interactions and, thus, could lead to this process, which, if observed, will be clear evidence for new physics beyond the SM and a unique confirmation of the Majorana nature of the neutrino. The oscillation experiments are sensitive to the neutrino mass difference; therefore, only the measured $0\nu2\beta$-decay rate can give the absolute scale of the effective Majorana neutrino mass, which could allow one to test different neutrino mixing models.

Despite numerous efforts, $0\nu2\beta$ decay still remains unobserved (see the latest reviews [5–7, 9]). Recently, the impressive half-life limits for the 0ν mode were set in direct measurements with several nuclides: $T^{0\nu}_{1/2} \geq 10^{23}$ yr for ^{116}Cd [10], ^{128}Te, ^{130}Te [11], and ^{136}Xe [12], and $T^{0\nu}_{1/2} \geq 10^{25}$ yr for ^{76}Ge [13, 14]. These limits and the corresponding restrictions on the Majorana neutrino mass are given in Table 1. The m_ν constraints are determined on the basis of the nuclear matrix elements (NME) calculations of [15], which were chosen because of the most extensive list of 2β nuclei calculated in this work, allowing one to compare the sensitivity of different experiments to the m_ν bound within the same scale. In addition, two new experiments (NEMO-3 [17] and CUORICINO [18]) are running now. The NEMO-3 apparatus allows direct detection of two electrons by a tracking device (6180 drift cells) and measurement of their energies by 1940 large blocks of plastic scintillators. The energy resolution at 3 MeV is 8.8%. For a 5-yr measuring time and with a passive source of 7 kg of ^{100}Mo $\approx$ 60-mg/cm^2 thickness ($\sim$ 50 mg/cm^2 of ^{100}Mo foil itself, plus $\approx$ 10 mg/cm^2 of scintillator wrapping, gas and wires of the tracking counters), the sensitivity of the NEMO-3 detector would be about $T^{0\nu}_{1/2} \geq 5 \times 10^{24}$ yr [17], which corresponds to $m_\nu \leq 0.5$ eV. The CUORICINO setup contains 56 low-temperature bolometers made of TeO$_2$ crystals (750 g each) with a total mass of 42 kg cooled down to a temperature of $\approx$ 10 mK [18]. The projected CUORICINO sensitivity is $T^{0\nu}_{1/2} \geq 10^{24}$–$10^{25}$ yr ($m_\nu \leq 0.2$–0.7 eV), depending on what background rate at the energy 2.5 MeV will be reached (0.1–0.05 counts/(yr kg keV)) [18].

Thus, one can conclude that present (and near future) 2β-decay results have already brought the most stringent restrictions on the values of the Majorana neutrino mass ($m_\nu \leq 0.3$–2 eV), the right-handed admixture in the weak interaction ($\eta \approx 10^{-8}$, $\lambda \approx 10^{-6}$), the neutrino–Majoron coupling constant ($g_M \approx 10^{-4}$), and the R-parity-violating parameter of the minimal supersymmetric SM ($\lambda \approx 10^{-4}$) [5–7, 9].

Moreover, nowadays the 2β-decay research is entering a new era, where discovery of $0\nu2\beta$ decay has

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Table 1. The best reported $T^{0\nu}_{1/2}$ and m_ν limits from direct 2β-decay experiments

Nuclide	Experimental limit $T^{0\nu}_{1/2}$, yr		Reference	Limit on m_ν [eV] on the basis of [15]	
	68% C.L.	90% C.L.		68% C.L.	90% C.L.
^{76}Ge	3.1×10^{25}	1.9×10^{25}	[13]	0.27	0.35
	–	1.6×10^{25}	[14]	–	0.38
	$4.2 \times 10^{25*}$	$2.5 \times 10^{25*}$	[16]	0.24	0.31
^{116}Cd	2.6×10^{23}	1.7×10^{23}	[10]	1.4	1.7
^{130}Te	–	2.1×10^{23}	[11]	–	1.5
^{136}Xe	–	4.4×10^{23}	[12]	–	2.2

* Results were established [16] by analyzing the cumulative data sets of the Heidelberg–Moscow [13] and IGEX [14] experiments.

become realistic. But to do it, the present level of the experimental sensitivity should be enhanced up to $m_\nu \approx 0.01$ eV (or at least up to $m_\nu \leq 0.05$ eV). It is a great challenge and a lot of projects have been proposed in the past few years aiming to reach this goal [5–7]. As regards these projects, two points should be noted.

First, it is widely recognized now that 2β-decay searches must be performed with several candidates. This is because a reliable value (or restrictions) of the neutrino mass can be derived from experiments on the basis of the calculation of the NME of $0\nu2\beta$ decay, whose uncertainties are often unknown [19, 20].[1] Another reason is the difficulties in developing the experimental techniques. If $0\nu2\beta$ decay is finally observed in one experiment, such a discovery certainly has to be confirmed with other nuclides and by using other experimental techniques, which should be well developed by then. However, because of the superlow-background nature of the 2β studies, the corresponding development is a multistage process and consequently a rather long one. For instance, the first valuable result for the $0\nu2\beta$ decay of ^{76}Ge was obtained in 1970 as $T^{0\nu}_{1/2} \geq 10^{21}$ yr [22]. Recently, after 30 yr of strong efforts, this limit was advanced up to $T^{0\nu}_{1/2} \geq 10^{25}$ yr [13, 14].

Secondly, practically all proposals require a large mass production of enriched isotopes; thus, their costs are comparable with those of accelerator experiments. Because most of these projects need strong efforts and a long time to prove their feasibility, it is very important to choose those which will really be able to observe the $0\nu2\beta$-decay rate corresponding to neutrino mass $m_\nu \approx 0.01$ eV and could be constructed within a reasonable time. With this aim in the present paper, we consider demands on the future high-sensitivity 2β-decay experiments and formulate requirements for their discovery potential. Then, recent projects are reviewed and discussed.

As is obvious from Table 1, the present ^{76}Ge studies [13, 14] (with ≈ 10 kg of enriched HP ^{76}Ge detectors) have brought the most stringent restrictions on the neutrino mass, at the level of ≈ 0.3 eV. Other experiments offer m_ν bounds in the range of ≈ 2 eV, which is not so drastically weaker, especially if taking into account that, e.g., the ^{116}Cd result was obtained with very small ^{116}CdWO$_4$ crystal scintillators (total mass of ~ 0.3 kg) [10]. It demonstrates the importance of the right choice of 2β-decay candidate for study, which we consider next by using the formula for the $0\nu2\beta$-decay probability (right-handed contributions are neglected) [20, 23]: $\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}_{mm}\,|\mathrm{NME}|^2\,\langle m_\nu\rangle^2$ (where $G^{0\nu}_{mm}$ is the phase-space integral of the $0\nu2\beta$ decay). The phase-space integral $G^{0\nu}_{mm}$ strongly depends on the available energy release, $Q_{\beta\beta}$, roughly as $Q^5_{\beta\beta}$ [20, 23]. Thus, if we skip for the moment the problem of the NME calculation, it is evident that the $Q_{\beta\beta}$ value is a very important parameter for the choice of the most sensitive 2β-decay candidates. Moreover, the larger the 2β-decay energy, the simpler, from an experimental point of view, it is to overcome background problems.[2]

Among 35 possible $2\beta^-$-decay candidates, there are only 13 nuclei with $Q_{\beta\beta}$ larger than ≈ 1.7 MeV

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[1] See, e.g., [21]: “The nuclear structure uncertainty can be reduced by further development of the corresponding nuclear models. At the same time, by reaching comparable experimental limits in several nuclei, the chances of a severe error in the NME will be substantially reduced.”

[2] Note that the background from natural radioactivity drops sharply above 2615 keV, which is the energy of the γ from ^{208}Tl decay (^{232}Th family).

Table 2. Double-β-decay candidates with $Q_{\beta\beta} \geq 1.7$ MeV

Nuclide	$Q_{\beta\beta}$, keV	Abundance δ, %	Parameter $G^{0\nu}_{mm}$, 10^{-14} yr	$T^{0\nu}_{1/2}\langle m_\nu\rangle^2$, yr eV^2 (after NME [15])
^{48}Ca	4272	0.187	6.4	–
^{76}Ge	2039	7.61	0.6	2.3×10^{24}
^{82}Se	2995	8.73	2.7	6.0×10^{23}
^{96}Zr	3350	2.80	5.7	5.3×10^{23}
^{100}Mo	3034	9.63	4.6	1.3×10^{24}
^{110}Pd	2000	11.72	–	2.0×10^{24}
^{116}Cd	2805	7.49	4.9	4.9×10^{23}
^{124}Sn	2287	5.79	2.6	1.4×10^{24}
^{130}Te	2529	34.08	4.1	4.9×10^{23}
^{136}Xe	2468	8.87	4.4	2.2×10^{24}
^{148}Nd	1929	5.7	–	1.4×10^{24}
^{150}Nd	3367	5.6	19	3.4×10^{22}
^{160}Gd	1730	21.86	–	8.6×10^{23}

[24]. They are listed in Table 2, where $Q_{\beta\beta}$, the natural abundance δ [25], and the calculated values of the phase-space integral $G^{0\nu}_{mm}$ [20, 23] and $T^{0\nu}_{1/2} \times \langle m_\nu\rangle^2$ [15] are given. Note that due to the low $Q_{\beta\beta}$ value of ^{76}Ge (2039 keV), its phase-space integral is about 7–10 times smaller as compared with those of ^{48}Ca, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, and ^{136}Xe.

Now let us consider the experimental sensitivity, which can be expressed in terms of a lower half-life limit as follows [6, 9]: $T_{1/2} \sim \varepsilon\delta\sqrt{mt/(RB)}$. Here, ε is the detection efficiency; δ is the abundance or enrichment of candidate nuclei contained in the detector; t is the measurement time; m and R are the total mass and the energy resolution of the detector, respectively; and B is the background rate in the energy region of the $0\nu2\beta$-decay peak. First of all, it is clear from the formula that efficiency and enrichment are the most important characteristics of a setup for 2β-decay studies, because any other parameters are under the square root. Obviously, 100% enrichment is very desirable. In order to reach the sensitivity to neutrino mass of about 0.01 eV, one has to exploit enriched sources whose masses should exceed at least some 100 kg. The latter restricts the list of candidate nuclei given in Table 2 because a large mass production of enriched materials is possible only for several of them. These are ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, and ^{136}Xe, which could be produced by means of centrifugal separation. Centrifugal isotope separation requires the substances to be in gaseous form. Thus, xenon gas can be used directly. There also exist volatile germanium, selenium, molybdenum, and tellurium hexafluorides, as well as the metal to organic cadmium–dimethyl compound [26]. Note that two nuclides from Table 2 (^{130}Te and ^{160}Gd) can be used without enrichment owing to their relatively high natural abundances ($\approx 34\%$ and $\approx 22\%$, respectively).

Secondly, one would require that the detection efficiency should be close to 100%, which is possible, in fact, only for the "active" source technique. There are two classes of 2β-decay experiments—with "passive" and "active" sources. In the last case, a detector, containing 2β-decay candidate nuclei, serves as a source simultaneously. If the $0\nu2\beta$ decay occurs in the source, the sharp peak at the $Q_{\beta\beta}$ value will be observed in the electron sum energy spectrum of the detector(s). Indeed, the mass of the "passive" source can be enlarged by increasing its thickness, which in turn lowers detection efficiency due to absorption of electrons in the source, broadening and shifting of the $0\nu2\beta$-decay peak to lower energies, etc.

Thirdly, the energy resolution of the detector is an extremely important characteristic for the $0\nu2\beta$-decay quest. Foremost, with high energy resolution, it is possible to minimize the irremovable background produced by the $2\nu2\beta$-decay events. It is because, for the case of a poor resolution, the events from the high-energy tail of the 2ν distribution could run into the energy window of the 0ν peak and, thus, generate a background which cannot be discriminated from the $0\nu2\beta$-decay signal, even in principle. However, the better the energy resolution, the smaller the fraction

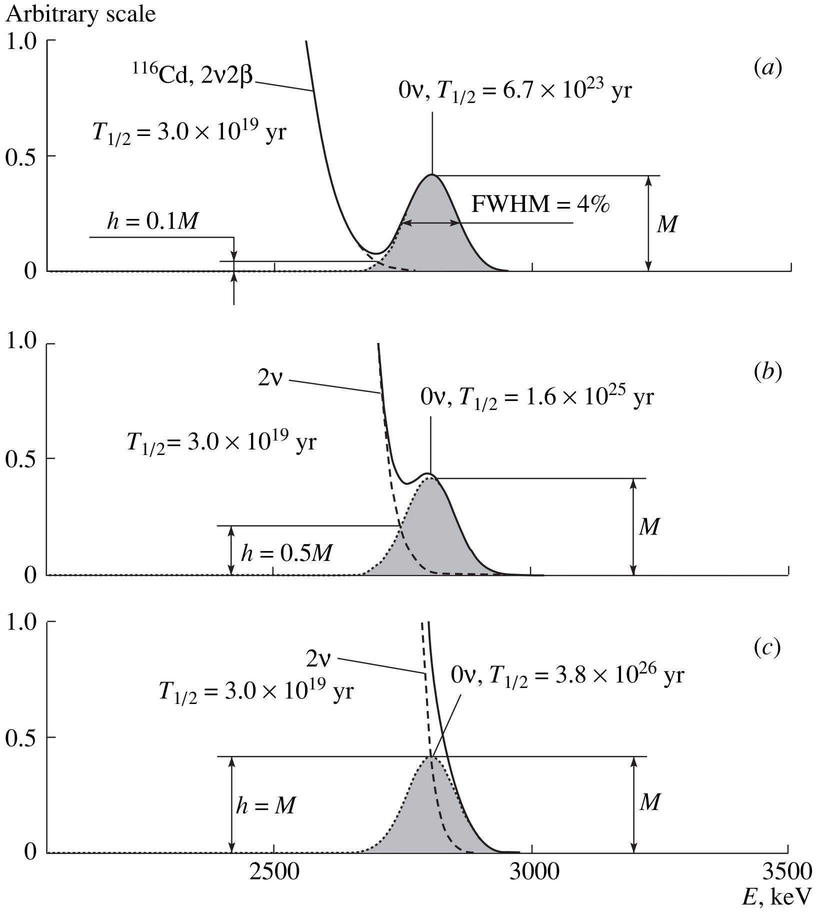

Fig. 1. Definition of the discovery potential of the 2β-decay studies. The 2ν distribution of ^{116}Cd (with $T^{2\nu}_{1/2} = 3 \times 10^{19}$ yr) overlaps the 0ν peaks with the half-life corresponding to (a) 6.7×10^{23}, (b) 1.6×10^{25}, and (c) 3.8×10^{26} yr. Correspondingly, the 0ν peak with the amplitude M (the energy resolution at 2.8 MeV is FWHM = 4%) and the 2ν spectrum meet at the relative height (a) $h/M = 0.1$, (b) $h/M = 0.5$, and (c) $h/M = 1$.

of the 2ν tail that can fall within the 0ν interval, and the irremovable background would be decreased too.

Likewise, the role of the energy resolution of the detector is even more crucial for the discovery of $0\nu2\beta$ decay. Indeed, this process manifests itself by the peak at $Q_{\beta\beta}$ energy; hence, the great advantage of $0\nu2\beta$-decay experiments is the possibility of searching for the sharp peak on the continuous background. Since the width of the $0\nu2\beta$-decay peak is determined by the energy resolution of the detector, the latter should be sufficient to discriminate this peak from the background and to recognize the effect. Practically, it would be very useful to determine the minimal level of the energy resolution which is needed to detect $0\nu2\beta$ decay with a certain $T^{0\nu}_{1/2}$ value and at a given $2\nu2\beta$-decay rate.

Aiming to make such an estimation quantitatively, let us consider Fig. 1 with three examples, in which the 2ν distribution of ^{116}Cd (with $T^{2\nu}_{1/2} = 3 \times 10^{19}$ yr) overlaps the three 0ν peaks with the half-life corresponding to (a) 6.7×10^{23}, (b) 1.6×10^{25}, and (c) 3.8×10^{26} yr. The spectrum of the sum of electron energies for $2\nu2\beta$ decay (0^+–0^+ transition, $2n$ mechanism) was obtained (as described in [27]) by integrating the theoretical two-dimensional energy distribution $\rho_{12}(t_1, t_2)$: $\rho_{1+2}(t) = \int_0^t \rho_{12}(t - t_2, t_2)\, dt_2$, where t_i is the kinetic energy of the ith electron and t is the sum of electron energies (t_i and t are in units of the electron mass m_0c^2). The basic two-dimensional distribution is taken from [28]: $\rho_{12}(t_1, t_2) = (t_1 + 1)p_1F(t_1, Z)(t_2 + 1)p_2F(t_2, Z)\,(t_0 - t_1 - t_2)^5$, where t_0 is the energy available in the 2β process ($Q_{\beta\beta}$ for decay to the ground state) and p_i is the momentum of the ith electron, $p_i = \sqrt{t_i(t_i + 2)}$ (in units of m_0c). The Fermi function is defined as [29] $F(t, Z) = \text{const} \cdot p^{2s-2}e^{\pi\eta}|\Gamma(s + i\eta)|^2$, where $s = \sqrt{1 - (\alpha Z)^2}$, $\eta = \alpha Z(t + 1)/p$, $\alpha = 1/137.036$, Z is the atomic number of the daughter nucleus, and Γ is the gamma

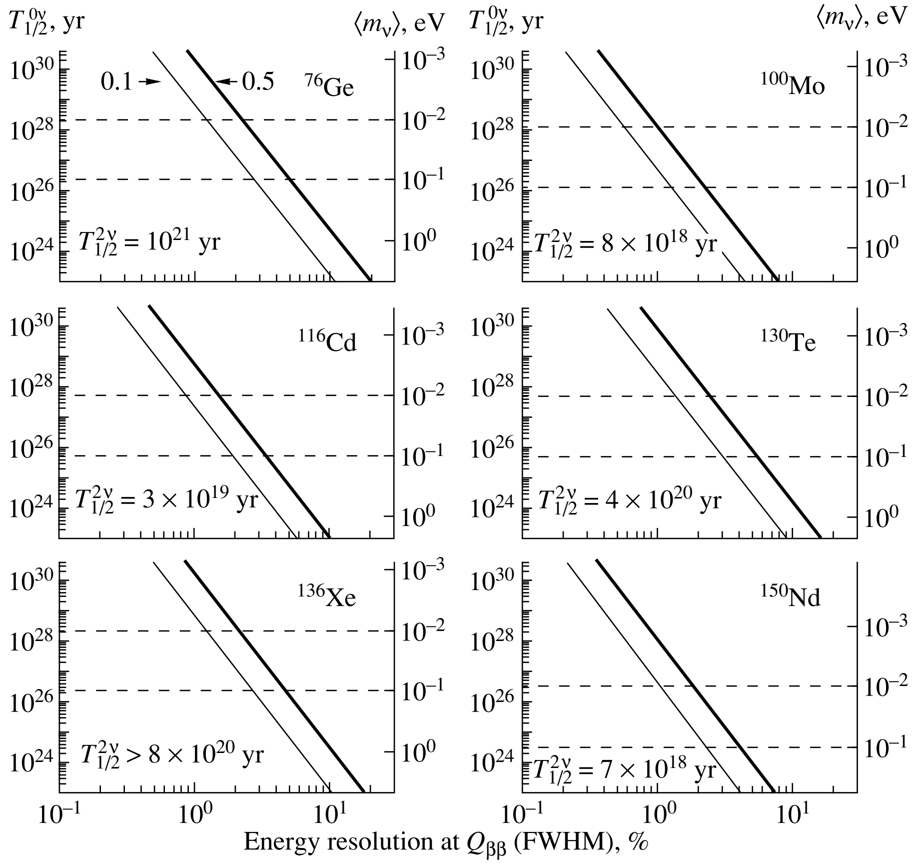

Fig. 2. The dependences of the discovery potential versus the energy resolution calculated (bold line for $h/M = 0.5$; thin line for $h/M = 0.1$) for 2β-decay candidate nuclei (^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, and ^{150}Nd). Neutrino mass scale (right) is shown in accordance with [15].

function. Then the obtained 2ν distribution for the sum of electron energies was properly convoluted with the response function of the detector, whose relative energy resolution given at $Q_{\beta\beta}$ varies as the square root of energy.

In Fig. 1*a*, the 0ν peak (with the amplitude M) and $2\nu2\beta$-decay spectrum meet at the relative height $h/M = 0.1$, and due to this, the separation of the effect is excellent. However, it seems that such a demand ($h/M = 0.1$) is too severe. At the same time, Fig. 1*c* demonstrates another extreme case (they meet at the relative height $h/M = 1$), which does not allow one to discriminate the effect at all.[3] In our opinion, the example shown in Fig. 1*b*, where the 2ν distribution and the 0ν peak meet at $h/M = 0.5$, represents the minimal requirement for recognition of the effect, which can still be reasonable in experimental practice. Therefore, if we accept the last criteria, the discovery potential of a setup with fixed energy resolution can be defined as the half-life of the $0\nu2\beta$ decay, which could be registered by satisfying this demand ($h/M = 0.5$) at a given $T^{2\nu}_{1/2}$ value. The dependences of this quantity (let us call it "the discovery potential") versus the energy resolution were determined for several 2β-decay candidate nuclei, and they are depicted in Fig. 2. Similarly, the exposures (product of detector mass and measuring time), which are needed to collect ten counts in the 0ν peak at a given $T^{0\nu}_{1/2}$ value, were calculated for each nucleus (under assumption that detection efficiency and enrichment both equal 100%), and the results are shown in Fig. 3. We will use these dependences below when discussing different projects.

In summary, on the basis of this brief analysis, we can formulate the following requirements for the future ultimate-sensitivity 2β-decay experiments:

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[3] The discrimination of the effect and background in the case $h/M = 1$ could be, in principle, possible if (i) the theoretical shape of the $2\nu2\beta$-decay spectrum near the $Q_{\beta\beta}$ energy is known exactly; (ii) the statistics accumulated in the experiment are very high, which, however, is a great technical challenge (Fig. 3); and (iii) the contributions from the different background origins to the measured spectrum near the $Q_{\beta\beta}$ value are precisely known, which appears to be a quite unrealistic task (see discussion in [16]).

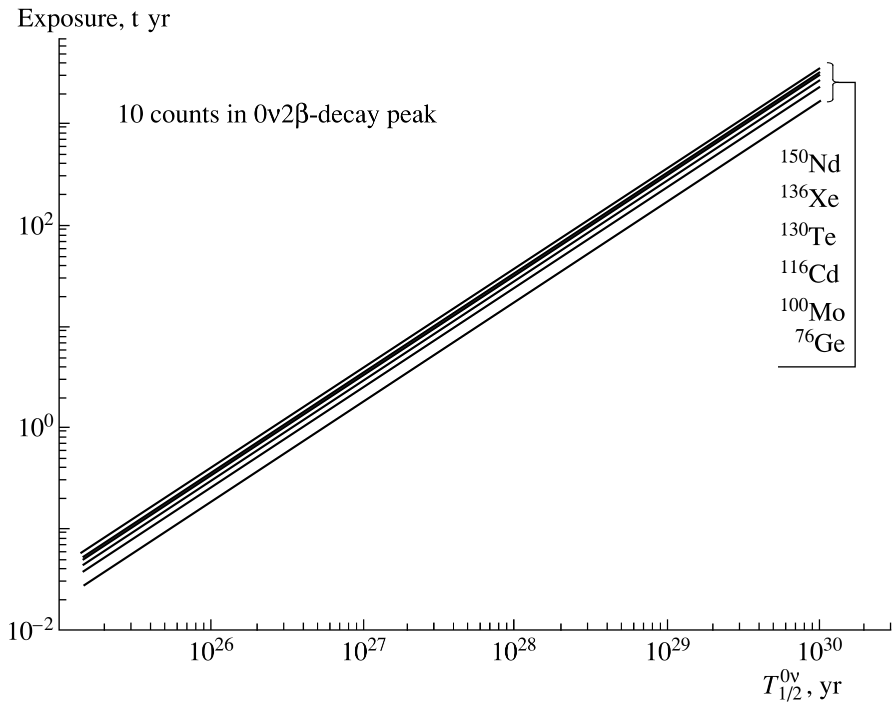

Fig. 3. The exposure (product of detector mass and measuring time) needed to collect ten counts in the 0ν peak at given $T^{0\nu}_{1/2}$ value calculated for different nuclei under the assumption that detection efficiency and enrichment both are equal to 100%.

(i) The use of highly enriched ($\delta \to 100\%$) detectors and an "active" source technique because only in this case could the total detection efficiency be close to 100%.

(ii) The energy resolution is a crucial characteristic, and its value at $Q_{\beta\beta}$ energy must correspond to the required discovery potential for a given nucleus (Fig. 2).

(iii) The exposure (mt) needed to reach a certain $T^{0\nu}_{1/2}$ value should be in accordance with Fig. 3 (20–30 t yr for $T^{0\nu}_{1/2} \approx 10^{28}$ yr).

(iv) Because of the square root dependence of the sensitivity versus source mass and measuring time, it is not enough, however, to increase the exposure alone. The background must be reduced practically to zero.

(v) The measuring time of the future experiments will be of the order of ≈ 10 yr; hence, detectors and setups should be as simple as possible to provide stable and reliable operation over such a long period.

Evidently, it could be very difficult to find the project and construct the experiment which would completely satisfy these severe requirements. However, perhaps some of the recent proposals could do it to certain extent, so let us consider them briefly.

The MOON project [30] to study the $0\nu2\beta$ decay of ^{100}Mo ($Q_{\beta\beta} = 3034$ keV) calls for the use of 34 t of natural Mo (i.e., 3.3 t of ^{100}Mo) per detector module in the form of passive foil (≈ 50 mg/cm^2). The module will be composed of ≈ 60 000 plastic scintillators (6 m × 0.2 m × 0.25 cm), the light outputs from which are collected by 866 000 wavelength shifter fibers (∅1.2 mm × 6 m), viewed through clear fibers by 6800 16-anode photomultiplier tubes (PMT). The sensitivity to the neutrino mass could be of the order of ≈ 0.05 eV [30].

The XMASS project [31] intends to use ultrapure liquid Xe scintillator with ≈ 10-t fiducial mass as a real time, low-energy solar neutrino detector. Such a detector (with ≈ 1 t of enriched ^{136}Xe) could allow a simultaneous search for the $0\nu2\beta$ decay of ^{136}Xe ($Q_{\beta\beta} = 2468$ keV) with a sensitivity to neutrino mass of ≈ 0.02 eV [32].

The DCBA project is under development in KEK (Japan) [33]. The drift chamber placed in a uniform magnetic field (0.6 kG) can measure the momentum of each β particle emitted in 2β decay and the position of the decay vertex by means of a three-dimensional reconstruction of the tracks. With 18 kg of an enriched ^{150}Nd ($Q_{\beta\beta} = 3367$ keV) passive source (50 mg/cm^2), the projected sensitivity to the Majorana neutrino mass is ≈ 0.05 eV [33].

^{160}Gd ($Q_{\beta\beta} = 1730$ keV) is an attractive candidate due to large natural abundance (21.9%), allowing one to construct a sensitive apparatus with nonenriched Gd_2SiO_5:Ce crystal scintillators (GSO). A large-scale experiment with ^{160}Gd using a GSO multicrystal array with a total mass of 1–2 t (≈ 200–400 kg of ^{160}Gd) is suggested with the sensitivity to the Majorana neutrino mass ≈ 0.05 eV [34].

All proposals mentioned above require a significant amount of research and development to demonstrate their feasibility. Because of this, we are going to discuss the following safer proposals, which were designed on the basis of the best performed (Table 1) or running experiments.

CUORE. The running CUORICINO setup is designed as a pilot step for a future CUORE project, which would consist of one thousand TeO_2 bolometers (with total mass of 760 kg) operating at ≈ 10 mK. The excellent energy resolution of TeO_2 bolometers (≈ 5 keV at 2.5 MeV) is a powerful tool for discriminating the 0ν signal from the background. The CUORE sensitivity is quoted by the authors for different background rate at 2.5 MeV (0.1–0.01 counts/(yr kg keV)) and would be as high as $T^{0\nu}_{1/2} \geq (0.3\text{–}4) \times 10^{26}$ yr ($m_\nu \leq 0.1\text{–}0.04$ eV) [18].

EXO. A new approach to study 2β decay of ^{136}Xe ($Q_{\beta\beta} = 2468$ keV) makes use of the coincident detection of $^{136}Ba^{2+}$ ions (the final state of the ^{136}Xe decay on the atomic level) and the $0\nu2\beta$ signal with the energy of 2.5 MeV in a time projection chamber (TPC) filled with liquid or gaseous Xe [35, 36]. The EXO project intends to use the resonance ionization spectroscopy for the identification of $^{136}Ba^{2+}$ ions in a 40-m^3 TPC (the energy resolution at 2.5 MeV is FWHM $\approx 5\%$) operated at 5–10-atm pressure of enriched xenon (≈ 1 t of ^{136}Xe). The estimated sensitivity to neutrino mass is ≈ 0.05 eV [37]. The conventional pilot TPC (no Ba ion detection) with 200 kg of enriched ^{136}Xe is under construction now.

There are three large-scale projects for the 2β-decay quest of ^{76}Ge.

MAJORANA. The idea of this proposal is to use 210 HP Ge (enriched in ^{76}Ge to $\approx 86\%$) semiconductor detectors (≈ 2.4-kg mass of a single crystal), which are contained in "conventional" superlow background cryostats [38]. The detectors are shielded by HP lead or copper. Each crystal will be supplied with six azimuthal and two axial contacts, and hence spatial information will be available for the detected events. It is anticipated that a segmentation of the crystals and a pulse-shape analysis of the data would reduce the background rate of the detectors to the level of ≈ 0.01 counts/(yr kg keV) at the energy 2 MeV. On this basis, the projected half-life limit can be determined as $T^{0\nu}_{1/2} \geq 10^{27}$ yr, and depending on the NME calculations, one expects the following neutrino mass limits: $m_\nu \leq 0.05\text{–}0.15$ eV.

GENIUS. This project intends to operate 1 t of "naked" HP Ge (enriched in ^{76}Ge to $\approx 86\%$) detectors placed in extremely high purity liquid nitrogen (LN_2), which simultaneously serves as a cooling medium and as a shielding for the detectors [39]. In accordance with Monte Carlo simulations, the necessary dimensions of the liquid nitrogen shield which could fully suppress the radioactivity from the surroundings are about 12 m in diameter and 12 m in height, and the required radioactive purity of the liquid nitrogen should be at the level of $\approx 10^{-15}$ g/g for ^{40}K and ^{238}U, $\approx 5 \times 10^{-15}$ g/g for ^{232}Th, and 0.05 mBq/m^3 for ^{222}Rn. Due to this, the total GENIUS background rate in the energy region of the 2β decay of ^{76}Ge may be reduced down to ≈ 0.2 counts/(yr keV t) [39, 40]. The projected sensitivity is estimated for a 10-yr measuring time as $T^{0\nu}_{1/2} \geq 10^{28}$ yr, i.e., a neutrino mass constraint $m_\nu \leq 0.015\text{–}0.05$ eV.

GEM. Aiming to make realization of the high-sensitivity ^{76}Ge experiment simpler, the GEM design is based on the following ideas [41]: (a) Similarly to GENIUS ≈ 400 "naked" HP Ge detectors (enriched in ^{76}Ge to 86%, mass of ≈ 2.5 kg each) will operate in ultrahigh-purity liquid nitrogen. (b) Liquid nitrogen is contained in the vacuum cryostat (made of HP copper), whose dimensions are as small as possible consistent with necessity of eliminating contributions of the radioactive contaminants in the Cu cryostat to the background of the HP Ge detectors. (c) The shield is composed of two parts: an inner shielding—ultrahigh-purity liquid nitrogen ($\approx 10^{-15}$ g/g for ^{40}K and ^{238}U, $\sim 5 \times 10^{-15}$ g/g for ^{232}Th, and 0.05 mBq/m^3 for ^{222}Rn); an outer part—high-purity water, whose volume is large enough ($\oslash 11 \times 11$ m) to suppress external background. It was proved by Monte Carlo simulations that, for such a design, the necessary LN_2 volume will be reduced substantially (≈ 40 t instead of ≈ 1000 t in GENIUS), and the GEM sensitivity is similar to that of GENIUS: $T^{0\nu}_{1/2} \geq 10^{28}$ yr ($m_\nu \leq 0.015$ eV) [41].

CAMEO. This project [42] is a further development of the pilot 2β-decay studies of ^{116}Cd performed by the Kiev–Florence collaboration in the Solotvina Underground Laboratory since 1989 [43]. Let us briefly recall their main results. Cadmium tungstate ($^{116}CdWO_4$) crystal scintillators, enriched in ^{116}Cd to 83%, have been grown for the search. Their light output (peak emission at 480 nm with decay time of ≈ 13 μs) is ≈ 30–35% as compared with that of NaI(Tl). Four $^{116}CdWO_4$ crystals with a total mass of 330 g are viewed by a low-background 5 in.-PMT through one light guide 10 cm in diameter and 55 cm long. The ^{116}CdWO$_4$ crystals are surrounded by an active shield made of 15 CdWO$_4$ crystals of large volume with a total mass of 20.6 kg. These are viewed by a low-background PMT through an active plastic light guide ($\oslash 17 \times 49$ cm). The whole CdWO$_4$ array is situated within an additional active shield made of plastic scintillator $40 \times 40 \times 95$ cm; thus, together with both active light guides, a complete 4π active shield of the main (^{116}CdWO$_4$) detector is provided. The outer passive shield consists of high-purity copper (3–6 cm), lead (22.5–30 cm), and polyethylene (16 cm). Two plastic scintillators installed above the passive shield serve as cosmic muon veto. The data acquisition records the amplitude, arrival time, and pulse shape (PS) of each ^{116}CdWO$_4$ event. The PS analysis is based on an optimal digital filter and ensures clear discrimination between γ rays and α particles [44], as well as selection of "illegal" events: double pulses, signals from active light guide, etc.

Due to active and passive shields and as a result of the time-amplitude and PS analysis of the data, the background rate of the ^{116}CdWO$_4$ detector in the energy region 2.5–3.2 MeV ($Q_{\beta\beta}$ of ^{116}Cd is 2.8 MeV) is reduced to 0.04 counts/(yr kg keV). It is the lowest background rate which has ever been reached with crystal scintillators. After 14 183 h of measurements the half-life limit on the neutrinoless 2β decay of ^{116}Cd has been set as $T^{0\nu}_{1/2} \geq 1.7(2.6) \times 10^{23}$ yr at 90% (68%) C.L. The latter corresponds to a restriction on the neutrino mass of $m_\nu \leq 1.7(1.4)$ eV at 90% (68%) C.L. [10].

Substantial advancement of this bound would be possible in the case of further enhancement of sensitivity, which is the main goal of the CAMEO project. It is proposed [42] to operate ≈ 100 kg of enriched ^{116}CdWO$_4$ crystals (total number of ^{116}Cd nuclei is $\approx 1.5 \times 10^{26}$) allocated in the liquid scintillator of the BOREXINO Counting Test Facility (CTF [45]). The CTF consists of an external ≈ 1000-t water tank ($\oslash 11 \times 10$ m), which serves as a passive shield for a 4.8-m^3 liquid scintillator contained in an inner vessel, 2.1 m in diameter. The radiopurity of water is $\approx 10^{-14}$ g/g for U/Th and $\approx 10^{-10}$ g/g for K. The high-purity ($\approx 5 \times 10^{-16}$ g/g for U/Th) liquid scintillator (1.5 g/l of PPO in pseudocumene) has an attenuation length ≥ 5 m and a principal scintillator decay time of ≈ 5 ns. The inner transparent vessel made of nylon film (0.5 mm thick) allows one to collect the scintillation light with the help of 100 PMTs (8 in.) fixed on the 7-m-diameter support structure.

In the preliminary CAMEO design, 40 enriched ^{116}CdWO$_4$ crystals (≈ 2.5 kg each) are allocated in the liquid scintillator of the CTF and homogeneously distributed on a sphere with diameter 0.8 m. It is supposed that 200 PMTs with light concentrators are fixed at a diameter of 5 m, providing an optical coverage of 80%. The GEANT Monte Carlo simulation of the CdWO$_4$ scintillation light[4] propagation in the considered geometry gives ≈ 4000 photoelectrons for a 2.8-MeV energy deposit; thus, a $0\nu2\beta$-decay peak of ^{116}Cd would be measured with an energy resolution of FWHM = 4%. The feasibility of obtaining such an energy resolution with CdWO$_4$ crystal has been successfully demonstrated by the measurements with a CdWO$_4$ crystal ($\oslash 40 \times 30$ mm) placed in transparent paraffin oil [42]. An increase in the light collection up to ≈ 42% has been obtained, which leads to improvement of the CdWO$_4$ energy resolution in the whole energy region. The FWHM values (7.4% at 662 keV, 5.4% at 1173 keV, and 4.3% at 2615 keV) are similar to those for NaI(Tl) crystals and have never been reached before with CdWO$_4$ scintillators.

The background simulation for CAMEO was performed with the help of the GEANT3.21 [46] and DECAY4 [47] codes. The simulated contributions from various background sources and the response functions for 2β decay of ^{116}Cd with $T^{2\nu}_{1/2} = 2.7 \times 10^{19}$ yr and $T^{0\nu}_{1/2} = 10^{25}$ yr are depicted in Fig. 4. On this basis, the sensitivity of the CAMEO experiment can be calculated as $T^{0\nu}_{1/2} \geq 10^{26}$ yr, which translates to a neutrino mass bound of $m_\nu \leq 0.06$ eV. On the other hand, it is evident from Fig. 4 that $0\nu2\beta$ decay of ^{116}Cd with a half-life of $\approx 10^{25}$ yr would be clearly registered [42].

Moreover, these results can be advanced further by exploiting 1 t of ^{116}CdWO$_4$ detectors ($\approx 1.5 \times 10^{27}$ nuclei of ^{116}Cd) placed in one of the existing or future large underground neutrino detectors such as BOREXINO, SNO, or KamLAND. The sensitivity is estimated as $T^{0\nu}_{1/2} \geq 10^{27}$ yr ($m_\nu \leq 0.02$ eV) [42]. The proposed CAMEO technique with ^{116}CdWO$_4$ crystals is extremely simple and reliable; thus, such experiments can run stably for decades.

Now let us analyze the discovery potential of the projects reviewed by using calculated dependences of that quantity versus the energy resolution of the detector (Fig. 2) and by taking into account the energy resolutions claimed in each particular proposal. Unfortunately, the results of such an analysis are not optimistic, and one conclusion is clear: only projects with high energy resolution (GEM,

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[4] We recall that the CdWO$_4$ scintillator yields $\approx 1.5 \times 10^4$ emitted photons per 1 MeV of energy deposited.

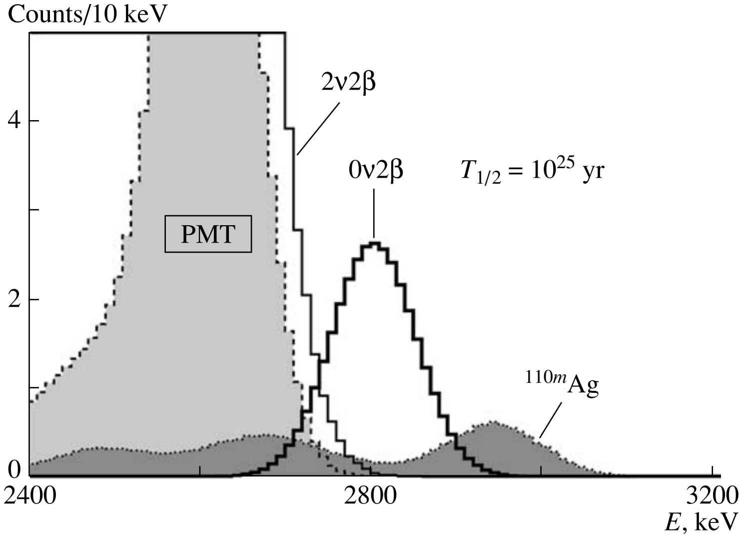

Fig. 4. The response functions of the CTF with 100 kg of ^{116}CdWO$_4$ crystals (5-yr measuring time) for $2\nu2\beta$ decay of ^{116}Cd ($T^{2\nu}_{1/2} = 2.7 \times 10^{19}$ yr) and $0\nu2\beta$ decay with $T^{0\nu}_{1/2} = 10^{25}$ yr (solid histograms). The simulated contribution from ^{208}Tl in the PMTs (dashed histogram) and from cosmogenic ^{110m}Ag in ^{116}CdWO$_4$ crystals (dotted curve).

GENIUS, MAJORANA with the HP ^{76}Ge detectors, and CUORE with ^{130}TeO$_2$ bolometers) have a chance of detecting $0\nu2\beta$ decay with the rate corresponding to neutrino mass $m_\nu \approx 0.01$ eV. As regards the CUORE, it should be noted, however, that the complexity of the cryogenic technique requires the use of a lot of different construction materials in the setup, which makes it quite difficult to reduce background to the same superlow level as that obtained in the best experiments with TPC [12], semiconductor [13, 14], and scintillation [10] detectors. Because of this, the CUORE sensitivity would be limited, and in fact, the expected results are quoted by the authors for different background rate at 2.5 MeV [18].

The discovery potential of other proposals is much more modest. For example, for the EXO (FWHM = 5% at the $Q_{\beta\beta}$ energy), it equals $T^{0\nu}_{1/2} \approx 10^{26}$ yr (i.e., $m_\nu \approx 0.15$ eV); for the MOON (FWHM = 7% at the $Q_{\beta\beta}$ energy), it is $T^{0\nu}_{1/2} \approx 2 \times 10^{23}$ yr ($m_\nu \approx 2$ eV); and for the CAMEO (FWHM = 4%), the corresponding value is $T^{0\nu}_{1/2} \approx 2 \times 10^{25}$ yr ($m_\nu \approx 0.15$ eV). Let us recall, however, that ^{116}CdWO$_4$ crystals, which will be used in the CAMEO experiment, can also work as cryogenic detectors with an energy resolution of about 10 keV [48]. Therefore, if the ^{116}CdWO$_4$ crystals produced for the CAMEO project were measured (at the next step of research) in the CUORE apparatus, the discovery potential of such an experiment would be greatly enhanced (see Fig. 2). At the same time, such a measurement would allow one to overcome the drawback of the CUORE setup associated with the background limitation. First, it is because the $Q_{\beta\beta}$ energy of ^{116}Cd (2.8 MeV) is higher than that for ^{130}Te (2.5 MeV). Secondly, as was successfully demonstrated with CaWO$_4$ crystals [49], simultaneous phonon and scintillation light detection—which is also possible with ^{116}CdWO$_4$ crystals—is a very powerful tool for additional background discrimination.

Hence, we can conclude that a challenging scientific goal to observe $0\nu2\beta$ decay with the rate corresponding to neutrino mass $m_\nu \approx 0.01$ eV could be feasible for several of the future 2β-decay experiments (namely, GEM, GENIUS, MAJORANA with HP ^{76}Ge detectors, and CUORE with ^{116}CdWO$_4$ crystals), while other projects (CAMEO, CUORE with ^{130}TeO$_2$ crystals, DCBA, EXO, ^{160}Gd, MOON, etc.) would be able to set the restrictions on the neutrino mass at the level of $m_\nu \leq 0.05$ eV.

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