INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **30** (2004) 971–981 PII: S0954-3899(04)75009-4

Sensitivity and discovery potential of the future 2β decay experiments

Yu G Zdesenko, F A Danevich and V I Tretyak

Institute for Nuclear Research, MSP 03680 Kiev, Ukraine

E-mail: zdesenko@kinr.kiev.ua

Received 20 January 2004
Published 2 August 2004
Online at stacks.iop.org/JPhysG/30/971
doi:10.1088/0954-3899/30/9/002

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

Recent observations of neutrino oscillations [1–4], strongly suggesting that neutrinos have nonzero mass (m_ν), provide important motivation for the double beta (2β) decay experiments [5–7]. Indeed, the neutrinoless (0ν) double β decay—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 a new physics beyond the SM and a unique confirmation of the Majorana nature of the neutrino. Because oscillation experiments are sensitive to the neutrino mass difference, 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, the $0\nu2\beta$ decay still remains unobserved (see the latest reviews [5–7, 9]). Recently the impressive half-life limits for 0ν mode were set in direct measurements with several nuclides: $T_{1/2}^{0\nu} \geqslant 10^{23}$ yr for ^{116}Cd [10], ^{128}Te, ^{130}Te [11], ^{136}Xe [12], and $T_{1/2}^{0\nu} \geqslant 10^{25}$ yr for ^{76}Ge [13, 14].

The best half-life limits on the $0\nu2\beta$ decay at present and the corresponding restrictions on the Majorana neutrino mass are given in table 1. These results were obtained in experiments, which have already finished now. Besides, there are two new running experiments: NEMO-3 [15] and CUORICINO [11].

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

Nuclide	Experimental limit $T_{1/2}^{0\nu}$ (yr) 68% CL	90% CL	Reference	Limit on m_ν (eV) on the basis of [31][a] 68% CL	90% CL
^{76}Ge	3.1×10^{25}	1.9×10^{25}	[13]	0.27	0.35
	–	1.6×10^{25}	[14]	–	0.38
	$4.2 \times 10^{25\,\mathrm{b}}$	$2.5 \times 10^{25\,\mathrm{b}}$	[26]	0.24	0.31
^{116}Cd	2.6×10^{23}	1.7×10^{23}	[10]	1.4	1.7
^{130}Te	–	5.5×10^{23}	[11]	–	0.94
^{136}Xe	–	4.4×10^{23}	[12]	–	2.2

[a] The m_ν constraints are determined on the basis of the NME calculations [31], which were chosen because of the most extensive list of 2β nuclei calculated there, allowing one to compare the sensitivity of different experiments to the m_ν bound within the same scale.

[b] Results were established [26] by analysing the cumulative data sets of the Heidelberg–Moscow [13] and IGEX [14] experiments.

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. 7 kilogram of ^{100}Mo passive source in the form of foil has an equivalent thickness $\approx$60 mg cm^{-2} ($\approx$50 mg cm^{-2} of ^{100}Mo foil itself, plus $\approx$10 mg cm^{-2} of scintillators' wrapping, gas and wires of the tracking counters). The energy resolution of the scintillators is $\approx$9% at 3 MeV. After 160 days of operation the half-life limit on $0\nu2\beta$ decay of ^{100}Mo was set as $T_{1/2}^{0\nu} \geqslant 1.8 \times 10^{23}$ yr at 90% CL [16]. For a 5 yr measuring time the projected sensitivity of the NEMO-3 detector would be about $T_{1/2}^{0\nu} \geqslant 8 \times 10^{24}$ yr [15], which corresponds to $m_\nu \leqslant 0.3$ eV.

The CUORICINO set-up contains 62 low-temperature bolometers made of TeO$_2$ crystals with a total mass of 42 kg cooled down to a temperature of $\approx$10 mK [11]. The energy resolution of the detector is around 5 keV at 2615 keV, and the current background rate in the region of $0\nu2\beta$ decay of ^{130}Te ($Q_{\beta\beta} = 2529$ keV) is about 0.2 counts (yr kg keV)$^{-1}$. After $\approx$6 kg × yr exposure the half-life limit on $0\nu2\beta$ decay of ^{130}Te was established as $T_{1/2}^{0\nu} \geqslant 7.5 \times 10^{23}$ yr at 90% CL [17]. Under the assumption that the background rate at the energy 2.5 MeV will be reduced to $\approx$0.05 counts (yr kg keV)$^{-1}$, the projected CUORICINO sensitivity is $T_{1/2}^{0\nu} \geqslant 3 \times 10^{25}$ yr (that is, $m_\nu \leqslant 0.15$ eV) [11].

Thus, one can conclude that the present (and near future) 2β decay results have already brought the most stringent restrictions on the values of the Majorana neutrino mass ($m_\nu \leqslant$ 0.2–2 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 standard model ($\approx 10^{-4}$) [5–7, 9].

Moreover, nowadays the 2β decay research is entering a new era, when *discovery* of the $0\nu2\beta$ decay has become realistic. However, the present level of the experimental sensitivity should be enhanced up to $m_\nu \approx 0.01$ eV (or at least up to $m_\nu \approx 0.05$ eV) [18, 19]. It is a great challenge and a lot of projects were proposed during the past few years aiming to reach this goal (see reviews [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 nuclear matrix elements (NME) of the $0\nu2\beta$ decay, whose uncertainties are often unknown [20, 21]. However, as is written, e.g. in [22]: "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". Another reason is the difficulties in developing the experimental techniques. If the $0\nu2\beta$ decay will be finally observed in one experiment, e.g. with ^{76}Ge,[1] 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 super-low background nature of the 2β studies, the corresponding development is a multi-stage 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 $T_{1/2}^{0\nu} \geqslant 10^{21}$ yr [27]. Recently, after 30 years of persistent efforts, this limit was advanced up to $T_{1/2}^{0\nu} \geqslant 10^{25}$ yr [13, 14].

Secondly, practically all proposals require a large mass production of enriched isotopes, thus their costs have become comparable with those of the accelerator experiments. Because most of these projects need a lot of effort and perhaps 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 for 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 $\approx$10 kg of enriched HP ^{76}Ge detectors) have brought the most stringent restrictions on the neutrino mass, at the level of $\approx$0.3 eV. Other experiments offer m_ν bounds in the range of $\approx$1–2 eV, which is not so drastically weak, especially if taking into account that, e.g., the ^{116}Cd result was obtained with very small ^{116}CdWO$_4$ crystal scintillators (total mass of $\approx$0.3 kg) [10]. It demonstrates the importance of the right choice of 2β decay candidate for study, for which the $Q_{\beta\beta}$ value is the most important parameter. This is because the $0\nu2\beta$ decay probability (namely, the phase space integral of the $0\nu2\beta$ decay, $G_{\mathrm{mm}}^{0\nu}$) strongly depends on the available energy release, roughly as $Q_{\beta\beta}^5$ [21, 28]. 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 it is—from an experimental point of view—to overcome background problems. Let us remember that the background from natural radioactivity drops sharply above 2615 keV, which is the energy of the γ's from ^{208}Tl decay (^{232}Th family).

Among 35 possible $2\beta^-$ decay candidates, there are only 13 nuclei with $Q_{\beta\beta}$ larger than 1.5 MeV [29]. They are listed in table 2, where $Q_{\beta\beta}$, the natural abundance δ [30] and the calculated values of the phase space integral $G_{\mathrm{mm}}^{0\nu}$ [21, 28] and $T_{1/2}^{0\nu} \times \langle m_\nu \rangle^2$ [31] are given. Note that due to the lower $Q_{\beta\beta}$ value of ^{76}Ge (2039 keV), its phase space integral is about 7–30 times smaller as compared with those of ^{48}Ca, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe and ^{150}Nd.

Now let us consider the experimental sensitivity, which can be expressed in terms of a lower half-life limit as follows [6, 9]:

$$T_{1/2}^{0\nu} \sim \varepsilon \cdot \delta \sqrt{\frac{m \cdot t}{R \cdot B}} \qquad (1)$$

where 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.

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[1] The discovery of the $0\nu2\beta$ decay of ^{76}Ge with half-life of 1.5×10^{25} yr (0.8–18×10^{25} yr is the 95% confidence interval) has been claimed [23], which, however, was criticized in [24–26].

Table 2. Double β decay candidates with $Q_{\beta\beta} \geqslant 1.5$ MeV.

Nuclide	$Q_{\beta\beta}$ (keV)	Abundance δ (%)	Parameter $G^{0\nu}_{\mathrm{mm}}$ (10^{-14} yr)	$T^{0\nu}_{1/2} \times \langle m_\nu \rangle^2$ (yr eV^2) (after NME [31])
^{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}

First, it is clear from the formula that efficiency and enrichment are the most important characteristics of the detector for 2β decay study, because any other parameters are under the square root. Obviously, the 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 hundred 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. The centrifugal method 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 [32]. 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 (where a detector, containing 2β candidate nuclei, serves as a source simultaneously). There also exist 2β decay experiments with 'passive' sources, where the latter is placed (e.g., in the form of foil) between two detectors. However, the drawback of the 'passive' source technique is the self-absorption of emitted electrons in the source, which decreases detection efficiency, and causes the broadening and shifting of the $0\nu2\beta$ decay peak to the lower energies.

Thirdly, the energy resolution of the detector is an extremely important characteristic for the $0\nu2\beta$ decay quest. Foremost, with the high energy resolution it is possible to minimize the irremovable background produced by the $2\nu2\beta$ decay events. This 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 the background which cannot be discriminated from the $0\nu2\beta$ decay signal, even in principle. However, the better is the energy resolution, the smaller part of the 2ν tail 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 the $0\nu2\beta$ decay. Indeed, this process manifests itself by the peak at $Q_{\beta\beta}$ energy, hence, the great advantage of the $0\nu2\beta$ decay experiments is the possibility of searching

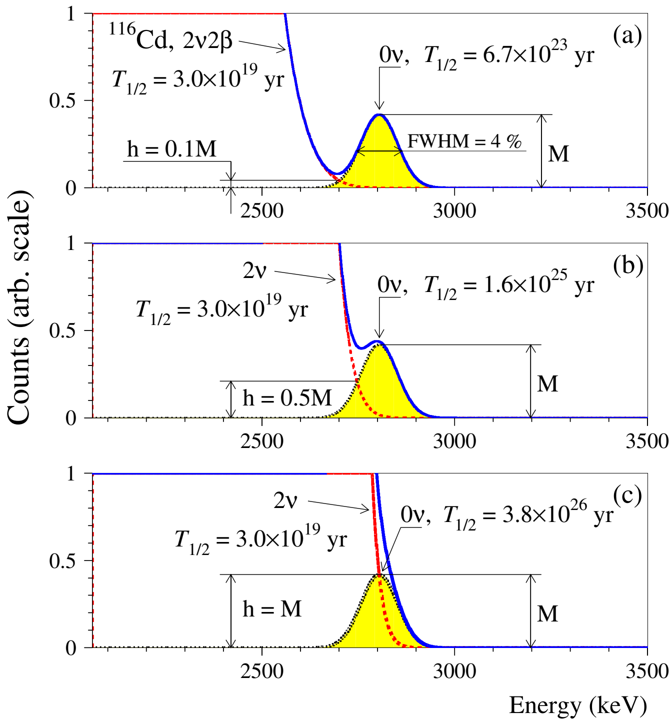

Figure 1. Definition of the discovery potential of the 2β decay studies. The 2ν distribution of ^{116}Cd (with $T^{2\nu}_{1/2} = 3 \times 10^{19}$ yr) overlaps the 0ν peaks with half-life corresponding to (a) 6.7×10^{23} yr; (b) 1.6×10^{25} yr and (c) 3.8×10^{26} yr. Correspondingly, the 0ν peak with 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) $h/M = 0.5$; (c) $h/M = 1$.

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 the $0\nu2\beta$ decay with the 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 figure 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 half-life corresponding to (a) 6.7×10^{23} yr, (b) 1.6×10^{25} yr and (c) 3.8×10^{26} yr.[2] In figure 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

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[2] The spectrum of the sum of electron energies for $2\nu2\beta$ decay (0^+–0^+ transition, $2n$-mechanism) was obtained (as described in [33]) by integrating the theoretical two-dimensional energy distribution $\rho_{12}(t_1, t_2)$: $\rho_{1+2}(t) = \int_0^t \rho_{12}(t - t_2, t_2)\, \mathrm{d}t_2$, where t_i is the kinetic energy of the ith electron, 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 [34]: $\rho_{12}(t_1, t_2) = (t_1 + 1) p_1 F(t_1, Z)(t_2 + 1) p_2 F(t_2, Z)(t_0 - t_1 - t_2)^5$, where t_0 is the energy available in the 2β process ($Q_{\beta\beta}$ for decay to the ground state), 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 [35]: $F(t, Z) = \mathrm{const}\cdot p^{2s-2}\, \mathrm{e}^{\pi\eta} |\Gamma(s + \mathrm{i}\eta)|^2$, 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 function. Then the 2ν distribution obtained for the sum of electron energies was properly convoluted with the response function of the detector, whose relative energy resolution given at $Q_{\beta\beta}$ depends on the square root of energy.

that such a demand ($h/M = 0.1$) is too severe. At the same time figure 1(c) demonstrates the other extreme case (meet at the relative height $h/M = 1$), which does not allow one to discriminate the effect at all. In principle, the discrimination of the effect at $h/M = 1$ could be possible if (i) the theoretical shape of the $2\nu 2\beta$ decay spectrum near the $Q_{\beta\beta}$ energy and the response function of the detector are known very precisely; (ii) the statistics accumulated in this tiny fraction of the experimental spectrum are high, which, however, is a great technical challenge (see figure 3) and (iii) the contributions from the different background origins to the measured spectrum near the $Q_{\beta\beta}$ value are precisely known, which looks quite an unrealistic task (see discussion in [26]).

In our opinion, the example shown in figure 1(b), where the 2ν distribution and the 0ν peak meet at $h/M = 0.5$, represents the minimal requirement for the effect recognition, which can still be reasonable in the experimental practice. Therefore, if we accept the last criterion, the discovery potential of the set-up with the fixed energy resolution can be defined as the half-life of the $0\nu 2\beta$ decay, which could be registered by satisfying this demand ($h/M = 0.5$) at the given $T_{1/2}^{2\nu}$ value. The dependences of this quantity (let us call it 'discovery potential') versus the energy resolution were determined for several 2β decay candidate nuclei, and they are depicted in figure 2. We would like to stress that the introduced 'discovery potential' (in fact, it is a sensitivity to measure effect) is not the same as a sensitivity to set the limit on the effect searched for, which we discussed earlier. The latter could be usually higher than the discovery potential by one or even by several orders of magnitude.

The exposures (product of detector mass and measuring time), which are needed to collect ten counts in the 0ν peak at a given $T_{1/2}^{0\nu}$ value, were calculated for each nucleus (under the assumption that detection efficiency and enrichment both equal 100%) and the results are shown in figure 3. We will use these dependences (figures 2 and 3) 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.

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

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

(iii) Large exposure ($m \times t$) is needed (e.g., ≈ 2.5 t × yr in order to collect ten counts in the $0\nu 2\beta$ decay peak for $T_{1/2}^{0\nu} \approx 10^{27}$ 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) Measuring time of the future experiments will be of the order of ≈5–10 yr, hence, detectors, set-ups and techniques should be as simple as possible to provide stable and reliable operation during such a long period.

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

The project **MOON** [36] to study the $0\nu 2\beta$ decay of ^{100}Mo ($Q_{\beta\beta} = 3034$ keV) calls for the use of 34 tons of natural Mo (i.e. 3.3 tons 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 fibres ($\phi 1.2$ mm × 6 m), viewed through clear fibres by 6800 16-anode photomultiplier

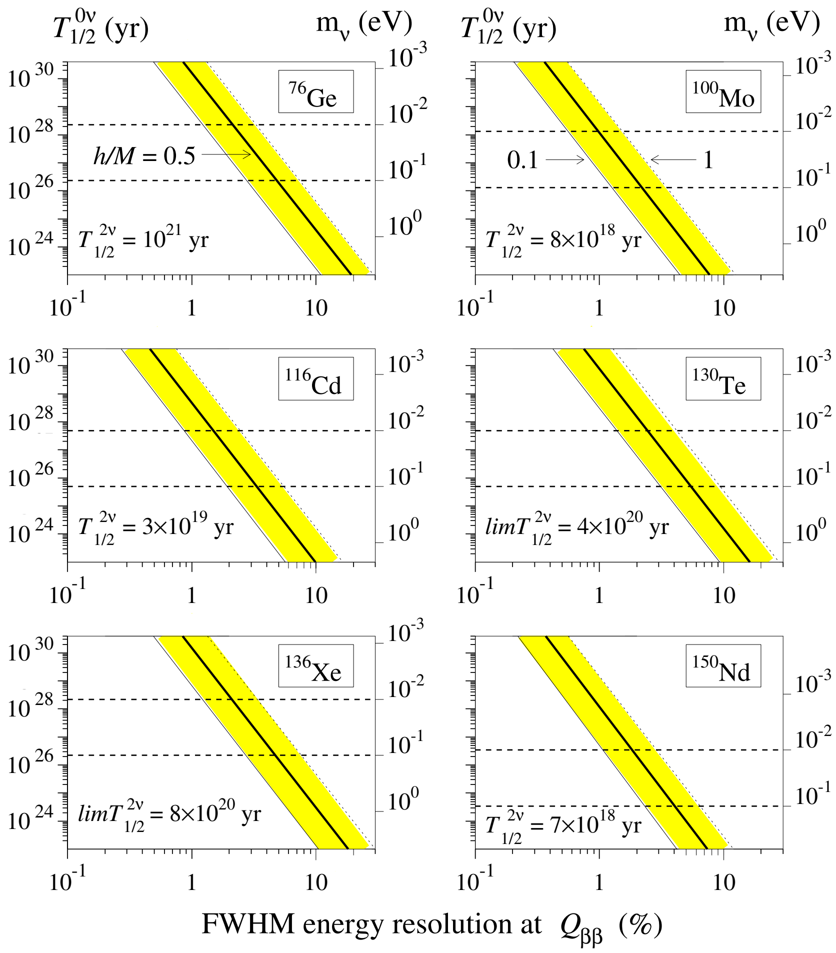

Figure 2. The dependences of the discovery potential versus the energy resolution calculated (bold line for $h/M = 0.5$; thin line for $h/M = 0.1$ and dotted line for $h/M = 1$) for the 2β decay candidate nuclei ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe and ^{150}Nd. Neutrino mass scale (right) is shown in accordance with [31].

tubes (PMT). Reported sensitivity to the neutrino mass could be of the order of $m_\nu \leqslant 0.03$ eV [36].

The **XMASS** project [37] intends to use ultrapure liquid Xe scintillator with $\approx$10 tons fiducial mass as a real time, low-energy solar neutrino detector. Such a detector (with $\approx$1.5 tons 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 $m_\nu \leqslant 0.05$ eV [38].

The **DCBA** project is under development in KEK (Japan) [39]. The drift chamber placed in the uniform magnetic field (0.6 kG) can measure the momentum of each β particle emitted in the 2β decay and the position of the decay vertex by means of a three-dimensional reconstruction of the tracks. With 18 kg of enriched ^{150}Nd ($Q_{\beta\beta} = 3367$ keV) passive source (50 mg cm^{-2}), the projected sensitivity to the Majorana neutrino mass is $m_\nu \leqslant 0.05$ eV [39].

The **^{160}Gd** ($Q_{\beta\beta} = 1730$ keV) due to its large natural abundance (21.9%), could allow one to construct a sensitive apparatus with non-enriched Gd$_2$SiO$_5$:Ce crystal scintillators (GSO).

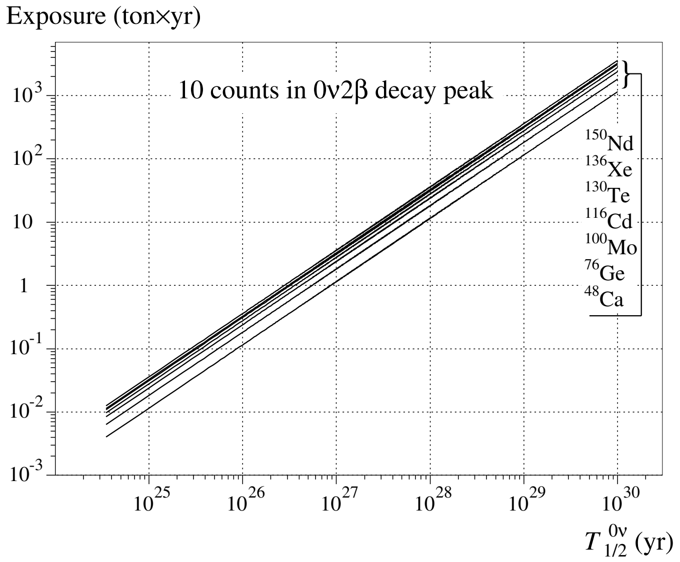

Figure 3. The exposure (product of detector mass by measuring time) needed to collect ten counts in the 0ν peak at a given $T^{0\nu}_{1/2}$ value calculated for different nuclei under the assumption that detection efficiency and enrichment both are equal to 100%.

The large-scale experiment with ^{160}Gd by using the GSO multi-crystal array with a total mass of 2 tons ($\approx$400 kg of ^{160}Gd) is suggested with the sensitivity to the Majorana neutrino mass $m_\nu \leqslant 0.06$ eV [40].

All proposals mentioned above require a significant amount of research and development to demonstrate their feasibility. Therefore, we are going to discuss the following safer proposals, which were designed on the basis of the best already finished (table 1) or running [11, 15] experiments.

CAMEO. In the project CAMEO [41] for the 2β decay study of ^{116}Cd ($Q_{\beta\beta} = 2805$ keV), it is supposed to operate $\approx$100 kg of enriched cadmium tungstate (^{116}CdWO$_4$) crystal scintillators ($\approx$30 kg of ^{116}Cd) allocated in the liquid scintillator of the Borexino Counting Test Facility (CTF) [42]. On the basis of the ^{116}Cd pilot experiment, performed in the Solotvina Underground Laboratory [10], and taking into account the results of the Monte Carlo (MC) simulation, the sensitivity of the CAMEO experiment has been calculated as $T^{0\nu}_{1/2} \geqslant 10^{26}$ yr. The latter translates into a neutrino mass bound of $m_\nu \leqslant 0.06$ eV [41]. Moreover, with one ton of ^{116}CdWO$_4$ detectors ($\approx 1.5 \times 10^{27}$ nuclei of ^{116}Cd), the sensitivity is estimated as $T^{0\nu}_{1/2} \geqslant 10^{27}$ yr ($m_\nu \leqslant 0.02$ eV) [41].

CUORE. The running CUORICINO set-up is designed as a pilot step for a future CUORE project, which would consist of 1000 TeO$_2$ bolometers (with a total mass of 760 kg) operating at $\approx$10 mK. The excellent energy resolution of TeO$_2$ bolometers ($\approx$5 keV at 2.5 MeV) is a powerful tool for discriminating the 0ν signal from the background. The CUORE sensitivity is quoted by the authors for the different background rate at 2.5 MeV (0.1 − 0.01 counts (yr kg keV)$^{-1}$ and would be as high as $T^{0\nu}_{1/2} \geqslant (0.3–4) \times 10^{26}$ yr ($m_\nu \leqslant 0.1 - 0.04$ eV) [11].

EXO. A new approach to study the 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 [43, 44]. The EXO project intends to use resonance ionization spectroscopy for the $^{136}\mathrm{Ba}^{2+}$ ions identification in a large volume TPC (the energy resolution at 2.5 MeV is FWHM $\approx 5\%$) operated at 5–10 atm pressure of xenon. With ≈ 1 ton of enriched ^{136}Xe an estimated sensitivity to neutrino mass is $m_\nu \leqslant 0.05$ eV [45]. The pilot conventional TPC (no Ba ions detection) with 200 kg of enriched ^{136}Xe is under construction now.

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

MAJORANA. The idea 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 a 'conventional' super-low background cryostat [46]. 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 crystals and a pulse-shape analysis would reduce the background of the detectors at the energy 2 MeV to the negligible level. The projected half-life limit can be determined as $T_{1/2}^{0\nu} \geqslant 8 \times 10^{27}$ yr, thus, one expects the neutrino mass limits $m_\nu \leqslant 0.02$ eV [46].

GENIUS. This project intends to operate 1 ton 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 [47]. In accordance with the MC 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. The total GENIUS background rate in the energy region of the 2β decay of ^{76}Ge may be reduced to ≈ 0.2 counts (yr keV t)$^{-1}$ [47, 48]. The projected sensitivity is estimated for 10 yr measuring time as $T_{1/2}^{0\nu} \geqslant 10^{28}$ yr, that is a neutrino mass constraint $m_\nu \leqslant 0.015$ eV.

GEM. To make realization of GENIUS simpler, the GEM design is based on the following ideas [49]: (a) similar to GENIUS, 1 ton of 'naked' HP Ge detectors (enriched in ^{76}Ge to 86%) will operate in ultra-high-purity liquid nitrogen; (b) LN_2 is contained in the vacuum cryostat (made of HP copper), the dimensions of which are as small as possible consistent with the necessity of eliminating the contributions of the radioactive contaminants in the Cu cryostat to the background of the HP Ge detectors and (c) the shield is composed of two parts: an inner shielding—ultra-high-purity LN_2, an outer part—high purity water in a large tank ($\phi 11 \times 11$ m) to suppress external background. It was proved by the MC simulations that the necessary LN_2 volume will be reduced substantially (≈ 40 tons instead of ≈ 1000 tons in GENIUS), and that the GEM sensitivity is similar to that of GENIUS: $T_{1/2}^{0\nu} \geqslant 10^{28}$ yr ($m_\nu \leqslant$ 0.015 eV) [49].

Now let us analyse the discovery potential of reviewed projects by using calculated dependences of that quantity versus the energy resolution of the detector (figure 2), and by taking into account the energy resolutions claimed in each particular proposal. The results of such an analysis are clear: only projects with the high energy resolution (GEM, GENIUS, MAJORANA with the HP ^{76}Ge detectors and CUORE with TeO_2 bolometers) have a chance to detect the $0\nu2\beta$ decay with the rate corresponding to neutrino mass $m_\nu \approx 0.01$ eV.

The discovery potential of other proposals is more modest. For example, for the EXO (FWHM = 5% at the $Q_{\beta\beta}$ energy) it equals $T_{1/2}^{0\nu} \approx 10^{26}$ yr (that is, $m_\nu \approx 0.2$ eV), for the MOON (FWHM = 7% at the $Q_{\beta\beta}$ energy) it is $T_{1/2}^{0\nu} \approx 2 \times 10^{23}$ yr ($m_\nu \approx 2$ eV), for the CAMEO (FWHM = 4%) the corresponding value is $T_{1/2}^{0\nu} \approx 2 \times 10^{25}$ yr ($m_\nu \approx 0.15$ eV), etc. However, it does not mean that mentioned projects would not be able to set the much higher half-life limit on the $0\nu2\beta$ decay. Such a sensitivity is determined by formula (1), thus with the proper values of the parameters (in this formula) it could be higher than the discovery potential even by several orders of magnitude.

Hence, we can conclude that a challenging scientific goal to observe the neutrinoless double beta decay with the rate corresponding to neutrino mass $m_\nu \approx 0.01$ eV could be, in principle, feasible for several future 2β experiments (namely, those with HP ^{76}Ge detectors and TeO_2 bolometers), while other projects (CAMEO, DCBA, EXO,^{160}Gd, etc.) would be able to set the restriction on the neutrino mass at the level of $m_\nu \leqslant 0.05$ eV.

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