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STUDY OF NEUTRINO PROPERTIES AND WEAK INTERACTION IN DOUBLE BETA DECAY EXPERIMENTS

F.A. Danevich
Institute for Nuclear Research
prospekt Nauky 47 MSP 03680 Kyiv, Ukraine
e-mail: danevich@kinr.kiev.ua
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Investigation of the neutrinoless double beta decay is a unique way to probe physics beyond the Standard Model. The process is sensitive to the lepton number violation, the nature of neutrino (Majorana or Dirac particle), an absolute scale of neutrino mass and the neutrino mass hierarchy. Neutrinoless double beta decay is still not observed, only limits on its half-life were set in the most sensitive experiments. The searches for double beta decay are carried out by different methods, in particular with low-background scintillation and semiconductor detectors. To determine a neutrino mass hierarchy new generation experiment should be sensitive to the effective neutrino mass 0.02 – 0.05 eV, which corresponds to the half-lives $T_{1/2} \sim 10^{26} – 10^{27}$ years and requires ultra-low background detectors with a high energy resolution applying hundreds kilograms of the isotope of interest. Low temperature scintillating bolometers are the most promising technique for such experiments.
KEY WORDS: double beta decay, neutrino, weak interaction, low counting experiment

ИССЛЕДОВАНИЯ СВОЙСТВ НЕЙТРИНО И СЛАБОГО ВЗАИМОДЕЙСТВИЯ В ЭКСПЕРИМЕНТАХ ПО ПОИСКУ ДВОЙНОГО БЕТА-РАСПАДА АТОМНЫХ ЯДЕР

Ф.А. Даневич
Институт ядерных исследований НАН Украины
проспект Науки 47, МСП 03680 Киев, Украина

Исследования безнейтринного двойного бета-распада атомных ядер представляют собой уникальную возможность поиска новых физических эффектов за рамками стандартной модели элементарных частиц. Этот процесс чувствителен к нарушению закона сохранения лептонного числа, природе нейтрино (частица Дирака или Майораны), величине массы и схеме массовых состояний нейтрино. Безнейтринный двойной бета-распад все еще не обнаружен, во все более чувствительных экспериментах устанавливаются лишь пределы на его вероятность. Поиски двойного бета-распада ведутся разными методами, в частности с помощью низкофоновых сцинтилляционных и полупроводниковых детекторов. Для определения схемы массовых состояний нейтрино эксперимент должен иметь чувствительность к эффективной массе нейтрино на уровне 0.02 – 0.05 эВ, что соответствует периодам полураспада $T_{1/2} \sim 10^{26}$ - 10^{27} лет и требует создания сверхнизкофоновых детекторов с высоким энергетическим разрешением и массой исследуемого изотопа сотни килограммов. Низкотемпературные сцинтилляционные болометры представляют собой наиболее перспективную технику для осуществления таких опытов.
КЛЮЧЕВЫЕ СЛОВА: двойной бета-распад, нейтрино, слабое взаимодействие, низкофоновый эксперимент

ДОСЛІДЖЕННЯ ВЛАСТИВОСТЕЙ НЕЙТРИНО І СЛАБКОЇ ВЗАЄМОДІЇ В ЕКСПЕРИМЕНТАХ З ПОШУКУ ПОДВІЙНОГО БЕТА-РОЗПАДУ

Ф.А. Даневич
Інститут ядерних досліджень НАН України
проспект Науки 47, МСП 03680 Київ, Україна

Дослідження безнейтринного подвійного бета-розпаду атомних ядер являють собою унікальну можливість пошуку нових фізичних ефектів за рамками стандартної моделі елементарних частинок. Цей процес чутливий до порушення закону збереження лептонного числа, природи нейтрино (частинка Дірака чи Майорани), величини маси і схеми масових станів нейтрино. Безнейтринний подвійний бета-розпад все ще не виявлений, у все більш чутливих експериментах встановлюються лише межі на його вірогідність. Пошуки подвійного бета-розпаду ведуться різними методами, зокрема з допомогою низькофонових сцинтиляційних і напівпровідникових детекторів. Для визначення схеми масових станів нейтрино експеримент повинен мати чутливість до ефективної масі нейтрино на рівні 0.02 – 0.05 еВ, що відповідає періодам напіврозпаду $T_{1/2} \sim 10^{26} – 10^{27}$ років і вимагає створення наднизькофонових детекторів з високою енергетичною роздільною здатністю та масою досліджуваного ізотопу сотні кілограмів. Низькотемпературні сцинтиляційні болометри є найбільш перспективною технікою для здійснення таких дослідів.
КЛЮЧОВІ СЛОВА: подвійний бета-розпад, нейтрино, слабка взаємодія, низькофоновий експеримент

Properties of neutrino and weak interaction play a key role in particle physics, cosmology and astrophysics. Measurements of neutrino fluxes from the Sun, from cosmic rays in atmosphere, from reactors and accelerators give strong evidence of neutrino oscillations, an effect which cannot be explained in framework of the Standard Model of particles [1]. Search for neutrinoless double beta decay is considered now as an unique tool to study properties of neutrino. Study of this extremely rare nuclear decay with the help of nuclear spectrometry methods, without building of expensive accelerators, allows to investigate effects beyond the Standard Model: nature of neutrino (is neutrino Dirac or

Majorana particle), an absolute scale and the mass scheme of neutrino, to check the lepton number conservation, to probe existence of hypothetical Nambu-Goldstone bosons (majorons) and right-handed currents in weak interaction [2-9].

The half-life of 0ν2β decay rate depends on the effective Majorana mass of neutrino and admixtures of right handed currents in weak interaction:

$$\left(T_{1/2}^{0\nu2\beta}\right)^{-1} = C_{mm}^{0\nu}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + C_{m\lambda}^{0\nu}\langle\lambda\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right) + C_{m\eta}^{0\nu}\langle\eta\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right) + C_{\lambda\lambda}^{0\nu}\langle\lambda\rangle^2 + C_{\eta\eta}^{0\nu}\langle\eta\rangle^2 + C_{\lambda\eta}^{0\nu}\langle\lambda\rangle\langle\eta\rangle,$$

where m_e is the electron mass, $\langle m_\nu\rangle$ is the effective Majorana neutrino mass, $\langle\lambda\rangle$ and $\langle\eta\rangle$ are the coupling strengths of the right-handed currents [10], coefficients $C_{ij}^{0\nu}$ can be defined through the nuclear matrix elements and phase space integrals of the 0ν2β decay. The effective Majorana mass of neutrino can be defined as following:

$$\langle m_\nu\rangle = \left|\sum U_{ej}^2 m_{\nu_i}\right|,$$

where m_{ν_i} are the mass eigenstates of neutrino, U_{ej} are the matrix elements of mixing between the mass eigenstates and flavor states of neutrino.

Investigations of double β decay are carrying out by different methods: geochemical, radiochemical, direct detection of the events by nuclear spectrometry. Taking into account an extremely low probability of the decay, the experimental facilities are placed deep underground in laboratories build in mines or tunnels. The two neutrino mode of the double β decay, being allowed in the Standard Model, is detected for 11 nuclei: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd and ^{238}U (see review [11] and references therein; for the recent observation of ^{136}Xe see [12,13]) with the half-lives in the range $T_{1/2} \sim 10^{19} - 10^{24}$ yr. In contrary, the neutrinoless decay is still not observed. Highest limits on the decay were set in direct experiments with several nuclei: $T_{1/2} \geq 10^{21}$ yr for ^{96}Zr [14], ^{114}Cd [15], ^{160}Gd [16], ^{150}Nd [17], ^{186}W [18]; $T_{1/2} \geq 10^{22}$ yr for ^{48}Ca [19], $T_{1/2} \geq 10^{23}$ yr for ^{82}Se [20,21], ^{100}Mo [22], ^{116}Cd [18], ^{128}Te [23], $T_{1/2} \geq 10^{24}$ yr for ^{130}Te [24] and $T_{1/2} \geq 10^{25}$ yr for ^{76}Ge [25,26] and ^{136}Xe [27,28]. These experiments restrict the effective Majorana neutrino mass $\langle m_\nu\rangle \leq (0.3 - 3)$ eV, the right-handed currents admixtures in the weak interaction ($\eta \leq 10^{-8}$, $\lambda \leq 10^{-8}$), the effective majoron-neutrino coupling constant ($g_M \leq 10^{-5}$). At the same time, HV Klapdor-Kleingrothaus with co-authors claims observation of 0ν2β decay of ^{76}Ge with the half-life $2.23^{+0.44}_{-0.31} \times 10^{25}$, which corresponds to the neutrino mass $\langle m_\nu\rangle = (0.32\pm0.03)$ eV [29]. Despite the skepticism of the scientific community, only new, more sensitive experiments could refute or confirm the claim.

Apart from the already running EXO and KamLand-Zen detectors [27,28], a few large-scale experiments are under construction or in R&D stage with the mass of isotopes of interest several tens – hundreds kg with the aim to achieve sensitivity to neutrinoless double β decay at the level of $T_{1/2} \sim 10^{26}$ yr, which corresponds to the neutrino mass $\langle m_\nu\rangle \sim 0.05$ eV. Taking into account the uncertainties of the theoretical calculations of the nuclear matrix elements, and the extremely low probability of the process, it is important to realize search for 0ν2β decay of different nuclei. Furthermore, to discard certainly an inverted hierarchy of the neutrino mass eigenstates one need to build experiments with the sensitivity to the neutrino mass on the level of 0.02 eV, which corresponds to the half-life $T_{1/2} \sim 10^{27}$ yr.

To achieve such a sensitivity a double β experiment should use about ton of isotope of interest, have an energy resolution of better than 1% and almost zero background. Cryogenic scintillating bolometers look only an option to realize such experiments with different nuclei [30] (in addition to germanium semiconductor detectors, which able to search by the calorimetric approach with high detection efficiency only ^{76}Ge). Currently, the most promising materials for cryogenic experiments are tellurium oxide crystals (assume simultaneous detection of Cerenkov light), zinc selenide, cadmium tungstate and zinc molybdate crystal scintillators.

Experimental investigations are concentrated mostly on $2\beta^-$ decays, processes featuring the emission of two electrons. Results for double positron decay ($2\beta^+$), electron capture with positron emission ($\varepsilon\beta^+$), and capture of two electrons from atomic shells (2ε) are much more modest. The most sensitive experiments give limits on the 2ε, $\varepsilon\beta^+$ and $2\beta^+$ processes on the level of $T_{1/2} \geq 10^{16} - 10^{21}$ yr. At the same time, studies of neutrinoless 2ε and $\varepsilon\beta^+$ decays could elaborate the mechanism of 0ν2β decay: is it due to the non-zero neutrino mass or to the right-handed admixtures in weak interactions [31,32]. Another important motivation to search for 0ν2ε decay appears from a possibility of a resonant process due to energy degeneracy between initial and final state of mother and daughter nuclei. Such a coincidence could give an enhancement of the 0ν2ε decay. The possibility of the resonant process was discussed in [33-36], where an increase of the decay rate by some orders of magnitude was predicted. Recent calculations show that the half-lives of some nuclei relatively to the neutrinoless electron capture can be comparable to the half-lives of the most promising 0ν2β decay candidates [37-39]. Several scintillation and HPGe experiments were performed to search for 2ε (including resonant processes on excited levels of daughter isotopes), $\varepsilon\beta^+$ and $2\beta^+$ decay in different nuclei.

In this paper, we review recent progress in the area of double beta decay experiments, in particular the results obtained in the Institute for Nuclear Research (Kyiv, Ukraine) by using scintillation method and low-background HPGe gamma spectrometry. Development of cryogenic scintillating bolometers, which is extremely promising technique to go towards the inverted hierarchy of the neutrino mass, is briefly discussed.

SCINTILLATION EXPERIMENTS

Scintillators are successfully used in experiments to search for double β decay. It is worth to mention a pioneering work of der Mateosian and Goldhaber to search for neutrinoless 2β decay of ^{48}Ca by using enriched and depleted in ^{48}Ca ($^{48}CaF_2$(Eu) and $^{40}CaF_2$(Eu)) crystal scintillators [40]. Several 2β experiments were realized using crystal scintillators, which contain candidate nuclei (see Table I).

In the 2β experiment carried out in the Solotvina Underground Laboratory (Ukraine) with the help of enriched in ^{116}Cd cadmium tungstate crystal scintillators [18] a very low counting rate of 0.04 counts/(year keV kg) was reached in the energy window 2.5 – 3.2 MeV where a peak from the 0ν2β decay of ^{116}Cd was expected. The half-life limit on the neutrinoless 2β decay of ^{116}Cd was set as $T_{1/2} \geq 1.7 \times 10^{23}$ years at 90% confidence level, which corresponds to one of the strongest restriction on the effective Majorana neutrino mass $\langle m_\nu \rangle \leq 1.7$ eV.

Table 1.

The most sensitive double β experiments with crystal scintillators

2β transition	Scintillator	Main results: half-life (channels)	Years [References]
^{40}Ca → ^{40}Ar	CaF_2(Eu)	$\geq 5.9 \times 10^{21}$ yr (2ν2ε) $\geq 3.0 \times 10^{21}$ yr (0ν2ε)	1997 [41]
^{48}Ca → ^{48}Ti	CaF_2(Eu)	$\geq 1.4 \times 10^{22}$ yr (0ν2β) $\geq 5.8 \times 10^{22}$ yr (0ν2β)	2004 [42] 2008 [19]
^{64}Zn → ^{64}Ni	$ZnWO_4$	$\geq 6.2 \times 10^{18}$ yr (2ν2K) $\geq 1.1 \times 10^{19}$ yr (2ν2K) $\geq 9.4 \times 10^{20}$ yr (2νεβ$^+$)	2008 [43] 2011 [44] 2011 [44]
^{70}Zn → ^{70}Ge	$ZnWO_4$	$\geq 3.8 \times 10^{18}$ yr (2ν2β) $\geq 3.2 \times 10^{19}$ yr (0ν2β)	2011 [44]
^{100}Mo → ^{100}Ru	$^{40}Ca^{100}MoO_4$	$\geq 4.0 \times 10^{21}$ yr (0ν2β)	2011 [45]
^{106}Cd → ^{106}Pd	$CdWO_4$	$\geq 2.6 \times 10^{17}$ yr (2νεβ$^+$) $\geq 5.5 \times 10^{19}$ yr (0νεβ$^+$)	1996 [46]
	$^{116}CdWO_4$	$\geq 1.2 \times 10^{18}$ yr (2νεβ$^+$) $\geq 7.0 \times 10^{19}$ yr (0νεβ$^+$)	2003 [18]
	$^{106}CdWO_4$	$\geq 2.1 \times 10^{20}$ yr (2νεβ$^+$) $\geq 2.2 \times 10^{21}$ yr (0νεβ$^+$) $\geq 4.3 \times 10^{20}$ yr (2ν2β$^+$) $\geq 1.2 \times 10^{21}$ yr (0ν2β$^+$)	2012 [47]
^{108}Cd → ^{108}Pd	$CdWO_4$	$\geq 1.0 \times 10^{18}$ yr (0ν2ε)	2008 [15]
^{114}Cd → ^{114}Sn	$CdWO_4$	$\geq 1.3 \times 10^{18}$ yr (2ν2β) $\geq 1.1 \times 10^{21}$ yr (0ν2β)	2008 [15]
^{116}Cd → ^{116}Sn	$^{116}CdWO_4$	$\geq 1.7 \times 10^{23}$ yr (0ν2β) $= 2.9 \times 10^{19}$ yr (2ν2β)	2003 [18]
^{130}Ba → ^{130}Xe	BaF_2	$\geq 1.4 \times 10^{17}$ yr (0νεβ$^+$)	2004 [48]
^{136}Ce → ^{136}Ba	CeF_3 $CeCl_3$	$\geq 2.7 \times 10^{16}$ yr (2ν2K) $\geq 2.4 \times 10^{16}$ yr (2νεβ$^+$)	2003 [49] 2011 [50]
^{138}Ce → ^{138}Ba	CeF_3 $CeCl_3$	$\geq 3.7 \times 10^{16}$ yr (2ν2K) $\geq 4.4 \times 10^{16}$ yr (2ν2K)	2003 [49] 2011 [50]
^{142}Ce → ^{142}Nd	GSO(Ce) $CeCl_3$	$\geq 1.6 \times 10^{17}$ yr (2ν2β) $\geq 1.4 \times 10^{18}$ yr (2ν2β)	2003 [16] 2011 [50]
^{160}Gd → ^{160}Dy	GSO(Ce)	$\geq 1.3 \times 10^{21}$ yr (0ν2β) $\geq 1.9 \times 10^{19}$ yr (2ν2β)	2001 [16]
^{180}W → ^{180}Hf	$ZnWO_4$	$\geq 1.0 \times 10^{18}$ yr (2ν2K) $\geq 1.3 \times 10^{18}$ yr (0ν2ε)	2011 [44]
^{186}W → ^{18O}Os	$ZnWO_4$ $^{116}CdWO_4$	$\geq 2.3 \times 10^{19}$ yr (2ν2β) $\geq 1.1 \times 10^{21}$ yr (0ν2β)	2011 [44] 2003 [18]

High concentration of isotope of interest is one of the most important requirements to 2β detectors. This requirement can be satisfied by production of crystal scintillators from enriched isotopes [51]. High cost of enriched materials imposes a few specific requirements to the technology on all the stages of scintillators production: as low as possible loss of enriched materials, high output of crystals, prevention of radioactive contamination, recovery and purification of the isotopes and their return to the production cycle. The most important issue is to minimize as much as possible radioactive contamination of scintillators, especially by radium and thorium. Low-thermal-gradient Czochralski method provides a few advantages in comparison to the standard Czochralski technique: large output of crystals up to 90%, low losses of high cost enriched isotopes (less than 1%), higher optical quality. One could expect also higher radiopurity, which feature needs additional studies.

Recently high quality radiopure cadmium tungstate crystal scintillators were developed from enriched ^{106}Cd [52] and ^{116}Cd [53]. Excellent optical and scintillation properties of these scintillators were obtained thanks to the deep purification of raw materials and low-thermal-gradient Czochralski technique to grow the crystals. The experiments to search for double β decay of ^{106}Cd and ^{116}Cd are in progress in the Gran Sasso underground laboratory (Italy). Calcium molybdate crystal scintillators from enriched ^{100}Mo and depleted in ^{40}Ca were developed by AMoRE collaboration to search for 0ν2β decay of ^{100}Mo [54]. Development of enriched in ^{100}Mo zinc molybdate crystal scintillators is in progress [55].

A first stage experiment to search for double β processes in ^{106}Cd was realized at the Gran Sasso underground laboratory with the help of the $^{106}CdWO_4$ crystal scintillator [52]. After 6590 h of data taking, new improved half-life limits on the double β decay of ^{106}Cd were established at the level of 10^{19}–10^{21} yr. In particular, $T_{1/2}^{2\nu\varepsilon\beta+} \geq 2.1 \times 10^{20}$ yr, $T_{1/2}^{2\nu2\beta+} \geq 4.3 \times 10^{20}$ yr, and $T_{1/2}^{0\nu2\varepsilon} \geq 1.0 \times 10^{21}$ yr. The resonant neutrinoless double-electron captures to the 2718 keV, 2741 keV, and 2748 keV excited states of ^{106}Pd are restricted on the level of $T_{1/2} \sim 10^{20}$ yr. A new phase of the experiment with the enriched $^{106}CdWO_4$ crystal operating in coincidence with four HPGe detectors of 225 cm^3 volume each is in progress [47].

A low background experiment to search for double β decay of ^{116}Cd with the help of the enriched $^{116}CdWO_4$ crystal scintillators is in progress [56]. A sensitivity of a 5 yr experiment (depending on a level of background) can be estimated as $T_{1/2} \sim (0.5 - 1.5) \times 10^{24}$ yr. It corresponds, taking into account the recent calculations of matrix elements [57-58], to the effective neutrino mass $\langle m_\nu \rangle \sim 0.4 - 1.4$ eV. Very low segregation of K, Th and Ra was observed in the compound, which can be used to reduce the radioactive contamination of the crystals by recrystallization.

INVESTIGATION OF DOUBLE β PROCESSES BY γ SPECTROMETRY

Ultra-low background γ spectrometry is successfully used to search for double β processes accompanied by γ and X rays: $2\beta^-$ transitions to excited levels of daughter nuclei, double electron capture (2ε), electron capture with positron emission ($\varepsilon\beta^+$), double positron decay ($2\beta^+$).

Table. 2.

Half-life limits on resonant 0ν double electron capture in ^{96}Ru, ^{156}Dy, ^{158}Dy, ^{184}Os and ^{190}Pt.

Process of decay		Level of daughter nucleus (keV)	Experimental limit (yr) at 90% confidence level	Years References
$^{96}Ru \to {}^{96}Mo$	*KL*	2^+ 2700	5.8×10^{18}	2009 [59]
	2L	2713	1.3×10^{19}	
$^{156}Dy \to {}^{156}Gd$	*2K*	2^+ 1914.8	1.1×10^{16}	2011 [60]
	KL_1	1^- 1946.4	9.6×10^{15}	
	KL_1	0^- 1952.4	2.6×10^{16}	
	$2L_1$	0^+ 1988.5	1.9×10^{16}	
	$2L_3$	2^+ 2003.8	2.8×10^{14}	
$^{158}Dy \to {}^{158}Gd$	$2L_1$	4^+ 261.5	3.2×10^{16}	
$^{184}Os \to {}^{184}W$	*2K*	$(0)^+$ 1322.2	2.8×10^{16}	2012 [61]
	KL	2^+ 1386.3	6.7×10^{16}	
	2L	2^+ 1431.0	8.2×10^{16}	
$^{190}Pt \to {}^{158}Gd$	*MM, MN, NN*	$(0,1,2^+)$ 1382.4	2.9×10^{16}	2011 [62]

An experiment to measure 2β decay of ^{100}Mo to excited states of ^{100}Ru was realized deep underground in the Gran Sasso laboratory with the help of an ultra-low background semiconductor germanium detector. A 1.2 kg sample of molybdenum oxide enriched in ^{100}Mo to 99.5% was measured over 18120 h. Two γ quanta of 540 keV and of 591 keV emitted in the de-excitation process after two neutrino double β decay of ^{100}Mo to the 0^+_1 excited level of ^{100}Ru with the energy 1131 keV were observed both in coincidence and in the sum spectra. The measured half-life of ^{100}Mo relatively to the transition is $T_{1/2} = 6.9^{+1.0}_{-0.8}$ (stat.) ± 0.7 (syst.) $\times 10^{20}$ yr [63], in agreement with results of previous experiments [64-66].

Possible resonant processes were studied in ^{96}Ru, ^{156}Dy, ^{158}Dy, ^{184}Os, and ^{192}Pt with the help of ultra-low background HPGe detectors at the Gran Sasso laboratory. For this purpose samples of ruthenium, dysprosium, platinum and osmium of high purity grade were measured a few thousand hours each. No peculiarities have been observed in the data which can be ascribed to the effects searched for. Half-life limits on resonant double electron capture in ruthenium, dysprosium, osmium and platinum isotopes established in the experiments are presented in Table 2.

LOW TEMPERATURE SCINTILLATING BOLOMETERS

According to Zdesenko [2] a sensitivity of a double β decay experiment (in terms of the lower half-life limit, lim $T_{1/2}$) can be expressed as following:

$$\lim T_{1/2} \sim \varepsilon \cdot \delta \sqrt{\frac{m \cdot t}{R \cdot BG}},$$

where ε is the detection efficiency, δ is the concentration of the isotope of interest, t is the measurement time, m, R and BG are the mass, energy resolution and background of the detector. Therefore, energy resolution is an important characteristic of a double β decay detector. Furthermore, as it was demonstrated in [67], the energy resolution plays a crucial role due to irremovable background coming from the two neutrino decay. It should be stressed that a few % energy resolution remains acceptable as far as the phenomenon is *not observed*: it still allows to suppress the background caused by two neutrino 2β decay events in the energy region of interest. However, the energy resolution becomes a crucial parameter in case if *an indication* of 0ν2β decay is obtained. Indeed, even in a case of high resolution HPGe detectors (with typical energy resolution over long time measurements FWHM ≈ 4 keV at $Q_{2\beta}$ of ^{76}Ge), one cannot exclude possibility to falsify the effect of the 0ν2β decay of ^{76}Ge (see e.g. [68]).

Apart from HPGe detectors (at present the most sensitive technique to search for 0ν2β decay of ^{76}Ge [25,69]), only cryogenic bolometers [30,70,71] are able to provide comparable energy resolution to realize large scale high sensitivity experiments to search for 0ν2β decay of different isotopes thanks to high energy resolution (a few keV) and detection efficiency (near 70% – 90% depending on crystal composition and size). Development, during the last decade, the technique of low temperature *scintillating* bolometers give a "second wind" for the scintillation method allowing to reach very high energy resolution, which are especially important feature for the next generation double β experiments. In addition to excellent energy resolution on the level of a few keV at energies 2 – 3 MeV, cryogenic scintillators allows almost complete particle discrimination ability. The technique also offers a very important possibility to use compounds with nuclei of interest. A few R&D projects are in progress to build double β decay experiments with aim to explore inverted hierarchy of neutrino mass by using $CaMoO_4$ [54], ZnSe [72], $CdWO_4$ [73], and $ZnMoO_4$ [55,74] crystal scintillators.

However, a disadvantage of cryogenic bolometers is a poor time resolution, typically a few ms. It can lead to background up to the energy of $2 \times Q_{2\beta}$ due to random coincidence of 2ν2β events. The random coincidence of 2ν2β events as a source of background in high-sensitivity 0ν2β cryogenic experiments was considered and discussed for the first time in [55]. The contribution of random coincidences of 2ν2β events to the counting rate in the energy region of the expected 0ν2β peak was estimated in [75]. It was shown that the pile-up effect can be substantially reduced by pulse-shape analysis and application of faster sensors in cryogenic scintillating bolometers.

CONCLUSIONS

Search for neutrinoless double β decay is one of the most promising ways to prove new physics beyond the Standard Model of particles. Despite almost seventy years of attempts the process still remains unobserved. Only half-life limits on the level of $T_{1/2} \sim 10^{22} - 10^{25}$ yr were set in the most sensitive experiments, which allow to restrict a Majorana neutrino mass on the level of 0.3 – 3 eV, set strong limits on admixture of right currents in weak interactions and on the decay with emission of majorons. Several experiments are in preparation or in R&D stage to explore the inverted hierarchy of the neutrino mass. In a case of non-observation of the decay on the level of sensitivity to the neutrino mass ≈ 0.02 eV one could conclude that a normal scheme of the neutrino mass eigenstates is realized.

Investigation of transitions to excited levels of daughter nuclei and search for "double beta plus processes" are carried out with the help of ultra-low background HPGe γ spectrometry. Investigation of neutrinoless 2ε and $\varepsilon\beta^+$ decays, as well as measurements of 0ν2β decay to 2^+ excited levels of daughter nuclei, could refine mechanism of 0ν2β decay if the process will be observed: is it due to the light neutrino mass mechanism or due to an admixture of right handed currents in weak interactions. Search for resonant neutrinoless double electron capture is considered as an alternative way to study properties of neutrino.

Scintillation detectors are widely used in the double β decay experiments. Using of crystal scintillators as scintillating bolometers with high energy resolution and low background is especially promising approach. A few high sensitivity experiments intending to apply this technique are under construction or in R&D stage to explore an inverted hierarchy of the neutrino mass.

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