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DOUBLE BETA DECAY

CAMEO/GEM Program and Future of Double-β-Decay Research*

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Abstract—The current results and future prospects of the 2β-decay research are reviewed. The requirements for supersensitivity experiments are formulated and a conclusion is derived that, in the developed CAMEO and GEM projects, the restrictions on the neutrino mass would be pushed down to $m_\nu \leq$ (0.015–0.05) eV. Moreover, the GEM I setup with natural HPGe detectors could advance the best current limits on the existence of neutralinos—as dark matter candidates—by three order of magnitudes and, at the same time, would be able to identify unambiguously the dark matter signal by detection of its seasonal modulation. *© 2002 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

Studies on double-beta (2β) decay play a very important role in neutrino physics [1–4], which has undergone a revolution. Indeed, the latest solar neutrino data [5, 6], the measured deficit of the atmospheric muon neutrinos flux [7], and the result of the LSND accelerator experiment [8] all could be explained by means of the neutrino oscillations, requiring nonzero neutrino masses (m_ν) and demonstrating an existence of new physical effects beyond the Standard Model (SM) [9]. However, oscillation experiments are sensitive to neutrino mass difference, while only the measured $0\nu2\beta$-decay rate can indicate the Majorana nature of the neutrino and give the absolute scale of its effective mass [10, 11]. The neutrinoless $(0\nu)2\beta$ decay is forbidden in the SM since it violates lepton-number (L) conservation. However, many extensions of the SM incorporate such interactions and could lead to $0\nu2\beta$ decay, whose nonvanishing rate requires neutrinos to be massive Majorana particles [12].

Therefore, the $0\nu2\beta$ decay is considered now as a powerful test of new physical effects beyond the SM, which allows one to narrow a wide choice of theoretical models and to reach the multi-TeV energy range competitive to accelerator experiments [1–4].

Despite many efforts to detect $0\nu2\beta$ decay, this process still remains unobserved [13]. The highest half-life limits were set in direct experiments: $T^{0\nu}_{1/2} \geq 10^{22}$ yr for ^{82}Se [14], ^{100}Mo [15]; $T^{0\nu}_{1/2} \geq 10^{23}$ yr for ^{116}Cd [16], ^{128}Te, ^{130}Te [17], ^{136}Xe [18]; and $T^{0\nu}_{1/2} \geq 10^{25}$ yr for ^{76}Ge [19, 20]. These results have brought the most stringent restrictions on the Majorana neutrino mass $m_\nu \leq$ (0.5–5.0) eV, right-handed admixture in the weak interaction $\lambda \approx 10^{-5}$, the ν–Majoron coupling constant $g_M \approx 10^{-4}$, and the R-parity[1)]-violating parameter of the minimal SUSY model $\varepsilon \approx 10^{-4}$. It is very desirable to improve this level of sensitivity by one to two orders of magnitude [2, 4]. There are strong reasons that such a goal has to be reached with several nuclei. First, there are large discrepancies between calculated [1, 3] and measured half-lives of the $2\nu2\beta$ decay of ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, and ^{150}Nd [13]; therefore, a variety of 2β candidates has to be studied.[2)] Second, the 2β-decay research is on the front edge of modern technology; thus, new development could bring an advantage to particular 2β-decay candidates, and, hence, several of them should be used. Third, if $0\nu2\beta$ decay is observed by one experiment, such a discovery will have to be confirmed with other nuclides and by using another technique that should be properly developed by then. For instance, the ^{76}Ge result $T^{0\nu}_{1/2} \geq 10^{21}$ yr obtained in 1970 [21] was advanced up to $T^{0\nu}_{1/2} \geq 10^{25}$ yr after 30 years of strong efforts [19, 20].

There are two classes of 2β-decay experiments: with a "passive" source and with an "active" source, where the detector containing 2β candidate nuclei

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[1)] R-parity is defined as $R_p = (-1)^{3B+L+2S}$, where B and L are the baryon and lepton numbers, respectively, and S is the spin.

[2)] Let us reinforce it by a citation from [4]: "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."

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serves as source and detector simultaneously. If the $0\nu2\beta$ decay occurred, the sharp peak at the $Q_{\beta\beta}$ value would be observed in the electron sum energy spectrum of the detector. The sensitivity of the setup can be expressed in terms of a lower half-life limit as following [22, 23]: $\lim T_{1/2} \sim \eta\delta\sqrt{(mt)/(R\cdot \mathrm{Bg})}$. Here, η is the detection efficiency; δ is the abundance or enrichment of candidate nuclei contained in the detector; t is the measuring time; m is the total mass of the active or passive source; R is the energy resolution (FWHM) of the detector; and Bg is the background rate in the energy region of the 0ν-decay peak. It is clear from this equation that η and δ are the most important characteristics, because all other parameters are under the square root. Obviously, $\approx$ 100% enrichment and detection efficiency are very desirable. The energy resolution of the detector is very essential because events from the high-energy tail of the 2ν distribution run into the energy window of the 0ν peak, generating background that cannot be discriminated from the 0ν signal. Better energy resolution minimizes this irreducible background. Taking into account these considerations and on the basis of the present status of 2β-decay experiments, one can formulate the following requirements for the future projects:

(i) The best 0ν limits were reached with the help of the active source method; thus, most likely, the future projects will belong to the same class because only in this case can the detection efficiency be close to 100%.

(ii) The highest ^{76}Ge results were obtained with $\approx$10 kg of enriched detectors; hence, in the future one has to exploit enriched sources with masses of hundreds of kilograms. Only several candidate nuclei (^{76}Ge, ^{82}Se, ^{116}Cd, ^{130}Te and ^{136}Xe) could be mass-produced by means of centrifugal separation [23].

(iii) Because of the square-root dependence of the sensitivity vs. mass, it is not enough to increase the detector mass alone. The background should also be reduced down practically to zero.

(iv) The energy resolution is a crucial characteristic, and for challenging projects the FWHM value cannot be worse than $\approx$4% at $Q_{\beta\beta}$ energy.

(v) The setups should be as simple as possible to provide reliable operation during long ($\approx$10 yr) future experiments.

Evidently, it is difficult to find a project that would completely satisfy these severe requirements. Let us consider those proposed during the past few years briefly.

A new approach to study 2β decay of ^{136}Xe ($Q_{\beta\beta} = 2468$ keV) makes use of the coincident detection of $^{136}\mathrm{Ba}^{2+}$ ions 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 [24–26]. In the recent EXO project [27], the resonance ionization spectroscopy for the identification of $^{136}\mathrm{Ba}^{2+}$ ions would be applied in a 40-m^3 TPC operated at 5–10-atm pressure of 1–2 t of ^{136}Xe. The claimed sensitivity to neutrino mass is 0.01 eV [27]. Another idea is to dissolve 80 kg (1.5 t) of enriched (natural) Xe in the liquid scintillator of the BOREXINO Counting Test Facility (CTF) in order to reach the $T^{0\nu}_{1/2}$ limit in the range of 10^{24}–10^{25} yr [28].

The project MOON aims to make both the study of $0\nu2\beta$ decay of ^{100}Mo ($Q_{\beta\beta} = 3034$ keV) and the real-time studies of low-energy solar ν by inverse β decay [29]. The detector module will be composed of 60 000 plastic scintillators (6 m × 0.2 m × 0.25 cm) with 34 t of natural Mo in the form of foil (50 mg/cm^2). The sensitivity of such a module to the neutrino mass could be on the order of 0.05 eV [29].

In the DCBA proposal (KEK, Japan) [30], the drift chamber placed in the magnetic field (0.6 kG) can measure the momentum of each β particle emitted in 2β decay and the position of the decay vertex with the $3D$ reconstruction of the tracking. With 18 kg of an enriched ^{150}Nd ($Q_{\beta\beta} = 3367$ keV) passive source (50 mg/cm^2), the sensitivity to the Majorana neutrino mass is 0.05 eV [30].

The experiment with ^{160}Gd ($Q_{\beta\beta} = 1730$ keV; $\delta = 21.9\%$) by using the GSO multicrystal array with the total mass of 1–2 t (200–400 kg of ^{160}Gd) is suggested with the projected sensitivity to the Majorana neutrino mass of 0.04 eV [31].

The future Yb-loaded liquid scintillation detectors LENS, which is under development for solar neutrino spectroscopy [32], would also be used for studies on $2\beta^-$ decay of ^{176}Yb ($Q_{\beta\beta} = 1087$ keV) and $\varepsilon\beta^+$ decay of ^{168}Yb ($Q_{\beta\beta} = 1422$ keV). With 20 tons of natural Yb (2.5 t of ^{176}Yb), the limit $T^{0\nu}_{1/2} \geq 10^{26}$ yr could be set on $0\nu2\beta$ decay of ^{176}Yb ($m_\nu \leq 0.1$ eV) [33].

There are also two projects, NEMO-3 [34] and CUORICINO [35], under construction now. The sensitivity of the NEMO-3 tracking detector with a passive source of 10 kg of ^{100}Mo would be on the level of 4×10^{24} yr ($m_\nu \leq 0.3$–0.5 eV) [36]. The CUORICINO setup consists of 60 low-temperature bolometers made of TeO$_2$ crystals (mass of 750 g each) and is designed as a pilot step for a future CUORE project for the 2β decay quest of ^{130}Te with the help of one thousand TeO$_2$ bolometers (total mass of 750 kg) [35, 37]. With the energy resolution of TeO$_2$ bolometers of 5–10 keV at 2.5 MeV, the CUORE sensitivity is quoted by authors for a different background rate (0.5–0.05 counts/(yr kg keV) at 2.5 MeV) and would be as high as $T_{1/2}^{0\nu} \geq (1–5) \times 10^{25}$ yr ($m_\nu \leq 0.05–0.2$ eV) [35, 37].

In addition, there are two projects for the 2β-decay quest of ^{76}Ge (MAJORANA [38] and GENIUS [39]). The idea of the MAJORANA is to use 210 HPGe (enriched in ^{76}Ge to 86%) semiconductor detectors (total mass of 500 kg) contained in a conventional superlow-background cryostat and shielded by HP lead or copper [38]. The segmentation of crystals and pulse-shape analysis of data would reduce background rate to the level of 0.01 counts/(yr kg keV) at an energy of 2 MeV, i.e., 6 times lower than that already reached in the ^{76}Ge experiments [19, 20]. The MAJORANA sensitivity can be expressed with the help of formula

$$\lim T_{1/2}^{0\nu} = (\ln 2)\eta N t / \lim S, \tag{1}$$

where N is the number of ^{76}Ge nuclei, η is the detection efficiency, t is the measuring time, and $\lim S$ is the maximal number of $0\nu 2\beta$ events which can be excluded with a given confidence level. To estimate value of $\lim S$, we can use the so-called “one (two, ...) σ approach,” in which $\lim S$ value is determined simply as the square root of the number of background counts in the energy region of interest, multiplied by the parameter 1 (1.6 or 2) for the confidence level of 68% (90 or 95%). After 10 yr of measurements, about 200 background counts will be recorded in the vicinity of 0ν peak (in a 4-keV energy interval), and whereby one can get $\lim S \approx 20$ counts at 90% C.L. On this basis, the half-life limit can be determined by formula (1) as $T_{1/2}^{0\nu} \geq 10^{27}$ yr. Depending on the nuclear matrix element (NME) calculations [1, 3, 19, 40, 41], it leads to the following interval of the neutrino mass limit: $m_\nu \leq 0.05–0.15$ eV.

The GENIUS project intends to operate one ton of “naked” HPGe (enriched in ^{76}Ge to 86%) detectors placed in extremely high purity liquid nitrogen (LN$_2$), which simultaneously serves as a cooling medium and shield [39]. Owing to that, the background of the GENIUS setup would be reduced by a factor of 300 compared to that of present experiments [19, 20]. The feasibility of operating naked Ge detectors in LN$_2$ was demonstrated with three HPGe crystals placed inside liquid nitrogen—the energy threshold of 2 keV and the resolution of 1 at 300 keV were obtained [42]. In accordance with the Monte Carlo background simulations [39, 43], the necessary dimensions of the LN$_2$ shield (to fully suppress the radioactivity from the surroundings) should be about 12 m in diameter and 12 m in height. The required radiopurity of the liquid nitrogen should be as low as 10^{-15} g/g for ^{40}K and ^{238}U, 5×10^{-15} g/g for ^{232}Th, and 0.05 mBq/m^3 for ^{222}Rn [39, 43]. All these requirements (except for radon) are less stringent than those already reached for the liquid scintillators of the BOREXINO CTF (5×10^{-16} g/g for ^{232}Th and ^{238}U) [44]. The final conclusion is derived that the total GENIUS background rate in the energy region of the $0\nu 2\beta$-decay peak of ^{76}Ge could be reduced down to 0.2 count/(yr t keV) [39, 43]. On this basis, the $T_{1/2}$ limit can be estimated similarly as for the MAJORANA proposal. For a 10-yr measuring time, the value of $\lim S$ is equal to 5 counts (90% C.L.); thus, with 7×10^{27} nuclei of ^{76}Ge, the bound $T_{1/2}^{0\nu} \geq 10^{28}$ yr could be achieved, which translates to the neutrino mass constraints $m_\nu \leq 0.015–0.05$ eV.

However, all the aforementioned projects require a significant amount of R&D to demonstrate their feasibility; thus, strong efforts and perhaps a long time will be needed before their realization. To this effect, in the present paper, we suggest the CAMEO program of the high-sensitivity 2β-decay experiments, whose accomplishment seems to be realistic.

2. CAMEO EXPERIMENT WITH ^{116}CdWO$_4$ SCINTILLATORS

It is proposed [45] to use the already existing BOREXINO CTF [44, 46, 47] for the 2β-decay study of ^{116}Cd by placing 100 kg of enriched ^{116}CdWO$_4$ crystal scintillators in the liquid scintillator of the CTF, serving as light guide and veto shield. The CTF (installed in the Gran Sasso Underground Laboratory) consists of an external 1000-t water tank (⊘11 × 10 m) serving as shield for 4.8 m^3 of liquid scintillator contained in an inner vessel of ⊘2.1 m. The radiopurity of water is 10^{-14} g/g for U/Th, 10^{-10} g/g for K, and <5 μBq/l for ^{222}Rn [44, 47]. The high-purity (5×10^{-16} g/g for U/Th) liquid scintillator (1.5 g/l of PPO in pseudocumene) has an attenuation length ≥ 5 m above 380 nm and a principal scintillator decay time of 5 ns [48]. The inner transparent vessel made of nylon film, 500 μm thick, allows one to collect the scintillation light with the help of 100 phototubes (PMT) 8 in. in diameter fixed at a diameter of 7 m inside the water tank.

The ^{116}Cd studies performed by the INR (Kiev) in the Solotvina Underground Laboratory with the help of ^{116}CdWO$_4$ crystals [16, 49–52] is considered as the pilot step of the CAMEO project. Let us briefly recall their main results. The light output of cadmium tungstate crystal scintillators (enriched in ^{116}Cd to 83%) [49] is 40% of NaI(Tl), and maximal peak emission is at 480 nm with a principal decay time of 14 μs [53]. The refractive index of CdWO$_4$ crystal is 2.3, the density is 7.9 g/cm^3, and the material is nonhygroscopic and chemically inert. In the latest phase of the experiment, four ^{116}CdWO$_4$ crystals (total mass 339 g) have been used. The detectors are viewed by the low background 5 in. EMI tube (with RbCs photocathode) through one light guide $\oslash 10 \times 55$ cm. Enriched detectors are surrounded by an active shield made of 15 natural CdWO$_4$ crystals [54] with a total mass of 20.6 kg. The latter are viewed by a PMT through an active plastic light guide $\oslash 17 \times 49$ cm. The whole CdWO$_4$ array is situated in an additional active shield made of plastic scintillator $40 \times 40 \times 95$ cm^3. The outer passive shield consists of HP copper (3–6 cm), lead (22.5–30 cm), and polyethylene (16 cm). The data acquisition records the amplitude, arrival time, and pulse shape (PS) of each ^{116}CdWO$_4$ event. The PS technique is based on an optimal digital filter and ensures clear discrimination between γ rays and α particles and, hence, selection of "illegal" events: double pulses, α events, etc. [53].

The energy resolution of the main detector is 11.5% at 1064 keV and 8.0% at 2615 keV. For the energy spectrum measured for 4629 h with four ^{116}CdWO$_4$ crystals [16], the background rate in the energy region of 2.5–3.2 MeV is 0.03 count/(yr kg keV), which is achieved due to PS and time-amplitude analysis of the data. For example, the following sequence of α decays from ^{232}Th family was sought: $^{220}\mathrm{Rn}(Q_\alpha = 6.40\ \mathrm{MeV}, T_{1/2} = 55.6\ \mathrm{s}) \rightarrow {}^{216}\mathrm{Po}(Q_\alpha = 6.91\ \mathrm{MeV}, T_{1/2} = 0.145\ \mathrm{s}) \rightarrow {}^{212}\mathrm{Pb}$. The activity of ^{228}Th in ^{116}CdWO$_4$ crystals was determined at 38(3) μBq/kg. The same technique applied to the sequence of α decays from the ^{235}U family yields 5.5(14) μBq/kg for ^{227}Ac impurity in the crystals [16].

The $T_{1/2}$ limits for $0\nu2\beta$ decay are set at $T_{1/2}^{0\nu} \geq 0.7\ (2.5) \times 10^{23}$ yr at 90% (68%) C.L., while, for 0ν decay with Majoron emission, they are set at $T_{1/2}^{0\nu}(\mathrm{M1}) \geq 3.7\ (5.8) \times 10^{21}$ yr at 90% (68%) C.L. [16]. These translate into constraints on the neutrino mass $m_\nu \leq 2.6$ (1.4) eV (using calculations [55]) and on the neutrino-Majoron coupling constant $g_M \leq 12\ (9.5) \times 10^{-5}$ (with [56]), both at 90% (68%) C.L. [16]. However, further advance of the neutrino mass limit into the sub-eV domain could be possible only in case of substantial sensitivity enhancement, which is the main goal of the CAMEO project.

In the preliminary design of the CAMEO experiment, 40 enriched ^{116}CdWO$_4$ crystals of large volume (320 cm^3) are placed in the liquid scintillator of the CTF and homogeneously spread on the sphere 0.8 m in diameter. With 2.5 kg of mass for each crystal ($\oslash 7 \times 8$ cm), the total number of ^{116}Cd nuclei is 1.5×10^{26}. It is assumed that 200 PMTs with light concentrators are fixed at a diameter of 5 m, providing an optical coverage of 80%. The CdWO$_4$ scintillator yields 1.5×10^4 emitted photons per 1 MeV of the energy deposited. The GEANT Monte Carlo simulation of the light propagation in this geometry gives 4000 p.e. for 2.8-MeV energy deposit; thus, the $0\nu2\beta$-decay peak of ^{116}Cd would be measured with an energy resolution FWHM equal to 4%. The principal feasibility of obtaining such an energy resolution with CdWO$_4$ crystal has been demonstrated by the measurements with cylindrical CdWO$_4$ crystal ($\oslash 40 \times 30$ mm) placed in transparent paraffin oil (refractive index 1.5) [45]. A 42% increase of the light collection and improvement of the energy resolution has been obtained: the FWHM values (7.4% at 662 keV, 5.8% at 1064 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 [45].

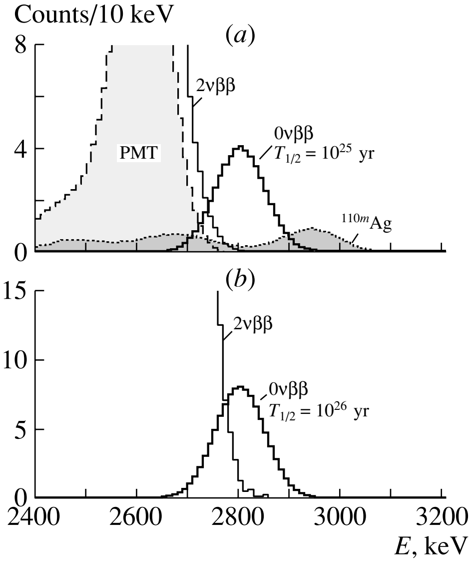

Fig. 1. (*a*) The response functions of the CAMEO [45] with 100 kg of ^{116}CdWO$_4$ crystals in the CTF (after 5-yr measuring period) for 2β decay of ^{116}Cd with $T_{1/2}^{2\nu} = 2.7 \times 10^{19}$ yr and $T_{1/2}^{0\nu} = 10^{25}$ yr (solid histogram). The simulated contribution from ^{208}Tl in the PMTs (dashed line) and from cosmogenic ^{110m}Ag (dotted line). (*b*) The response functions of the 1000 kg of ^{116}CdWO$_4$ crystals placed into a large liquid neutrino detector (BOREXINO, etc.) for 2β decay of ^{116}Cd with $T_{1/2}^{2\nu} = 2.7 \times 10^{19}$ yr and $T_{1/2}^{0\nu} = 10^{26}$ yr (solid histogram) and for 10-yr measuring time.

The background simulation for the CAMEO was performed with the help of the GEANT3.21 [57] and DECAY4 [58] codes. The simulated contributions from different background sources and response functions for 2β decay of ^{116}Cd with $T_{1/2}^{2\nu} =$

2.7×10^{19} yr and $T_{1/2}^{0\nu} = 10^{25}$ yr are depicted in Fig. 1*a*. The sensitivity of the CAMEO experiment is $T_{1/2}^{0\nu} \geq 10^{26}$ yr, which translates to the neutrino mass bound $m_\nu \leq 0.06$ eV [45]. It is also evident from Fig. 1*a* that $0\nu2\beta$ decay of ^{116}Cd with a half-life of 10^{25} yr would be clearly registered. Moreover, with 1 t of $^{116}CdWO_4$ detectors placed in one of the existing or future large underground neutrino detectors as BOREXINO [44], the sensitivity is estimated at $T_{1/2}^{0\nu} \geq 10^{27}$ yr (Fig. 1*b*), which corresponds to the restriction on the neutrino mass of 0.02 eV [45]. The simplicity and reliability are the main advantages of the CAMEO technique with $^{116}CdWO_4$ crystals, but the poor energy resolution of the latter is a factor that limits further sensitivity enhancement. Thus, in the next section, we will consider the GEM project devoted to the 2β-decay study of ^{76}Ge with the help of HPGe semiconductor detectors.

3. THE GEM PROJECT FOR THE 2β-DECAY QUEST OF ^{76}Ge

As it was mentioned, the project GENIUS [39] is aimed at reaching the bound $T_{1/2}^{0\nu} \geq 10^{28}$ yr for the 2β decay of ^{76}Ge ($m_\nu \leq 0.015$–0.05 eV). However, to achieve such a goal, the GENIUS apparatus must satisfy very stringent and contradicting demands. For example, a super-low background rate of detectors requires an ultrahigh purity of liquid nitrogen and large dimensions of the vessel ($\oslash 12 \times 12$ m) with 1000 t of LN_2. The power and maintenance costs of the LN_2 purification system strongly depend on the liquid nitrogen consumption, which, in turn, depends on the dimensions of the LN_2 tank (heat losses through the walls are directly proportional to their square) and the quality of the thermoinsulation. In the GENIUS, a polyethylene foam insulation 1.2 m thick is accepted [39], which would lead to a large LN_2 consumption. Thus, it could be very difficult to maintain the required ultrahigh purity of LN_2 during running of the experiment because evaporation of LN_2 is the method of purification, so pure vapor will leave vessel, while all impurities will stay in the remaining LN_2. These problems would be checked and perhaps solved with the help of the test facility (GENIUS-TF), which is under development now [59]. Anyhow, it is clear that production, purification, operation, and maintenance of more than one kiloton of ultrahigh purity liquid nitrogen in an underground laboratory would require additional efforts and a considerable amount of time.

Aiming to make realization of the high-sensitivity ^{76}Ge experiment simpler, the GEM design is based on the following keystone ideas [60]:

(a) "Naked" HPGe detectors (enriched in ^{76}Ge to 86–90%) operate in the ultrahigh purity liquid nitrogen serving as the cooling medium and the first layer of the shield simultaneously.

(b) LN_2 is contained in the vacuum cryostat made of HP copper. The dimensions of the cryostat are as minimal as necessary to eliminate the contribution of the radioactive contaminations of the Cu cryostat to the detector background.

(c) The shield is composed of two parts: (i) inner shield—ultra-high purity LN_2 (10^{-15} g/g for ^{40}K and ^{238}U, 5×10^{-15} g/g for ^{232}Th, and 0.05 mBq/m^3 for ^{222}Rn); (ii) outer part—HP water, whose volume is large enough to suppress external background to a negligible level.

The optimization of the setup design was performed with the help of the GEANT3.21 package and event generator DECAY4. About 400 HP Ge detectors ($\oslash 8.5 \times 8.5$ cm, weight of 2.5 kg each) are located in the center of a Cu sphere (inner enclosure of the cryostat 4.5 m in diameter and 0.6 cm thick) filled with liquid nitrogen. The detectors, arranged in nine layers, occupied a space of 90 cm in diameter. It is supposed that crystals are fixed with the help of a holder system made of nylon strings. The thin Cu wire $\oslash 0.2$ mm is attached to each detector to provide signal connection. The outer encapsulation of the cryostat 5 m in diameter is also made of HP Cu 0.6 cm thick. Both spheres are connected by two concentric Cu pipes with vacuum pump maintaining 10^{-6}-torr pressure in the space between two walls of the cryostat. The latter allow one to reduce the heat current through the walls of the cryostat to the value of 2.5 W/m^2 [61]; thus, total heat losses (including heat conduction through pipes, support structure, and cables) are near 200 W. This corresponds to a LN_2 consumption less than 100 kg/d. The cryostat is placed into the HP (10^{-14} g/g for ^{40}K, ^{232}Th, and ^{238}U and 10 mBq/m^3 for ^{222}Rn) water shield with a mass of 1000 t contained in the steel tank $\oslash 11 \times 11$ m^2. The dimensions of the CTF water tank are practically the same ($\oslash 11 \times 10$ m); hence, this shield could be also used for the GEM experiment. The design of the GEM setup reduces the LN_2 volume and allows us to solve problems of thermoinsulation, ultrahigh purity conditions, LN_2 consumption, safety requirements, etc.

The described model of the setup was used for background simulations. The total mass of detectors is equal to 1 t, liquid nitrogen mass is about 40 t, Cu cryostat mass is 7 t, mass of the water shield is 1000 t, holder-system mass is 2 kg, and mass of Cu wires is 1 kg. The internal and external origins of the background were investigated carefully. Internal background arises from residual impurities in the Ge crystals themselves and surroundings (crystal holder system, liquid nitrogen, Cu cryostat, water, steel vessel) and from activation of all aforementioned materials at the Earth's surface. External background is generated by events originating outside the shield, such as photons and neutrons from the Gran Sasso rock, muon interactions, and muon induced activities.

The possible radioactive contaminations of the Ge detectors and materials by ^{40}K and ^{232}Th/^{238}U chains were taken from the real measurements [19, 44, 59, 62, 63]. The radiopurity criteria supposed for the liquid nitrogen (10^{-15} g/g for ^{40}K and ^{238}U, 5×10^{-15} g/g for ^{232}Th) seem to be realistic in light of the purity of the liquid scintillators already achieved by the BOREXINO collaboration [44]. Moreover, recently, the ^{222}Rn contamination of the LN$_2$ was also reduced down to the level of 1 μBq/m^3 [64]. It was shown by our calculation that requirements for the purity of the GEM water shield can be lowered to the level of about 10^{-13} g/g for U/Th contaminations [60].

Cosmogenic activities in HP ^{76}Ge detectors were estimated with the help of the program COSMO [65]. An activation time of 30 d at sea level[3] and a deactivation time of 3 yr underground were assumed. It was found that background at 2038 keV is caused mainly by ^{22}Na, ^{60}Co, and ^{68}Ga (a daughter of cosmogenic ^{68}Ge), whose contributions could be lowered to a value less than $3{\times}10^{-2}$ count/(yr t keV) near 2038 keV [60].

Summarizing all background origins (internal and external), the total background rate of the GEM experiment is less than 0.2 count/(yr t keV) at 2038 keV. The simulated response functions of the GEM setup after a 10-yr measuring time for 2β decay of ^{76}Ge with $T_{1/2}^{2\nu} = 1.8 \times 10^{21}$ yr [62] and $T_{1/2}^{0\nu} = 10^{27}$ yr, as well as the background contribution from the holder system and Cu cryostat, are depicted in Fig. 2. The background at energies below 1950 keV is dominated by $2\nu 2\beta$ decay of ^{76}Ge ($2.6{\times}10^7$ counts), while at 2040 keV the main contributions are from contamination of the holder system and Cu cryostat by U/Th chains. It is evident from Fig. 2 that $0\nu 2\beta$ decay of ^{76}Ge with $T_{1/2}^{0\nu} = 10^{27}$ yr would be clearly registered (42 counts in the $0\nu 2\beta$-decay peak). For a 10-yr measuring time, the value of $\lim S$ is equal to 5 counts (90% C.L.); thus, taking into account the number of ^{76}Ge nuclei (7×10^{27}) and detection efficiency ($\eta \approx 0.95$), the sensitivity of the GEM (expressed in the same manner as for the GENIUS project) is equal to $T_{1/2}^{0\nu} \geq 10^{28}$ yr ($m_\nu \leq 0.015$–0.05 eV).

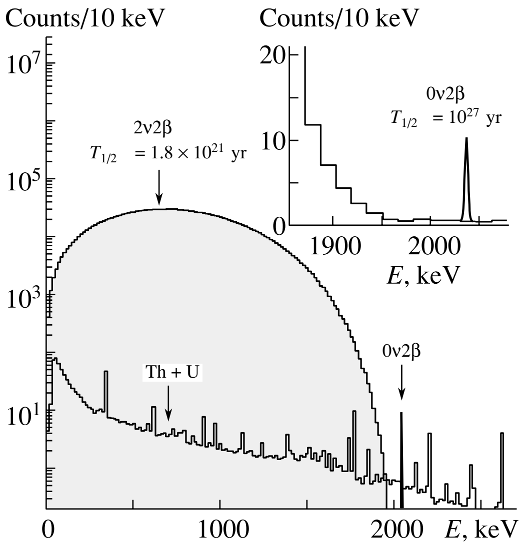

Fig. 2. The response functions of the GEM II setup [60] with 1000 kg of HP ^{76}Ge crystals and after 10 yr of measurements for 2β decay of ^{76}Ge with $T_{1/2}^{2\nu} = 1.8 \times 10^{21}$ yr and $T_{1/2}^{0\nu} = 10^{27}$ yr (solid histogram), as well as the background contribution from contaminations of the holder system and Cu cryostat by ^{232}Th and ^{238}U families. In the inset, the summed spectrum in the vicinity of the $0\nu 2\beta$-decay peak of ^{76}Ge is shown on a linear scale.

The realization of the GEM experiment seems to be reasonably simple due to possibility of using the existing BOREXINO CTF as an outer water shield. One of the forthcoming large underground neutrino detectors such as KamLand [66] or BOREXINO [44] could also be appropriate for this purpose. The cost of GEM is estimated at $150 million, whose main part would be for the production of enriched materials. However, the first phase of the project will be performed with 1 t of natural HPGe detectors (total cost is about $6 million), which nevertheless would bring outstanding physical results. Indeed, the reachable half-life limit is directly proportional to the enrichment (abundance) of candidate nuclei contained in the detector. For the GEM I, the natural abundance of ^{76}Ge (7.6%) is about 11 times smaller compared to the enrichment assumed for the second stage (86%). Because all other characteristics of the setup (η, m, t, R, Bg) could be the same, the $T_{1/2}$ bound, which would be obtained with natural HPGe detectors, is about one order of magnitude lower: $T_{1/2}^{0\nu} \geq 10^{27}$ yr. This value translates to the neutrino mass constraint $m_\nu \leq 0.05$ eV, which is also of great interest for many theoretical models.

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[3] It was assumed that Ge materials and crystals were shielded against activation during production and transportation.

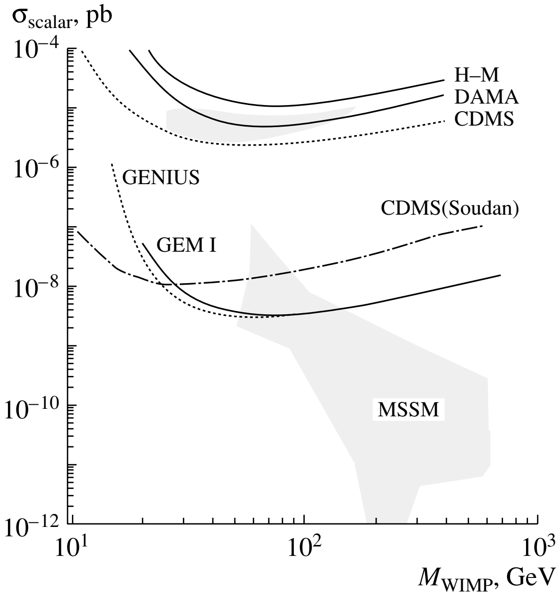

Fig. 3. Exclusion plots of the spin-independent WIMP–nucleon elastic cross section vs. WIMP mass. The regions above the curves are excluded at 90% C.L. Current limits from Heidelberg–Moscow (H–M) [73], DAMA [74], and CDMS [75] experiments are shown in the upper part of figure. The small shaded area: 2σ-evidence region from the DAMA experiment [76]. Projected exclusion plots for the CDMS [77], GENIUS [70], and GEM I [60] experiments are depicted too. The large shaded area represents the theoretical prediction for the allowed spin-independent elastic WIMP–proton scattering cross section calculated in [78].

Furthermore, another important issue of the GEM project is the quest for the dark matter particles (see reviews [67–69]). It has been already shown by Monte Carlo simulations [39, 43] that, for the GENIUS project exploiting 100 kg of natural HPGe detectors, the background rate of 40 counts/(yr t keV) could be obtained in the low-energy region (10–100 keV) relevant for the WIMP dark matter study. The main contributions to this rate are from (a) $2\nu2\beta$ decay of ^{76}Ge (50%); (b) cosmogenic activities in HP Ge crystals (25%); and (c) internal radioactive contamination of the liquid nitrogen, Cu wires, and holder system (25%). It is estimated that even lower background could be reached in the GEM I setup, where only an inner volume with 200 kg of HPGe detectors will be used for the dark matter search, while outer layers with the remaining 800 kg of HPGe crystals would serve as a superhigh-purity passive and active shield for the inner detectors [60]. Thus, the GEM I setup with the energy threshold of 10 keV and background rate of 40 counts/(yr t keV) (below 100 keV)[4] would provide the highest sensitivity for the WIMP dark matter search compared to other projects (see, for example, [71, 72]). It is demonstrated by the exclusion plots of the WIMP–nucleon elastic-scattering cross section, which are calculated for GEM I and depicted in Fig. 3 together with the best current and other projected limits [73–77]. The theoretical prediction for allowed spin-independent elastic WIMP-proton scattering cross section obtained in the framework of the constrained minimal supersymmetric standard model (MSSM) [78] is also shown there.[5] It is obvious from Fig. 3 that GEM I (and GENIUS) would test the MSSM by covering a larger part of the predicted SUSY parameter space. In that sense, both experiments could be competitive even with LHC in the SUSY quest [80]. At the same time, with a fiducial mass of HPGe detectors of 100–200 kg, it would be possible to test and identify unambiguously (within one year of data taking [81]) the seasonal modulation signature of the dark matter signal from the DAMA experiment [76] by using an alternative detector technology.

4. IMPLICATIONS AND CONCLUSIONS

Let us briefly discuss the physical implications of the future 2β-decay experiments. As was mentioned in the Introduction, the modern gauge theories offer many possibilities (besides conventional left-handed neutrino-exchange mechanism) to trigger the $0\nu2\beta$ decay [1–3]. For instance, in left-right symmetric GUT models, $0\nu2\beta$ decay can be mediated by heavy right-handed neutrinos [82]. It was shown [83] that 2β-decay experiments with the sensitivity level of $m_\nu \leq 0.01$ eV would be at the same time sensitive to right-handed W_R boson masses up to $m_{W_R} \geq 8$ TeV (for a heavy right-handed neutrino mass $\langle m_N \rangle = 1$ TeV) or $m_{W_R} \geq 5.3$ TeV (for $\langle m_N \rangle = m_{W_R}$). These limits, which could be established by the GEM II/GENIUS experiments, are nearly the same as expected for LHC [80].

Leptoquarks (LQ), new type of gauge bosons predicted by some GUTs, can induce $0\nu2\beta$ decay via LQ–Higgs couplings; thus, restrictions on their masses and coupling constants can be derived [84]. Direct searches for LQ in deep inelastic ep scattering at HERA give lower limits on their masses $M_{\text{LQ}} \geq 225$–275 GeV (depending on the LQ type and coupling) [85]. A detailed study [86] shows that

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[4] The main background origin for the dark matter quest with Ge detectors is cosmogenic activity of ^{3}H produced in Ge [39, 43, 70]. For GEM I, the total ^{3}H activity is estimated at 5000 decays/(yr t), which contributes 10 counts/(yr t keV) to the total background rate (10–100 keV) [60] and is in good agreement with the result of [70].

[5] Very similar predictions from theoretical considerations in the MSSM with relaxed unification condition were derived in [79].

a GENIUS-like experiment would reduce the limit on LQ–Higgs couplings down to 10^{-7} for LQ with masses of 200 GeV. If no effect ($0\nu 2\beta$ decay) is found, this means that either LQ-Higgs coupling must be smaller than 10^{-7} or there exist no LQ (coupled to electromagnetic strength) with masses below 10 TeV [86].

A hypothetical substructure of quarks and leptons can give rise to a new $0\nu 2\beta$-decay mechanism by exchange of composite heavy Majorana neutrinos [87]; thus, compositeness could be checked at low energy. Recent analysis [88] shows that the most sensitive $0\nu 2\beta$ results at present with ^{76}Ge [19, 20] yield the bound on the excited Majorana neutrino mass $m_N \geq 272$ GeV, which already exceeds the ability of LEP II to test compositeness, while future ^{76}Ge experiments (GEM II, GENIUS) would shift this limit to $m_N \geq 1$ TeV, competitive with the sensitivity of LHC [88].

There are also possible $0\nu 2\beta$-decay mechanisms based on supersymmetric (SUSY) interactions: exchange of squarks, etc., within R-parity-violating [89–92] and exchange of sneutrinos, etc., in R-parity-conserving SUSY models [93]. It allows 2β-decay experiments to enter into the field of supersymmetry, where competitive restrictions on the sneutrino masses, R-parity-violating couplings, and other parameters could be obtained [94, 95].

Now, we are going to consider the role which future 2β experiments can play in the reconstruction of the neutrino mass spectrum. At present, this topic is widely discussed in the literature; thus, interested readers are referred to the latest publications [10, 11, 71, 96–100, 70], while we will summarize the most important results very briefly. There exist several schemes for the neutrino masses and mixing offered by theoretical models on the basis of observed oscillation data for the solar and atmospheric neutrinos [10, 11, 99]. Careful analysis of these schemes performed in [10, 11, 99] leads to the following statements: (a) effective neutrino mass, $\langle m_\nu \rangle$, which is allowed by oscillation data and could be observed in 2β decay, is different for different scenarios; hence, 2β-decay data could substantially narrow or restrict this wide choice of possible models; (b) the whole range of allowed $\langle m_\nu \rangle$ values is 0.001–1 eV, where there are three key scales of $\langle m_\nu \rangle$: 0.1, 0.02, and 0.005 eV [10]. Hence, it is obvious that future 2β-decay experiments, whose sensitivity to the neutrino mass limit would be on the order of 0.05 eV (CAMEO, CUORE, EXO, GEM I, MAJORANA, etc.) and 0.01 eV (GEM II, GENIUS), will bring crucial results for the reconstruction of the neutrino mass spectrum. The following citation [99] emphasizes our statement: “The observation of the $0\nu 2\beta$ decay with a rate corresponding to $\langle m_\nu \rangle \approx 0.02$ eV can provide unique information on the neutrino mass spectrum and on the CP violation in the lepton sector, and if CP-invariance holds, on the relative CP parities of the massive Majorana neutrinos.”

We can conclude that the challenging scientific goal to reach the (0.01–0.05)-eV neutrino mass domain would indeed be feasible for the CAMEO and GEM experiments, whose realization seems to have practically no technical risk and could be relatively simple due to the attractive possibility of using the already existing BOREXINO CTF. Both experiments will bring outstanding results for the 2β-decay studies as well as for the dark matter searches (GEM I stage), which are of great interest and would provide crucial tests of the key theoretical models of modern astroparticle physics.

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