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

J. Phys. G: Nucl. Part. Phys. **27** (2001) 2129–2146 PII: S0954-3899(01)26078-2

High sensitivity GEM experiment on 2β decay of ^{76}Ge

Yu G Zdesenko[1], **O A Ponkratenko and V I Tretyak**

Institute for Nuclear Research, MSP 03680 Kiev, Ukraine

E-mail: zdesenko@kinr.kiev.ua

Received 8 June 2001
Published 13 September 2001
Online at stacks.iop.org/JPhysG/27/2129

Abstract

The GEM project is designed for the next-generation 2β decay experiments with ^{76}Ge. One ton of 'naked' HP Ge detectors (natural at the first GEM-I phase and enriched in ^{76}Ge to 86% at the second GEM-II stage) are operating in super-high-purity liquid nitrogen contained in a Cu vacuum cryostat (sphere of diameter 5 m). The latter is placed in the water shield (of dimensions 11×11 m^2). Monte Carlo simulation evidently shows that the sensitivity of the experiment (in terms of the $T_{1/2}$ limit for $0\nu2\beta$ decay) is $\approx 10^{27}$ yr with natural HP Ge crystals and $\approx 10^{28}$ yr with enriched ones. These bounds correspond to the restrictions on the neutrino mass $m_\nu \leqslant 0.05$ eV and $m_\nu \leqslant 0.015$ eV with natural and enriched detectors, respectively. Besides, the GEM-I set-up could advance the current best limits on the existence of neutralinos—as dark matter candidates—by three orders of magnitude, and at the same time would be able to identify unambiguously the dark matter signal by detection of its seasonal modulation.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, neutrino physics has undergone a revolution (see [1] and references therein), and the search for 2β decay now plays an even more important role in modern physics[2] than several years ago [3–8]. Indeed, the solar neutrino problem [9], the measured deficit of the atmospheric muon neutrino flux [10] and the result of the LSND accelerator experiment [11] could be explained by means of neutrino oscillations, requiring in turn non-zero neutrino masses (m_ν). However, oscillation experiments are sensitive to the neutrino mass difference, while only a

---

[1] Author to whom correspondence should be addressed.

[2] The neutrinoless (0ν) double β decay is forbidden in the standard model (SM) since it violates lepton number (L) conservation. However, many extensions of the SM incorporate L-violating interactions and thus could lead to $0\nu2\beta$ decay. In that sense $0\nu2\beta$ decay has a great conceptual importance due to the strong statement obtained in a gauge theory of the weak interaction that a non-vanishing $0\nu2\beta$ decay rate, independently of which mechanism induces it, requires neutrinos to be massive Majorana particles [2].

0954-3899/01/102129+18$30.00

measured neutrinoless (0ν) double β decay rate can give the absolute scale of the effective Majorana neutrino mass[3], and hence provide a crucial test of neutrino mass models [12, 13]. Therefore, the $0\nu2\beta$ decay is considered as a powerful test of new physical effects beyond the SM. The absence of this process yields strong restrictions on m_ν, lepton violation constants and other parameters of the manifold SM extensions, which allow one to narrow the wide choice of theoretical models and to reach the multi-TeV energy range in competition with the accelerator experiments [5–8, 12].

Despite the numerous efforts to detect $0\nu2\beta$ decay, this process still remains unobserved [3, 4]. The highest half-life limits were set in direct experiments with several nuclides: $T_{1/2}^{0\nu} \geqslant 10^{22}$ yr for ^{82}Se [14], ^{100}Mo [15]; $T_{1/2}^{0\nu} \geqslant 10^{23}$ yr for ^{116}Cd [16], ^{128}Te, ^{130}Te [17], ^{136}Xe [18]; and $T_{1/2}^{0\nu} \geqslant 10^{25}$ yr for ^{76}Ge [19, 20]. These results have already given the most stringent restrictions on the values of the Majorana neutrino mass $m_\nu \leqslant 0.5$–5.0 eV, right-handed admixture in the weak interaction $\eta \approx 10^{-7}$, $\lambda \approx 10^{-5}$, the neutrino–Majoron coupling constant $g_M \approx 10^{-4}$ and the R-parity-violating[4] parameter of the minimal SUSY standard model $\varepsilon \approx 10^{-4}$. However, on the basis of the current status of astroparticle physics it is very desirable to improve the present level of sensitivity by one to two orders of magnitude [1,6,8].

Many projects have been proposed over the past few years with regard to these goals, however, most of them require strong efforts and a long time to prove their feasibility (see the next section). To this end, in the present paper we suggest the GEM project, i.e. a high-sensitivity 2β decay experiment with ^{76}Ge, for which the accomplishment of these goals seems to be realistic. Before entering upon the project itself (section 3), the sensitivity limitations and current status of 2β decay studies, as well as requirements for future projects, are considered briefly in section 2.

2. Sensitivity limitation, present status and the future of 2β decay studies

There are two different classes of 2β decay experiments: with a ‘passive’ source, which can be simply placed as a foil between two detectors, and with an ‘active’ source, where a detector containing 2β candidate nuclei serves as a source and detector simultaneously [3, 4]. If neutrinoless 2β decay occurs in the ‘active’ or ‘passive’ source, the sharp peak at the $Q_{\beta\beta}$ value would be observed in the electron sum energy spectrum of the detector(s). The width of this peak is determined by the detector energy resolution. The sensitivity of the set-up for 2β decay study can be expressed in terms of a lower half-life limit as follows [3, 4]: $T_{1/2} \sim \eta\,\delta\sqrt{(m\,t)/(R\,Bg)}$. Here η is the detection efficiency; δ the abundance or enrichment of candidate nuclei contained in the detector; t the measurement time; m the total mass of the ‘active’ or ‘passive’ source; R the energy resolution (FWHM) of the detector; and Bg the background rate in the energy region of the $0\nu2\beta$ decay peak (expressed, for example, in counts/(yr keV kg)).

First of all, it is clear from this equation that efficiency and enrichment are the most important characteristics, because all other parameters are under the square root. Obviously, ≈100% enrichment is very desirable[5].

One could also require ≈100% detection efficiency, which is possible, in fact, only for the ‘active’ source technique. Indeed, the strength of a ‘passive’ source can be enlarged

---

[3] Obviously, its accuracy depends on the uncertainties of the nuclear matrix elements calculation.

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

[5] Let us consider two detectors with different masses (m_1, m_2) and enrichment (δ_1, δ_2). Supposing that their other characteristics (η, t, R, Bg) are the same and requiring equal sensitivities ($T'_{1/2} = T''_{1/2}$), we can obtain the relation between the masses and enrichment of the detectors $m_1/m_2 = (\delta_2/\delta_1)^2$, which speaks for itself.

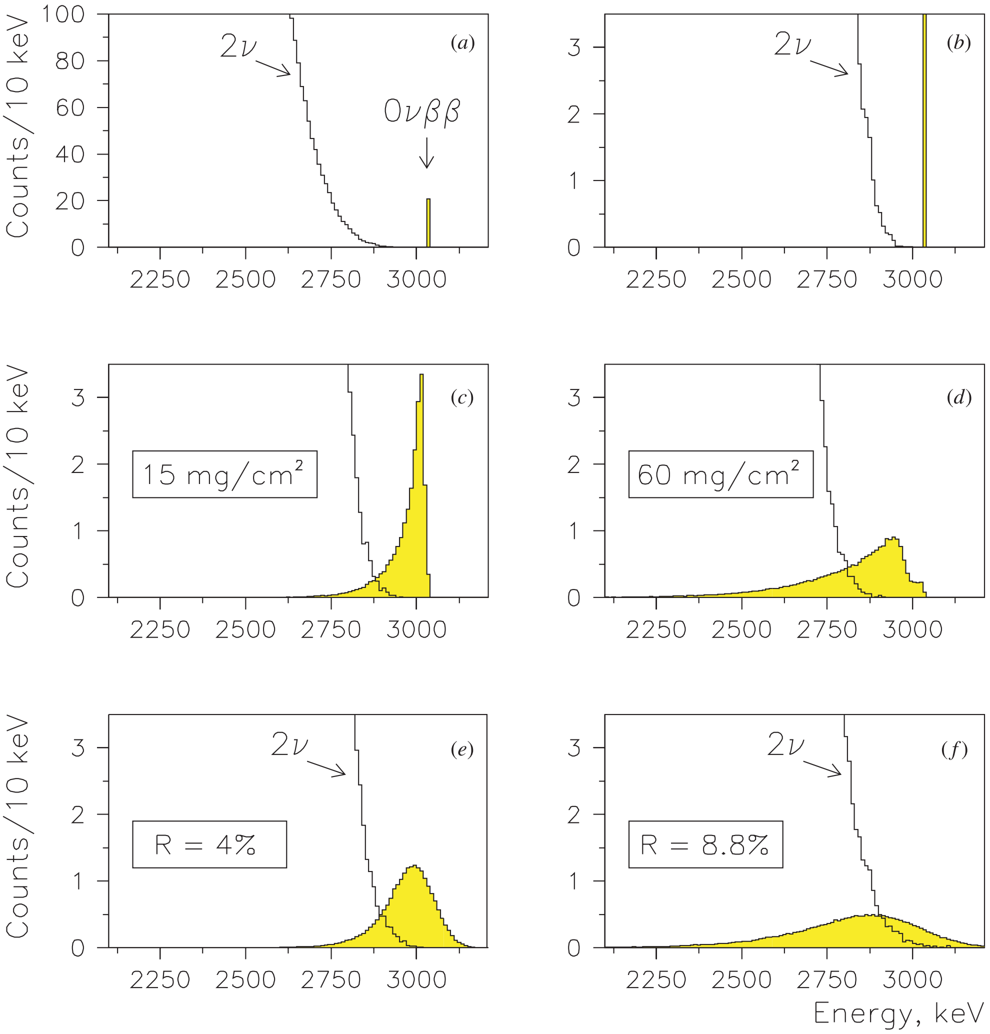

Figure 1. Simulated spectra of the model 2β decay experiment (5 yr measurement time) with 1 kg of ^{100}Mo. (*a*) and (*b*) 'Active' source technique: ^{100}Mo nuclei in a detector with 100% efficiency, zero background, and with 10 keV energy resolution. (*c*) and (*d*) 'Passive' source technique: ^{100}Mo source in the same detector with foil thickness 15 mg cm^{-2} (*c*) and 60 mg cm^{-2} (*d*). (*e*) The same as (*c*) but the energy resolution (FWHM) of the detector at 3 MeV is 4%. (*f*) The same as (*d*) but with FWHM = 8.8%.

by increasing its thickness, which in turn lowers the detection efficiency due to absorption of electrons in the source, broadening and shifting the 2β decay peak. Hence, the energy resolution of the detector is essential because events from the high-energy tail of the continuous 2ν distribution run into the energy window of the 0ν peak, generating a background which cannot be discriminated from the 0ν signal[6]. Better energy resolution minimizes the 2ν tail falling within the 0ν interval, hence lowering this irreducible background.

---

[6] In both cases all features of the events are similar: two electrons with the same energies and identical angular distribution are emitted from one point of the source simultaneously.

All of the mentioned statements are illustrated in figure 1, where results of the model experiment to study 2β decay of ^{100}Mo are presented. The simulations were performed with the help of the GEANT3.21 package [21] and event generator DECAY4 [22]. The following assumptions were accepted: the mass of the ^{100}Mo source is 1 kg; the measurement time is 5 yr; half-lives of ^{100}Mo 2β decay are $T_{1/2}(2\nu) = 10^{19}$ yr and $T_{1/2}(0\nu) = 10^{24}$ yr. The initial 2β decay spectra (shown in figures 1(*a*) and (*b*) for different vertical scales) were obtained with ^{100}Mo nuclei contained in the ideal ('active' source) detector with 100% efficiency, zero background and an energy resolution of FWHM = 10 keV. In the next step the ^{100}Mo source was introduced in the same detector but in the form of a foil ('passive' source technique). The simulated spectra are depicted in figure 1(*c*) (the thickness of the ^{100}Mo foil is 15 mg cm^{-2}) and figure 1(*d*) (60 mg cm^{-2}). Then, the energy resolution of the detector (FWHM) was taken into account and results are shown in figure 1(*e*) (FWHM = 4% at 3 MeV) and figure 1(*f*) (FWHM = 8.8% at 3 MeV). It is evident from figure 1 that the 'passive' source technique is not appropriate for observation of $0\nu2\beta$ decay with a ratio of $T_{1/2}(0\nu)$ to $T_{1/2}(2\nu)$ of greater than 10^5.

Hence, we conclude that the 'active' source approach provides a 4π geometry for the source, absence of self-absorption and better energy resolution, which does not depend on the angular and energy distribution of electrons emitted in 2β decay. These advantages of 'active' detectors were understood long ago and the first experiment of this type was performed in 1966 using a ^{48}CaF$_2$ scintillator to study 2β decay of ^{48}Ca [23]. In the next year semiconductor Ge(Li) crystal was applied in the quest for 2β decay of ^{76}Ge [24]. Due to the high purity and good energy resolution of the Ge(Li) detectors the first valuable result with ^{76}Ge ($T_{1/2}^{0\nu} \geqslant 10^{21}$ yr) was obtained in 1970 [25]. After 30 years of strong effort this limit was advanced up to $T_{1/2}^{0\nu} \geqslant 10^{25}$ yr in the two current experiments performed by the IGEX [20] and the Heidelberg–Moscow [19] collaboration.

The IGEX is operating three 2 kg HP Ge detectors (enriched with ^{76}Ge to $\approx 88\%$) in the Canfranc Underground Laboratory (Spain). The shield consists of 2.5 tons of archeological lead, 10 tons of 70 yr old low-activity lead and a plastic scintillator as a cosmic muon veto. Pulse shape discrimination techniques are applied to the data. The background rate is equal to ≈ 0.06 counts/(yr kg keV) (within the energy interval 2.0–2.5 MeV). The combined energy resolution for the $0\nu2\beta$ peak ($Q_{\beta\beta} = 2038.7$ keV) is 4 keV. Analysis of 116.75 mole yr (or 8.87 kg yr in ^{76}Ge) of data yields a lower bound $T_{1/2}^{0\nu} \geqslant 1.57 \times 10^{25}$ yr at 90% CL [20].

The Heidelberg–Moscow experiment in the Gran Sasso Underground Laboratory uses five HP Ge detectors (enriched with ^{76}Ge to 86%) with total active mass of 10.96 kg (125.5 moles of ^{76}Ge). The passive and active shielding, as well as pulse-shape analysis (PSA) of data allow one to reduce the background rate in the energy region of interest to a value of ≈ 0.06 counts/(yr kg keV). The energy resolution at an energy of 2038.7 keV is 3.9 keV. After 24 kg yr of data with PSA a lower half-life limit $T_{1/2}^{0\nu} \geqslant 1.6 \times 10^{25}$ yr with 90% CL has been set for ^{76}Ge [19].

Therefore, on the basis of this brief analysis of the present status of 2β decay experiments, we can formulate the following requirements for future ultimate sensitivity projects.

(a) The most sensitive 0ν limits were reached with the help of the 'active' source method (^{76}Ge, ^{116}Cd, ^{130}Te, ^{136}Xe), thus one can suppose that future projects will belong to the same kinds of technique, because only in this case can the detection efficiency be close to 100%.

(b) The best ^{76}Ge results were obtained using ≈ 10 kg of enriched detectors, hence, to reach the required level of sensitivity one has to exploit enriched sources with masses of hundreds of kg. This condition restricts the list of candidate nuclei because large mass production of enriched materials is possible only for several of them; these are ^{76}Ge, ^{82}Se, ^{116}Cd, ^{130}Te and ^{136}Xe, which could be produced by means of centrifugal separation[7] and therefore at a reasonable price [26].

(c) Because of the square root dependence of the sensitivity versus source mass, it is not enough, however, to increase the detector mass alone (even by two orders of magnitude). The background should also be reduced down substantially (practically to zero).

(d) It is obvious from figure 1 that energy resolution is a crucial characteristic, and for the challenging projects the FWHM value cannot be worse than $\approx 4\%$ at the $Q_{\beta\beta}$ energy.

(e) It is anticipated that the measurement time of future experiments will be of the order of $\approx$10 yr, hence detectors and set-ups should be as simple as possible to provide stable and reliable operation over such a long period.

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

An interesting approach to studying 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 ^{136}Xe decay on the atomic level) and the $0\nu 2\beta$ signal with an energy of 2.5 MeV in a time projection chamber (TPC) filled with liquid or gaseous Xe [27–29]. Recently, the EXO project has been considered [30], where resonance ionization spectroscopy for ^{136}Ba^{2+} ion identification would be applied in a 40 m^3 TPC operated at 5–10 atm pressure of enriched xenon ($\approx$1–2 tons of ^{136}Xe). The estimated sensitivity to neutrino mass is ≈ 0.01 eV [30]. Another proposal (which originated from [31]) is to dissolve ≈ 80 kg ($\approx$1.5 tons) of enriched (natural) Xe in the liquid scintillator of the BOREXINO counting test facility (CTF) in order to reach the $T_{1/2}^{0\nu}$ limit in the range of 10^{24}–10^{25} yr [32].

The project MOON aims at both the study of $0\nu 2\beta$ decay of ^{100}Mo ($Q_{\beta\beta} = 3034$ keV) and at real-time studies of low-energy solar ν by inverse β decay [33]. The detector module will be composed of $\approx 60\,000$ plastic scintillators (6 m × 0.2 m × 0.25 cm), the light outputs from which are collected by 866 000 wavelength shifter fibres ($\oslash$1.2 mm × 6 m), viewed through clear fibres by 6800 16-anode photomultiplier tubes. The proposal calls for the use of 34 tons of natural Mo (i.e. 3.3 tons of ^{100}Mo) per module in the form of foil (≈ 50 mg cm^{-2}). The sensitivity of such a module to the neutrino mass could be of the order of ≈ 0.05 eV [33].

The ^{160}Gd ($Q_{\beta\beta} = 1730$ keV) is an attractive candidate due to its large natural abundance (21.9%), allowing one to construct a sensitive apparatus with natural Gd_2SiO_5:Ce crystal scintillators (GSO). A large-scale experiment with ^{160}Gd by using the GSO multi-crystal array with a total mass of 1–2 ton ($\approx$ 200–400 kg of ^{160}Gd) is suggested with a projected sensitivity to the Majorana neutrino mass of ≈ 0.04 eV [34].

Using future large-scale Yb-loaded liquid scintillation detectors for solar neutrino spectroscopy [35] is assumed for the search for $2\beta^-$ decay of ^{176}Yb ($Q_{\beta\beta} = 1087$ keV) and $\varepsilon\beta^+$ decay of ^{168}Yb ($Q_{\beta\beta} = 1422$ keV). With about 20 tons of natural Yb (≈ 2.5 tons of ^{176}Yb) the limit $T_{1/2}^{0\nu} \geqslant 10^{26}$ yr could be set on $0\nu 2\beta$ decay of ^{176}Yb ($m_\nu \leqslant 0.1$ eV) [36].

However, we recall that all of the mentioned projects require a significant amount of research and development to demonstrate their feasibility, thus strong efforts and perhaps a long time will be needed before their realization. To this end, we offer the following safer proposals.

---

[7] As is known, centrifugal isotope separation requires the substances to be in gaseous form, thus xenon gas can be used directly. There also exist volatile germanium, selenium, molybdenum and tellurium hexafluorides, as well as a metal–organic cadmium–dimethyl compound [26].

First of all, there are two projects, NEMO-3 [37] and CUORICINO [38], under construction now. The sensitivity of the NEMO-3 tracking detector with a passive 10 kg ^{100}Mo source would be on the level of $\approx 4 \times 10^{24}$ yr ($m_\nu \leqslant 0.3$–0.5 eV) [39].

The CUORICINO set-up consists of 60 low-temperature bolometers made of TeO_2 crystals (750 g mass 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 1000 TeO_2 bolometers (total mass of 750 kg), which could reach a ≈ 0.05 eV neutrino mass bound [38, 40].

Recently, the project CAMEO has been suggested [41], where the super-low background and large sensitive volume of the already existing CTF are used to study ^{116}Cd. With $\approx$100 kg of enriched $^{116}CdWO_4$ crystal scintillators placed in the liquid scintillator of the CTF the calculated sensitivity (in terms of the $T_{1/2}^{0\nu}$ limit) is $\approx 10^{26}$ yr, which translates into a neutrino mass bound of $m_\nu \leqslant 0.06$ eV. Similarly, with 1 ton of $^{116}CdWO_4$ crystals located in the BOREXINO apparatus (under construction) the constraint on the neutrino mass can be pushed down to $m_\nu \leqslant 0.02$ eV [41].

Two large-scale projects for the 2β decay quest of ^{76}Ge (MAJORANA [42] and GENIUS [43]) are proposed, which we will discuss in more detail.

MAJORANA. The idea of this proposal is to use 210 HP Ge (enriched in ^{76}Ge to $\approx 86\%$) semiconductor detectors (each crystal of ≈ 2.4 kg mass), which are placed in a 'conventional' super-low background cryostat (21 crystals in one cryostat) [42]. The detectors are shielded by HP lead or copper. Each crystal will be supplied with six azimuthal and two axial contacts, hence proper spatial information will be available for the detected events. It is anticipated that segmentation of crystals and pulse-shape analysis of data would reduce the background rate for the detectors to a level of ≈ 0.01 counts/(yr kg keV) at an energy of 2 MeV, that is six times lower than that already reached in the most sensitive ^{76}Ge experiments [19, 20]. Thus, after 10 yr of measurements ≈ 200 background counts will be recorded in the vicinity of the $0\nu2\beta$ decay peak (≈ 4 keV energy interval) [42]. On this basis the half-life limit, $T_{1/2}$, can be determined with the help of the formula $\lim T_{1/2} = \ln 2\eta N t / \lim S$, where N is the number of ^{76}Ge nuclei ($N = 3.5 \times 10^{27}$) and $\lim S$ is the maximal number of $0\nu2\beta$ events which can be excluded with a given confidence level. To estimate the value of $\lim S$ we can use a so-called 'one (1.6; 2) σ approach', in which the excluded number of effect events is determined simply as the square root of the number of background counts in the energy region of interest, multiplied by a parameter (1, 1.6 or 2) in accordance with the confidence level chosen (68%, 90% or 95%). Notwithstanding its simplicity, this method gives the right scale of sensitivity for any experiment. Applying it to the projected MAJORANA data, one can obtain $\lim S \approx 20$ counts at 90% CL, and whereby the bound $T_{1/2} \approx 10^{27}$ yr. Depending on the nuclear matrix elements calculations used (see [5, 7, 19]), it leads to the interval of the neutrino mass limit $m_\nu \leqslant 0.05$–0.15 eV.

GENIUS. The project intends to operate 1 ton of HP Ge (enriched in ^{76}Ge to $\approx 86\%$) semiconductor detectors [43]. It is scheduled that the background of the GENIUS set-up would be reduced by ≈ 200 times compared with that of present experiments [19, 20]. To reach this goal, 'naked' Ge crystals will be placed in extremely high-purity liquid nitrogen (LN_2), which simultaneously serves as a cooling medium and shielding for the detectors.

The feasibility of operating Ge detectors in liquid nitrogen was demonstrated by measurements with three HP Ge crystals (mass of ≈ 0.3 kg each) [44]. With 6 m cables between detectors (placed on a common plastic holder inside liquid nitrogen) and outer preamplifiers an energy threshold of ≈ 2 keV and an energy resolution of ≈ 1 keV (at 300 keV) were obtained [44]. The second question—is it indeed possible to achieve such an extremely low background level—has been answered by means of Monte Carlo simulations. The latest were performed independently by the MPI, Heidelberg [43] and INR, Kiev [45] groups. In accordance with simulations [43, 45] the necessary dimensions of the liquid nitrogen shield, which could fully suppress the radioactivity from the surroundings (such as that measured, for instance, in the Gran Sasso Underground Laboratory) should be about 12 m in diameter and 12 m in height. The required radioactive purity of the liquid nitrogen should be at the level of $\approx 10^{-15}$ g g^{-1} for ^{40}K and ^{238}U, $\approx 5 \times 10^{-15}$ g g^{-1} for ^{232}Th, and 0.05 mBq m^{-3} for ^{222}Rn [43,45]. All of these requirements (except for radon) are less stringent than those already achieved in the BOREXINO CTF: (2–5) $\times$ 10^{-16} g g^{-1} for ^{232}Th and ^{238}U contamination in the liquid scintillators [46]. Therefore, purification of the liquid nitrogen to satisfy the GENIUS demands seems to be quite realistic. The only problem is radon contamination, for which the required value is about 20 times less than that measured in liquid nitrogen, ≈ 1 mBq m^{-3} [46]. The final conclusions are derived that in the GENIUS experiment the total background rate of ≈ 0.2 counts/(yr keV ton) could be obtained in the energy region of the $\beta\beta$ decay of ^{76}Ge [43, 45]. On this basis the projected $T_{1/2}$ limit can be estimated similarly to that for the MAJORANA proposal. For 10 yr measuring time the value of lim S is equal ≈ 5 counts (90% CL), thus with 7×10^{27} nuclei of ^{76}Ge the bound $T_{1/2} \approx 10^{28}$ yr could be achieved, which translates to a neutrino mass constraint of $m_\nu \leqslant 0.015$–0.05 eV.

However, to reach the scheduled sensitivity the GENIUS apparatus must satisfy very stringent and in some cases contradicting demands. For example, a super-low background rate for the detectors requires ultra-high purity liquid nitrogen and a vessel of large dimensions ($\oslash 12 \times 12$ m^2) with a total mass of LN$_2$ of $\approx$1000 ton. Ultra-high purity liquid nitrogen requires continuous purification of LN$_2$ over the whole running time of the experiment. The power of the LN$_2$ purification system (and maintenance costs) depends strongly on the liquid nitrogen consumption, which in turn depends on the quality of the thermoinsulation of the LN$_2$ tank. The method of passive thermoinsulation with the help of 1.2 m thick polyethylene foam isolation was accepted for the GENIUS set-up [43]. Despite its simplicity, the disadvantage of this solution is the large LN$_2$ consumption because of the huge dimensions of the LN$_2$ tank (heat losses through the walls are proportional to the square of the dimensions). First, it leads to a substantial maintenance cost for the experiment. Secondly, and more importantly, this solution makes it very difficult to maintain the required ultra-high purity of LN$_2$ over the whole running period. This is because evaporation of LN$_2$ is the method of purification, thus pure vapour will leave the vessel, while all impurities will be kept in the remaining LN$_2$. In the case of a large liquid nitrogen consumption this process will lead to a permanently increasing LN$_2$ contamination level. Therefore, it is clear that production, purification, operation and maintenance (together with safety requirements) of more than 1 kton of ultra-high-purity liquid nitrogen in an underground laboratory would require additional efforts and lead to considerable costs and time for realization of the GENIUS project.

With the aim of overcoming all the mentioned difficulties and making realization of the high-sensitivity ^{76}Ge experiment simpler, the GEM project is presented below.

3. The GEM design and background simulation

The GEM design is based on the following key ideas.

(a) ‘Naked’ HP Ge detectors (enriched with ^{76}Ge to 86–90%) are operating in the ultra-high purity liquid nitrogen serving as a cooling medium and the first shielding layer simultaneously.

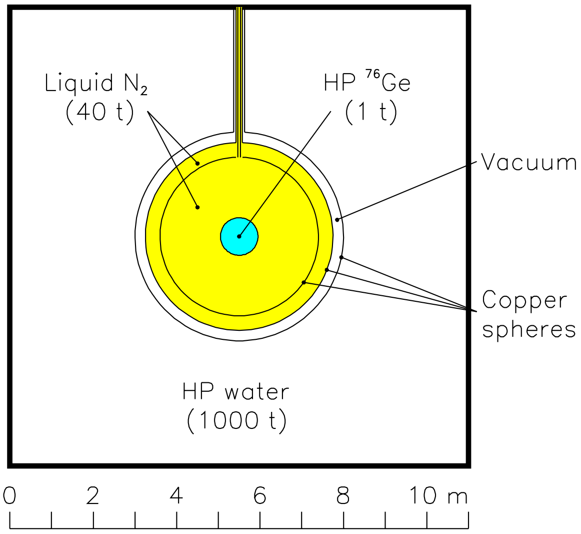

Figure 2. The scheme of the GEM set-up.

(b) Liquid nitrogen is contained in the vacuum cryostat made of HP copper. The dimensions of the cryostat and consequently the volume of liquid nitrogen are minimal, which is necessary to eliminate the contribution of the radioactive contaminants of the Cu cryostat to the background of the HP Ge detectors.

(c) The shield is composed of two parts: (i) inner shielding, ultra-high-purity liquid nitrogen, with contaminants at a level of less than $\approx 10^{-15}$ g g^{-1} for ^{40}K and ^{238}U, $\approx 5 \times 10^{-15}$ g g^{-1} for ^{232}Th, and 0.05 mBq m^{-3} for ^{222}Rn; (ii) outer part, high-purity water, whose volume is large enough to suppress any external background to a negligible level.

The optimization of the set-up design as well as the background simulation for the GEM experiment were performed with the help of the GEANT3.21 package and the event generator DECAY4. The scheme of the GEM device created on the basis of the simulation is shown in figure 2. About 400 enriched HP Ge detectors ($\oslash 8.5 \times 8.5$ cm^2, weight ≈ 2.5 kg each) are located in the centre of a copper sphere (inner enclosure of the cryostat) with diameter 4.5 m and 0.6 cm thick, which is filled with liquid nitrogen. The detectors, arranged in nine layers, occupied a space ≈ 90 cm in diameter. It is assumed that crystals are fixed with the help of a holder system made of nylon strings. Thin copper wire (diameter 0.2 mm) is attached to each detector to provide a signal connection.

The outer encapsulation of the cryostat with diameter 5 m is also made of HP Cu with thickness 0.6 cm. Both cryostat enclosures are connected by two concentric copper pipes with an outer vacuum pump, which maintains $\approx 10^{-6}$ Torr pressure in the space between the two walls of the cryostat. The latter (in combination with several layers of ≈ 5 μm thick aluminized mylar film enveloping the inner Cu vessel and serving as a thermal radiation reflector) allows one to reduce the heat current through the walls of the cryostat to a value of ≈ 2.5 W m^{-2} [47], thus total heat losses (including heat conduction through pipes, the support structure and cables) are near 200 W. This corresponds to a reasonable LN$_2$ consumption of about 150 kg d^{-1}.

Moreover, to provide the most stable and quiet operation of HP Ge detectors, the volume with liquid nitrogen is divided in turn into two zones with the help of an additional Cu sphere with diameter 3.8 m and 1 mm thick. The HP Ge detectors are contained in this, where only a tiny fraction of the heat current through thin signal cables and holder strings could reach this volume. The outer LN_2 zone between the inner wall of the cryostat and sphere with Ge crystals would serve as an additional and very efficient thermal shield [47]. Hence, LN_2 consumption in the inner volume with detectors would be extremely low, which allows one to maintain ultra-high purity of LN_2 and stable operation conditions over the whole running period.

Another important advantage of the proposed solution is that detectors are located inside a module, and all procedures for cleaning, mounting of crystals, testing, etc can be performed in a special clean room with all available precautions to avoid any contaminations of the detectors and the inner vessel.

The cryostat is placed into the HP ($\approx 10^{-14}$ g g^{-1} for ^{40}K, ^{232}Th, ^{238}U and $\approx$10 mBq m^{-3} for ^{222}Rn) water shield with mass $\approx$1000 ton contained in a steel tank of dimensions 11×11 m^2. We remind the reader that slightly better radio-purity levels have already been achieved for the water shield of the BOREXINO CTF operating in the Gran Sasso Underground Laboratory [46]. The dimensions of the CTF water tank are practically the same (11×10 m^2), hence this shield could be used for the GEM experiment easily. Because water is a Cherenkov medium with excellent optical properties, such a shield equipped with a limited number of photomultipliers would serve as an additional veto system for muons in the GEM detector.

The developed design of the GEM set-up reduces the dimensions of the LN_2 volume substantially and allows one to solve the problems of thermoinsulation, ultra-high purity conditions, LN_2 consumption, safety requirements, etc.

3.1. Background simulations

In the calculations the model of the GEM experiment described above was used (see figure 2). The total mass of detectors is equal to $\approx$1 ton, liquid nitrogen, $\approx$40 ton, copper cryostat, $\approx$7 ton, water shield, 1000 ton, holder system, $\approx$2 kg, and copper wires, $\approx$1 kg. As already mentioned the simulation of the background and, in particular, the decay of various radioactive nuclides in the installation was performed with the help of the GEANT3.21 package and event generator DECAY4. The energy threshold of the HP Ge detectors was set to 1 keV and only single signals in one out of all of the detectors (anticoincidence mode) were taken into account. The origins of the background can be divided into internal and external sources. The internal background arises from residual impurities in the crystal holder system, in the Ge crystals themselves, in the liquid nitrogen, copper cryostat, water, in the steel vessel and from activation of all the mentioned materials at the Earth's surface. The 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.

3.1.1. Radioactive impurities of the detectors and materials. The values of radioactive contamination of the Ge detectors and materials used (liquid nitrogen, copper wires and cryostat, water, steel vessel) by ^{40}K and nuclides from natural radioactive chains of ^{232}Th and ^{238}U, accepted for our calculations, are listed in table 1. Possible contamination of ^{76}Ge crystals was calculated using the data from the Heidelberg–Moscow experiment with ^{76}Ge detectors [19, 48]. The absence of any α peaks in the measured spectra (for 17.7 kg yr statistics) leads to the upper limits (90% CL) presented in table 1. Data on the purity of copper for ^{40}K, ^{232}Th and ^{238}U are taken from [48]. The copper cosmogenic activities of ^{54}Mn (23 μBq kg^{-1}), ^{57}Co (30 μBq kg^{-1}), ^{58}Co (50 μBq kg^{-1}), ^{60}Co (70 μBq kg^{-1}), as well as anthropogenic activities of ^{125}Sb (50 μBq kg^{-1}), ^{207}Bi (8 μBq kg^{-1}), ^{134}Cs (150 μBq kg^{-1}) and ^{137}Cs (11 μBq kg^{-1}) are accepted on the basis of measurements with the Ge detectors of the Heidelberg–Moscow experiment [48]. For steel, the upper limits from [49] are assumed. For the water the actual radiopurity levels obtained in the already operated BOREXINO water

Table 1. Radioactive impurities of the detectors and materials accepted for the simulation.

Materials (mass)	^{40}K (g g^{-1})	^{232}Th (g g^{-1})	^{238}U (g g^{-1})	^{222}Rn (mBq m^{-3})
HP ^{76}Ge (1 ton)	—	5.7×10^{-15}	1.8×10^{-15}	—
Liquid N_2 (40 ton)	1.0×10^{-15}	5.0×10^{-15}	1.0×10^{-15}	0.05
Holder system (2 kg)	—	1.0×10^{-12}	1.0×10^{-12}	—
Copper wires (1 kg) and vessels (7 ton)	4.5×10^{-10}	3.0×10^{-12}	5.4×10^{-12}	—
Water (1000 ton)	1.0×10^{-14}	1.0×10^{-14}	1.0×10^{-14}	10
Steel vessel (90 ton)	5.0×10^{-10}	1.0×10^{-9}	1.0×10^{-9}	—

Table 2. Calculated background rate of the detectors at an energy of 2038 keV due to internal impurities of the materials. For LN_2 and water the ^{222}Rn contributions are included in the column for ^{238}U.

	Background rate at 2 MeV (counts/(yr keV ton))		
Material	^{232}Th	^{238}U	Total
HP ^{76}Ge	2.0×10^{-3} $[4.6 \times 10^{-2}]$	4.3×10^{-3} $[1.6 \times 10^{-1}]$	6.3×10^{-3} $[2.1 \times 10^{-1}]$
Liquid N_2	5.3×10^{-3}	1.2×10^{-2}	1.7×10^{-2}
Holder system	2.0×10^{-3}	1.4×10^{-2}	1.6×10^{-2}
Cu wires	1.5×10^{-4}	2.5×10^{-3}	2.7×10^{-3}
Inner Cu sphere, diameter 3.8 m	4.3×10^{-3}	3.0×10^{-3}	7.3×10^{-3}
Two Cu cryostat walls	1.9×10^{-2}	8.6×10^{-3}	2.8×10^{-2}
Water	3.0×10^{-3}	2.0×10^{-3}	5.0×10^{-3}
Steel vessel	1.4×10^{-3}	—	1.4×10^{-3}
Total	3.7×10^{-2}	4.7×10^{-2}	8.4×10^{-2}

plant [46] are quoted in table 1. The radiopurity criteria assumed for the liquid nitrogen ($\approx 10^{-15}$ g g^{-1} for ^{40}K and ^{238}U, $\approx 5 \times 10^{-15}$ g g^{-1} for ^{232}Th) seem to be realistic in light of the results already achieved by the BOREXINO collaboration for the purity of the liquid scintillators: 2–5 $\times 10^{-16}$ g g^{-1} for ^{232}Th and ^{238}U [46]. Moreover, due to the recent development of a liquid nitrogen purification system for the BOREXINO experiment [50], the ^{222}Rn contamination of the liquid nitrogen was reduced down to the level of ≈ 1 μBq m^{-3} [50], which is lower than our requirement ≈ 50 μBq m^{-3}. For the radiopurity of the holder system we assume the value of 10^{-12} g g^{-1} for the U/Th decay chains, which has already been achieved by the SNO collaboration for acrylic [51].

The full decay chains were simulated with the assumption of chain equilibrium. The results of the calculation are presented in table 2. For internal impurities in HP Ge detectors, two values are given: without (in square brackets) and with time–amplitude analysis of events, where information concerning the energies and arrival time of each event is used for analysis and selection of some decay chains in U and Th families (see, e.g., [16]).

It is obvious from table 2 that two Cu enclosures of the cryostat and holder system give the main contribution to the background. Besides, the results of simulations show that demands on the purity of the water shield can be lowered to a level of about 10^{-13} g g^{-1} for U (Th) contaminants. This means that the maintenance costs of the GEM experiment can also be lowered.

Table 3. Cosmogenic activities produced in HP ^{76}Ge detectors. The background rate at an energy of 2038 keV is averaged during a 1 yr period of data taking.

Nuclide ($T_{1/2}$)	Mode of decay (Q (keV))	Activity after 3 yr (μBq/kg)	Background at 2 MeV (counts/(yr keV ton))
^{22}Na (2.6 yr)	EC/β^+ (2842)	2.0×10^{-3}	3.5×10^{-3}
^{46}Sc (83.8 d)	β^- (2367)	2.5×10^{-5}	1.0×10^{-4}
^{56}Co (78.8 d)	EC/β^+ (4568)	1.9×10^{-5}	3.2×10^{-6}
^{58}Co (70.8 d)	EC/β^+ (2308)	6.0×10^{-5}	1.4×10^{-5}
^{60}Co (5.27 yr)	β^- (2824)	6.6×10^{-2}	5.4×10^{-2}
^{68}Ga (68.1 m)	EC/β^+ (2921)	5.0×10^{-2}	0.018 [0.15]
Total			0.07 [0.22]

3.1.2. Cosmogenic activities in HP ^{76}Ge detectors. To estimate the cosmogenic activity produced in the HP Ge crystals, the program COSMO [52] was used. This code calculates the production of all radionuclides with half-lives in the range of 25 d–5×10^6 yr by nucleon-induced reactions in a given target, taking into account the variation of spallation, evaporation, fission and peripheral reaction cross sections with nucleon energy, target and product charge and mass numbers, as well as the energy spectrum of cosmic ray nucleons near the Earth's surface [52].

Cosmogenic activities in Ge were calculated for HP Ge detectors enriched in ^{76}Ge to 86% (other Ge isotopes: ^{70}Ge, 3.2%, ^{72}Ge, 4.2%, ^{73}Ge, 1.2%, ^{74}Ge, 5.4%). An activation time of 30 days at sea level[8], and a deactivation time of 3 yr underground were assumed. From a total number of 41 nuclides with $T_{1/2} \geqslant 25$ d produced in Ge crystals, we present in table 3 the most dangerous ones which give a notable background near the energy 2038 keV (the $Q_{\beta\beta}$ value of ^{76}Ge). For ^{68}Ga activity two values are given: without (in square brackets) and with time–amplitude analysis of events.

It is clear from table 3 that the background at 2038 keV is caused mainly by ^{22}Na, ^{60}Co and ^{68}Ga (a daughter of cosmogenic ^{68}Ge). The remaining ^{68}Ga contribution could be suppressed significantly by using the time–amplitude analysis due to specific features of the $^{68}\text{Ge} \rightarrow {}^{68}\text{Ga}$ decay chain. Indeed, 88% of the electron captures in ^{68}Ge to the ground state of ^{68}Ga result in a sharp 10.4 keV peak (K capture). Using these events as triggers for time–amplitude analysis of the subsequent counts during a few half-lives of ^{68}Ga ($T_{1/2} = 68.1$ m), it is possible to remove up to 88% of the remaining activity of ^{68}Ga. The expected rate of ^{68}Ge decay (one event per 60 d per detector) would allow one to use such an approach. The background from ^{60}Co can also be decreased by additional annealing of Ge crystals in the underground laboratory. A preliminary study shows that ^{60}Co can be removed from the detectors due to its large diffusion mobility in Ge at high temperatures [53]. All of the mentioned approaches will reduce the cosmogenic background rate to a value of less than 3×10^{-2} counts/(yr keV ton) near 2038 keV.

3.1.3. External background. There are several origins for the external background for the proposed GEM detector. These are neutrons and γ quanta from natural environmental radioactivity, cosmic muons (μ showers and muon-induced neutrons, inelastic scattering and capture of muons), etc. From all of them only γ quanta from the environment were simulated

---

[8] We have assumed that Ge materials and crystals were additionally shielded against activation during production and transportation. For example, 20 cm of Pb would lower the cosmic nucleon flux by one order of magnitude, which means the same reduction factor for most of the cosmogenic activities.

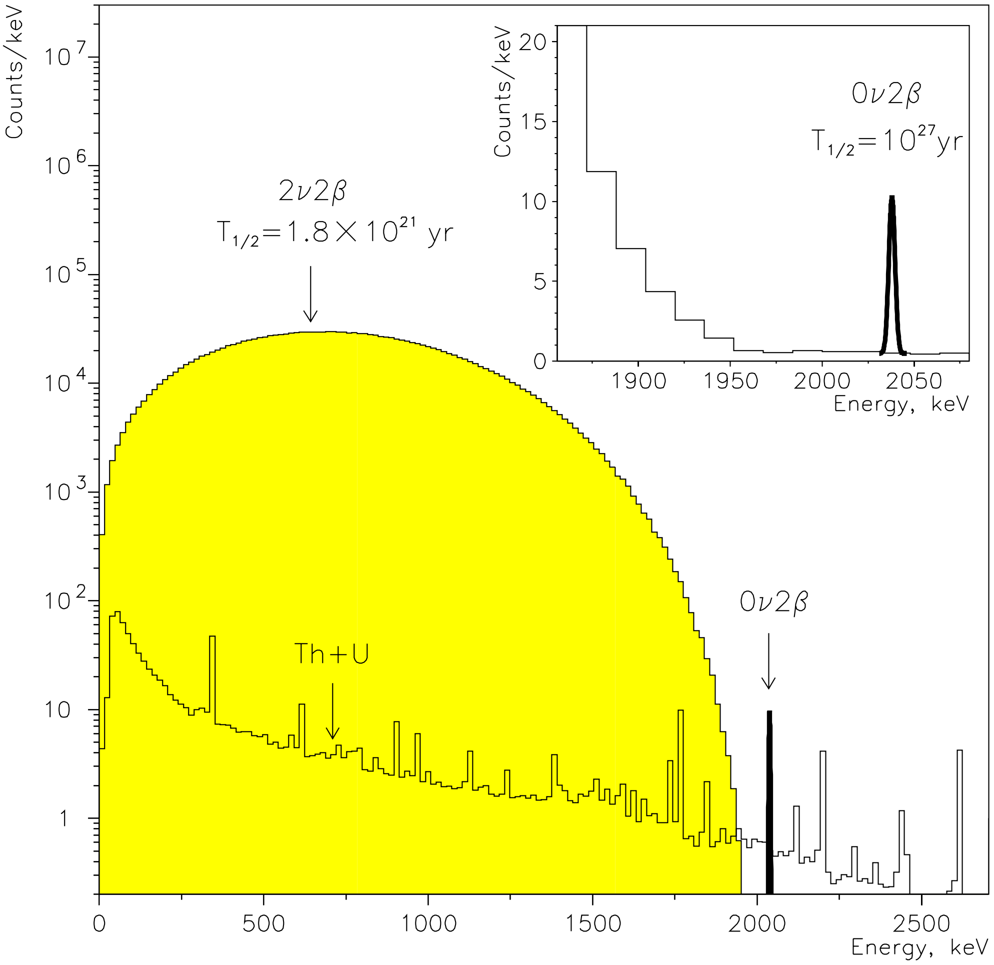

Figure 3. The response functions of the GEM-II set-up with 1000 kg of HP ^{76}Ge crystals and after 10 yr of measurements for the 2β decay of ^{76}Ge with $T_{1/2}^{2\nu} = 1.8 \times 10^{21}$ yr [48] and $T_{1/2}^{0\nu} = 10^{27}$ yr (full histogram), as well as the background contribution from contamination of the holder system and copper cryostat walls by nuclides from ^{232}Th and ^{238}U families. In the inset the summed spectrum in the vicinity of the $0\nu2\beta$ decay peak of ^{76}Ge is shown on a linear scale.

in this paper, while others were simply estimated as being negligible on the basis of the results of [43, 45], where such origins and contributions were investigated carefully.

We simulated the influence of the photon flux with energies up to 3 MeV measured in hall C of the Gran Sasso laboratory [54], where the main contributions originate from U and Th contamination of concrete walls. Among them mainly γs with an energy of 2614 keV (flux $\approx 5 \times 10^9$ m^{-2} yr^{-1}) can be dangerous for the experiment. In our calculations approximately 10^{15} external γs with $E_\gamma = 2614$ keV were simulated, yielding a detector background at an energy of 2038 keV of about 0.01 counts/(yr keV ton).

Summarizing all background sources (internal and external) we obtain a total background rate of the GEM experiment of less than 0.2 counts/(yr keV ton) (at 2038 keV). The simulated response functions of the GEM set-up after a 10 yr measurement time for 2β decay of ^{76}Ge ($T_{1/2}^{2\nu} = 1.8 \times 10^{21}$ yr [48] and $T_{1/2}^{0\nu} = 10^{27}$ yr), as well as the background contribution from contaminants in the holder system and copper cryostat walls are depicted in figure 3.

It is obvious from this figure that the measured background at energies below 1950 keV is dominated by a two-neutrino 2β decay distribution of ^{76}Ge (a total number of $\approx 2.6 \times 10^7$ counts are recorded), while at 2040 keV the main sources of background are contamination of the holder system and copper cryostat walls by nuclides from U and Th chains. On the other hand, it is also evident from figure 3 that $0\nu2\beta$ decay of ^{76}Ge with a half-life of 10^{27} yr would be clearly registered (there are 42 counts in the $0\nu2\beta$ decay peak).

The sensitivity of GEM can be expressed in the same manner as for the MAJORANA and GENIUS proposals (see section 2). For a 10 yr measuring period the value of lim S is equal to ≈ 5 counts (90% CL), thus taking into account the number of ^{76}Ge nuclei (7×10^{27}) and detection efficiency ($\eta \approx 0.95$), the half-life bound $T_{1/2} \approx 10^{28}$ yr could be achieved. Depending on the nuclear matrix elements calculations [5,7,19], the projected limit corresponds to the following range of neutrino mass constraints: $m_\nu \leqslant 0.015$–0.05 eV.

The realization of the GEM experiment seems to be reasonably simple due to fact that the developed design of the set-up has practically no technical risk. To this end, the very attractive feature of the project is the possibility of using the already existing BOREXINO CTF [46] as the outer shield, because the CTF fits all of the GEM requirements concerning radiopurity and dimensions of the water shield. In addition, one of the forthcoming large underground neutrino detectors such as KamLand [55] or BOREXINO could also be appropriate for this purpose.

The cost of the GEM experiment is estimated as about 150 M$, of which the main part would be for the production of enriched materials. However, we consider that in the first phase of the project the measurements will be performed with 1 ton of natural HP Ge detectors, whose cost (together with the cost of the cryostat) does not exceed 5 M$. Beside the important technical tasks which must be solved in the first stage of GEM to prove the feasibility of the project and to test the developed design, the GEM-I phase with its relatively modest cost would bring outstanding physical results. Indeed, in accordance with the formula for sensitivity of any $0\nu2\beta$ decay experiment (see section 2) the reachable half-life limit depends directly on the abundance or enrichment of candidate nuclei contained in the detector. For the GEM-I the natural abundance of ^{76}Ge (7.6%) is about 11 times smaller than the enrichment assumed for the second stage (86%). Because any other characteristics of the set-up (η, m, t, R, Bg) are the same for both GEM-I and GEM-II phases, the half-life bound, which would be obtained with natural HP Ge detectors, is about one order of magnitude lower: $T_{1/2} \approx 10^{27}$ yr. The latter translates into the neutrino mass constraints $m_\nu \leqslant 0.05$ eV, which is also of great interest for many theoretical models.

Another and very important issue of the GEM-I stage is the quest for dark matter particles (see the reviews [56–58]). It has been shown by Monte Carlo simulations [43, 45] that for the GENIUS project exploiting $\approx$100 kg of natural HP Ge detectors the background rate of $\approx$40 counts/(yr keV ton) could be obtained in the low-energy region (10–100 keV) relevant for the study of WIMP dark matter. The main contributions to this rate are from: (a) $2\nu2\beta$ decay of ^{76}Ge with $T^{2\nu}_{1/2} = 1.8 \times 10^{21}$ yr [48] ($\approx$20 counts/(yr keV ton)); (b) cosmogenic activities in HP Ge crystals ($\approx$10 counts/(yr keV ton)); (c) internal radioactive contamination of the liquid nitrogen, copper wires and holder system ($\approx$10 counts/(yr keV ton)). We estimated that an even lower background rate could be reached in the GEM-I set-up, where only an inner volume with $\approx$200 kg of HP Ge detectors will be used for the dark matter search, while outer layers with the remaining $\approx$800 kg of HP Ge crystals would serve as super-high-purity passive and active shields for the inner detectors. Our simulation shows that in such a configuration additional suppression of the background component (c) could be obtained, which would allow one to reach the highest sensitivity for the dark matter search compared with other projects (see, e.g., [59, 60]).

4. Implications of the high-sensitivity 2β decay experiments and conclusions

In this section we will briefly discuss the physical implications of future 2β decay experiments, whose sensitivity to the neutrino mass limit would be of the order of 0.05 eV (CAMEO, CUORE, EXO, GEM-I, MAJORANA, MOON, etc) and ≈ 0.01 eV (GEM-II, GENIUS).

As was already mentioned in the introduction, many extensions of the standard model incorporate lepton-number-violating interactions and thus could lead to $0\nu 2\beta$ decay. Besides the conventional left-handed neutrino exchange mechanism of $0\nu 2\beta$ decay, such theories offer many other possibilities to trigger this process [5–7].

For instance, in left–right symmetric GUT models neutrinoless 2β decay can be mediated by heavy right-handed neutrinos [61]. It was shown [62] that 2β decay experiments with sensitivity $m_\nu \leqslant 0.01$ eV would be at the same time sensitive to right-handed W_R boson masses up to $m_{W_R} \geqslant 8$ TeV (for a heavy right-handed neutrino mass $\langle m_N \rangle = 1$ TeV) or $m_{W_R} \geqslant 5.3$ TeV (for $\langle m_N \rangle = m_{W_R}$). These limits, which therefore could be established by the GEM-II experiment, are compared with those expected for LHC [63].

Another new type of gauge boson predicted by some GUTs are leptoquarks (LQ), which can transform quarks into leptons. Direct searches for leptoquarks in deep inelastic *ep*-scattering at HERA give lower limits on their masses $M_{LQ} \geqslant 225$–275 GeV (depending on the LQ type and coupling) [64]. Leptoquarks can induce $0\nu 2\beta$ decay via LQ–Higgs couplings, thus restrictions on leptoquark masses and coupling constants can be derived [65]. A detailed study performed in [66] yields the conclusion that a GENIUS-like experiment would be able to reduce the limit on LQ–Higgs couplings down to $\approx 10^{-7}$ for leptoquarks with masses in the range of 200 GeV. If no effect ($0\nu 2\beta$ decay) were found, it would mean that either LQ–Higgs coupling must be smaller than $\approx 10^{-7}$ or there exist no leptoquarks (coupling with electromagnetic strength) with masses below ≈ 10 TeV [66].

The hypothetical substructure of quarks and leptons (compositeness) can also give rise to a new $0\nu 2\beta$ decay mechanism by exchange of composite heavy Majorana neutrinos [67]. Recent analysis [68] shows that the at present most sensitive $0\nu 2\beta$ results with ^{76}Ge [19, 20] yield a bound on the excited Majorana neutrino mass of $m_N \geqslant 272$ 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 $m_N \geqslant 1$ TeV which is comparable to the sensitivity of LHC [68].

Moreover, there are also possible $0\nu 2\beta$ decay mechanisms based on the supersymmetric (SUSY) interactions: exchange of squarks, etc, within R-parity-violating [69–72] and exchange of sneutrinos, etc in R-parity-conserving SUSY models [73]. It allows 2β decay experiments to enter into the field of supersymmetry, where comparable restrictions on the sneutrino masses, R-parity-violating couplings and other parameters could be obtained [74,75].

Now we are going to consider the relations between $0\nu 2\beta$ decay studies and neutrino oscillation searches to demonstrate 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 [12, 13, 59, 76–82], 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 the observed oscillation data for solar and atmospheric neutrinos [12, 13, 80]. These are schemes with: normal and inverse neutrino mass hierarchy; partial and complete mass degeneracy, as well as scenarios with four neutrinos, etc. For each of these schemes several solutions exist: small mixing angle (SMA) Mikheyev–Smirnov–Wolfenstein (MSW) solution; large mixing angle (LMA) MSW solution; low-mass MSW (LOW) solution; vacuum oscillation (VO) solution. The careful analysis of these schemes

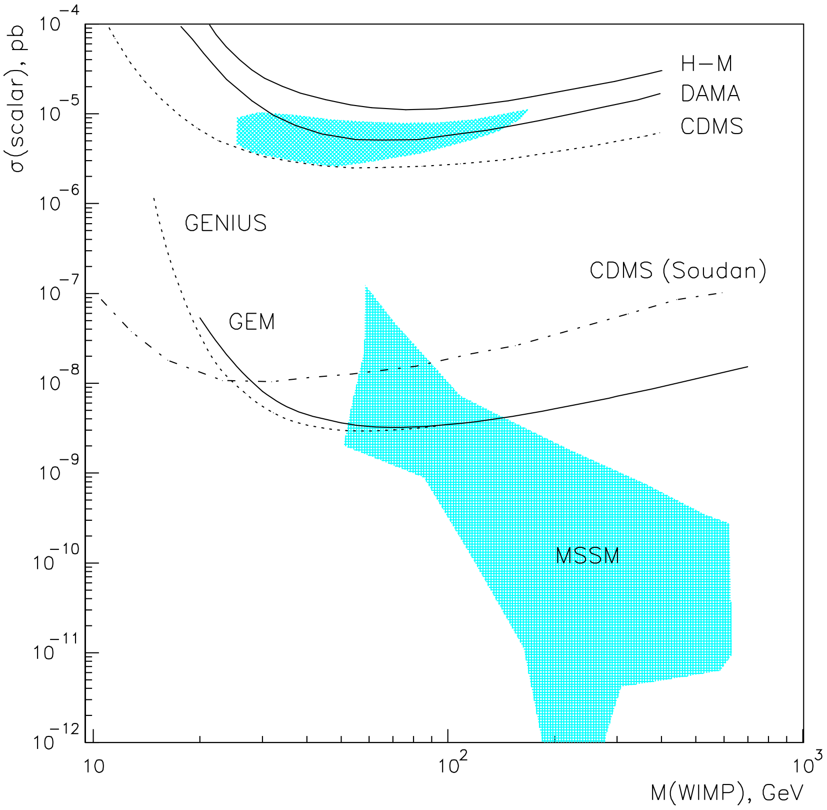

Figure 4. Exclusion plots of the spin-independent WIMP–nucleon elastic cross section versus WIMP mass. The regions above the curves are excluded at 90% CL. Current limits from Heidelberg–Moscow (H-M) [85], DAMA [86] and CDMS [87] experiments are shown in the upper part of figure. The small shaded area: 2σ evidence region from the DAMA experiment [88]. Projected exclusion plots for the CDMS [89], GENIUS [82] and GEM-I experiments are depicted too. The large shaded area represents the theoretical prediction for allowed spin-independent elastic WIMP–proton scattering cross section calculated in [83].

and solutions performed in [12, 13, 80] leads to the following statements: (a) the effective neutrino mass, $\langle m_\nu \rangle$, which is allowed by oscillation data and could be observed in 2β decay, is different for different schemes and solutions, hence the 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. If future 2β decay experiments prove that $\langle m_\nu \rangle \geqslant 0.1$ eV, then all schemes would be excluded, except those with neutrino mass degeneracy or with four neutrinos and an inverse mass hierarchy [12]. With the $\langle m_\nu \rangle$ bound of about 0.02–0.05 eV several other solutions will be excluded, while if the neutrino mass limit is $\langle m_\nu \rangle \leqslant 0.005$ eV the surviving schemes are those with a mass hierarchy or with partial degeneracy. The following extract from [80] emphasizes the importance of the future 2β decay searches: '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.'

Hence, it is obvious that the GEM experiment will bring crucial results for the reconstruction of the neutrino mass spectrum and mixing not only in its final GEM-II stage with enriched detectors ($\langle m_\nu \rangle \approx 0.015$ eV), but also in the first phase with natural HP Ge crystals ($\langle m_\nu \rangle \approx 0.05$ eV). This statement is true for any of the topics discussed above.

Furthermore, GEM-I with a realistic energy threshold of 10 keV and with an anticipated background rate of $\approx$40 counts/(yr keV ton) below 100 keV would provide the highest sensitivity for the WIMP dark matter search. This is demonstrated by the exclusion plot of the WIMP–nucleon elastic scattering cross section for GEM-I, which is depicted in figure 4 together with the best current and other projected limits[9]. The theoretical prediction for an allowed spin-independent elastic WIMP–proton scattering cross section calculated in [83] within the framework of the constrained minimal supersymmetric standard model (MSSM) is also shown there[10]. It is obvious from figure 4 that GEM-I would test the MSSM prediction by covering the larger part of the predicted SUSY parameter space. In that sense the GEM experiment could be competitive even with LHC in the SUSY quest [63]. At the same time with a fiducial mass of HP Ge detectors of $\approx$ 200 kg, GEM-I would be able to test and identify unambiguously (within 1 yr of data taking [90]) the seasonal modulation signature of the dark matter signal from the DAMA experiment [88] by using an alternative detector technology.

Hence, we can conclude that the challenging scientific goal reaching the $\approx$ 0.01 eV neutrino mass domain, would indeed be feasible for the GEM project, the realization of which seems to have practically no technical risk. To this end, the possibility of using the already existing BOREXINO CTF as an outer water shield is very attractive. The GEM experiment will bring outstanding results for the 2β decay studies (GEM-I and GEM-II stages) as well as for the dark matter searches (GEM-I), which are of great interest and would provide crucial tests of the many key problems and theoretical models of modern astroparticle physics.

Acknowledgments

The authors express their gratitude to Y Ramachers for fruitful discussions and remarks and S Yu Zdesenko for valuable suggestions concerning design of the GEM set-up.

References

[1] Zuber K 1998 *Phys. Rep.* **305** 295
[2] Schechter J and Valle J W F 1982 *Phys. Rev.* D **25** 2951
[3] Moe M and Vogel P 1994 *Ann. Rev. Nucl. Part. Sci.* **44** 247
[4] Tretyak V I and Zdesenko Yu G 1995 *At. Data Nucl. Data Tables* **61** 43
[5] Faessler A and Simkovic F 1998 *J. Phys. G: Nucl. Part. Phys.* **24** 2139
[6] Klapdor-Kleingrothaus H V 1998 *Int. J. Mod. Phys.* A **13** 3953
Hirsch M and Klapdor-Kleingrothaus H V 1998 *Prog. Part. Nucl. Phys.* **40** 323
[7] Suhonen J and Civitarese O 1998 *Phys. Rep.* **300** 123
[8] Vogel P 2000 *Current Aspects of Neutrino Physics* ed D Caldwell (Berlin: Springer) ch 8
(Vogel P 2000 *Preprint* nucl-th/0005020)
[9] Kirsten T A 1999 *Rev. Mod. Phys.* **71** 1213
[10] Fukuda Y *et al* (Super-Kamiokande Collaboration) 1998 *Phys. Rev. Lett.* **81** 1562
Fukuda Y *et al* (Super-Kamiokande Collaboration) 1999 *Phys. Rev. Lett.* **82** 1810

---

[9] The serious background problem for the dark matter quest with Ge detectors is cosmogenic activity of ^{3}H produced in Ge [43,45,82]. For GEM-I we estimated the total ^{3}H activity as $\approx$ 5000 decays/(yr ton), which is in good agreement with the result of [82] and contributes $\approx$10 counts/(yr keV ton) to the total background rate in the energy interval 10–100 keV.

[10] Very similar predictions from theoretical considerations in the MSSM with a relaxed unification condition were derived in [84].

Fukuda Y *et al* (Super-Kamiokande Collaboration) 1999 *Phys. Rev. Lett.* **82** 2430

[11] Church E D (for the LSND Collaboration) 2000 *Nucl. Phys.* A **663–4** 799
Aguilar A *et al* 2001 *Preprint* hep-ex/0104049

[12] Klapdor-Kleingrothaus H V *et al* 2001 *Phys. Rev.* D **63** 073005
(Klapdor-Kleingrothaus H V *et al* 2000 *Preprint* hep-ph/0003219)

[13] Bilenkij S M *et al* 1999 *Phys. Lett.* B **465** 193

[14] Elliot S R *et al* 1992 *Phys. Rev.* C **46** 1535

[15] Ejiri H *et al* 2001 *Phys. Rev.* C **63** 065501

[16] Danevich F A *et al* 2000 *Phys. Rev.* C **62** 045501

[17] Alessandrello A *et al* 2000 *Phys. Lett.* B **486** 13

[18] Luescher R *et al* 1998 *Phys. Lett.* B **434** 407

[19] Baudis L *et al* 1999 *Phys. Rev. Lett.* **83** 41

[20] Aalseth C E *et al* 1999 *Phys. Rev.* C **59** 2108
Gonzalez D *et al* 2000 *Nucl. Phys.* B (*Proc. Suppl.*) **87** 278

[21] Brun R *et al* 1994 *CERN Program Library Long Write-up* W5013 (CERN)

[22] Ponkratenko O A *et al* 2000 *Phys. At. Nucl.* **63** 1282

[23] der Mateosian E and Goldhaber M 1966 *Phys. Rev.* **146** 810

[24] Fiorini E *et al* 1967 *Phys. Lett.* B **25** 607

[25] Fiorini E *et al* 1970 *Lett. Nuovo Cimento* **3** 149

[26] Artyukhov A A *et al* 1998 *Phys. At. Nucl.* **61** 1236
Pokidychev A and Pokidycheva M 1999 *Nucl. Instrum. Methods* A **438** 7

[27] Moe M K 1991 *Phys. Rev.* C **44** 931

[28] Miyajima M *et al* 1991 *KEK Proc.* 91-5 19

[29] Miyajima M *et al* 1997 *AIP Conf. Proc.* **338** 253

[30] Danilov M *et al* 2000 *Phys. Lett.* B **480** 12

[31] Raghavan R S 1994 *Phys. Rev. Lett.* **72** 1411

[32] Caccianiga B, Giammarchi M G 2000 *Astropart. Phys.* **14** 15

[33] Ejiri H *et al* 2000 *Phys. Rev. Lett.* **85** 2917

[34] Danevich F A *et al* 1996 *Nucl. Phys.* B (*Proc. Suppl.*) **48** 235
Danevich F A *et al* 2001 *Nucl. Phys.* A **694** 254

[35] Raghavan R S 1997 *Proc. 4th Int. Solar Neutrino Conf. (Heidelberg)* (Heidelberg: Max-Planck-Institut für Kernphysik) p 248

[36] Zuber K 2000 *Phys. Lett.* B **485** 23

[37] Piquemal F (for the NEMO Collaboration) 1999 *Nucl. Phys.* B (*Proc. Suppl.*) **77** 352

[38] Fiorini E 1998 *Phys. Rep.* **307** 309

[39] NEMO Collaboration 2000 *Preprint* hep-ex/0006031

[40] Gervasio G (for the CUORE collaboration) 2000 *Nucl. Phys.* A **663–4** 873

[41] Bellini G *et al* 2000 *Phys. Lett.* B **493** 216
Bellini G *et al* 2001 *Eur. Phys. J.* C **19** 43

[42] Majorana project website: http://majorana.pnl.gov

[43] Klapdor-Kleingrothaus H V *et al* 1998 *J. Phys. G: Nucl. Part. Phys.* **24** 483

[44] Baudis L *et al* 1999 *Nucl. Instrum. Methods* A **426** 425

[45] Ponkratenko O A *et al* 1999 *Proc. Int. Conf. on Dark Matter in Astro and Particle Physics (Heidelberg, 1998)* ed H V Klapdor-Kleingrothaus and L Baudis (Bristol: IOP Publishing) p 738

[46] Bellini G (for the BOREXINO Collaboration) 1996 *Nucl. Phys.* B (*Proc. Suppl.*) **48** 363
Alimonti G *et al* 1998 *Nucl. Instrum. Methods* A **406** 411

[47] Kropschot R H 1961 *Cryogenics* **1** 171

[48] Gunther M *et al* 1997 *Phys. Rev.* D **55** 54
Baudis L *et al* 2000 *Preprint* hep-ex/0012022

[49] Jagam P and Simpson J J 1993 *Nucl. Instrum. Methods* A **324** 389

[50] Heusser G *et al* 2000 *Appl. Rad. Isotopes* **52** 691

[51] McDonald A B 1999 *Nucl. Phys.* B (*Proc. Suppl.*) **77** 43
Boger J *et al* 2000 *Nucl. Instrum. Methods* A **449** 172

[52] Martoff C J and Lewin P D 1992 *Comput. Phys. Commun.* **72** 96

[53] Grigoriev I S *et al* (ed) 1991 *Physical Quantities: the Handbook* (Moscow: Energoatomizdat)

[54] Arpesella C 1992 *Nucl. Phys.* A **28** 420

[55] Suzuki A 1999 *Nucl. Phys.* B (*Proc. Suppl.*) **77** 171

[56] Jungmann G *et al* 1996 *Phys. Rep.* **267** 195

[57] Ramachers Y 1999 *Preprint* astro-ph/9911260
[58] Baudis L and Klapdor-Kleingrothaus H V 2000 *Preprint* astro-ph/0003434
[59] Klapdor-Kleingrothaus H V 2001 *Preprint* hep-ph/0102319
[60] Klapdor-Kleingrothaus H V *et al* 2001 *Preprint* hep-ph/0103082
[61] Doi M *et al* 1983 *Prog. Theor. Phys. Suppl.* **69** 602
Doi M *et al* 1993 *Prog. Theor. Phys.* **89** 139
[62] Klapdor-Kleingrothaus H V and Hirsch M 1997 *Z. Phys.* A **359** 361
[63] Rizzo T 1996 *Preprint* SLAC-PUB-7365, hep-ph/9612440
Cvetic M and Godfrey S 1995 *Preprint* hep-ph/9504216
Godfrey S *et al* 1997 *Preprint* hep-ph/9704291
[64] Aida S *et al* (H1 Collaboration) 1996 *Phys. Lett.* B **369** 173
[65] Hirsch M *et al* 1996 *Phys. Lett.* B **378** 17
Hirsch M *et al* 1996 *Phys. Rev.* D **54** 4207
[66] Klapdor-Kleingrothaus H V *et al* 1999 *MPI-Report* MPI-H-V26-1999 Heidelberg
[67] Cabibbo N *et al* 1984 *Phys. Lett.* B **139** 459
Panella O *et al* 1997 *Phys. Rev.* D **56** 5766
[68] Panella O *et al* 2000 *Phys. Rev.* D **62** 015013
[69] Mohapatra R 1986 *Phys. Rev.* D **34** 3457
[70] Hirsch M *et al* 1995 *Phys. Rev. Lett.* **75** 17
Hirsch M *et al* 1996 *Phys. Rev.* D **53** 1329
Hirsch M *et al* 1996 *Phys. Lett.* B **372** 181
Hirsch M *et al* 1999 *Phys. Lett.* B **459** 450
[71] Faessler A *et al* 1997 *Phys. Rev. Lett.* **78** 183
Faessler A *et al* 1998 *Phys. Rev.* D **58** 055004
Faessler A *et al* 1998 *Phys. Rev.* D **58** 115004
[72] Wodecki A *et al* 1999 *Phys. Rev.* D **60** 115007
[73] Hirsch M *et al* 1997 *Phys. Lett.* B **398** 311
Hirsch M *et al* 1997 *Phys. Lett.* B **403** 291
Hirsch M *et al* 1998 *Phys. Rev.* D **57** 2020
[74] Hirsch M *et al* 1998 *Phys. Rev.* D **57** 1947
[75] Bhattacharyya G *et al* 1999 *Phys. Lett.* B **463** 77
[76] Vissani F 1999 *J. High Energy Phys.* JHEP06(1999)022
[77] Czakon M *et al* 1999 *Acta Phys. Polon.* B **30** 3121
[78] Czakon M *et al* 2000 *Preprint* hep-ph/0010077
[79] Czakon M *et al* 2000 *Acta Phys. Polon.* B **31** 1365
[80] Bilenky S M *et al* 2001 *Phys. Rev.* D **64** 053010
(Bilenky S M *et al* 2001 *Preprint* hep-ph/0102265)
Bilenky S M *et al* 2001 *Preprint* hep-ph/0104218
[81] Klapdor-Kleingrothaus H V 2001 *Nucl. Phys. B (Proc. Suppl.)* **100** 309
(Klapdor-Kleingrothaus H V 2001 *Preprint* hep-ph/0102276)
Klapdor-Kleingrothaus H V 2001 *Preprint* hep-ph/0103074
[82] Klapdor-Kleingrothaus H V and Majorovits B 2001 *Preprint* hep-ph/0103079
[83] Ellis J *et al* 2000 *Phys. Lett.* B **481** 304
[84] Bednyakov V A and Klapdor-Kleingrothaus H V 2001 *Phys. Rev.* D **63** 095005
[85] Baudis L *et al* 1999 *Phys. Rev.* D **59** 022001
[86] Bernabei R *et al* 1998 *Nucl. Phys.* B (*Proc. Suppl.*) **70** 79
Bernabei R *et al* 1996 *Phys. Lett.* B **389** 757
[87] Abusaidi R *et al* 2000 *Phys. Rev. Lett.* **84** 5699
[88] Bernabei R *et al* 2000 *Phys. Lett.* B **480** 23
[89] Abusaidi R *et al* 2000 *Nucl. Instrum. Methods* A **444** 345
[90] Cebrian S *et al* 2001 *Astropart. Phys.* **14** 339