High sensitivity GEM experiment on $2\beta$ decay of $^{76}$Ge

Yu.G. Zdesenko, O.A. Ponkratenko, V.I. Tretyak

Institute for Nuclear Research, MSP 03680 Kiev, Ukraine

Abstract

The GEM project is designed for the next generation $2\beta$ 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 the Cu vacuum cryostat (sphere $\varnothing 5$ m). The latest is placed in the water shield $\varnothing 11 \times 11$ m. Monte Carlo simulation evidently shows that 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 corresponds to the restrictions on the neutrino mass $m_\nu \leq 0.05$ eV and $m_\nu \leq 0.015$ 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 order of magnitudes, and at the same time would be able to identify unambiguously the dark matter signal by detection of its seasonal modulation.

PACS: 23.40.-s; 12.60.-i; 27.60.+j

Keywords: $2\beta$ decay, Majorana neutrino mass, HP $^{76}$Ge detectors

1 Introduction

At present, when neutrino physics has undergone a revolution (see [1] and refs. therein), the $2\beta$ decay search plays even more important role in modern physics than several years ago [3, 4, 5, 6, 7, 8]. Indeed, the solar neutrino problem [4], the measured deficit of the atmospheric muon neutrinos flux [10] and the result of the LSND accelerator experiment [11] could be explained by means of the neutrino oscillations, requiring in turn nonzero neutrino masses ($m_\nu$). However, oscillation experiments are sensitive to neutrino mass difference, while only measured neutrinoless ($0\nu$) double $\beta$ decay rate can give the absolute scale of the effective Majorana neutrino mass, 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 $m_\nu$, lepton violation constants and other parameters of the manifold SM extensions, which allow to narrow a wide choice of

---

1Corresponding author. Address: Institute for Nuclear Research, Prospekt Nauki 47, MSP 03680 Kiev, Ukraine; fax: 380 44 265 4463; phone: 380 44 265 2210; e-mail: zdesenko@kinr.kiev.ua

2The neutrinoless ($0\nu$) double $\beta$ 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 on which mechanism induces it, requires neutrinos to be massive Majorana particles [2].

3Obviously, its accuracy depends on the uncertainties of the nuclear matrix elements calculation.
the theoretical models and to touch the multi-TeV energy range competitive to the accelerator experiments.

Despite the numerous efforts to detect $0\nu2\beta$ decay, this process still remains unobserved. The highest half-life limits were set in direct experiments with several nuclides: $T_{1/2}^{0\nu} \geq 10^{22}$ yr for $^{82}\text{Se}$, $^{100}\text{Mo}$; $T_{1/2}^{0\nu} \geq 10^{23}$ yr for $^{116}\text{Cd}$, $^{128}\text{Te}$, $^{130}\text{Te}$, $^{136}\text{Xe}$; and $T_{1/2}^{0\nu} \geq 10^{25}$ yr for $^{76}\text{Ge}$. These results have already brought the most stringent restrictions on the values of the Majorana neutrino mass $m_\nu \leq (0.5-5.0)$ 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 parameter of minimal SUSY standard model $\varepsilon \approx 10^{-4}$. However, on the basis of current status of astroparticle physics it is very desirable to improve the present level of sensitivity by one-two orders of magnitude.

Many projects were proposed during a past few years with regard to these goals, however most of them require strong efforts and long time to prove their feasibility (see next section). To this effect, in the present paper we suggest the GEM project of the high sensitivity $2\beta$ decay experiment with $^{76}\text{Ge}$, those accomplishment seems to be realistic. Before enter upon the project itself (section 3), the sensitivity limitations and current status of the $2\beta$ decay studies, as well as requirements to the future projects are considered briefly in section 2.

## 2 Sensitivity limitation, present status and future of $2\beta$ decay studies

There are two different classes of $2\beta$ decay experiments: with "passive" source, which can be simply placed as foil between two detectors, and with "active" source, where detector containing $2\beta$ candidate nuclei serves as source and detector simultaneously. If neutrinoless $2\beta$ 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 $2\beta$ decay study can be expressed in terms of a lower half-life limit as following:

$$T_{1/2} \sim \eta \cdot \delta \frac{(m \cdot t)}{(R \cdot Bg)}.$$

Here $\eta$ is the detection efficiency; $\delta$ the abundance or enrichment of candidate nuclei contained in the detector; $t$ the measuring 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 square root. Obviously, $\approx 100\%$ enrichment is very desirable.

One could also require $\approx 100\%$ detection efficiency, which is possible, in fact, only for the "active" source technique. Indeed, the strength of "passive" source can be enlarged by increasing its thickness, which in turn lowers detection efficiency due to absorption of electrons in the source, broadening and shifting of the $2\beta$ decay peak. To this effect, the energy resolution of the detector is very essential because events from the high energy tail of the continuous $2\nu$

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

\footnote{Let us consider two detectors with different masses ($m_1$, $m_2$) and enrichment ($\delta_1$, $\delta_2$). Supposing that their other characteristics ($\eta$, $t$, $R$, $Bg$) are the same and requiring the equal sensitivities ($T_{1/2}^1 = T_{1/2}^2$), we can obtain the relation between masses and enrichment of the detectors $m_1/m_2 = (\delta_2/\delta_1)^2$, which speaks for itself.}
distribution run into the energy window of the 0ν peak, generating background which cannot be discriminated from the 0ν signal. Better energy resolution minimizes the 2ν tail falling within the 0ν interval, hence lowering this irreducible background.

All mentioned statements are illustrated by fig. 1, where results of model experiment to study 2β decay of $^{100}$Mo are presented. The simulation were performed with the help of GEANT3.21 package [21] and event generator DECAY4 [22]. The following assumptions were accepted: mass of $^{100}$Mo source is one kg; measuring time is 5 years; half-lives of $^{100}$Mo 2β decay are $T_{1/2}(2ν) = 10^{19}$ yr and $T_{1/2}(0ν) = 10^{24}$ yr. The initial 2β decay spectra (shown in fig. 1a and 1b for different vertical scales) were obtained with $^{100}$Mo nuclei contained in the ideal ("active") source detector with 100% efficiency, zero background and the energy resolution of FWHM=10 keV. On the next step the $^{100}$Mo source was introduced in the same detector but in the form of foil ("passive" source technique). The simulated spectra are depicted in fig. 1c (thickness of $^{100}$Mo foil is 15 mg/cm²) and fig. 1d (60 mg/cm²). Then, the energy resolution of the detector (FWHM) was taken into account and results are shown in fig. 1e (FWHM = 4% at 3 MeV) and fig. 1f (FWHM = 8.8% at 3 MeV). It is evident from fig. 1 that "passive" source technique is not appropriate for the observation of 0ν/2β decay with ratio of $T_{1/2}(0ν)$ to $T_{1/2}(2ν)$ more than $10^5$.

![Figure 1: Simulated spectra of the model 2β decay experiment (5 yr measuring time) with 1 kg of $^{100}$Mo.](image)

Figure 1: Simulated spectra of the model 2β decay experiment (5 yr measuring time) with 1 kg of $^{100}$Mo. (1a, 1b) "Active" source technique: $^{100}$Mo nuclei in a detector with 100% efficiency, zero background, and with 10 keV energy resolution. (1c, 1d) "Passive" source technique: $^{100}$Mo source in the same detector with foil thickness 15 mg/cm² (1c) and 60 mg/cm² (1d). (1e) The same as (1c) but the energy resolution (FWHM) of the detector at 3 MeV is 4%. (1f) The same as (1d) but with FWHM = 8.8%.

Hence, we conclude that "active" source approach provides 4π geometry for the source,\(^6\) In both cases all features of events are similar: two electrons with the same energies and identical angular distribution are emitted from one point of the source simultaneously.
absence of self-absorption, and better energy resolution, which does not depend on the angular and energy distribution of the electrons emitted in $2\beta$ decay. These advantages of “active” detectors were understood a long ago and the first experiment of this type was performed in 1966 by using $^{48}$CaF$_2$ scintillator to study $2\beta$ decay of $^{48}$Ca [23]. In the next year semiconductor Ge(Li) crystal was applied in the quest for $2\beta$ decay of $^{76}$Ge [24]. Due to high purity and good energy resolution of the Ge(Li) detectors the first valuable result with $^{76}$Ge ($T_{1/2}^{0\nu} \geq 10^{21}$ yr) was obtained in 1970 [25]. After 30 years of strong efforts this limit was advanced up to $T_{1/2}^{0\nu} \geq 10^{25}$ yr in the two current experiments performed by the IGEX [20] and Heidelberg-Moscow [19] collaboration.

The IGEX is operating three 2-kg HP Ge detectors (enriched in $^{76}$Ge to $\approx 88\%$) in the Canfranc Underground Laboratory (Spain). The shield consists of 2.5 tons of archeological and 10 tons of 70-yr-old low-activity lead, and plastic scintillator as cosmic muon veto. The pulse shape discrimination techniques is applied to data. The background rate is equal to $\approx 0.06$ 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-years (or 8.87 kg·yr in $^{76}$Ge) of data yields a lower bound $T_{1/2}^{0\nu} \geq 1.57 \times 10^{25}$ yr at 90% C.L. [20].

The Heidelberg-Moscow experiment in the Gran Sasso Underground Laboratory uses five HP Ge detectors (enriched in $^{76}$Ge to 86%) with the 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 allows to reduce background rate in the energy region of interest to the value of $\approx 0.06$ counts/yr·kg·keV. The energy resolution at the energy of 2038.7 keV is 3.9 keV. After 24 kg·yr of data with PSA a lower half-life limit $T_{1/2}^{0\nu} \geq 1.6 \times 10^{25}$ yr with 90% C.L. has been set for $^{76}$Ge [19].

Therefore, on the basis of this brief analysis of the present status of $2\beta$ decay experiments, we can formulate the following requirements to the future ultimate sensitivity projects:

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

(ii) The best $^{76}$Ge results were obtained by using $\approx 10$ kg of enriched detectors, hence, to reach the required level of sensitivity one has to exploit the enriched sources with masses of hundreds kg. The latest restricts the list of candidate nuclei because a 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 with a reasonable price [26].

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

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

(v) It is anticipated that measuring time of the 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 during such a long period.

Evidently, it could be very difficult to find the project and to build up the experiment, which would completely satisfy these severe requirements. However, perhaps some of recent

---

7As it is known, the 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 metal–organic cadmium–dimethyl compound [26].
proposals could do it to a great extent, thus let us consider them briefly.

An interesting approach to study $2\beta$ decay of $^{136}\text{Xe}$ ($Q_{\beta\beta} = 2468 \text{ keV}$) makes use of the coincident detection of $^{136}\text{Ba}^{2+}$ ions (the final state of the $^{136}\text{Xe}$ decay on the atomic level) and the $0\nu2\beta$ signal with the energy of 2.5 MeV in a time projection chamber (TPC) filled with liquid or gaseous Xe [27, 23, 24]. Recently, the EXO project has been considered [30], where the resonance ionization spectroscopy for the $^{136}\text{Ba}^{2+}$ ions identification would be applied in a 40 m$^3$ TPC operated at 5–10 atm pressure of enriched xenon ($\approx$1–2 tons of $^{136}\text{Xe}$). Estimated sensitivity to neutrino mass is $\approx$0.01 eV [30]. Another proposal (originated from [31]) is to dissolve $\approx$80 kg ($\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 to make both the study of $0\nu2\beta$ decay of $^{100}\text{Mo}$ ($Q_{\beta\beta} = 3034 \text{ keV}$) and the real time studies of low energy solar $\nu$ by inverse $\beta$ 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 wave length shifter fibers (2×1.2 mm × 6 m), viewed through clear fibers by 6800 16-anode photomultiplier tubes. The proposal calls for the use of 34 tons of natural Mo (i.e. 3.3 tons of $^{100}\text{Mo}$) per module in the form of foil ($\approx$50 mg/cm$^2$). The sensitivity of such a module to the neutrino mass could be of the order of $\approx$0.05 eV [33].

The $^{160}\text{Gd}$ ($Q_{\beta\beta} = 1730 \text{ keV}$) is an attractive candidate due to large natural abundance (21.9%), allowing to construct sensitive apparatus with natural Gd$_2$SiO$_5$:Ce crystal scintillators (GSO). The large scale experiment with $^{160}\text{Gd}$ by using the GSO multi-crystal array with the total mass of one-two tons ($\approx$200–400 kg of $^{160}\text{Gd}$) is suggested with the projected sensitivity to the Majorana neutrino mass $\approx$0.04 eV [34].

Using future large scale Yb-loaded liquid scintillation detectors for solar neutrino spectroscopy [35] it is supposed to search for $2\beta^-$ decay of $^{176}\text{Yb}$ ($Q_{\beta\beta} = 1087 \text{ keV}$) and $\varepsilon\beta^+$ decay of $^{168}\text{Yb}$ ($Q_{\beta\beta} = 1422 \text{ keV}$). With about 20 tons of natural Yb ($\approx$2.5 tons of $^{176}\text{Yb}$) the limit $T_{1/2}^{0\nu} \geq 10^{26}$ yr could be set on $0\nu2\beta$ decay of $^{176}\text{Yb}$ ($m_\nu \leq 0.1 \text{ eV}$) [36].

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

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 of $^{100}\text{Mo}$ source would be on the level of $\approx$4×$10^{24}$ yr ($m_\nu \leq 0.3$–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 $2\beta$ decay quest of $^{130}\text{Te}$ with the help of one thousand TeO$_2$ bolometers (total mass of 750 kg), which could reach $\approx$0.05 eV neutrino mass bound [38, 40].

Recently a project CAMEO has been suggested [41], where the super-low background and large sensitive volume of the already existing CTF are used to study $^{116}\text{Cd}$. With $\approx$100 kg of enriched $^{116}\text{CdWO}_4$ 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 to the neutrino mass bound $m_\nu \leq 0.06 \text{ eV}$. Similarly with one ton of $^{116}\text{CdWO}_4$ crystals located in the BOREXINO apparatus (under construction) the constraint on the neutrino mass can be pushed down to $m_\nu \leq 0.02 \text{ eV}$ [41].

Besides, two large scale projects for the $2\beta$ decay quest of $^{76}\text{Ge}$ (MAJORANA [42] and GENIUS [43]) are proposed, which we are going to discuss in more details.

**MAJORANA.** The idea of this proposal is to use 210 HP Ge (enriched in $^{76}\text{Ge}$ to $\approx$ 86%)
semiconductor detectors (≈2.4 kg mass of one crystal), which are placed in "conventional" super-low background cryostat (21 crystals in one cryostat) [12]. The detectors are shielded by HP lead or copper. Each crystal will be supplied with six azimuthal and two axial contacts, hence a proper spatial information will be available for detected events. It is anticipated that segmentation of crystals and pulse shape analysis (PSA) of data would reduce background rate of the detectors to the level of ≈0.01 counts/yr-kg-keV at the energy 2 MeV, that is 6 times lower than that already reached in the most sensitive 76 Ge experiments [13, 29]. Thus, after 10 yr of measurements ≈200 background counts will be recorded in the vicinity of 0ν2β decay peak (≈ 4 keV energy interval) [14]. On this basis the half-life limit, $T_{1/2}$, can be determined with the help of formula: $\lim T_{1/2} = \ln 2 \cdot \eta \cdot N \cdot t / \lim S$, where $N$ is the number of 76 Ge nuclei ($N = 3.5 \times 10^{27}$) and $\lim S$ is the maximal number of 0ν2β events which can be excluded with a given confidence level. To estimate value of $\lim S$ we can use so called "one (1.6; 2) $\sigma$ approach", in which the excluded number of effect’s events is determined simply as square root of the number of background counts in the energy region of interest, multiplied by 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 the sensitivity of any experiment. Applying it to the projected MAJORANA data, one can get $\lim S \approx 20$ counts at 90% C.L., and whereby the bound $T_{1/2} \approx 10^{27}$ yr. Depending on the nuclear matrix elements calculations used (see for ref. [14]), it leads to the interval of the neutrino mass limit $m_{\nu} \leq 0.05 - 0.15$ eV.

**GENIUS.** The project intends to operate one ton of HP Ge (enriched in 76 Ge to ≈ 86%) semiconductor detectors [13]. It is scheduled that background of the GENIUS set up would be reduced by ≈200 times as compared with that of present experiments [19, 20]. To reach this goal, ”naked” Ge crystals will be placed in an extremely high-purity liquid nitrogen (LN$_2$), which simultaneously serves as cooling medium and shielding for the detectors.

The feasibility of operating Ge detectors in liquid nitrogen was demonstrated by the measurements with three HP Ge crystals (mass of ≈0.3 kg each) [14]. With the 6 m cables between detectors (placed on a common plastic holder inside liquid nitrogen) and outer preamplifiers the energy threshold of ≈2 keV and the energy resolution of ≈1 keV (at 300 keV) were obtained [14]. The second question – is it indeed achievable to obtain so extremely low background level – has been answered by means of the Monte Carlo simulations. The latest were independently performed by MPI, Heidelberg [14] and INR, Kiev [15] groups. In accordance with simulations [14, 15] the necessary dimensions of the liquid nitrogen shield, which could fully suppress the radioactivity from the surroundings (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 for 40 K and 238 U, $\approx 5 \times 10^{-15}$ g/g for 232 Th, and 0.05 mBq/m$^3$ for 222 Rn [14, 15]. All these requirements (except for radon) are less stringent than those already achieved in the BOREXINO CTF: $(2-5) \times 10^{-16}$ g/g for 232 Th and 238 U contamination in the liquid scintillators [14]. Therefore purification of the liquid nitrogen to satisfy the GENIUS demands seems to be quite realistic. The only problem is the radon contamination, those required value is about 20 times less than that measured in liquid nitrogen as $\approx 1$ mBq/m$^3$ [16]. The final conclusions are derived that in the GENIUS experiment the total background rate of $\approx 0.2$ counts/yr-keV-t could be obtained in the energy region of the $\beta\beta$ decay of 76 Ge [14, 15]. On this basis the projected $T_{1/2}$ limit can be estimated similarly as for the MAJORANA proposal. For 10 yr measuring time the value of $\lim S$ is equal $\approx 5$ counts (90% C.L.), thus with $7 \times 10^{27}$ nuclei of 76 Ge the bound $T_{1/2} \approx 10^{28}$ yr could be achieved, which translates to the neutrino mass constraints $m_{\nu} \leq 0.015 - 0.05$ eV.
However, to reach the scheduled sensitivity the GENIUS apparatus must satisfy very stringent and in some cases contradicting demands. For example, super-low background rate of detectors requires the ultra-high purity of liquid nitrogen and large dimensions of the vessel (\(\varnothing 12 \times 12 \text{ m}\)) with the total mass of a LN\(_2\) of \(\approx 1000\) t. Ultra-high purity of liquid nitrogen means that continuous purification of LN\(_2\) during a whole running experiment is needed. The power of the LN\(_2\) purification system (and maintenance costs) strongly depends on the liquid nitrogen consumption, which in turn depends on the quality of the LN\(_2\) tank thermoinsulation. The method of passive thermoinsulation with the help of the polyethylene foam isolation of 1.2 m thick was accepted for the GENIUS set up [13]. Despite its simplicity, the disadvantage of this solution is a large LN\(_2\) consumption because of huge dimensions of the LN\(_2\) tank (heat losses through the walls are straight proportional to their square). First, it leads to the substantial maintenance cost of the experiment. Secondly, and more important, this solution makes it very difficult to keep the required ultra-high purity of LN\(_2\) during the whole running period. It is because that evaporation of LN\(_2\) is the method of purification, thus pure vapor will leave vessel, while all impurities will be kept in remaining LN\(_2\). In case of a large liquid nitrogen consumption this process will lead to a permanent increasing of the LN\(_2\) contamination level. Therefore, it is clear that production, purification, operation and maintenance (together with safety requirements) of more than one kiloton of ultra-high purity liquid nitrogen in underground laboratory would require additional efforts and lead to considerable costs and time for realization of the GENIUS project.

With the aim to overcome all mentioned difficulties and make realization of the high sensitivity \(^{76}\text{Ge}\) experiment simpler, the GEM project is presented below.

### 3 The GEM design and background simulation

The GEM design is based on the following keystone ideas:

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

(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 as minimal as necessary to eliminate the contribution of the radioactive contaminations of the Cu cryostat to the background of HP Ge detectors.

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

The optimization of the set up design as well as background simulation for the GEM experiment were performed with the help of GEANT3.21 package and event generator DECAY4. Scheme of the GEM device created on the basis of simulation is shown in fig. 2. About 400 enriched HP Ge detectors (\(\varnothing 8.5 \times 8.5\) cm, weight of \(\approx 2.5\) kg each) are located in the center 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 space of \(\approx 90\) cm in diameter. It is supposed that crystals are fixed with the help of holder-system made of nylon strings. The thin copper wire \(\varnothing 0.2\) mm is attached to each detector to provide signal connection.
The outer encapsulation of the cryostat with diameter 5 m is also made of HP Cu with 0.6 cm thickness. Both enclosures of cryostat are connected by two concentric copper pipes with outer vacuum pump, which maintains $\approx 10^{-6}$ torr pressure in the space between two walls of the cryostat. The latest (in combination with several layers of $\approx 5 \mu$m thick aluminized mylar film enveloping the inner Cu vessel and serving as thermal radiation reflector) allows to reduce heat current through the walls of the cryostat to the value of $\approx 2.5 \text{ W/m}^2$ [47], thus total heat losses (including heat conduction through pipes, support structure and cables) are near 200 W. This corresponds to a reasonable LN$_2$ consumption of about 150 kg per day.

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 the latest, where only tiny fraction of heat current through thin signal cables and holder strings could reach this volume. Outer LN$_2$ zone between inner wall of the cryostat and sphere with Ge crystals would serve as additional and very efficient thermal shield [47]. Hence, LN$_2$ consumption in the inner volume with detectors would be extremely low, which allows to keep there the ultra-high purity of LN$_2$ and stable operation conditions for a whole running period.

Another important advantage of the proposed solution is that detectors are located inside a module, and all procedures of cleaning, mounting of crystals, testing, etc. can be performed in 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 for $^{40}$K, $^{232}$Th, $^{238}$U, and $\approx 10$ mBq/m$^3$ for $^{222}$Rn) water shield with mass $\approx 1000$ t contained in the steel tank $\bowtie 11 \times 11$ m. We remind that even slightly better radio-purity levels were already achieved for the water shield of the BOREXINO CTF operating in the Gran Sasso Underground Laboratory [10]. The dimensions of the CTF water tank are practically the same ($\bowtie 11 \times 10$ m), 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 limited number of photomultipliers would serve as 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 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 fig. 2). The total mass of detectors is equal $\approx 1$ t, liquid nitrogen – $\approx 40$ t, copper cryostat – $\approx 7$ t, water shield – 1000 t, holder-system – $\approx 2$ kg, and copper wires – $\approx 1$ kg. As it is 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 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 of all detectors (anti-coincidence mode) were taken into account. The origins of background can be divided into internal and external ones. 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 mentioned materials at the Earth 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.

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 were calculated by using the data of the Heidelberg-Moscow experiment with $^{76}$Ge detectors [19, 18]. The absence of any $\alpha$ peaks in the measured spectra (for 17.7 kg×yr statistics) leads to the upper limits (90% C.L.) presented in Table 1. Data on purity of copper for $^{40}$K, $^{232}$Th and $^{238}$U are taken from [18]. The copper cosmogenic activities of $^{54}$Mn (23 $\mu$Bq/kg), $^{57}$Co (30 $\mu$Bq/kg), $^{58}$Co (50 $\mu$Bq/kg), $^{60}$Co (70 $\mu$Bq/kg), as well as anthropogenic activities of $^{125}$Sb (50 $\mu$Bq/kg), $^{207}$Bi (8 $\mu$Bq/kg), $^{134}$Cs (150 $\mu$Bq/kg) and $^{137}$Cs (11 $\mu$Bq/kg) are accepted on the basis of measurements with the Ge detectors of the Heidelberg-Moscow experiment [18]. For steel, the upper limits from [19] are assumed. For the water the actual radio-purity levels obtained in the already operated BOREXINO water plant [19] are quoted in Table 1. The radiopurity criteria supposed for the liquid nitrogen ($\approx 10^{-15}$ g/g for $^{40}$K and $^{238}$U, $\approx 5\times10^{-15}$ g/g 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: $(2–5)\times10^{-16}$ g/g for $^{232}$Th and $^{238}$U [10]. Moreover, due to recent development of the liquid nitrogen purification system for the BOREXINO experiment [70] the $^{222}$Rn contamination of the liquid nitrogen was also reduced down to the level of $\approx 1$ $\mu$Bq/m$^3$ [51], which is lower than our requirement $\approx 50$ $\mu$Bq/m$^3$. For the radiopurity of the holder-system we assume the value of $10^{-12}$ g/g for the U/Th decay chains, which is already achieved by the SNO collaboration for the acrylic [51].

The full decay chains were simulated in assumption of the chains equilibrium. Results of calculation are presented in Table 2. For internal impurities in HP Ge detectors, two values
Table 1: Radioactive impurities of the detectors and materials accepted for the simulation

| Materials                  | ⁴⁰K (mass) | ²³²Th (mass) | ²³⁸U (mass) | ²²²Rn (mass) |
|----------------------------|-----------|-------------|-------------|--------------|
| HP ⁷⁶Ge (1 t)              | –         | 5.7×10⁻¹⁵   | 1.8×10⁻¹⁵   | –            |
| Liquid N₂ (40 t)           | 1.0×10⁻¹⁵ | 5.0×10⁻¹⁵   | 1.0×10⁻¹⁵   | 0.05         |
| Holder system (2 kg)       | –         | 1.0×10⁻¹²   | 5.4×10⁻¹²   | –            |
| Copper wires (1 kg)        | 4.5×10⁻¹⁰ | 3.0×10⁻¹²   | –           | –            |
| and vessels (7 t)          |           |             |             | –            |
| Water (1000 t)             | 1.0×10⁻¹⁴ | 1.0×10⁻¹⁴   | 1.0×10⁻¹⁴   | 10           |
| Steel vessel (90 t)        | 5.0×10⁻¹⁰ | 1.0×10⁻⁹    | 1.0×10⁻⁹    | –            |

Table 2: Calculated background rate of the detectors at the energy 2038 keV due to internal impurities of the materials. For the LN₂ and water the ²²²Rn contributions are included in column for ²³⁸U

| Material                  | Background rate at 2 MeV, counts/yr·keV·t⁻¹ | ²³²Th | ²³⁸U | total |
|----------------------------|-------------------------------------------|------|------|-------|
| HP ⁷⁶Ge                   | 2.0×10⁻³                                   | 4.3×10⁻³ | 6.3×10⁻³ |
| [4.6×10⁻²]                 |                                          | [1.6×10⁻¹] | [2.1×10⁻¹] |
| Liquid N₂                 | 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 ⊙3.8m     | 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 |

are given: without (in square brackets) and with time-amplitude analysis of events, where information about the energies and arrival time of each event is used for analysis and selection of some decay chains in U and Th families (see, f.e., ref. [16]).

It is obvious from Table 2 that two Cu enclosures of the cryostat and holder system give the main contribution to background. Besides, the results of simulations show that demands to the purity of water shield can be lowered to the level of about 10⁻¹³ g/g for U (Th) contaminations. The latest means that maintenance costs of the GEM experiment can be lowered too.

### 3.1.2 Cosmogenic activities in HP ⁷⁶Ge 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 days – 5 million years by nucleon-induced reactions in a given target, taking into account the variation of spallation, evaporation, fission and peripheral reaction cross-sections.
Table 3: Cosmogenic activities produced in HP $^{76}$Ge detectors. The background rate at the energy 2038 keV is averaged during one year period of data taking

| Nuclide     | Mode of decay | Activity after 3 yr, $\mu$Bq/kg | Background at 2 MeV, counts/yr·keV·t |
|-------------|---------------|---------------------------------|--------------------------------------|
| $^{22}$Na (2.6 yr) | EC/β$^+$ (2842) | $2.0 \times 10^{-3}$ | $3.5 \times 10^{-3}$ |
| $^{46}$Sc (83.8 d)  | β$^-$ (2367)     | $2.5 \times 10^{-5}$ | $1.0 \times 10^{-4}$ |
| $^{56}$Co (78.8 d)  | EC/β$^+$ (4568)  | $6.0 \times 10^{-5}$ | $5.4 \times 10^{-2}$ |
| $^{58}$Co (70.8 d)  | EC/β$^+$ (2308)   | $1.9 \times 10^{-5}$ | $3.2 \times 10^{-6}$ |
| $^{60}$Co (5.27 yr) | β$^-$ (2824)     | $6.0 \times 10^{-5}$ | $4.0 \times 10^{-2}$ |
| $^{68}$Ga (68.1 m)  | EC/β$^+$ (2921)   | $5.0 \times 10^{-2}$ | $0.018$ [0.15] |
| **Total**         |                |                                 | $0.07$ [0.22] |

with nucleon energy, target and product charge and mass numbers, as well as energy spectrum of cosmic ray nucleons near the Earth’s surface [12].

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 three years in underground were assumed. From the total number of 41 nuclides with $T_{1/2} \geq 25$ d produced in Ge crystals, we present in Table 3 the most dangerous ones which give the noticeable background near the energy 2038 keV ($Q_{\beta\beta}$ 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 background at 2038 keV is caused mainly by $^{22}$Na, $^{60}$Co and $^{68}$Ga (a daughter of cosmogenic $^{68}$Ge). Remaining $^{68}$Ga contribution could be suppressed significantly by using the time-amplitude analysis due to specific features of the $^{68}$Ge $\rightarrow$ $^{68}$Ga decay chain. Indeed, 88% of the electron captures in $^{68}$Ge to the ground state of $^{68}$Ga result in the sharp 10.4 keV peak (K capture). Using these events as triggers for time-amplitude analysis of the subsequent counts during 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 days per detector) would allow to use such an approach. The background from $^{60}$Co can be also decreased by additional annealing of Ge crystals in the underground laboratory. Preliminary study shows that $^{60}$Co can be removed out of detectors due to its large diffusion mobility in Ge at high temperatures [53]. All mentioned approaches will reduce the cosmogenic background rate to the value less than $3 \times 10^{-2}$ counts/yr·keV·t near 2038 keV.

### 3.1.3 External background

There are several origins of external background for the proposed GEM detector. These are neutrons and $\gamma$ quanta from natural environmental radioactivity, cosmic muons ($\mu$ showers and muon induced neutrons, inelastic scattering and capture of muons), etc. From all of them

---

8We supposed that Ge materials and crystals were additionally shielded against activation during production and transportation. For example, 20 cm of Pb would lower the cosmic nucleons flux by one order of magnitude that means the same reduction factor for the most of cosmogenic activities.
only γ quanta from environment were simulated in the present work, while others were simply estimated as negligible on the basis of the results of ref. [43, 45], where such origins and contributions were investigated carefully.

We simulated the influence of the photon flux with the energies up to 3 MeV measured in hall C of the Gran Sasso laboratory [54], where the main contributions are originating from U and Th contamination of concrete walls. Among them mainly γ’s with the energy of 2614 keV (flux ≈5×10^9 m^{-2}·yr^{-1}) can be dangerous for the experiment. In our calculations approximately 10^{15} external γ’s with E_{γ} = 2614 keV were simulated, yielding the detector background at the energy 2038 keV of about 0.01 counts/yr·keV·t.

Summarizing all background origins (internal and external) we get the total background rate of the GEM experiment less than 0.2 counts/yr·keV·t (at 2038 keV). The simulated response functions of the GEM set up after 10 yr measuring time for 2β decay of ^{76}Ge (T^{2ν}_{1/2} = 1.8×10^{21} yr [18] and T^{0ν}_{1/2} = 10^{27} yr), as well as background contribution from contaminations of the holder system and copper cryostat walls are depicted in fig. 3. It is obvious from this figure that measured background at the energies below 1950 keV is dominated by two neutrino 2β decay distribution of ^{76}Ge (the total number of ≈2.6×10^7 counts are recorded), while at 2040 keV the main sources of background are contaminations of the holder system and copper cryostat walls by nuclides from U and Th chains. On the other hand, it is also evident from fig. 3 that 0ν2β decay of ^{76}Ge with half-life of 10^{27} yr would be clearly registered (there are 42 counts in the 0ν2β decay peak).

![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 2β decay of ^{76}Ge with T^{2ν}_{1/2} = 1.8×10^{21} yr [18] and T^{0ν}_{1/2} = 10^{27} yr (solid histogram), as well as background contribution from contaminations of the holder system and copper cryostat walls by nuclides from ^{232}Th and ^{238}U families. In the insert the summed spectrum in the vicinity of the 0ν2β decay peak of ^{76}Ge is shown in the linear scale.](image)

The sensitivity of the GEM can be expressed in the same manner as for the MAJORANA
and GENIUS proposals (see Section 2). For 10 yr measuring period the value of lim S is equal \( \approx 5 \) counts (90% C.L.), thus taking into account the number of \( ^{76}\text{Ge} \) nuclei \( (7 \times 10^{27}) \) 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 [3, 4, 19], the projected limit corresponds to the following range of the neutrino mass constraints: \( m_\nu \leq 0.015 - 0.05 \) eV.

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

The cost of the GEM experiment is estimated as about 150 M$, whose main part would be for the production of enriched materials. However, we consider that at the first phase of the project the measurements will be performed with one ton of natural HP Ge detectors, whose cost (together with cost of the cryostat) does not exceed 5 M$. Beside of important technical tasks which must be solved on the first stage of the GEM to prove feasibility of the project and to test the developed design, the GEM-I phase with its relatively modest cost would bring the outstanding physical results. Indeed, in accordance with the formula for sensitivity of any \( 0\nu2\beta \) decay experiment (see Sect. 2) the reachable half-life limit depends straight proportional on the abundance or enrichment of candidate nuclei contained in the detector. For the GEM-I the natural abundance of \( ^{76}\text{Ge} \) (7.6%) is about 11 times smaller as compared with the enrichment supposed for the second stage (86%). Because any other characteristics of the set up (\( \eta, m, t, R, Bg \)) 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 latest translates to the neutrino mass constrains \( m_\nu \leq 0.05 \) 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 the dark matter particles (see reviews [58, 59, 60]). It has been shown by Monte Carlo simulations [13, 15] that for the GENIUS project exploiting \( \approx 100 \) kg of natural HP Ge detectors the background rate of \( \approx 40 \) counts/yr-keV-t 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\( \nu \)2\( \beta \) decay of \( ^{76}\text{Ge} \) with \( T_{1/2}^{2\nu} = 1.8 \times 10^{21} \) yr [18] (\( \approx 20 \) counts/yr-keV-t); (b) cosmogenic activities in HP Ge crystals (\( \approx 10 \) counts/yr-keV-t); (c) internal radioactive contamination of the liquid nitrogen, copper wires and holder system (\( \approx 10 \) counts/yr-keV-t). We estimated that even lower background rate could be reached in the GEM-I set up, where only inner volume with \( \approx 200 \) kg of HP Ge detectors will be used for the dark matter search, while outer layers with 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 to reach the highest sensitivity for the dark matter search as compared with other projects (see f. e. refs. [58, 60]).
4 Implications of the high sensitivity $2\beta$ decay experiments and conclusions

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

As it was already mentioned in Introduction, many extensions of the Standard Model incorporate lepton number violating interactions and thus could lead to $0\nu2\beta$ decay. Besides conventional left-handed neutrino exchange mechanism of the $0\nu2\beta$ decay, such theories offer many other possibilities to trigger this process \cite{5, 6, 7}.

For instance, in left-right symmetric GUT models neutrinoless $2\beta$ decay can be mediated by heavy right-handed neutrinos \cite{61}. It was shown \cite{62} that $2\beta$ decay experiments with the sensitivity $m_\nu \leq 0.01$ 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 therefore could be established by GEM-II experiment, are compared with those expected for LHC \cite{63}.

Another new type of gauge bosons predicted by some GUTs are leptoquarks (LQ), which can transform quarks to leptons. Direct searches for leptoquarks in deep inelastic $ep$-scattering at HERA give lower limits on their masses $M_{LQ} \geq 225 - 275$ GeV (depending on the LQ type and coupling) \cite{64}. Leptoquarks can induce $0\nu2\beta$ decay via LQ-Higgs couplings, thus restrictions on leptoquark masses and coupling constants can be derived \cite{65}. Detailed study performed in ref. \cite{66} yields the conclusion that GENIUS-like experiment would be able to reduce limit on LQ-Higgs couplings down to $\approx 10^{-7}$ for leptoquarks with masses in the range of 200 GeV. If no effect ($0\nu2\beta$ decay) will be found, it means that either LQ-Higgs coupling must be smaller than $\approx 10^{-7}$ or there exist no leptoquarks (coupling with electromagnetic strength) with masses below $\approx 10$ TeV \cite{66}.

Hypothetical substructure of quarks and leptons (compositeness) can also give rise to a new $0\nu2\beta$ decay mechanism by exchange of composite heavy Majorana neutrinos \cite{67}. Recent analysis \cite{68} shows that the most sensitive at present $0\nu2\beta$ results with $^{76}$Ge \cite{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 \cite{68}.

Moreover, there are also possible $0\nu2\beta$ decay mechanisms based on the supersymmetric (SUSY) interactions: exchange of squarks, etc., within $R$-parity violating \cite{69, 70, 71, 72} and exchange of sneutrinos, etc. in $R$-parity conserving SUSY models \cite{73}. It allows $2\beta$ decay experiments to enter in the field of supersymmetry, where competitive restrictions on the sneutrino masses, $R$-parity violating couplings and other parameters could be obtained \cite{74, 75}.

Now we are going to consider the relations between $0\nu2\beta$ decay studies and neutrino oscillation searches to demonstrate the role which future $2\beta$ experiments can play in the reconstruction of the neutrino mass spectrum. At present this topic is widely discussed in literature, thus interested readers are referred to the latest publications \cite{12, 13, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32}, while we will summarize the most important results very shortly.

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 \cite{12, 13, 23}. These are schemes with: normal and inverse neutrino mass hierarchy; partial and complete mass
degeneracy, as well as scenario with 4 neutrinos, etc. For each of these schemes several solutions exist: (SMA) small mixing angle Mikheyev-Smirnov-Wolfenstein (MSW) solution; (LMA) large mixing angle MSW solution; (LOW) low mass MSW solution; (VO) vacuum oscillation solution. Careful analysis of these schemes and solutions performed in refs. [12, 13, 80] lead to the following statements: (a) effective neutrino mass, $\langle m_\nu \rangle$, which is allowed by oscillation data and could be observed in $2\beta$ decay, is different for different schemes and solutions, hence $2\beta$ 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 eV; 0.02 eV and 0.005 eV. If future $2\beta$ decay experiments will prove that $\langle m_\nu \rangle \geq 0.1$ eV, then all schemes would be excluded, except those with neutrino mass degeneracy or with 4 neutrinos and inverse mass hierarchy [13]. With the $\langle m_\nu \rangle$ bound of about 0.02 – 0.05 eV several other solutions will be excluded, while if neutrino mass limit is $\langle m_\nu \rangle \leq 0.005$ eV the survived schemes are those with mass hierarchy or with partial degeneracy. The following citation from [80] emphasizes importance of the future $2\beta$ decay searches: “The observation of the $0\nu2\beta$ 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 GEM experiment will bring crucial results for the reconstruction of the neutrino mass spectrum and mixing not only at its final GEM-II stage with enriched detectors ($\langle m_\nu \rangle \approx 0.015$ eV), but also at the first phase with natural HP Ge crystals ($\langle m_\nu \rangle \approx 0.05$ eV). This statement is true for any other topics discussed above.

Furthermore, namely the GEM-I with the realistic energy threshold of 10 keV and with anticipated background rate of $\approx 40$ counts/yr-kEVT below 100 keV would provide the highest sensitivity for the WIMP dark matter search. It is demonstrated by the exclusion plot of the WIMP-nucleon elastic scattering cross section for the GEM-I, which is depicted in fig. 4 together with the best current and other projected limits. The theoretical prediction for allowed spin-independent elastic WIMP-proton scattering cross section calculated in ref. [82] in the framework of the constrained minimal supersymmetric standard model (MSSM) is also shown there. It is obvious from fig. 4 that GEM-I would test the MSSM prediction by covering the larger part of the predicted SUSY parameter space. In that sense GEM experiment could be competitive even with LHC in the SUSY quest [63]. At the same time with fiducial mass of HP Ge detectors of $\approx 200$ kg GEM-I would be able to test and identify unambiguously (within one year 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 challenging scientific goal to touch $\approx 0.01$ eV neutrino mass domain, would be indeed feasible for the GEM project, which realization seems to have practically no technical risk. To this effect, the possibility to use already existing BOREXINO CTF as outer water shield is very attractive. The GEM experiment will bring the outstanding results for the $2\beta$ decay studies (GEM-I and GEM-II stages) as well as for the dark matter searches

---

9 The serious background problem for the dark matter quest with Ge detectors is cosmogenic activity of $^3$H produced in Ge [13, 15, 82]. For the GEM-I we estimated the total $^3$H activity as $\approx 5000$ decays/yr-t, which is in good agreement with the result of [82] and contributes $\approx 10$ counts/yr-keV-t to the total background rate in the energy interval 10-100 keV.

10 Very similar predictions from theoretical considerations in the MSSM with relaxed unification condition were derived in ref. [84].
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% C.L. Current limits from Heidelberg-Moscow (H-M) \cite{85}, DAMA \cite{86} and CDMS \cite{87} experiments are shown in the upper part of figure. The small shaded area: 2σ evidence region from the DAMA experiment \cite{88}. Projected exclusion plots for the CDMS \cite{89}, GENIUS \cite{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 \cite{83}.

(GEM-I), which are of great interest and would provide crucial tests of the many key problems and theoretical models of the modern astroparticle physics.

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] K. Zuber, Phys. Rep. 305 (1998) 295.
[2] J. Schechter and J.W.F. Valle, Phys. Rev. D 25 (1982) 2951.
[3] M. Moe and P. Vogel, Ann. Rev. Nucl. Part. Sci. 44 (1994) 247.
[4] V.I. Tretyak and Yu.G. Zdesenko, At. Data Nucl. Data Tables 61 (1995) 43.
[5] A. Faessler and F. Simkovic, J. Phys. G: Nucl. Part. Phys. 24 (1998) 2139.
[6] H.V. Klapdor-Kleingrothaus, Int. J. Mod. Phys. A 13 (1998) 3953; M. Hirsch and H.V. Klapdor-Kleingrothaus, Prog. Part. Nucl. Phys. 40 (1998) 323.
[7] J. Suhonen and O. Civitarese, Phys. Rep. 300 (1998) 123.

[8] P. Vogel, nucl-th/0005020 9 May 2000.

[9] T.A. Kirsten, Rev. Mod. Phys. 71 (1999) 1213.

[10] Y. Fukuda et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. 81 (1998) 1562; 82 (1999) 1810; 82 (1999) 2430.

[11] E.D. Church (for the LSND Collaboration), Nucl. Phys. A 663&664 (2000) 799; A. Aguilar et al., hep-ex/0104049 27 Apr 2001.

[12] H.V. Klapdor-Kleingrothaus et al., Phys. Rev. D 63 (2001) 073005; hep-ph/0003219 v4 8 Oct 2000.

[13] S.M. Bilenkij et al., Phys. Lett. B 465 (1999) 193.

[14] S.R. Elliot et al., Phys. Rev. C 46 (1992) 1535.

[15] H. Ejiri et al., Phys. Rev. C 63 (2001) 065501.

[16] F.A. Danevich et al., Phys. Rev. C 62 (2000) 045501.

[17] A. Alessandrello et al., Phys. Lett. B 486 (2000) 13.

[18] R. Luescher et al., Phys. Lett. B 434 (1998) 407.

[19] L. Baudis et al., Phys. Rev. Lett. 83 (1999) 41.

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

[21] R. Brun et al., CERN Program Library Long Write-up W5013, CERN, 1994.

[22] O.A. Ponkratenko et al., Phys. Atom. Nucl. 63 (2000) 1282.

[23] E. der Mateosian and M. Goldhaber, Phys. Rev. 146 (1966) 810.

[24] E. Fiorini et al., Phys. Lett. B 25 (1967) 607.

[25] E. Fiorini et al., Lett. Nuovo Cimento vol. III, n. 5 (1970) 149.

[26] A.A. Artyukhov et al., Phys. Atom. Nucl. 61 (1998) 1236; A. Pokidychev, M. Pokidycheva, Nucl. Instrum. Meth. A 438 (1999) 7.

[27] M.K. Moe, Phys. Rev. C 44 (1991) 931.

[28] M. Miyajima et al., KEK Proc. 91-5 (1991) 19.

[29] M. Miyajima et al., AIP Conf. Proc. 338 (1997) 253.

[30] M. Danilov et al., Phys. Lett. B 480 (2000) 12.
[31] R.S. Raghavan, Phys. Rev. Lett. 72 (1994) 1411.

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

[33] H. Ejiri et al., Phys. Rev. Lett. 85 (2000) 2917.

[34] F.A. Danevich et al., Nucl. Phys. B (Proc. Suppl.) 48 (1996) 235;
    F.A. Danevich et al., nucl-ex/0011020 24 Nov 2000; Nucl. Phys. A (2001) in press.

[35] R.S. Raghavan, Proc. 4th Int. Solar Neutrino Conf., Heidelberg, Germany, 8-11 April
    1997. - Max-Planck-Institut fur Kernphysik, Heidelberg, 1997, p. 248.

[36] K. Zuber, Phys. Lett. B 485 (2000) 23.

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

[38] E. Fiorini, Phys. Rep. 307 (1998) 309.

[39] NEMO Collaboration, hep-ex/0006031 26 June 2000.

[40] G. Gervasio (for the CUORE collaboration), Nucl. Phys. A 663&664 (2000) 873.

[41] G. Bellini et al., Phys. Lett. B 493 (2000) 216.

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

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

[44] L. Baudis et al., Nucl. Instrum. Meth. A 426 (1999) 425.

[45] O.A. Ponkratenko et al., Proc. Int. Conf. on Dark Matter in Astro and Particle Phys.,
    Heidelberg, Germany, 20-25 July 1998, eds. H.V. Klapdor-Kleingrothaus and L. Baudis,
    IOP, Bristol, Philadelphia, 1999, p.738.

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

[47] R.H. Kropschot, Cryogenics 1 (1961) 171.

[48] M. Gunther et al., Phys. Rev. D 55 (1997) 54;
    L. Baudis et al., hep-ex/0012022 7 Dec 2000.

[49] P. Jagam and J.J. Simpson, Nucl. Instrum. Meth. A 324 (1993) 389.

[50] G. Heusser et al., Appl. Rad. and Isotopes 52 (2000) 691.

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

[52] C.J. Martoff and P.D. Lewin, Comp. Phys. Comm. 72 (1992) 96.
[53] Physical Quantities: The Handbook, eds. I.S. Grigoriev et al., Energoatomizdat, Moscow, 1991.

[54] C. Arpesella, Nucl. Phys. A 28 (1992) 420.

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

[56] G. Jungmann et al., Phys. Rep. 267 (1996) 195.

[57] Y. Ramachers, astro-ph/9911260 15 Nov 1999.

[58] L. Baudis and H.V. Klapdor-Kleingrothaus, astro-ph/0003434 29 Mar 2000.

[59] H.V. Klapdor-Kleingrothaus, hep-ph/0102319 26 Feb 2001.

[60] H.V. Klapdor-Kleingrothaus et al., hep-ph/0103082 8 Mar 2001.

[61] M. Doi et al., Prog. Theor. Phys. Suppl. 69 (1983) 602; Prog. Theor. Phys. 89 (1993) 139.

[62] H.V. Klapdor-Kleingrothaus, M. Hirsch, Z. Phys. A 359 (1997) 361.

[63] T. Rizzo, SLAC-PUB-7365, hep-ph/9612440 20 Dec 1996; M. Cvetic and S. Godfrey, hep-ph/9504216 4 Apr 1995; S. Godfrey et al., hep-ph/9704291 10 Apr 1997.

[64] H1 Collab., S. Aida et al., Phys. Lett. B 369 (1996) 173.

[65] M. Hirsch et al., Phys. Lett. B 378 (1996) 17; Phys. Rev. D 54 (1996) 4207.

[66] H.V. Klapdor-Kleingrothaus et al., MPI-Report MPI-H-V26-1999, Heidelberg, 1999.

[67] N. Cabibbo et al., Phys. Lett. B 139 (1984) 459; O. Panella et al., Phys. Rev. D 56 (1997) 5766.

[68] O. Panella et al., Phys. Rev. D 62 (2000) 015013.

[69] R. Mohapatra, Phys. Rev. D 34 (1986) 3457.

[70] M. Hirsch et al., Phys. Rev. Lett. 75 (1995) 17; Phys. Rev. D 53 (1996) 1329; Phys. Lett. B 372 (1996) 181; Phys. Lett. B 459 (1999) 450.

[71] A. Faessler et al., Phys. Rev. Lett. 78 (1997) 183; Phys. Rev. D 58 (1998) 055004; Phys. Rev. D 58 (1998) 115004.

[72] A. Wodecki et al., Phys. Rev. D 60 (1999) 115007.

[73] M. Hirsch et al., Phys. Lett. B 398 (1997) 311; 403 (1997) 291; Phys. Rev. D 57 (1998) 2020.

[74] M. Hirsch et al., Phys. Rev. D 57 (1998) 1947.

[75] G. Bhattacharyya et al., Phys. Lett. B 463 (1999) 77.

[76] F. Vissani, JHEP 9906 (1999) 022.
[77] M. Czakon et al., Acta Phys. Pol. B 30 (1999) 3121.

[78] M. Czakon et al., hep-ph/0010077 9 Oct 2000.

[79] M. Czakon et al., Acta Phys. Pol. B 31 (2000) 1365.

[80] S.M. Bilenky et al., hep-ph/0102265 21 Feb 2001; hep-ph/0104218 23 Apr 2001.

[81] H.V. Klapdor-Kleingrothaus, hep-ph/0102276 22 Feb 2001; hep-ph/0103074 7 Mar 2001.

[82] H.V. Klapdor-Kleingrothaus, B. Majorovits, hep-ph/0103079 7 Mar 2001.

[83] J. Ellis et al., Phys. Lett. B 481 (2000) 304.

[84] V. A. Bednyakov, H.V. Klapdor-Kleingrothaus, Phys. Rev. D 63 (2001) 095005.

[85] L. Baudis et al., Phys. Rev. D 59 (1999) 022001.

[86] R. Bernabei et al., Nucl. Phys. B (Proc. Suppl.) 70 (1998) 79; Phys. Lett. B 389 (1996) 757.

[87] R. Abusaidi et al., Phys. Rev. Lett. 84 (2000) 5699.

[88] R. Bernabei et al., Phys. Lett. B 480 (2000) 23.

[89] R. Abusaidi et al., Nucl. Inst. Meth. A 444 (2000) 345.

[90] S. Cebrian et al., Astrop. Phys. 14 (2001) 339.