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CAMEO/GEM program for future 2β decay and dark matter experiments

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The sensitivity ($T_{1/2}$ limit for $0\nu2\beta$ decay) of CAMEO experiment with ≈100 kg of $^{116}CdWO_4$ crystals placed in the liquid scintillator of the BOREXINO CTF is $\approx 10^{26}$ yr, which corresponds to a bound on the neutrino mass $m_\nu \leq 0.06$ eV. It would be improved by the GEM project with one ton of "naked" HP Ge detectors operating in HP liquid nitrogen. The latest is contained in the Cu cryostat placed in the CTF water tank. The sensitivity of the GEM-I phase with natural Ge crystals is $\approx 10^{27}$ yr (or $m_\nu \leq 0.05$ eV), while in the GEM-II stage with enriched (in ^{76}Ge to 86%) detectors it is $\approx 10^{28}$ yr (or $m_\nu \leq 0.015$ eV). Besides, the GEM-I set up could advance the best limits on the existence of neutralinos – as dark matter candidates – by three order of magnitude, and at the same time would be able to identify the dark matter signal by detection of its seasonal modulation.

Despite many efforts to detect $0\nu2\beta$ decay, this process still remains unobserved. The highest half-life limits were set in direct experiments: $T^{0\nu}_{1/2} \geq 10^{22}$ yr for ^{82}Se, ^{100}Mo; $T^{0\nu}_{1/2} \geq 10^{23}$ yr for ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe; and $T^{0\nu}_{1/2} \geq 10^{25}$ yr for ^{76}Ge [1]. These results have brought the most stringent restrictions on the Majorana neutrino mass $m_\nu \leq$ (0.5–5.0) eV, right-handed admixture in the weak interaction $\lambda \approx 10^{-5}$, the ν-Majoron coupling constant $g_M \approx 10^{-4}$, etc. It is very desirable to improve this level of sensitivity by one-two orders of magnitude [1–3].

Let us consider some recent proposals aiming this goal. There are two projects under construction: NEMO-3 [4] and CUORICINO [5]. The sensitivity of the NEMO-3 tracking detector with ≈10 kg of ^{100}Mo source would be on the level of $\approx 4\times10^{24}$ yr ($m_\nu \leq$ 0.3–0.5 eV) [4]. 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). With the energy resolution of ≈10 keV at 2.5 MeV, the CUORE sensitivity is quoted for the different background rate (0.5 – 0.05 counts/yr·kg·keV at 2.5 MeV) as $T^{0\nu}_{1/2} \geq$ (1 – 5)$\times10^{25}$ yr ($m_\nu \leq$ 0.05 – 0.2 eV) [6].

Besides, there are two projects for the 2β decay quest of ^{76}Ge (MAJORANA [7] and GENIUS [8]). The idea of the MAJORANA is to use 210 HP Ge (enriched in ^{76}Ge to ≈ 86%) semiconductor detectors (total mass ≈500 kg) contained in low background cryostat and shielded by HP lead or copper [7]. With the projected background rate of ≈0.01 counts/yr·kg·keV at the energy 2 MeV the sensitivity is estimated as $T^{0\nu}_{1/2} \geq 10^{27}$ yr, which leads to the following interval of the neutrino mass limit: $m_\nu \leq$ 0.05 – 0.15 eV (depending on the NME calculations [1,9]). GENIUS project intends to operate one ton of "naked" HP Ge (enriched in ^{76}Ge to ≈86%) detectors placed in a HP liquid nitrogen (LN_2), which simultaneously serves as cooling medium and shield. In accordance with the Monte Carlo background simulations the necessary dimensions of the LN_2 shield should be about 12 m in diameter and 12 m in height. The required radiopurity of the LN_2 should be as low as $\approx 10^{-15}$ g/g for ^{40}K and ^{238}U, $\approx 5\times10^{-15}$ g/g for ^{232}Th, and 0.05 mBq/m^3 for ^{222}Rn [8,10]. The background rate in the energy region of the $0\nu2\beta$ decay peak of ^{76}Ge could be reduced down to ≈ 0.2 counts/yr·keV·t [8,10]. On this basis the bound $T^{0\nu}_{1/2} \geq 10^{28}$ yr would be achieved, which translates to the neutrino mass constraints $m_\nu \leq$ 0.015 – 0.05 eV.

However, mentioned projects would require a significant amount of R&D to demonstrate their feasibility. In the present paper we suggest the

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CAMEO program of the high sensitivity 2β decay experiments, whose accomplishment seems to be simpler.

It is supposed [11] to use already existing BOREXINO CTF [12] for the 2β decay study of ^{116}Cd by placing ≈100 kg of enriched $^{116}CdWO_4$ crystal scintillators in the liquid scintillator of the CTF, serving as light guide and veto shield. The CTF (installed in the Gran Sasso Underground Laboratory) consists of an external ≈1000 t water tank (⌀11×10 m) served as shield for 4.8 m^3 liquid scintillator contained in an inner vessel ⌀2.1 m. The radiopurity of water is $\approx 10^{-14}$ g/g for U/Th, $\approx 10^{-10}$ g/g for K, and <5 μBq/l for ^{222}Rn [12]. The light from the high purity ($\approx 5\times 10^{-16}$ g/g for U/Th) liquid scintillator is collected with the help of 100 phototubes (PMT) with diameter 8" fixed at 7 m diameter inside the water tank.

The ^{116}Cd studies performed by the INR (Kiev) in the Solotvina Underground Laboratory with the help of the $^{116}CdWO_4$ crystals [13,14] is considered as the pilot step of the CAMEO project. The light output of cadmium tungstate crystal scintillators (enriched in ^{116}Cd to 83%) is ≈40% of NaI(Tl), maximal peak emission is at 480 nm with principal decay time of ≈14 μs [15]. The refractive index of $CdWO_4$ crystal is 2.3, the density is 7.9 g/cm^3, the material is non-hygroscopic and chemically inert. In the latest phase of the experiment four $^{116}CdWO_4$ crystals (total mass 330 g) have been used. The detectors are viewed by the low background 5" EMI tube (with RbCs photocathode) through one light guide ⌀10×55 cm. Enriched detectors are surrounded by an active shield made of 15 natural $CdWO_4$ crystals [16] with total mass 20.6 kg. The latest are viewed by a PMT through an active plastic light guide ⌀17×49 cm. The whole $CdWO_4$ array is situated in an additional active shield made of plastic scintillator 40×40×95 cm. The outer passive shield consists of HP copper (3–6 cm), lead (22.5–30 cm) and polyethylene (16 cm). The data acquisition records the amplitude, arrival time and pulse shape (PS) of each $^{116}CdWO_4$ event. The PS technique is based on the optimal digital filter and ensures clear discrimination between γ rays and α particles, and selection of "illegal" events like double pulses, noise events, etc. [15].

The energy resolution of the main detector is 11.5% at 1064 keV and 8.0% at 2615 keV. For the energy spectrum measured 13254 h with four $^{116}CdWO_4$ crystals [14] the background rate in the energy region 2.5–3.2 MeV is 0.04 counts/yr·kg·keV, which is achieved due to PS and time-amplitude analysis of the data. The $T_{1/2}$ limits for $0\nu2\beta$ decay are set as $T^{0\nu}_{1/2} \geq 1.3(1.8)\times 10^{23}$ yr at 90%(68%) C.L., while for 0ν decay with Majoron emission as $T^{0\nu}_{1/2}$(M1) $\geq 0.7(1.8)\times 10^{22}$ yr at 90%(68%) C.L. [14]. These correspond to the neutrino mass constraints $m_\nu \leq 1.9(1.6)$ eV (using calculations [17]) and to the neutrino-Majoron coupling constant $g_M \leq 8.8(5.4)\times 10^{-5}$ (after [18]), both at 90%(68%) C.L. [14].

In the preliminary design concept of the CAMEO experiment 40 enriched $^{116}CdWO_4$ crystals of large volume (≈320 cm^3) are placed in the liquid scintillator of the CTF on the sphere with diameter 0.8 m. It is supposed that 200 PMTs with light concentrators are fixed at diameter 5 m providing the optical coverage of 80%. The Monte Carlo simulation of the light propagation in considered geometry gives ≈4000 p.e. for 2.8 MeV energy deposit, which would result in the energy resolution $FWHM = 4\%$ for the $0\nu2\beta$ decay peak of ^{116}Cd. Such an energy resolution has been measured with $CdWO_4$ crystal (⌀40 × 30 mm) placed in transparent paraffin oil (refractive index ≈1.5) [11].

The background simulation for the CAMEO was performed with the help of GEANT3.21 [19] and DECAY4 [20] codes. The sensitivity of the CAMEO experiment is calculated as $T^{0\nu}_{1/2} \geq 10^{26}$ yr, which translates to the neutrino mass bound $m_\nu \leq 0.06$ eV [11]. The simplicity and reliability are the main advantages of the CAMEO technique with $^{116}CdWO_4$ crystals, but the poor energy resolution is the factor which limits further sensitivity enhancement. To this effect, below we consider the GEM project for the 2β decay quest of ^{76}Ge with the help of HP Ge detectors.

The GEM design is based on the following ideas [21]: (a) "Naked" HP Ge detectors (enriched in ^{76}Ge to 86%) are operating in the high purity liquid nitrogen serving as cooling medium and the first layer of shield; (b) LN_2 is contained in the vacuum cryostat made of HP copper; (c) The shield is composed of two parts: (i) inner shield - high purity LN_2 ($\approx 10^{-15}$ g/g for ^{40}K and ^{238}U, $\approx 5\times10^{-15}$ g/g for ^{232}Th, and 0.05 mBq/m^3 for ^{222}Rn); (ii) outer part - HP water.

About 400 HP Ge detectors (⌀8.5×8.5 cm, mass of ≈2.5 kg each) are located in the center of a Cu sphere (inner enclosure of the cryostat with diameter 4.5 m and 0.6 cm thick) filled with LN_2. The outer encapsulation of the cryostat with diameter 5 m is also made of HP Cu with 0.6 cm thickness. The vacuum pump maintains $\approx 10^{-6}$ torr pressure in the space between two walls of the cryostat. The latest allow one to reduce heat current through the walls of the cryostat to the value of ≈2.5 W/m^2 [22], thus total heat losses are near 200 W. This corresponds to a LN_2 consumption less than 100 kg per day. The cryostat is placed into the HP ($\approx 10^{-14}$ g/g for ^{40}K, ^{232}Th, ^{238}U) water shield with mass ≈1000 t contained in the steel tank ⌀11×11 m. The dimensions of the CTF water tank are practically the same (⌀11×10 m), hence this shield could be also used for the GEM experiment. The total mass of detectors is equal ≈1 t, liquid nitrogen - ≈40 t, Cu cryostat - ≈7 t, water shield - 1000 t, holder-system - ≈2 kg, and Cu wires - ≈1 kg.

The background simulations were performed with the help of GEANT3.21 and DECAY4 programs. The internal and external origins of background were investigated carefully. Internal background arises from residual impurities in the Ge crystals themselves and surroundings (crystal holder system, liquid nitrogen, Cu cryostat, water, steel vessel), and from activation of all 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.

Summarizing all background origins (internal and external) the total background rate of the GEM experiment is 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 with $T_{1/2}^{2\nu}=1.8\times10^{21}$ yr and $T_{1/2}^{0\nu}=10^{27}$ yr, as well as background contribution from the holder system and Cu cryostat are depicted in fig. 1. The background at the energies below 1950 keV is dominated by $2\nu2\beta$ decay of ^{76}Ge (≈2.6×10^7 counts), while at 2040 keV the main contributions are from contamination of the holder system and Cu cryostat by U/Th chains. It is evident from fig. 1 that $0\nu2\beta$ decay of ^{76}Ge with $T_{1/2}^{0\nu}=10^{27}$ yr would be clearly registered (42 counts in the $0\nu2\beta$ decay peak). For 10 yr measuring time the sensitivity of the GEM is equal to $T_{1/2}^{0\nu}\geq 10^{28}$ yr (or $m_\nu \leq 0.015 - 0.05$ eV).

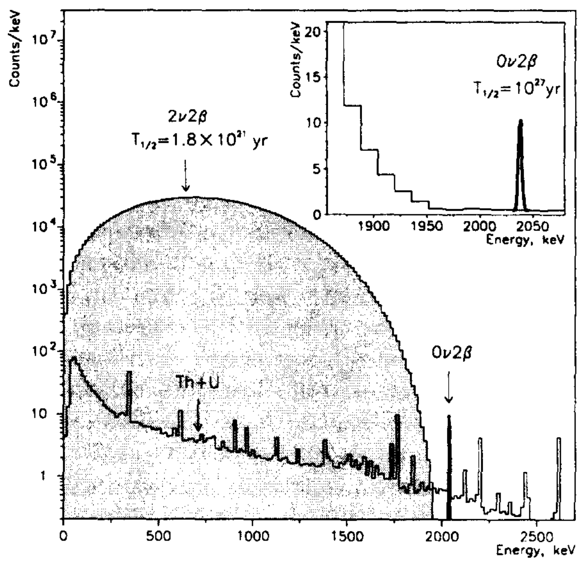

Figure 1. The response functions of the GEM-II set up [21] with 1000 kg of HP ^{76}Ge crystals and after 10 yr of measurements for 2β decay of ^{76}Ge with $T_{1/2}^{2\nu}=1.8\times10^{21}$ yr and $T_{1/2}^{0\nu}=10^{27}$ yr (solid histogram), as well as background contribution from contaminations of the holder system and Cu cryostat by ^{232}Th and ^{238}U families. In the insert the summed spectrum in the vicinity of the $0\nu2\beta$ decay peak of ^{76}Ge is shown in the linear scale.

The realization of the GEM experiment seems to be reasonably simple due to using of existing

BOREXINO CTF as outer water shield. The cost of GEM project is estimated as ≈150 M$, whose main part would be for the production of enriched materials. However, the first GEM phase will be performed with one ton of natural HP Ge detectors (total cost of about 6 M$), which nevertheless would bring the outstanding physical results. Indeed, with natural HP Ge detectors the $T_{1/2}$ bound would be $T^{0\nu}_{1/2} \geq 10^{27}$ yr. It corresponds to the neutrino mass constraint $m_\nu \leq 0.05$ eV, which is also of great interest for many theoretical models.

Furthermore, another important issue of the GEM experiment is the quest for the dark matter particles. It has been already shown by Monte Carlo simulations [8,10] that for the GENIUS project with ≈100 kg of natural HP Ge detectors the background rate of ≈40 counts/yr·keV·t could be obtained in the low energy region (10 – 100 keV) relevant for the WIMP dark matter study. It is estimated that even lower background could be reached in the GEM-I set up, where only inner volume with ≈200 kg of HP Ge detectors will be used for the dark matter search, while outer layers with remaining ≈800 kg of HP Ge crystals would serve as high purity passive and active shield for the inner detectors [21]. Thus, the GEM-I with the energy threshold of 10 keV and background rate ≈40 counts/yr·keV·t (below 100 keV) would provide the highest sensitivity for the WIMP dark matter search as compared with other projects. At the same time with fiducial mass of HP Ge detectors of ≈ 200 kg it would be possible to test and identify unambiguously (within one year of data taking) the seasonal modulation signature of the dark matter signal from the DAMA experiment [23] by using an alternative detector technology.

Hence, we can conclude that challenging scientific goal to touch (0.01 – 0.05) eV neutrino mass domain would be indeed feasible for the CAMEO and GEM experiments, whose realization seems to have no technical risk and could be relatively simple due to attractive possibility of using already existing BOREXINO CTF. Both experiments will bring outstanding results for the 2β decay studies as well as for the dark matter searches.

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