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High sensitivity quest for Majorana neutrino mass with the BOREXINO counting test facility

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Abstract

The unique features of the CTF and BOREXINO set ups are used for a high sensitivity study of ^{100}Mo and ^{116}Cd neutrinoless 2β decay. Pilot measurements with ^{116}Cd and Monte Carlo simulation show that the sensitivity of the CAMEO experiment (in terms of the $T_{1/2}$ limit for $0\nu 2\beta$ decay) is (3–5) $\times 10^{24}$ yr with a 1 kg source of ^{100}Mo (^{116}Cd, ^{82}Se, ^{150}Nd) and $\approx 10^{26}$ yr with 65 kg of ^{116}CdWO$_4$ crystals placed in the CTF. The last value corresponds to a limit on the neutrino mass of $m_\nu \leqslant 0.06$ eV. Moreover, with 1000 kg of ^{116}CdWO$_4$ crystals located in the BOREXINO apparatus the neutrino mass limit can be pushed down to $m_\nu \leqslant 0.02$ eV. © 2000 Published by Elsevier Science B.V.

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1. Introduction

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 $0\nu 2\beta$ decay [1,2]. Currently, besides the conventional neutrino (ν) exchange mechanism, there are many other possibilities to trigger this process [2]. Due to the strong statement obtained in a gauge theory of the weak interaction that a non-vanishing $0\nu 2\beta$ decay rate requires neutrinos to be massive Majorana particles, independently on which mechanism induces it [3], $0\nu 2\beta$ decay has a great conceptual importance and is considered as a powerful test of new physical effects beyond the SM. At the same time $0\nu 2\beta$ decay is very important in light of the measured deficit of the atmospheric neutrino flux [4,5] and the result of the LSND accelerator experiment [4,6], which could be explained by neutrino oscillations, requiring in turn non-zero neutrino masses (m_ν). Oscillation experiments are only sensitive to neutrino

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mass difference, while measuring the $0\nu2\beta$ decay rate can give the absolute value of the m_ν scale, and hence provide a crucial test of m_ν models.

Despite the numerous attempts to observe $0\nu2\beta$ decay from 1948 up to the present [1] this process still remains unobserved. The highest $T_{1/2}(0\nu)$ limits were set in direct experiments with several nuclides: $T_{1/2} \geqslant 10^{22}$ yr for ^{82}Se [7], ^{100}Mo [8]; $T_{1/2} \geqslant 10^{23}$ yr for ^{116}Cd [9,10], ^{130}Te [11] and ^{136}Xe [12]; and $T_{1/2} \geqslant 10^{25}$ yr for ^{76}Ge [13,14]. The present status of 2β decay research [1,2] makes it necessary to enlarge the number of nuclides studied at a sensitivity comparable to or better than that for ^{76}Ge ($m_\nu \leqslant$ 0.2–0.5 eV). With this aim we consider here the use of the BOREXINO Counting Test Facility (CTF) [15] for a high sensitivity 2β decay search.

2. CAMEO-I experiment with ^{100}Mo in the CTF

The CTF has been described elsewhere [15–17], thus we recall the main features of this apparatus. The CTF (installed in the Gran Sasso Underground Laboratory) consists of an external ≈ 1000 t water tank ($\oslash\, 11 \times 10$ m) serving as passive shielding for 4.8 m^3 of liquid scintillator (contained in an inner spherical vessel of $\oslash\, 2.1$ m). High purity (HP) water is supplied by the BOREXINO water plant (radiopurity level of $\approx 10^{-14}$ g/g for U/Th, $\approx 10^{-10}$ g/g for K, and < 5 μBq/l for ^{222}Rn) [15,17]. The liquid scintillator is a binary solution of 1.5 g/l of PPO in pseudocumene. The yield of emitted photons (peak emission 365 nm) is $\approx 10^4$ per MeV and the attenuation length is $\geqslant 5$ m above 380 nm [18]. The principal scintillator decay time is 3.5 ns (4.5–5.0 ns in the whole CTF volume). The purification of the liquid scintillator is provided by recirculating it from the inner vessel and maintains ^{232}Th and ^{238}U contamination less than (2–5) $\times 10^{-16}$ g/g. The inner vessel is made of transparent nylon film, 500 μm thick, which allows collection of the scintillation light with the help of 100 phototubes (PMT) fixed to a 7 m diameter support structure inside the water tank. The PMTs are 8” Thorn EMI 9351 tubes made of low radioactivity Schott 8246 glass, and characterized by high quantum efficiency (26% at 420 nm) and limited transit time spread ($\sigma = 1$ ns). The PMTs are fitted with light concentrators 57 cm long and 50 cm diameter aperture. They provide 20% optical coverage. The number of photoelectrons per MeV is measured as $(300 \pm 30)/\mathrm{MeV}$ on average. An upgrade of the CTF was realized in 1999 when an additional nylon barrier against radon convection and a muon veto system were installed.

Event parameters measured in the CTF include:

(a) the total charge collected by the PMTs during 0–500 ns (event energy);
(b) the tail charge (48–548 ns) used for pulse shape discrimination;
(c) the PMT timing (precision of 1 ns) to reconstruct the event in space (resolution of 10–15 cm);
(d) the time elapsed between sequential events, used to tag time-correlated events.

The total background rate of the CTF in the energy region 250–800 keV is about 0.3 counts/yr·keV·kg, and is dominated by external background from Rn in the shielding water (≈ 30 mBq/m^3), while internal background is less than 0.01 counts/yr·keV·kg.

For the choice of 2β candidate nuclei the most important parameter is the energy release ($Q_{\beta\beta}$). First, it is because the phase space integral (hence, $0\nu2\beta$ decay rate) strongly depends on $Q_{\beta\beta}$ value (roughly as $Q^5_{\beta\beta}$) [2]. Secondly, the larger $Q_{\beta\beta}$, the simpler it is to overcome background problems. There are 6 nuclei with $Q_{\beta\beta}$ larger than 2.6 MeV [19]: ^{48}Ca ($Q_{\beta\beta} = 4272$ keV; abundance $\delta = 0.187\%$), ^{82}Se (2995 keV; 8.73%), ^{96}Zr (3350 keV; 2.80%), ^{100}Mo (3034 keV; 9.63%), ^{116}Cd (2805 keV; 7.49%), and ^{150}Nd (3367 keV; 5.64%). From this list ^{100}Mo and ^{116}Cd were chosen for study with the CTF because the INR (Kiev) possesses 1 kg of ^{100}Mo enriched to 99%, and because the INR (Kiev) has performed 2β decay experiments with ^{116}Cd [9,10,20–22], considered as a pilot step for this project.

The sensitivity of 2β decay experiments with “active” source-detector or with a passive source is determined by the available source strengths, and by the detector background. Very essential for the sensitivity is the energy resolution of the detector because events from the high energy tail of the 2ν distribution run into the energy window of the 0ν peak, generating background which cannot be discriminated from the $0\nu2\beta$ decay signal. Better energy resolution minimizes the tail of the 2ν distribution falling within the 0ν interval, lowering this irreducible background.

For the passive source technique, the sensitivity is also restricted by the trade-off between source mass and detection efficiency. Source strengths can be enlarged by increasing the source thickness, which at the same time will lead to lower detection efficiency caused by absorption of electrons in the source and distortion of the measured 2β decay spectra. These statements are illustrated by Fig. 1, where results of a model experiment (5 yr measuring time) to study 2β decay of ^{100}Mo (1 kg source) are presented. The simulation were performed with the GEANT3.21 package [24] and event generator DECAY4 [25]. The initial 2β decay spectra with $T_{1/2}(2\nu) = 10^{19}$ yr (e.g., Ref. [23]) and $T_{1/2}(0\nu) = 10^{24}$ yr are shown in Fig. 1a and Fig. 1b. In this case ^{100}Mo nuclei are contained ("active" source technique) in an ideal detector with 100% efficiency and zero background (an energy resolution and energy threshold of 10 keV are supposed). In the next step the ^{100}Mo source was placed in the same detector as a passive foil. The simulated spectra are depicted in Fig. 1c (15 mg/cm^2 thick foil) and Fig. 1d (60 mg/cm^2). Finally, the energy resolution of the detector was taken into account and results are shown in Fig. 1e ($FWHM = 4\%$ at 3 MeV) and Fig. 1f (8.8% at 3 MeV). It is evident from Fig. 1e that $0\nu2\beta$ decay of ^{100}Mo with $T_{1/2} = 10^{24}$ yr can be clearly observed by using a 1 kg passive source (15 mg/cm^2) and a detector with resolution 4%.

The CTF allows such characteristics to be reached by performing a ^{100}Mo double β decay search with large square (≈ 7 m^2) and thin ^{100}Mo foils (15 mg/cm^2) located in the liquid scintillator. The ^{100}Mo source for the CTF is a complex system, which can be represented by three mutually perpendicular and crossing flat disks with diameter of 180 cm whose centers are aligned with the center of inner vessel of the CTF. Each disk is composed of three layers: inner ^{100}Mo source placed between two plastic scintillators of 1 mm thick. The inner side of each plastic is coated with thin Al foil serving as a light reflector. Plastic detectors have a much longer decay constant compared to the liquid scintillator (e.g., Bicron plastic BC-444 with $\tau \approx 260$ ns), thus their pulses can be discriminated easily. The signals from the plastics allow tagging of electrons emitted from the ^{100}Mo source, and therefore, reduction of background. The energy loss measured by the plastics are added to the electron energy deposited in the liquid scintillator. The required energy resolution can be obtained in the CTF if the total optical coverage will be increased significantly. The PMTs with the light concentrators can be mounted closer to the center of the vessel. For instance, if 200 PMTs are fixed at diameter 5 m (and correspondingly the light concentrators entrances at diameter 4 m), or 96 PMTs are fixed at diameter 3.8 m, the optical coverage is equal $\approx 80\%$. We consider below the last configuration because it is the worst case for background contribution from the PMTs.[1] Since the whole volume of the scintillator is divided by ^{100}Mo sources into 8 sectors, all PMTs are split into 8 groups of 12 PMTs each, so that each sector is viewed by one PMT group. The simulations of the light propagation in such a geometry were performed with GEANT3.21 [24], to which the emission spectrum and angular distribution of scintillation photons were added. The simulation finds that 3 MeV energy deposit would yield ≈ 3700 photoelectrons[2] allowing a measure of the neutrinoless 2β decay peak of ^{100}Mo with energy resolution $FWHM = 4\%$. This goal can be reached if the non-uniformity of light collection is corrected by using spatial information from each event. The Monte Carlo simulations prove that spatial resolution of ≈ 5–6 cm can be obtained with the upgraded CTF.[3] It is due to the fourfold increase in light collection, and owing to the spatial reconstruction method based on the comparison of pulse amplitudes from the different PMTs.

The simulations of the background and decays of radioactive nuclides in the set up were performed with the help of GEANT3.21 and event generator DECAY4 [25]. We distinguish here between "β" layers of the liquid scintillator 15 cm thick[4] on both sides of the complex ^{100}Mo source, and the rest of the scintillator volume serving as an active shield for the "β" layers.

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[1] Special R&D is in progress now to find optimal solution for the required 80% optical coverage in the CTF.

[2] This value can be justified in simple way. The number of photoelectrons (p.e.) per MeV measured in the CTF is 300/MeV on average. With fourfold increase of light collection it gives ≈ 3600 p.e. for 3 MeV.

[3] The spatial resolution obtained should be considered as indicative because in this preliminary phase of study a simplified model for light propagation in the CTF liquid scintillator was used.

[4] "β" layers are distinguished from the total volume of the liquid scintillator by using the spatial information. The thickness of 15 cm is chosen to guarantee the proper spatial reconstruction accuracy.

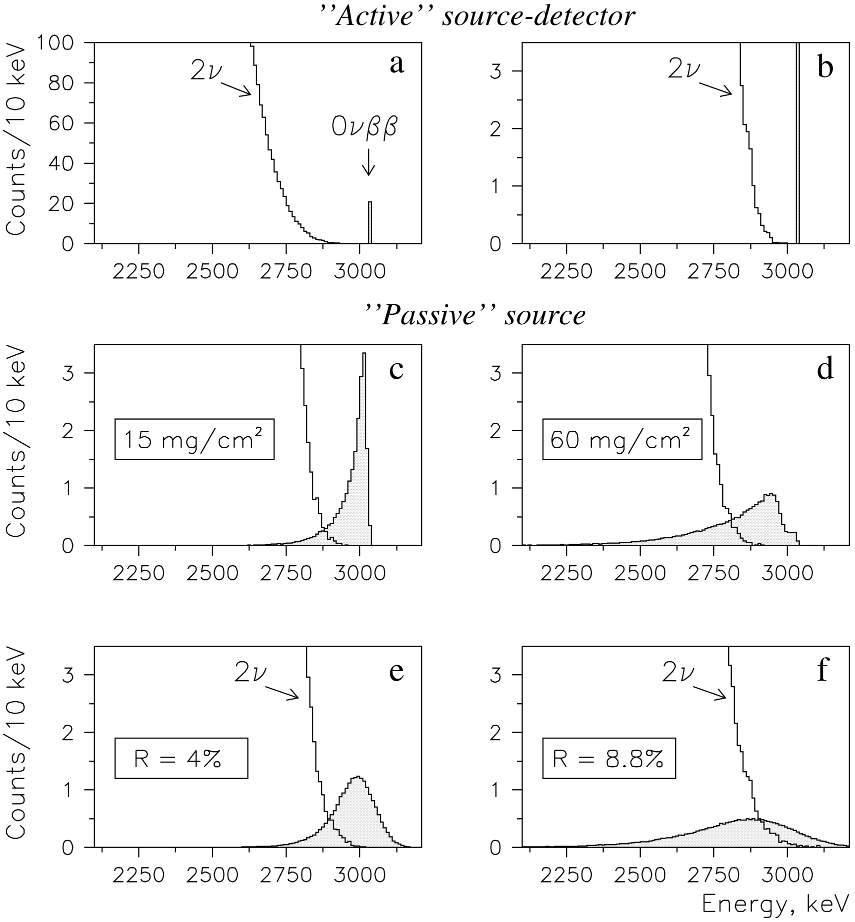

Fig. 1. Simulated spectra of the model 2β decay experiment with 1 kg source of ^{100}Mo. (a), (b) "active" source technique: ^{100}Mo nuclei in a detector with 100% efficiency, zero background, and with 10 keV energy resolution. (c), (d) passive ^{100}Mo source in the same detector with foil thickness 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 $FWHM = 8.8\%$.

In such a system the energy loss in the plastics (E_1^{pl} and E_2^{pl}), the energy deposits in the "β" layers (E_1^{β} and E_2^{β}), and the energy loss in the active shield (E^{ls}) are measured. The energy thresholds are set as $E_{\mathrm{thr}}^{\mathrm{pl}} = E_{\mathrm{thr}}^{\mathrm{ls}} = E_{\mathrm{thr}}^{\beta} = 15$ keV for the plastics and liquid scintillator. The following cuts are used in the simulation in order to recognize the double β decay events:

(i) E_1^{pl} or $E_2^{\mathrm{pl}} \geqslant E_{\mathrm{thr}}^{\mathrm{pl}}$;
(ii) $E_1^{\mathrm{pl}} + E_2^{\mathrm{pl}} \geqslant 300$ keV;
(iii) if $E_i^{\beta} \geqslant E_{\mathrm{thr}}^{\beta}$, the corresponding E_i^{pl} must be $\geqslant E_{\mathrm{thr}}^{\mathrm{pl}}$, necessarily;
(iv) $E^{\mathrm{ls}} \leqslant E_{\mathrm{thr}}^{\mathrm{ls}}$, i.e., there is no signal in the active shield.

The simulated response functions of the set up for $2\nu2\beta$ decay of ^{100}Mo with $T_{1/2} = 10^{19}$ yr as well as for $0\nu2\beta$ decay with $T_{1/2} = 10^{24}$ yr are depicted in Fig. 2a. The calculated values of efficiency for the 0ν channel are 80% (in the window 2.8–3.15 MeV), 74% (2.85–3.15 MeV), and 63.5% (2.9–3.15 MeV), with background from the 2ν tail being 3.9; 1.2, and ≈ 0.3 counts/yr, correspondingly. The radioactive impurities of 1 kg metallic Mo enriched in ^{100}Mo to $\approx 99\%$ were already measured as (12 ± 3) mBq/kg for ^{214}Bi, and $\leqslant 0.5$ mBq/kg for

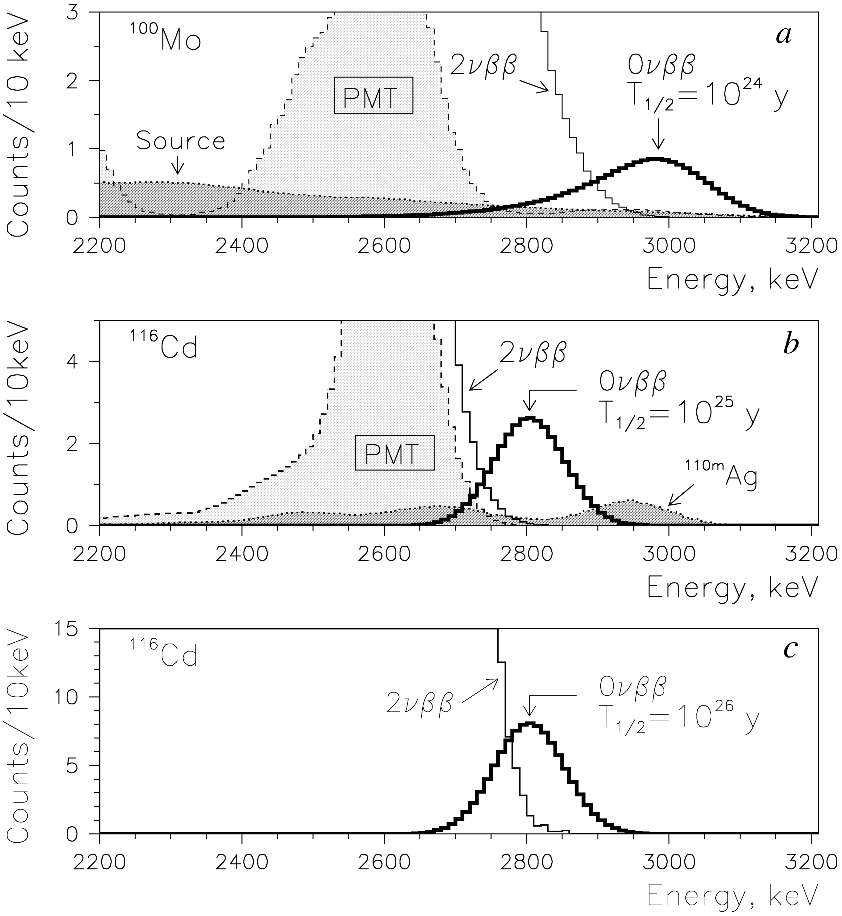

Fig. 2. (a) The response functions of the CTF (5 kg·yr statistics) for 2β decay of ^{100}Mo with $T_{1/2}(2\nu) = 10^{19}$ yr and $T_{1/2}(0\nu) = 10^{24}$ yr (solid histogram). Total simulated contributions due to ^{100}Mo contamination by ^{214}Bi and ^{208}Tl (dotted line), and from ^{214}Bi and ^{208}Tl in the PMTs (dashed histogram). (b) The response functions of the CTF with 65 kg of ^{116}CdWO$_4$ crystals (5 yr measuring period) for $2\nu 2\beta$ decay of ^{116}Cd ($T_{1/2} = 2.7 \times 10^{19}$ yr), and $0\nu 2\beta$ decay with $T_{1/2} = 10^{25}$ yr (solid histogram). The simulated contribution from ^{208}Tl in the PMTs (dotted line) and from cosmogenic ^{110m}Ag (dashed histogram). (c) The response functions of the BOREXINO set up with 1 t of ^{116}CdWO$_4$ crystals (10 yr measuring time) for $2\nu 2\beta$ decay of ^{116}Cd with $T_{1/2} = 2.7 \times 10^{19}$ yr, and $0\nu 2\beta$ decay with $T_{1/2} = 10^{26}$ yr (solid histogram).

^{208}Tl [26]. The background caused by source contamination was investigated in Ref. [27], where it was found that the maximum activities of ^{100}Mo acceptable for the NEMO-3 set up are 0.3 mBq/kg for ^{214}Bi and 0.02 mBq/kg for ^{208}Tl. These requirements can be reached by using presently available physical and chemical methods of ^{100}Mo purification [28]. On this basis we have accepted a contamination criterion for ^{214}Bi of 0.3 mBq/kg, while for ^{208}Tl as 0.1 mBq/kg. The calculated background in the energy interval 2.9–3.15 MeV is 6.5 counts/yr·kg from ^{214}Bi, and 0.06 counts/yr·kg from ^{208}Tl. It is possible to reduce these backgrounds substantially by using information on the arrival time of each event to tag correlated decays [21,29]. With this aim, let us consider the ^{226}Ra chain with ^{214}Bi:

$$
\begin{aligned}
&^{222}\mathrm{Rn}\ (T_{1/2} = 3.82\ \mathrm{d};\ Q_\alpha = 5.59\ \mathrm{MeV}) \\
&\quad \to {}^{218}\mathrm{Po}\ (3.10\ \mathrm{m};\ Q_\alpha = 6.11\ \mathrm{MeV}) \\
&\quad \to {}^{214}\mathrm{Pb}\ (26.8\ \mathrm{m};\ Q_\beta = 1.02\ \mathrm{MeV}) \\
&\quad \to {}^{214}\mathrm{Bi}\ (19.9\ \mathrm{m};\ Q_\beta = 3.27\ \mathrm{MeV}) \\
&\quad \to {}^{214}\mathrm{Po}\ (164.3\ \mu\mathrm{s};\ Q_\alpha = 7.83\ \mathrm{MeV}) \to {}^{210}\mathrm{Pb}.
\end{aligned}
$$

Thin ^{100}Mo sources (15 $\mathrm{mg/cm^2}$) allow detection of most of the α and β particles emitted before or after ^{214}Bi decay, and to tag the latter.[5] Indeed, the calculation gives the following detection efficiencies: $\varepsilon_1 = 55\%$ for ^{214}Po (α); $\varepsilon_2 = 80\%$ for ^{214}Pb (β); $\varepsilon_3 = 37\%$ for ^{218}Po (α); $\varepsilon_4 = 32\%$ for ^{222}Rn (α). The probability to detect at least one of these decays can be expressed as:

$$\varepsilon = 1 - (1-\varepsilon_1)\cdot(1-\varepsilon_2)\cdot(1-\varepsilon_3)\cdot(1-\varepsilon_4).$$

This formula yields $\varepsilon = 96.1\%$ with our calculated values which means that ^{214}Bi contribution to background can be reduced by a factor of 25 (to the value of ≈ 0.26 counts/yr·kg). The simulated spectrum from ^{100}Mo contamination by ^{214}Bi and ^{208}Tl is presented in Fig. 2a, where the total background rate in the energy interval 2.9–3.15 MeV is 0.3 counts/yr·kg.

The cosmogenic activities produced in the ^{100}Mo source were calculated with the program COSMO [30]. A 5-yr exposure period was assumed and a deactivation time of 1 yr deep underground. Only two nuclides can give background in the 0ν window. These are ^{88}Y ($Q_{EC} = 3.62$ MeV; $T_{1/2} = 107$ d) and ^{60}Co ($Q_\beta = 2.82$ MeV; $T_{1/2} = 5.3$ yr). Their activities are very low (≈ 190 decays/yr for ^{88}Y and ≈ 50 decays/yr for ^{60}Co), so the background in the energy region of 2.7–3.2 MeV is negligible: $\leqslant 0.02$ counts/yr·kg from ^{88}Y, and $\leqslant 0.005$ counts/yr·kg from ^{60}Co.

Among several sources of external background only γ quanta from PMTs and from ^{222}Rn activity in the shielding water (≈ 30 $\mathrm{mBq/m^3}$) were simulated, while others were estimated as negligible on the basis of the results of Ref. [31], where such sources and contributions for the GENIUS project [32] were studied carefully. The radioactivity of the PMTs were taken from Refs. [17,33]: 0.194 Bq (^{208}Tl); 1.383 Bq (^{214}Bi); and 191 Bq (^{40}K). The simulation gives the following background rate in the $0\nu2\beta$ decay energy interval 2.9–3.15 MeV: (i) 0.32 counts/yr·kg due to ^{214}Bi in PMT; (ii) practically zero rates from ^{208}Tl in PMT and ^{222}Rn in the shielding water. The total background spectrum from ^{214}Bi and ^{208}Tl contamination of the PMTs is shown in Fig. 2a. Summarizing all background sources for 5 years of measurements, one can obtain the total number of ≈ 4.4 counts in the energy range 2.9–3.15 MeV.

The sensitivity of the experiment can be expressed in term of a lower $T_{1/2}$ limit for $0\nu2\beta$ decay of ^{100}Mo as following: $T_{1/2} \geqslant \ln 2 \cdot N \cdot \eta \cdot t/S$, where N is the number of ^{100}Mo nuclei ($\approx 6\times10^{24}$ in our case); t is the measuring time (5 yr); η is the detection efficiency (63.5%); and S is the number of effect's events which can be excluded with a given confidence level on the basis of measured data. Taking into account the expected background of 4.4 counts, we can accept 3–5 events as the S value [34,35], which gives $T_{1/2} \geqslant$ (3–5) $\times 10^{24}$ yr and, corresponding to [36], a limit on the neutrino mass of $m_\nu \leqslant 0.5$ eV. On the other hand, it is evident from Fig. 2a that $0\nu2\beta$ decay of ^{100}Mo with $T_{1/2} = 10^{24}$ yr can be clearly registered: the signal (13 counts) to background (4.4 counts) ratio is approximately $3:1$.

Similar $T_{1/2}$ limits (3–5) $\times 10^{24}$ yr can be obtained by CAMEO-I with other nuclides, such as ^{82}Se, ^{96}Zr, ^{116}Cd, and ^{150}Nd. Due to reasonable cost the preferable second candidate is ^{116}Cd. Note, however, that the limit $T_{1/2}(0\nu) \approx 5\times10^{24}$ yr for ^{150}Nd would lead — on the basis of the calculation [36] — to a limit on the neutrino mass of $m_\nu \leqslant 0.08$ eV.

3. High sensitivity 2β decay study of ^{116}Cd with the CTF

The most sensitive $0\nu2\beta$ results were obtained by using the "active" source technique [1]. We recall the limits $T^{0\nu}_{1/2} \geqslant$ (1–2) $\times 10^{25}$ yr established for ^{76}Ge with the help of HP ^{76}Ge detectors [13,14], and $\geqslant \sim 10^{23}$ yr set for ^{136}Xe with Xe TPC [12], ^{130}Te with $\mathrm{TeO_2}$ low temperature bolometers [11], and ^{116}Cd with $^{116}\mathrm{CdWO_4}$ scintillators [10]. It is proposed to advance the experiment with ^{116}Cd to the sensitivity of $\approx 10^{26}$ yr by placing ≈ 65 kg of enriched $^{116}\mathrm{CdWO_4}$ crystals in the liquid scintillator of the CTF, serving as a light guide and veto shield. To prove the feasibility of this task we are considering first the pilot ^{116}Cd study, and then problems concerning light collection, energy and spatial resolution, and background.

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[5] The expected total α decay rate from ^{238}U and ^{232}Th families in the ^{100}Mo source is ≈ 300 decays/d, and ≈ 0.4 decays/d in an area of 10×10 cm. Thus, chains with $T_{1/2} = 26.8$ and 19.9 min can be used for time analysis.

Here we briefly recall the main results of ^{116}Cd research performed during the last decade by the INR (Kiev) [6] in the Solotvina Underground Laboratory (in a salt mine 430 m underground [37]), and published elsewhere [9,10,21,22]. The cadmium tungstate crystal scintillators, enriched in ^{116}Cd to 83%, were grown for research [20]. The light output of this scintillator is relatively large: $\approx 40\%$ of NaI(Tl) [38]. The refractive index is equal to 2.3. The fluorescence peak emission is at 480 nm with principal decay time of ≈ 14 µs [39]. The density of $CdWO_4$ crystal is 7.9 g/cm^3, the material is non-hygroscopic and chemically inert. In the first phase of study only one $^{116}CdWO_4$ crystal (15.2 cm^3) was used. The background rate in the energy range 2.7–2.9 MeV was ≈ 0.6 counts/yr·kg·keV [21]. With 19175 h statistics the $T_{1/2}$ limit for $0\nu 2\beta$ decay of ^{116}Cd was set as $T_{1/2}(0\nu) \geqslant 3.2 \times 10^{22}$ yr (90% C.L.) [9], and for $0\nu 2\beta$ decay with emission of one (M1) or two (M2) Majorons as $T_{1/2}(\mathrm{M1}) \geqslant 1.2 \times 10^{21}$ yr and $T_{1/2}(\mathrm{M2}) \geqslant 2.6 \times 10^{20}$ yr (90% C.L.) [22].

In 1998 a new set up with four $^{116}CdWO_4$ crystals (total mass 339 g) was mounted in the Solotvina Laboratory. These detectors are viewed by a low background 5” EMI tube (RbCs photocathode) through one light-guide ($\oslash 10 \times 55$ cm), which is composed of two glued parts: quartz 25 cm long and plastic scintillator (Bicron BC-412) 30 cm long. The enriched detectors are surrounded by an active shield made of 15 natural $CdWO_4$ crystals of large volume [38] (total mass 20.6 kg). The latter are viewed by a PMT (FEU-125) through an active plastic light-guide ($\oslash 17 \times 49$ cm). The whole $CdWO_4$ array is situated in an additional active shield made of plastic scintillator $40 \times 40 \times 95$ cm, thus, complete 4π active shielding of the $^{116}CdWO_4$ detectors is provided. The outer passive shield consists of HP copper (3–6 cm), lead (22.5–30 cm) and polyethylene (16 cm). The multichannel event-by-event data acquisition is based on two personal computers (PC) and a CAMAC crate with electronic units. For each event the following information is stored on the hard disk of the first PC: the amplitude, arrival time and additional tags. The second PC records the pulse shape of the $^{116}CdWO_4$ in the energy range 0.25–5 MeV [39]. A one-to-one correspondence between the pulse shape data recorded by the second computer and the information stored in the first PC is established with the help of proper software.

The energy scale and resolution of the main detector — four enriched crystals taken as a whole — were measured with different sources. In particular, the energy resolution is 11.5% at 1064 keV and 8.0% at 2615 keV. Routine calibrations are carried out weekly with ^{207}Bi and ^{232}Th sources. The background spectrum measured during 4629 h with four $^{116}CdWO_4$ crystals [10] is given in Fig. 3, where old data obtained with one $^{116}CdWO_4$ crystal [9] are also shown for comparison. The background is lower in the whole energy range, except for the β spectrum of ^{113}Cd ($Q_\beta = 316$ keV). [7] In the energy region 2.5–3.2 MeV the background rate is 0.03 counts/yr·kg·keV, twenty times lower than before. It is achieved first, due to the new passive and active shield, and secondly, as a result of the time–amplitude and pulse–shape analysis of the data. As an example we consider here the time–amplitude analysis of the following sequence of α decays from ^{232}Th family: ^{220}Rn ($Q_\alpha = 6.40$ MeV, $T_{1/2} = 55.6$ s) $\to$ ^{216}Po ($Q_\alpha = 6.91$ MeV, $T_{1/2} = 0.145$ s) $\to$ ^{212}Pb. The electron equivalent energy of a ^{220}Rn α particle in the $^{116}CdWO_4$ is ≈ 1.2 MeV, thus events in the energy region 0.7–1.8 MeV were used as triggers. All signals following the triggers in the time interval 10–1000 ms (94.5% of ^{216}Po decays) were selected. The spectra of the first and second events, as well as the distribution of the time intervals between them are in an excellent agreement with those expected from α particles of ^{220}Rn and ^{216}Po [10]. From these spectra, the activity of ^{228}Th in $^{116}CdWO_4$ crystals is determined as 38(3) µBq/kg [10]. The same technique applied to the sequence of α decays from ^{235}U family yields 5.5(14) µBq/kg for ^{227}Ac impurity in the crystals.

The pulse shape (PS) of $^{116}CdWO_4$ events (0.25–5 MeV) is digitized by a 12-bit ADC and stored in 2048 channels with 50 ns channel width. The PS technique based on the optimal digital filter was developed and clear discrimination between γ rays and α particles was achieved [39]. The PS selection ensures

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[6] From 1998 this experiment was carried out by the Kiev–Firenze collaboration [10].

[7] The abundance of ^{113}Cd in enriched $^{116}CdWO_4$ crystals is $\approx 2\%$ [21].

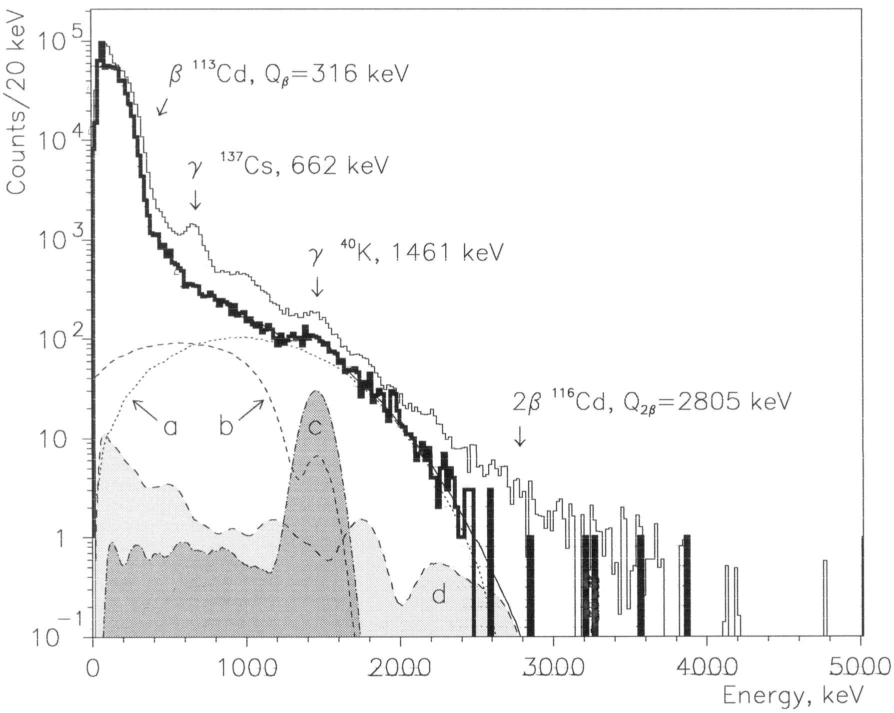

Fig. 3. Background spectrum of four enriched ^{116}CdWO$_4$ crystals (339 g) measured during 4629 h (solid histogram). The old data with one ^{116}CdWO$_4$ crystal (121 g; 19986 h) normalized to 339 g and 4629 h (thin histogram). The model components: (a) $2\nu2\beta$ decay of ^{116}Cd (fit value is $T_{1/2}(2\nu) = 2.6(1) \times 10^{19}$ yr); (b) ^{40}K in the ^{116}CdWO$_4$ detectors (0.8 ± 0.2 mBq/kg); (c) ^{40}K in the shielding CdWO$_4$ crystals (2.1 ± 0.3 mBq/kg); (d) ^{226}Ra and ^{232}Th in the PMTs.

the discrimination of “illegal” events: double pulses, α events, etc., and thus suppresses the background. For instance, the residual ^{228}Th activity of the ^{116}CdWO$_4$ crystals, deduced from the data selected by the PS method as α particles is 37(4) µBq/kg, that is in a good agreement with the value determined by the time analysis of the chain $^{220}\text{Rn} \to {}^{216}\text{Po} \to {}^{212}\text{Pb}$.

To estimate the $T_{1/2}$ limits for $0\nu2\beta$ decay modes, a simple background model with three background components (presented in Fig. 3) was used. These are: external γ from U/Th contamination of the PMTs; tail of the $2\nu2\beta$ decay spectrum; internal distribution expected from the $^{212}\text{Bi} \to {}^{212}\text{Po} \to {}^{208}\text{Pb}$ decay (^{228}Th chain). The limits for $0\nu2\beta$ decay (g.s. → g.s.) are set as $T_{1/2} \geqslant 0.7(2.5) \times 10^{23}$ yr at 90%(68%) C.L., while for transitions to the first 2_1^+ and second 0_1^+ excited levels of ^{116}Sn as $T_{1/2} \geqslant 1.3(4.8) \times 10^{22}$ yr and $\geqslant 0.7(2.4) \times 10^{22}$ yr at 90%(68%) C.L., respectively. For 0ν decay with emission of one or two Majorons, the limits are: $T_{1/2}(\text{M1}) \geqslant 3.7(5.8) \times 10^{21}$ yr and $T_{1/2}(\text{M2}) \geqslant 5.9(9.4) \times 10^{20}$ yr at 90%(68%) C.L. Also the half-life of $2\nu2\beta$ decay is measured as $T_{1/2}(2\nu2\beta) = 2.6 \pm 0.1(\text{stat})^{+0.7}_{-0.4}(\text{syst}) \times 10^{19}$ yr [10].

The following limits on the neutrino mass (using calculations [36]) and neutrino-Majoron coupling constant (on the basis of calculation [40]) are derived from the experimental results: $m_\nu \leqslant 2.6(1.4)$ eV and $g_M \leqslant 12(9.5) \times 10^{-5}$ at 90%(68%) C.L. [10]. It is expected that after ≈ 5 years of measurements the neutrino mass limit of $m_\nu \leqslant 1$ eV would be set. However, pushing this limit to the sub-eV neutrino mass domain could be achievable only by substantial sensitivity enhancement, which is the subject of present project.

In the preliminary design concept of the CAMEO-II experiment 24 enriched ^{116}CdWO$_4$ crystals of large volume (≈ 350 cm^3) are located in the liquid scintillator of the CTF and fixed at 0.4 m distance from the CTF center, thus homogeneously spread out on a sphere with diameter 0.8 m. Each crystal (⌀ 7 × 9 cm) has 2.7 kg mass, and the total number of ^{116}Cd nuclei is $\approx 10^{26}$. 200 PMTs with light concentrators are fixed at diameter 5 m providing optical coverage of 80% (see footnote 1). The $CdWO_4$ scintillator yields $\approx 1.5 \times 10^4$ emitted photons per MeV of energy deposited, hence with total light collection of $\approx 80\%$ and PMT quantum efficiency of $\approx 25\%$ an energy resolution of several % at 1 MeV can be obtained. To justify this value a GEANT Monte Carlo simulation of the light propagation in this geometry was performed, which gave ≈ 4000 p.e. for 2.8 MeV energy deposit. Thus the $0\nu 2\beta$ decay peak of ^{116}Cd would be measured with energy resolution $FWHM = 4\%$. The principal feasibility to obtain such an energy resolution with $CdWO_4$ crystal situated in a liquid has been successfully demonstrated by measurements. A cylindrical $CdWO_4$ crystal (⌀ 40 × 30 mm) was fixed in the centre of a teflon container with inner diameter 70 mm. The latter was coupled on opposite sides with two PMTs Philips XP2412, so that the distance from each flat surface of crystal to the corresponding PMT's photocathode was 30 mm, while the gap between the side surface of the crystal and inner surface of the container was 15 mm. The container was filled with pure and transparent paraffin oil (refractive index ≈ 1.5). Two PMTs worked in coincidence and results of measurements with ^{207}Bi source are depicted in Fig. 4,

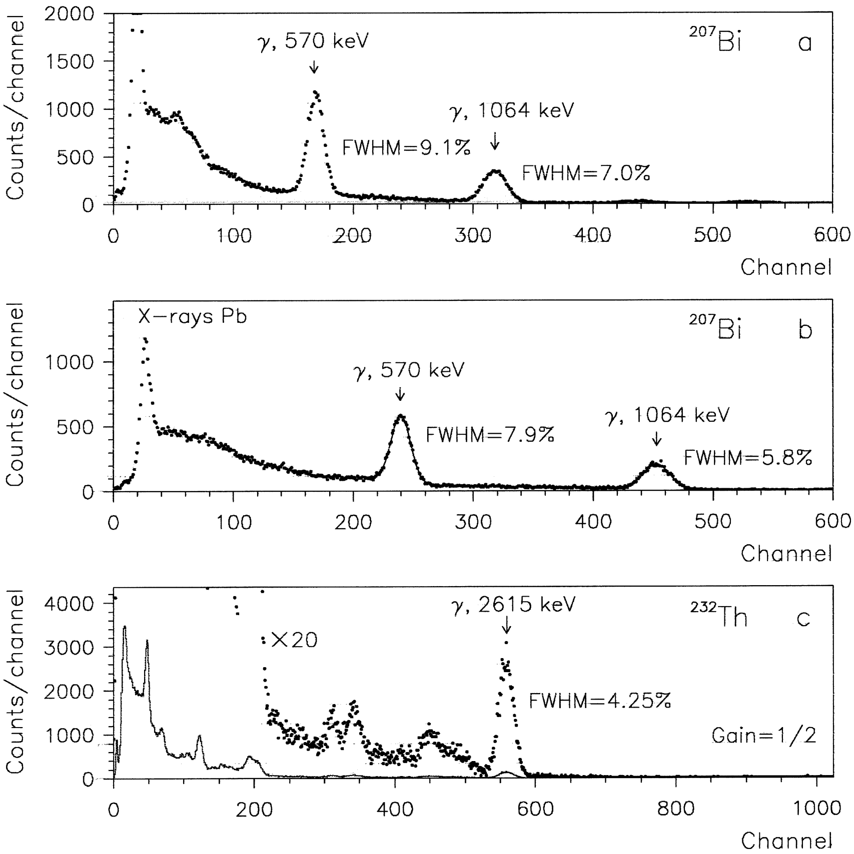

Fig. 4. The energy spectra of ^{207}Bi (^{232}Th) source measured with a $CdWO_4$ crystal (⌀ 40 × 30 mm) for two arrangements: (a) standard, where the $CdWO_4$ crystal is wrapped by teflon diffuser and directly coupled to the PMT's photocathode with optical glue; (b) the $CdWO_4$ crystal is located in the liquid and viewed by two distant PMTs (see text); (c) the same as (b) but with a ^{232}Th source.

where the spectrum obtained with standard detector arrangement ($CdWO_4$ crystal wrapped by teflon diffuser and directly coupled to the PMT's photocathode with optical glue) is also shown for comparison. As evident from Fig. 4, a substantial ($\approx 42\%$) increase in light collection was obtained with $CdWO_4$ in the liquid. This leads to improvement in detector energy resolution in the whole energy region 50–3000 keV (see Fig. 4c where the spectrum measured with a ^{232}Th source is presented). The *FWHM* values (7.4% at 662 keV; 5.8% at 1064 keV; 5.4% at 1173 keV and 4.3% at 2615 keV) obtained are similar to those for NaI(Tl) crystals and have been never reached before with $CdWO_4$ crystal scintillators [38].

Moreover, a strong dependence of the light collected by each PMT versus coordinate of the emitting source in the crystal was found. Such a dependence can be explained by the difference of the refraction indexes of the $CdWO_4$ crystal ($n = 2.3$) and liquid scintillator ($n' = 1.51$), which leads to a redistribution between reflected and refracted light due to change of the source's position. Our GEANT Monte Carlo simulation shows that with a $CdWO_4$ crystal ($\oslash 7 \times 9$ cm) viewed by 200 PMTs, spatial resolution of 1–5 mm can be reached depending on the event's location and the energy deposited (see, however, footnote 3). These interesting features of light collection from $^{116}CdWO_4$ would allow reduction of background from high energy γ quanta (e.g., ^{208}Tl) in the energy region of interest. In addition, non-uniformity of light collection can be corrected by using spatial information, hence, helping to reach the required energy resolution.

The background simulation for CAMEO-II was performed with GEANT and event generator DECAY4. The simulated response functions of the CAMEO-II set up for $2\nu2\beta$ decay[8] of ^{116}Cd with $T_{1/2} = 2.7 \times 10^{19}$ yr, as well as for $0\nu2\beta$ decay with $T_{1/2} = 10^{25}$ yr are depicted in Fig. 2b. The calculated values of efficiency for the 0ν channel are 86.1% (for 2.7–2.9 MeV) and 75.3% (2.75–2.9 MeV). Background in the corresponding energy interval from the 2ν distribution is 2.3 counts/yr (2.7–2.9 MeV) or 0.29 counts/yr (2.75–2.9 MeV).

The high radio-purity of enriched and natural $CdWO_4$ crystals was demonstrated by the INR (Kiev) experiment [38]. Thus, contamination criteria for ^{214}Bi and ^{208}Tl have been accepted as ≈ 10 μBq/kg, which are equal to actual activity values or limits determined for different samples of $CdWO_4$ [38]. The calculated background contribution from the sum of ^{208}Tl and ^{214}Bi activities is ≈ 2000 counts/yr in the energy interval 2.7–2.9 MeV. However, applying the time–amplitude analysis with spatial resolution and PS discrimination technique developed this rate can be reduced to ≈ 0.2 counts/yr.

The cosmogenic activities in the $^{116}CdWO_4$ detectors were calculated by the program COSMO [30]. A 1 month exposure period on the Earth's surface was assumed and a deactivation time of 3 years underground. Only 2 nuclides can give background in the $0\nu2\beta$ decay energy window. These are ^{110m}Ag ($Q_\beta = 3.0$ MeV; $T_{1/2} = 250$ d) and ^{106}Ru ($Q_\beta \approx 40$ keV; $T_{1/2} = 374$ d) $\rightarrow {}^{106}$Rh ($Q_\beta = 3.5$ MeV; $T_{1/2} = 30$ s). The activity of ^{106}Ru is low and time–amplitude analysis can be applied ($T_{1/2} = 30$ s), thus the estimated background is practically negligible: ≈ 0.1 counts/yr (2.7–2.9 MeV) and 0.05 counts/yr (2.75–2.9 MeV). Background from ^{110m}Ag is quite large: ≈ 23 (or ≈ 20) counts/yr in the energy interval 2.7–2.9 MeV (2.75–2.9 MeV). However its contribution can be reduced by using spatial information because ^{110m}Ag decays are accompanied by cascades of γ quanta with energies $\geqslant 600$ keV, which would be absorbed in spatially separated parts of the detector giving an anticoincidence signature. Simulation under assumption that the $^{116}CdWO_4$ crystal consists of small independent detectors with $h = d = 1.2$ cm, yields a residual background rates of ≈ 0.3 (or 0.2) counts/yr in the energy region 2.7–2.9 MeV (2.75–2.9 MeV). The simulated spectrum from the cosmogenic activity of ^{110m}Ag is depicted in Fig. 2b.

As previously, to calculate external background only γ quanta from PMTs and Rn impurities in the water were taken into account. We find that mainly ^{208}Tl activity from PMTs is important. The calculated background rates are ≈ 0.8 and 0.05 counts/yr in the energy interval 2.7–2.9 MeV (2.75–2.9 MeV). With the help of spatial information these values can be reduced to ≈ 0.08 (or 0.005) counts/yr in the energy region 2.7–2.9 MeV (2.75–2.9 MeV). The simulated contribution from ^{208}Tl in the PMTs

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[8] The $T_{1/2}$ of $2\nu2\beta$ decay of ^{116}Cd has been already measured as $\approx 2.7 \times 10^{19}$ yr [10,21,41].

is shown in Fig. 2b. Summarizing all background sources gives ≈ 3 (or 0.6) counts/yr in the energy interval 2.7–2.9 MeV (2.75–2.9 MeV).

We estimate the sensitivity of the CAMEO-II experiment in the same way as for ^{100}Mo. Taking into account the number of ^{116}Cd nuclei ($\approx 10^{26}$), measuring time of 5–8 years, detection efficiency of 75%, and expected background of 3–4 counts, one can obtain a limit $T_{1/2}(0\nu) \geqslant 10^{26}$ yr. Moreover, it is evident from Fig. 2b that $0\nu2\beta$ decay with $T_{1/2} \approx 10^{25}$ yr would be clearly registered. Such a sensitivity level cannot be reached in presently running 2β decay experiments (perhaps only with ^{76}Ge), or in projects, like NEMO-3 [27] or CUORICINO [42], which are under construction now. The sensitivity of NEMO-3 is limited to $\approx 4 \times 10^{24}$ yr by the detection efficiency and the energy resolution of the set up (see Fig. 1f). The CUORICINO[9] experiment is designed to study 2β decay of ^{130}Te with the help of 60 low temperature bolometers made of TeO_2 crystals (750 g mass of each). Despite the excellent energy resolution (≈ 5 keV at 2.5 MeV) the main disadvantage of a cryogenic technique is its complexity, which requires the use of many different construction materials in the apparatus. This fact, together with the lower 2β decay energy of ^{130}Te (2528 keV), makes it difficult to reach the super-low level of background. In that sense CAMEO-II has a great fundamental advantage because signaling from $^{116}CdWO_4$ crystals to PMTs (placed far away) is provided by light propagating in the super-low background medium of liquid scintillator, whereas cryogenic or semiconductor detectors must be connected to receiving modules by cables. Another drawback of cryogenic detectors is their low reliability. At the same time, CAMEO with $^{116}CdWO_4$ crystals is simple and reliable, therefore can run for decades without problems and with low maintenance cost.[10]

Moreover, CAMEO-II can be advanced farther by exploiting one ton of $^{116}CdWO_4$ detectors ($\approx 1.5 \times 10^{27}$ nuclei of ^{116}Cd) and the BOREXINO apparatus (CAMEO-III). With this aim 370 enriched $^{116}CdWO_4$ crystals (2.7 kg mass of each) would be placed at diameter 3.2 m in the BOREXINO liquid scintillator. The simulated response functions of such a detector system for $2\nu2\beta$ decay of ^{116}Cd with $T_{1/2} = 2.7 \times 10^{19}$ yr, and for $0\nu2\beta$ decay with $T_{1/2} = 10^{26}$ yr are depicted in Fig. 2c. Since background in the BOREXINO set up should be lower than in the CTF, the sensitivity of CAMEO-III is estimated as $T_{1/2} \geqslant 10^{27}$ yr, while $0\nu2\beta$ decay with $T_{1/2} \approx 10^{26}$ yr can be detected. This level of sensitivity can be compared only with that of the GENIUS project [32], which is under discussion now and intends to operate one ton of enriched HP ^{76}Ge detectors placed in a tank ($\oslash 12 \times 12$ m) with extremely HP liquid nitrogen serving as cooling medium and shield simultaneously. One ton of Ge detectors with enrichment $\approx 86\%$ would provide $\approx 7 \times 10^{27}$ nuclei of ^{76}Ge; thus in case of zero background a sensitivity of $T_{1/2} \geqslant 5 \times 10^{27}$ yr can be reached there. However, because of the lower 2β decay energy (2039 keV) the phase-space integral for $0\nu2\beta$ decay of ^{76}Ge is about ten times lower than for ^{116}Cd [2]. Hence, we can expect that CAMEO-III will bring at least the same restriction on the neutrino mass as GENIUS. Indeed, on the basis of the CAMEO limit $T_{1/2} \geqslant 10^{27}$ yr and using calculations [36,44] one can derive a bound on the neutrino mass of ≈ 0.02 eV. At the same time it is obvious that technical tasks, whose solutions are required for realization of these mentioned super-high sensitivity projects (GENIUS, CUORE and CAMEO) are simpler for CAMEO. In fact, the super-low background apparatus needed for the latter experiment is already running (the CTF) or under construction (BOREXINO), while for CUORE and GENIUS such unique set ups should be designed and constructed.

4. Conclusions

1. The unique features of the CTF and BOREXINO (super-low background and large sensitive volume) are used to develop a realistic, competitive, and efficient program for high sensitivity 2β decay research (CAMEO project), which includes three steps:

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[9] CUORICINO is a pilot step for a future CUORE project, which would consist of 1000 TeO_2 bolometers with total mass of 750 kg [42].

[10] The $^{116}CdWO_4$ crystals can also be used as cryogenic detectors with high energy resolution [43]. In the event of a positive effect seen by CAMEO-II these crystals could be measured in the CUORE apparatus; in this sense both projects are complementary.

CAMEO-I. With a passive 1 kg source of ^{100}Mo (^{116}Cd, ^{82}Se, ^{150}Nd) located in the liquid scintillator of the CTF, the sensitivity (in term of the $T_{1/2}$ limit for $0\nu2\beta$ decay) is (3–5) $\times 10^{24}$ yr. It corresponds to a bound on the neutrino mass $m_\nu \leqslant 0.1$–0.3 eV, which is similar to or better than those of running (^{76}Ge), and future NEMO-3 (^{100}Mo) and CUORICINO (^{130}Te) experiments.

CAMEO-II. With 24 enriched ^{116}CdWO$_4$ crystal scintillators (total mass 65 kg) placed as "active" detectors in the CTF the sensitivity is $\approx 10^{26}$ yr. Pilot ^{116}Cd research and Monte Carlo simulation show the feasibility of the CAMEO-II step, which will yield a limit on the neutrino mass of $m_\nu \leqslant 0.05$–0.07 eV.

CAMEO-III. By exploiting one ton of ^{116}CdWO$_4$ detectors (370 crystals) introduced in BOREXINO, the half-life limit can be advanced to the level of $\approx 10^{27}$ yr, corresponding to a neutrino mass bound of ≈ 0.02 eV.

2. In contrast to other projects CAMEO has three principal advantages:

(i) Practical realization of CAMEO is simpler due to the use of already existing super-low background CTF or presently under construction BOREXINO apparatus;
(ii) Signaling from ^{116}CdWO$_4$ crystals to PMTs (placed far away) is provided by light propagating in the high-purity medium of liquid scintillator — this allows practically zero background to be reached in the energy region of the $0\nu2\beta$ decay peak;
(iii) Extreme simplicity of the technique used for 2β decay study leads to high reliability and low maintenance costs for the CAMEO experiments, which therefore can run permanently and stably for decades.

3. Fulfillment of the CAMEO program would be a real breakthrough in the field of 2β decay investigation, and will bring outstanding results for particle physics, cosmology and astrophysics. Discovery of $0\nu2\beta$ decay will unambiguously manifest new physical effects beyond the SM. In the event of a null result the limits obtained would yield strong restrictions on parameters of manifold extensions of the SM (neutrino mass and models; right-handed contributions to weak interactions; leptoquark masses; bounds for parameter space of SUSY models; neutrino-Majoron coupling constant; composite heavy neutrinos; Lorentz invariance, etc.), which will help to advance basic theory and our understanding of the origin and evolution of the Universe.

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