IL NUOVO CIMENTO **46 C** (2023) 8
DOI 10.1393/ncc/i2023-23008-y

Colloquia: La Thuile 2022

Searching for neutrinoless double beta decay with the AMoRE experiments

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received 19 September 2022

Summary. — Searches for the neutrinoless double beta decay (0νDBD) have been pursued for decades by many researchers since it is a viable channel to probe the lepton number violating process and unveil some unknown properties of neutrino. The AMoRE experiments have been searching for 0νDBD of ^{100}Mo isotope using molybdate crystal scintillators. The experiments used the molybdate crystals as the absorber for the cryogenic calorimeter, which measures the energetic phonons and scintillation lights from the particle interaction in the crystal absorber. The experiments have been scheduled as several phases of AMoRE-pilot, AMoRE-I and AMoRE-II with the significant increase in the absorber mass and reduction of the background level for each upgrade. Currently, we are running AMoRE-I experiment, which uses 6.2 kg of molybdate crystal absorbers, and preparing for AMoRE-II experiment, which will exploit 100 kg of ^{100}Mo isotopes, ultimately. The overall status of the AMoRE experiments is presented in the paper.

1. – Introduction

Nuclei with an even number of protons and an even number of neutrons generally have lower masses than their counterparts with an odd number of protons and an odd number of neutrons. As a result, simple beta decay is energetically forbidden [1]. However, a second-order weak interaction process allows double beta decay in which two electrons and two neutrinos are emitted spontaneously. To date, this two neutrino double beta decay (2νDBD) has been observed with eleven nuclei with a half-life of 10^{18}–10^{24} years [2]. The possibility of the neutrinoless double beta decay (0νDBD), which is beyond the Standard Model, has attracted the particular interest for decades. The discovery of such a decay channel, first of all, means the presence of a lepton number violating process. This will provide critical input in formulating scenarios for leptogenesis and baryogenesis that explain our baryon-dominated universe. Secondly, 0νDBD will be an unambiguous signature that the neutrinos are Majorana particles. In the light neutrino exchange mechanism, which is the most discussed model in the particle physics community, the measurement of the half-life of 0νDBD will reveal the neutrino effective mass ($\langle m_{\beta\beta}\rangle = |\sum_i U_{ei}^2 m_i|$, where U_{ei} is Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix,

m_i is neutrino mass eigenstates) as $T_{1/2} = (G|M|^2\langle m_{\beta\beta}\rangle^2)^{-1} \simeq 10^{27-28}(\frac{0.01\ \mathrm{eV}}{\langle m_{\beta\beta}\rangle})^2$years, where G is the phase-space factor and M is nuclear matrix element [3]. Currently, the best experimental limit for $\langle m_{\beta\beta}\rangle$ is given as $\langle m_{\beta\beta}\rangle < 0.06$–$0.4$ eV [4-6]. Combined with the direct electron neutrino mass measurement ($m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$) [7] and cosmological observations which give strong constraints in the sum of the neutrino masses ($\Sigma = m_1 + m_2 + m_3$) [8], detection of 0νDBD will provide an excellent opportunity to probe the absolute scale of the neutrino mass. In terms of the experimental signature, unlike 2νDBD, the 0νDBD will be manifested as a sharp peak at the Q-value of the double beta decay.

The AMoRE experiments have carried out a 0νDBD search using ^{100}Mo as the target source, whose Q-value is 3.034 MeV. Because the natural high-energy gamma rays are significantly reduced above the 2.615 MeV ^{208}Tl peak, the expected 0νDBD signature will be in the region with minimal natural gamma backgrounds. The natural abundance of ^{100}Mo is 9.8%, which is relatively high among the most promising double beta decay candidates [3]. The isotope has been investigated for a long time for this purpose [9]. The experiments use massive scintillating molybdate crystals as the absorber for the cryogenic calorimeter, an experimental technique that measures the energetic phonons from the particle interaction in the absorber with excellent energy resolution, $\Delta E/E \lesssim 0.2\%$ around the Q-value. Since the target source is equal to the detector absorber, the detection efficiency of the 0νDBD signal is as high as around 80%. Simultaneous scintillation detection can help identify alpha particles because the light yield of the molybdate crystal scintillator depends on the particle types. Using the light-to-heat signal ratio, background from the degraded alpha signals which occur near the crystal surface can be rejected from entering the energy region of interest (ROI). The scintillating mechanism also affects the pulse shape of the phonon signals, which can provide additional informations about the particle type [10].

The experiments have been scheduled in several phases as AMoRE-pilot, AMoRE-I and AMoRE-II with a significant increase in the absorber mass for each upgrade. The AMoRE-pilot experiment using 1.9 kg of molybdate crystals was successfully finished with encouraging technical and physics results [11]. Currently, the AMoRE-I experiment is running with 6.2 kg of molybdate crystal absorbers [12]. Based on the smooth data collection accumulated for longer than a year, we expect to report the results of the AMoRE-I experiment soon. The preparation for the AMoRE-II experiment, which will exploit 100 kg of ^{100}Mo isotopes contained in hundreds of molybdate crystals, is also being carried out. In addition to the significant increase in the detector mass, the AMoRE-II aims the reduction of the background in the ROI to the level of 10^{-4} counts/keV/kg/year (ckky).

2. – AMoRE detector

The AMoRE detectors use MMC (Metallic Magnetic Calorimeter) sensors to measure the energetic phonons from the particle interaction in the crystal absorber [13]. The MMC uses paramagnetic materials such as erbium-doped gold (Au:Er) or silver (Ag:Er), whose magnetizations are very sensitive to temperature change. The crystal has a gold film ("phonon collector") with a diameter of 1–2 cm and thickness of 300–400 nm. The energetic phonons will heat up the electrons in the phonon collector. The excessive heat from the electrons will conduct through 10–20 gold wires with a 25 μm diameter to the MMC sensor, which is in small magnetic field provided by a superconducting loop underneath. The magnetization of the MMC will change due to the excessive heat flow and concurrently, the current in the superconducting loop will vary due to the

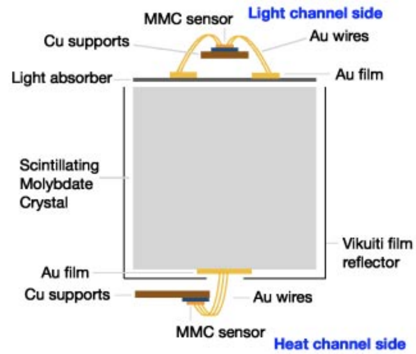
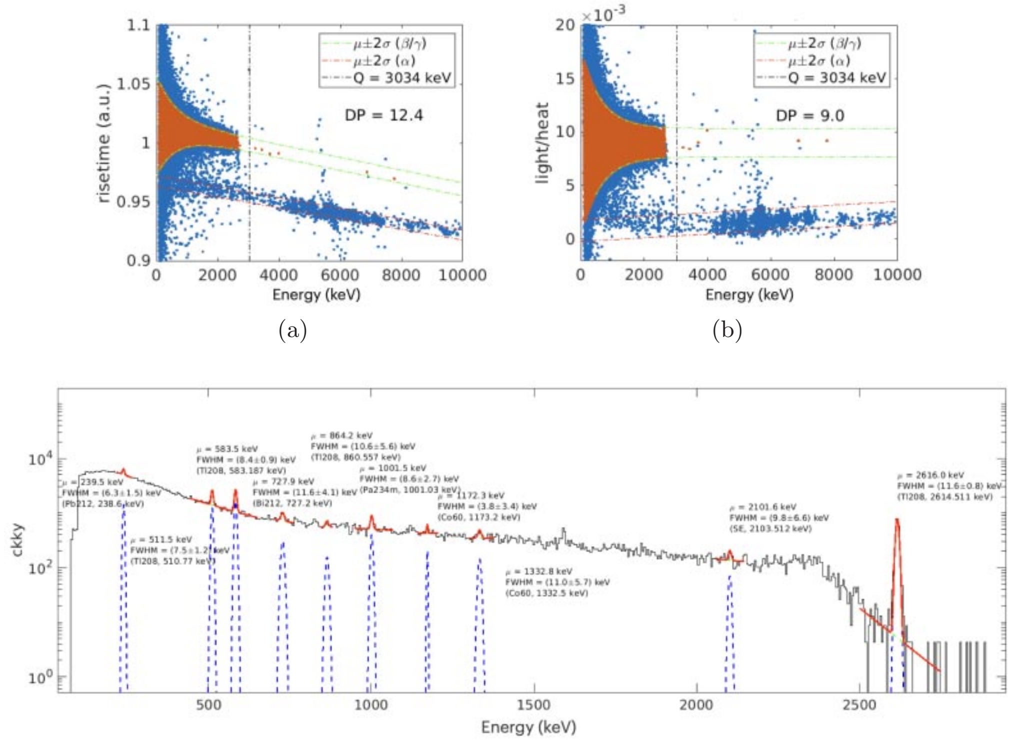


Fig. 1.: Schematic diagram of the AMoRE detector.

change in the MMC magnetization. The superconducting loop is coupled to a SQUID (Superconducting QUantum Interference Device) sensor, which measures the change in current as a signal. The measurement of these energetic phonons is called the heat channel. At the opposite crystal surface of the heat channel side, a thin light absorber such as Si and Ge wafer with a few hundreds μm thickness is installed. The absorption of the scintillation lights in the light absorber will generate energetic phonons, which will be detected in the same way as the heat channel. The crystal is surrounded by the Vikuiti reflector film (3M) to increase the light collection at the light absorber. A schematic diagram of the AMoRE detector is shown in fig. 1. More details of the AMoRE detector can be found in other literatures [14-16].

2˙1. *Scintillating molybdate crystals*. – At the early stage, calcium molybdate ($CaMoO_4$) crystals were chosen as the main target material for the experiments [17]. The calcium molybdate crystal has the highest light output among the molybdate crystals. Good energy resolutions and particle identifications based on the light-to-heat ratio and the pulse shapes were demonstrated with the massive crystals. The crystal is easy to handle and allows relatively easy deposition of the gold phonon collector film on the crystal surface. However, the crystals have some drawbacks. To ensure an optical quality to collect the scintillation signal, they must undergo annealing process, which takes some additional preparation time. ^{48}Ca depletion is also necessary to reduce background caused by the 2νDBD of ^{48}Ca. Besides, the radioactive contamination of $CaMoO_4$ is rather high due to chemical affinity of Ca and Ra. The need to use depleted calcium leads to a substantial increase of the experimental cost. For an alternative option, lithium molybdate (Li_2MoO_4) crystals have been chosen as the primary target material for the later phases of the experiments. The lithium molybdate crystals tend to contain more Mo isotopes for a given mass compared to other molybdate crystals. The melting point of the crystal is low, and it does not require annealing for optical transparency. The relatively easy crystal growing reduces the effort and cost for crystal preparation significantly. Li_2MoO_4 crystals have a very low radioactive background in general [18]. Good energy resolutions and particle identifications have been demonstrated using massive crystals as well [19]. The lithium molybdate crystals also have some weak points, which cause treatment with cautions. They are hygroscopic crystals, so their detector performances deteriorate if they are exposed to the air with a relative humidity well above 20%. They have a small light output; therefore, the detection of the light signal embedded in the vibration noise from the pulse tube cryocooler of the cryogen-free dilution refrigerator, which is a practical choice for the cryogenic detector operations, can be a difficult task.

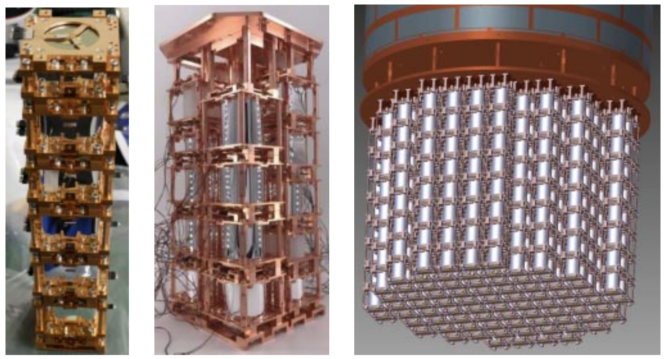


(a) (b)

(c)

Fig. 2.: AMoRE detector performance. Discriminations between alpha and gamma/beta signals for one calcium molybdate crystal detector based on (a) pulse shape (rise time) and (b) light-to-heat ratio. DPs were estimated in the energy region around the Q-value. (c) Energy resolutions for one lithium molybdate crystal detector. Both detectors are from the AMoRE-I experiment.

2$\dot{}$2. *Detector performance.* – The detector is usually operated at 10–20 mK. At the low temperatures, the particle interaction in the crystal absorber generates high energetic phonons in the early part, which is called athermal phonons. Gradually, via impurity and surface scatterings, the athermal phonons convert to thermal phonons, which reflect the overall thermal properties of the crystal absorbers, such as heat capacity and the thermal conductance to the sensor and the heat bath. Owing to the fast response of the MMC sensor, the detector signal is sensitive to both the athermal and thermal phonons, and the athermal part mainly determines the primary pulse height. Based on the pulse shape such as the rise time, the particle types can be discriminated as illustrated in fig. 2(a). The discrimination power is defined as $\mathrm{DP} = |\mu_\alpha - \mu_{\beta/\gamma}|/\sqrt{\sigma_\alpha^2 + \sigma_{\beta/\gamma}^2}$, where μ and σ are the mean and standard deviation for alpha or beta/gamma distributions. For the data presented in the figure, the DP is estimated to be 12.4, which indicates the excellent alpha particle rejection in the ROI. The light-to-heat signal ratio also allows the efficient discrimination of alpha signals as shown in fig. 2(b). The illustration of fig. 2(a) and (b) are from one calcium molybdate detector in the AMoRE-I experiment. The energy resolution of the detectors in full width at half maximum (FWHM) is typically



(a) (b) (c)

Fig. 3.: Detector towers for the AMoRE experiments. (a) AMoRE-pilot (6 modules, total crystal mass = 1.9 kg), (b) AMoRE-I (18 modules, total crystal mass = 6.2 kg), (c) Plan for AMoRE-II (hundreds modules, total crystal mass $\sim$ 180 kg).

10–20 keV for the 2.615 MeV gamma rays of ^{208}Tl (the closest calibration point to the ROI). Figure 2(c) shows the energy resolution of one lithium molybdate crystal detector in the AMoRE-I experiment measured at various calibration peaks.

3. – Experimental campaigns

The AMoRE-pilot experiment was carried out from year 2015 to 2018. The detector was built with six ^{100}Mo-enriched and ^{48}Ca-depleted calcium molybdate crystals with the total crystal mass of 1.9 kg (fig. 3(a)). The crystals were provided by FOMOS materials, Russia. Based on the total exposure of 0.3 kg·year and background rate of about 0.55 ckky at ROI, the first result of the AMoRE-pilot experiment was reported as $T^{0\nu}_{1/2} > 9.5 \times 10^{22}$ years at 90% C.L. for the 0νDBD of ^{100}Mo [11]. This experiment provided important learning experiences in terms of the radioactive background control. Radioactively "hot" components, such as some epoxy and pin connectors, were identified in the detector modules and they were replaced with a low background components. Later, Borated material layers and Polyethylene (PE) layers were added to the shielding structure to reduce the background induced by the neutron flux. The reduction of background level for each experimental configuration is shown in fig. 4. With this reduced background level and the further increased experimental exposure of 0.68 kg·year, new limit of $T^{0\nu}_{1/2} > 3.4 \times 10^{23}$ years at 90% C.L. was obtained. The full detailed discussion about this new results will be presented in other report [20].

The AMoRE-I experiment started in 2020 and is planned to run through 2023. In addition to the crystals of the AMoRE-pilot experiment, seven calcium molybdate crystals and five lithium molybdate crystals were added (fig. 3(b)). One lithium molybdate crystal was produced by the Center for Underground Physics (CUP) of the Institute of Basic Science (IBS) and the other crystals were provided by the Nikolaev Institute of Inorganic Chemistry (NIIC), Russia. All of the crystals are ^{100}Mo enriched and the total crystal mass is 6.2 kg. Based on experiences from the AMoRE-pilot experiment, shielding layers for the neutron flux were upgraded and an additional PID temperature controller was installed at the detector tower to realize more stable temperature baseline.

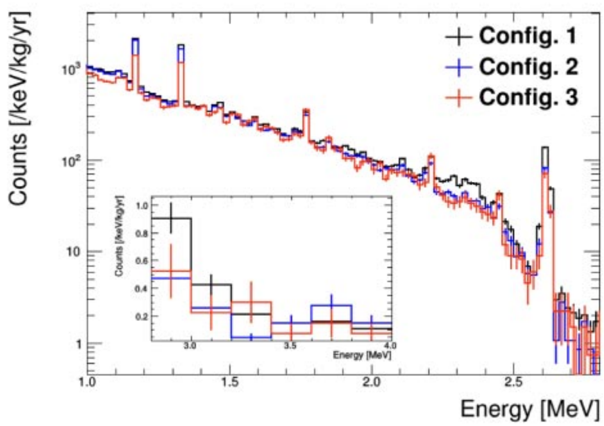
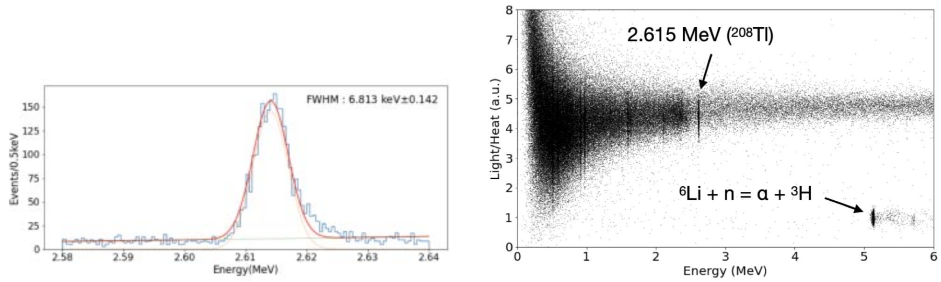


Fig. 4.: Background levels by the three configurations of AMoRE-pilot experiment. Config. 1: the original setup. Config. 2: "hot" radioactive components removed from the detector module. Config. 3: enhanced neutron shielding. The inset shows the region around the ROI.

Owing to the smooth operation, the exposure have reached approximately 5 kg·year in terms of the crystal mass and detector operation time. A preliminary analysis showed that the background level in the ROI is about 0.06 ckky. As this is a preliminary value based on conservative estimation, the final background level is likely to be much lower than this estimation. As a full analysis is being carried out vigorously, the first result of the AMoRE-I experiment is expected to come out soon.

The AMoRE-II experiment is scheduled to start in 2022 and run through 2028. The AMoRE-II experiment will exploit 100 kg of the isotope ^{100}Mo in hundreds of detector modules (fig. 3(c)). The total crystal mass will be around 180 kg. Most of the crystals will be lithium molybdate crystals, which will be provided by the NIIC and CUP. The detector tower will be hung by kevlar wire system to suppress the vibration noises more effectively than in the previous phases. In preparing for the large scale experiments, a lot of effort has been dedicated to optimize the detector module in terms of performance and preparation. This task is essential to prepare hundreds of detector modules in a reasonably good time schedule aiming also advancement of the whole detector performance. As a result of this dedicated efforts, we have demonstrated that using a massive 516 g lithium molybdate crystal, an energy resolution of 6.8 keV (FWHM) at 2.615 MeV can be achieved (fig. 5(a)). We also demonstrated that using a 299 g lithium molybdate crystal, the particle discrimination between alpha and beta/gamma particles based on the light-to-heat signal ratio can be as good as DP = 14.25 in the energy range of $5\,\mathrm{MeV} < \mathrm{E} < 6\,\mathrm{MeV}$. The improved distribution of the light-to-heat ratio *versus* energy is shown in fig. 5(b). As the AMoRE-II experiment is expected to use more sophisticated mechanism to suppress the vibration noise, DP of 10 seems to be readily achievable in the ROI with the lithium molybdate crystals.

In addition to improving the detector sensitivity by significant mass increase and performance improvement, considerable work has been put into reducing the background level. We tried to measure the radioactive background levels of most of the components used in the detector setup and check their contributions to the background level in the



(a) (b)

Fig. 5.: Performances of lithium molybdate crystal detectors for AMoRE-II experiments. (a) Energy resolution (FWHM) of 6.8 keV at 2.615 MeV gamma line demonstrated using a 516 g crystal. (b) light-to-heat signal ratio *versus* energy of the signal, which shows an improved discrimination between alpha and beta/gamma particles. The DP at $5\,\mathrm{MeV} < \mathrm{E} < 6\,\mathrm{MeV}$ is estimated to be 14.25 ± 0.06.

ROI through a simulation. The components which introduce high background will be replaced with alternative materials or used with a limited amount. The goal is to achieve the total background level in ROI as 10^{-4} ckky and for each component, $1.5{\times}10^{-5}$ ckky is set as a target limit (fig. 6). Estimating the background is an iterative process until the final design and material choices are determined.

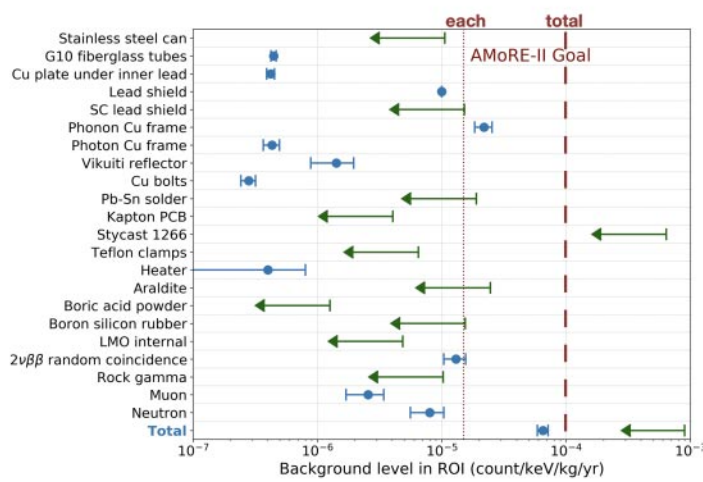


Fig. 6.: Projected background contributions in the ROI from various components in the detector setup for AMoRE-II experiments. If the background measurement of a component was given by a limit, its projected background contribution is represented by the arrow. In estimating the total contribution, the components with the positive values and those with limit values are summed separately. The target value of the background from each component is $1.5{\times}10^{-5}$ ckky (dotted line) and the overall target background level is 10^{-4} ckky (dashed line).

The AMoRE-pilot and AMoRE-I experiments have been conducted in Yangyang underground laboratory (Y2L) in Yangyang, South Korea. Y2L is located in a Yangyang pumped-storage power plant's tunnel, whose minimum depth from the covering mountain surface is 700 m. The underground lab houses several experiments such as the COSINE dark matter search experiments [21] and the AMoRE experiments. Y2L supplies Radon-free air to the experimental halls. The AMoRE-II experiments will be conducted in a new underground laboratory, Yemilab, Jeongseon, South Korea [22]. The construction of Yemilab is almost completed and the experimental hall is expected to be opened in October, 2022. Yemilab, an underground research facility dedicated to basic sciences, lies 1000 m below the Yemi mountain surface. It will provide enough space for the new large-scale experiments with a strict control of dust and radon in the air [23].

4. – Conclusion

The AMoRE experiments have been searching for the neutrinoless double beta decay of ^{100}Mo using scintillating molybdate crystals such as calcium molybdate and lithium molybdate. The experiments use the crystals as the absorbers of the cryogenic calorimeter with simultaneous light detection using the MMC sensors. The AMoRE detector modules demonstrated an excellent energy resolution and alpha particle discrimination using the light-to-heat signal ratio enabling a competitive probe of the neutrinoless double beta decay. The AMoRE-pilot demonstrated a good sensitivity potential with a result of $T^{0\nu}_{1/2} > 3.4 \times 10^{23}$ years at 90% C.L. for ^{100}Mo decay using 1.9 kg of calcium molybdate crystals. The AMoRE-I experiment has accumulated data corresponding to about 5 kg·year using 6.2 kg of calcium and lithium molybdate crystals. Combined with the improved background level compared to the AMoRE-pilot experiment, results with significantly improved sensitivity will come out soon. The experiments are gradually entering into the AMoRE-II phase, which will utilize 100 kg of enriched isotope ^{100}Mo. In a series of efforts to optimize the detectors, an FWHM resolution below 7 keV was demonstrated at the 2.615 MeV gamma rays using a massive 516 g lithium molybdate crystal and DP of 14.25 was achieved in the energy range of 5 MeV < E < 6 MeV with the light-to-heat ratio using a 299 g crystal. The AMoRE-II experiment will be commissioned starting from the end of 2022. The experiment is aiming at $T^{0\nu}_{1/2} > 8.2 \times 10^{26}$ years and $m_{\beta\beta} < 0.013$–$0.025\,\text{eV}$ after 5 year operation with background level less than 1×10^{-4} ckky.

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This work was supported by Grant Nos. IBS-R016-D1, IBS-R016-A2, Grant No. 2020.02/0011 (the National Research Foundation of Ukraine) and the MEPhI Program Priority 2030 (National Research Nuclear University MEPhI, Russia).

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