PROCEEDINGS OF SCIENCE

AMoRE-II preparation status

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The main phase of AMoRE, AMoRE-II, is about to start its data taking to probe the neutrinoless double decay of molybdenum-100. The experiment takes place 1000 meters underground at YemiLab in Jeongseon, Korea. A cryogenic system containing molybdenum-100 enriched crystal detector modules is surrounded by heavy passive shields and muon counters made of plastic scintillator panels and water Cherenkov detectors. We expect the background level to be below 10^{-4} count/keV/kg/year with a 10 keV full-width-half-maximum energy resolution at the region of interest. Starting with 90 detector modules consisting of about 27 kg of lithium-molybdate crystals, the detector will eventually be upgraded using 157 kg of crystals. Data-taking will last for more than five years. The projected sensitivity covers the half-life of neutrinoless double beta decay of molybdenum-100 up to about 4×10^{26} years, corresponding to the effective Majorana mass of 18-31 meV.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08_01.09.2023
University of Vienna

[*] Speaker

PoS(TAUP2023)214

An observation of the 0νDBD process is a unique probe for determining whether neutrinos are Dirac or Majorana particles as well as their absolute mass scale. The so-called effective Majorana mass is expected to be smaller than tens of meV according to the constraints from cosmological observations and measured neutrino oscillation parameters [1]. The half-life of 0νDBD is inversely proportional to the square of the effective Majorana mass and different for isotopes for their nuclear matrix elements. Currently, all isotopes are expected to have 0νDBD half-life longer than 10^{26} years at least. The sensitivity of measuring 0νDBD, therefore, depends primarily on [number of isotope ($N_{\rm ISO}$)]×[time (t)] exposure, which should be much larger than the expected half-life for discovery. Other key parameters for the experimental sensitivity are the background level at around Q-value, and the energy resolution on which the region of interest (ROI) and the number of background event depend.

Among various even(-proton)-even(-neutron) nuclei that are capable of double beta decay, molybdenum-100 has practical advantages for the 0νDBD measurement: its Q-value is 3034 keV whereas majority of the natural radioactive γ-rays exist below 2615 keV; the enrichment is rather easy for its natural abundance is as high as 9.7%; scintillation crystal can be made in the form of $X_aMo_bO_c$ (XMO), where X can be one of Li, Na, Ca, Pb, etc. AMoRE uses the XMO crystals with the ^{100}Mo enrichment at 95% in the cryogenic detector system [2]. Utilizing a much larger quenching of the scintillation light for α signals than for β/γ signals, detection of both the heat and light signals enables us to reject α background efficiently. We use metallic magnetic calorimeters (MMCs) with superconducting quantum interference devices (SQUIDs), which provides a fast signal timing among the low temperature sensors, and a fairly good energy resolution [3].

There are three phases in the AMoRE project. The two previous phases, AMoRE-pilot and AMoRE-I, were conducted in the Yangyang Underground Laboratory (Y2L). Performances of the detector such as energy resolution and the particle identification capability are demonstrated [4]. Major radioactive background sources were identified, and removal and replacement of the radioactive detector components and enhancement of shielding helped reduce the background level at ROI from 0.4 counts/keV/kg/year (ckky) in AMoRE-pilot to 0.03 ckky in AMoRE-I. It is also found in AMoRE-I that despite its lower scintillation light yield, Li_2MoO_4 (LMO) crystal is much radio-purer than the $CaMoO_4$ (CMO) crystal.

The main phase of AMoRE, AMoRE-II, is in preparation to start its data taking in 2024. It is located at 1000 meter underground in Yemi Underground Laboratory (YemiLab), Jeongseon, Korea. AMoRE-II will be conducted in two stages: the first stage using 90 LMO crystals (27 kg) for about a year and the next one using 360 LMO crystals (157 kg). There are two different sizes of the cylindrical LMO crystals for AMoRE-II: one is 5 cm, and the other is 6 cm in both diameter and height.

It is advantageous to use larger-size crystals and to reduce the number of channels. One concern was so-called pile-up, because the random coincidence event rate by two neutrino double beta decay grows as the crystal volume gets larger. The other concern was that the non-uniform response might be larger as the crystal volume grows and makes the energy resolution and β/α discrimination worse. We compared the performances of LMO crystals of the different sizes, and the surface of a crystal was either polished to optical grade or made diffusive through lapping. It was found out that the diffusive-surfaced crystals did not yield any significant size effect, meaning that the detectors showed much less non-uniform response regardless of their sizes. The energy resolution for both sizes were found to be similar, about 8 keV full-width-half-maximum (FWHM) for 2.6 MeV γ-ray peak in the best cases and better than 15 keV FWHM in any cases in the temperature range between 10 and 30 mK. The β/α discrimination of the 6 cm crystal detector was also as good as the smaller one. The discrimination power using the light-to-heat signal ratio defined as the difference of β/α peak positions divided by the quadratic sum of their Gaussian widths is higher than 10 at around 5 MeV. It was also studied that the expected pile-up event rate is below $3{\times}10^{-5}$ counts/keV/kg/year for the 6 cm crystal, using a multivariate analysis such as the boosted decision tree.

By September 2023, about 82 kg of crystals have been produced, at Center for Underground Physics (CUP/IBS) and at Nikolaev Institute of Inorganic Chemistry (NIIC). All the crystals needed for the second stage of AMoRE-II are expected to be ready by mid 2025. The raw materials for the crystal growing, MoO_3 and Li_2CO_3 powder, have been being purified at CUP/IBS for reducing radioactivity [5].

To contain hundreds of crystal detector modules, a new pulse tube dilution refrigerator was manufactured and delivered by Leiden Cryogenics. The most inner volume of the cryogenic system is about 1 m in both diameter and height. It can contain 76 towers of 12 crystal detector modules ultimately, with the current detector module design. The cryo-system should hold up to 3.3 tons of Pb, Cu, and crystals in the inner vacuum chamber, and thousands of cables pass through the cooling stages. To efficiently cool down such a large volume and mass, the refrigerator is equipped with 3 pulse tubes and the cooling stages contact softly between one and another with copper foils. Dampers such as the spring suspended still with the Eddy current dampers in the cryostat and the air dampers at the supporting structure reduce the vibration by the pulse tube operation [6]. The system has been tested in the ground laboratory and the temperature reached 6 mK without wirings. It is scheduled to be moved to YemiLab in late 2023.

Inside of the inner vacuum chamber, the internal shielding of 26 cm thick lead is placed over the crystal detector towers. The external shielding structure is being ready in YemiLab. The refrigerator's sides and bottom are enveloped in a shielding layer sequence, starting from the innermost layer with 1 cm of boric acid rubber, followed by 2 cm of copper, 25 cm of lead, another 1 cm of boric acid rubber, and a substantial 70 cm of polyethylene. The outermost layer comprises muon counter panels constructed from plastic scintillator. The muon rate was measured using the bottom panels to be about 1 muon/cm^2/s, preliminarily, which is about one-fourth of Y2L [7]. Above the cryo-chamber, the space is dedicated to the detector control room and the data acquisition system, encased within a 70-80 cm thick water tank that functions as the passive shielding and the Cherenkov muon detector. Radon-free air is circulated into the vinyl housing that envelops the cryo-chamber.

Materials and components for detector modules and shielding were carefully chosen and measured for their radioactivities. The expected background at around $Q_{\beta\beta}$ is estimated to be less than 2×10^{-4} count/keV/kg/year, using an extensive detector simulation based on the radioassay results. The level corresponds to less than one background event after 500 kg·year of crystal-mass$\times$time exposure given the 10 keV FWHM energy resolution. The fine energy resolution becomes more important because the β-decay of ^{214}Bi emits a 3050-keV γ-ray and it is expected that this background level is higher than 10^{-3} count/keV/kg/year. The major contributors of this background are ^{238}U elements in lead and the radon in the air. We are looking for the most radio-pure Pb and trying to reduce the air-radon level as low as possible. Another important concern on the background is about the surface contamination of crystals and copper holders which is not easy to be estimated by radioassay or simulations. We try to keep the materials in the clean condition in all process such as the crystal production, surface treatment, detector module assembly, storage, and transportation.

It is currently scheduled that the first stage of AMoRE-II will run for about one year, upgrade to next phase will take another year, and then the second stage will run for longer than 5 years. After about 7 years of AMoRE-II data taking, about 500 kg·year of ^{100}Mo-mass × time exposure which roughly correspond to 3×10^{27} ^{100}Mo-atom·year. With the expected 10^{-4} count/keV/kg/year background level and 10 keV FWHM energy resolution, we expect to observe a 0νDBD peak signal for a half-life of 4×10^{26} years at 3-σ confidence level.

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