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Neutrinoless double-beta decay search with the AMoRE-II experiment

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The AMoRE collaboration has been investigating the neutrinoless double beta decay of ^{100}Mo using cryogenic calorimeters with scintillating molybdate crystals and metallic magnetic calorimeters (MMCs). The AMoRE-pilot and AMoRE-I phases of the experiment demonstrated the promising potential for this search, and the experiment is rapidly moving toward the AMoRE-II phase, which will ultimately exploit about 90 kg of ^{100}Mo isotope. The AMoRE-II detector will consist of hundreds of cryogenic calorimeters and surrounding muon veto detectors, made up of an array of plastic scintillators and a water Cherenkov detector. The materials for the detector system have been carefully chosen, and the radiation shielding structure has been optimized to achieve a background level of 10^{-4} counts/kg/keV/year in the region of interest for the signal search. The new experiment will be built in Yemilab, a new underground laboratory 1000 meters below Mountain Yemi in Jeongseon, South Korea. This facility provides the necessary space and infrastructure to support a large-scale experiment with significantly enhanced sensitivity. The ongoing status of the AMoRE-II experiment is discussed in this article.

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1. AMoRE experiment

Double beta decay occurs in certain even-even nuclei that are more tightly bound than their odd-odd neighbor nuclei with the same mass number. The decay mode without emitting neutrinos, known as neutrinoless double beta decay (0νDBD), is of great importance because it is a powerful tool for clarifying the nature of neutrinos as either Dirac or Majorana particles and for probing the unknown neutrino mass. Furthermore, observing this decay would indicate a lepton number violating process, which could provide insights into the baryon asymmetry of the Universe through the leptogenesis scenario. The signature of 0νDBD would be a sharp excess of event counts at the energy corresponding to the Q-value of the decay. However, the event rates are anticipated to be extremely low, with the half-life ($T^{0\nu}_{1/2}$) longer than 10^{26} years.

The AMoRE collaboration is searching for the 0νDBD of ^{100}Mo (Q-value = 3034 keV) using a cryogenic calorimetric technique with scintillating molybdate crystals as absorbers, typically operated at 10 – 20 mK temperatures. The crystals were grown from molybdenum powder enriched to about 96% in ^{100}Mo to increase target exposure. When a particle interacts with the crystal absorber, most energy is deposited as heat, causing a temperature rise in the crystal, while a small fraction generates a scintillation signal. A small gold film (phonon collector) on the crystal surface undergoes a temperature change as the energetic phonons produced by the particle interaction reach it. A metallic magnetic calorimeter (MMC), thermally connected to the phonon collector, senses changes in the magnetization as a function of temperature, which are detected by the SQUID as heat channel signals. The simultaneous scintillation is absorbed by a light absorber made of Si or Ge wafers, and the resulting temperature rise in the light absorber is measured by the MMC as the light channel signal. The dual MMC detection allows for high energy resolution measurement of the decay and particle identification to reject the continuum of surface alpha events with degraded energy, which can appear in the energy region of interest (ROI).

2. Previous AMoRE experimental campaigns

The first phase of the experiment, AMoRE-pilot, was built with six $CaMoO_4$ crystals (total mass of 1.9 kg) with Ca depleted in ^{48}Ca and Mo enriched in ^{100}Mo. The experiment was conducted in the Yangyang Underground Laboratory (Y2L) with a 700 m rock overburden. After the operation from 2015 to 2018, the experiment collected 0.33 kg·year of the target exposure (overall ^{100}Mo mass × experiment duration). With a background rate of about 0.5 counts/keV/kg/year at the ROI, the half-life for 0νDBD of ^{100}Mo has been constrained as $T^{0\nu}_{1/2} > 3.0 \times 10^{23}$ years at 90 % C.L. [1, 2]. In the next phase, AMoRE-I, the detector was upgraded to accommodate more crystals, achieving a total crystal mass of 6.2 kg with thirteen $CaMoO_4$ and five Li_2MoO_4 crystals [3]. This upgrade also featured enhanced shielding against the radioactive background and the replacement of components with high-radioactivity, reducing the background level at the ROI to about 0.025 counts/keV/kg/year. The AMoRE-I phase ran from 2020 to 2023, achieving an accumulated target exposure of 3.89 kg·year. This phase improved the limit for the half-life to $T^{0\nu}_{1/2} > 3.0 \times 10^{24}$ years at 90 % C.L. [4].

3. AMoRE-II

The experiment rapidly moves toward the next phase, AMoRE-II, featuring a large detector array with significantly increased crystal mass. The AMoRE-II experiment will utilize about 90 kg of ^{100}Mo nuclide contained in approximately 360 pieces of Li_2MoO_4 crystals, with a total mass of 157 kg. The crystals will have a cylindrical shape in two sets of dimensions in height (H) and diameter (D): 5 cm (H) × 5 cm (D), 6 cm (H) × 6 cm (D) [5]. Performance tests conducted at 10 mK using the R&D detector setup, built according to the AMoRE-II baseline detector design, showed the energy resolution (FWHM) of 7.55 – 8.82 keV at 2.615 MeV gamma rays (^{208}Tl) in the heat channel [6]. The light channel performance achieved a baseline energy resolution of 83 – 393 eV FWHM and scintillation light measurement of 0.79 – 0.96 keV/MeV. The detectors efficiently differentiate alpha signals from the signal band associated with electrons, gammas and muons, demonstrating a separation of 12.37 – 19.50 σ (standard deviation) around ^{6}Li neutron capture signals (E = 4.785 MeV) based on the light/heat signal ratio. This capability indicates strong suppression of surface alpha backgrounds in the ROI region. The rise time of the pulses in these tests varied from 3.82 to 5.92 ms at 10 mK, leading to an estimation of a pile-up background from the random coincidence of DBD with two neutrino emissions at a level of less than 3.5×10^{-5} counts/keV/kg/year in the ROI.

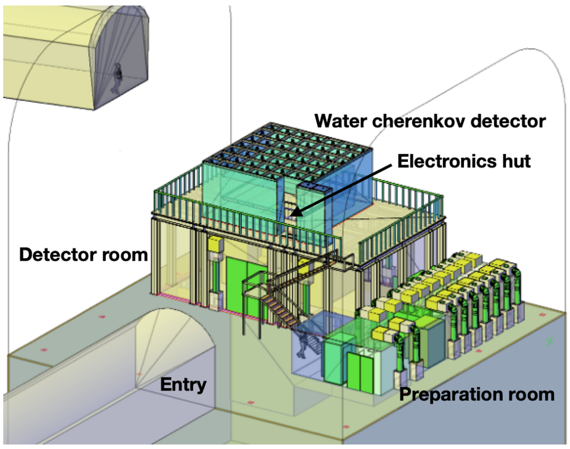
The detector array will be installed in a large cryogen-free dilution refrigerator. The cryostat's mixing chamber features a circular Cu plate with a 1-meter diameter, allowing for the installation of the large detector array. The cryostat offers approximately 7μW of cooling power at 10 mK, with a base temperature of around 5 mK. To mitigate the vibration of the detector system, the cryostat is designed to have a soft mechanical contact with the pulse tube cryocoolers. Additionally, further vibration-damping enhancements are planned, including an internal vibration damper at the still stage and Kevlar suspension at the detector array. Recently, wire cables for the detector array were added to the cryostat, and the system is under commissioning following its relocation to its designated experimental site in the Yemilab underground laboratory.

The most essential component of the experiment is 157 kg of $Li_2{}^{100}MoO_4$ crystals. The preparation of these crystals has been an extensive, multi-year campaign involving raw material purification, crystal growth, verification of the low radioactive background, and proper crystal packaging and cleaning for the fabrication process. The crystals have been steadily provided by the Center for Underground Physics (CUP) at the Institute for Basic Science (IBS) and the Nikolaev Institute of Inorganic Chemistry (NIIC), with production scheduled to continue until the end of 2025. The deployment of the detector array will occur in two stages: stage 1 involves the installation of 90 detector modules containing a total of 27 kg of crystals, which is expected to be completed by early 2025. This stage will operate for about a year, while, during this period, preparations for stage 2 will be ongoing. Stage 2 will expand the setup to approximately 360 detector modules, incorporating the full 157 kg of crystals. Following the completion of stage 1 operation, the installation of stage 2 will be carried out, and the detector operation is planned to continue for over five years.

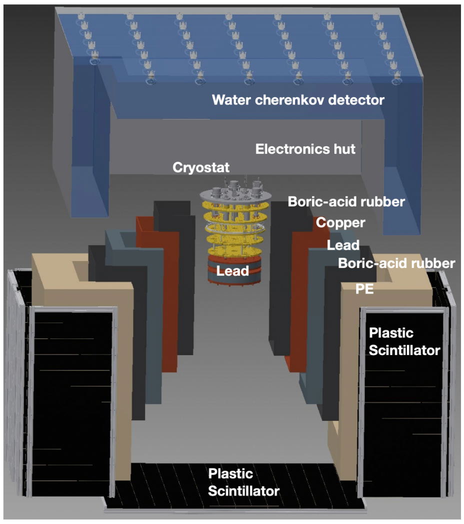
The experimental site is the AMoRE hall in Yemilab, which lies 1000 m below Mountain Yemi in Jeongseon, Gangwon province, South Korea [7]. The AMoRE hall provides a controlled environment for the detector preparation area, which includes a chamber with the cryostat. It maintains a low dust level (Class 100) and very low humidity (less than 1 % RH at room temperature).

PoS(TIPP2023)014

Radon-free air is also supplied to the detector preparation area. The cryostat will be housed within a radiation shielding structure composed of layers of polyethylene, boric acid rubber, lead, copper, and an additional layer of boric acid rubber at the innermost layer. This shielding is designed to reduce the gamma and neutron backgrounds effectively. A muon veto system is in place, consisting of two main parts: the water Cherenkov detector, which encloses the top part of the cryostat and the electronics hut above it, and an array of plastic scintillators covering the detector system which lies below the water Cherenkov detector. The water Cherenkov detector is filled with approximately 60 tonnes of deionized water. It uses forty-nine PMTs with 8 or 10-inch diameters to detect Cherenkov light produced by muons passing through the detector. It also serves as a good neutron shield. The plastic scintillator array consists of 136 boxes, equipped with two plastic scintillating panels, wavelength-shifting fibers and four SiPMs for signal readout [8]. The entire muon veto system has already been installed and is currently undergoing commissioning. Preliminary measurements with the muon veto system indicate $\sim 1 \times 10^{-7}$ /cm^2/s at the experimental hall. Figure 1 shows the layout of the AMoRE-II experimental site, including the AMoRE hall at Yemilab, along with the radiation shielding structure and the muon veto system.



(a)



(b)

Figure 1: The layout of the AMoRE-II experimental site. (a) The AMoRE hall in Yemilab. (b) The radiation shielding structure including a muon veto system.

Aiming at 1×10^{-4} counts/keV/kg/year of the background at the ROI, we conducted an exhaustive survey of the radioactivity in nearly every material candidate for the experimental components [9]. Materials with high activity were either discarded or determined to be used with a limited amount. A stringent cleaning protocol was also established for the copper components of the detector holder to prevent the contamination of the surfaces of the components near the crystal absorbers from naturally occurring radioactive elements such as ^{238}U and ^{232}Th. By combining the measured radioactivity of the detector materials and the environment of the experimental hall and considering the design of the detector system, including the detector array, cryostat, shielding structure, and muon veto detectors, we simulated the expected background level in the ROI based on the realistic detector performance. The results indicate that the expected background is below 2×10^{-4} counts/keV/kg/year [10]. Given that the results include upper limits for some materials' radioactivity, there is a good chance that the target background level in the ROI will be achieved in AMoRE-II.

After deploying the complete AMoRE-II detector array, the experiment is expected to achieve approximately 500 kg·year of the target exposure over five years of detector operation. With the target background level set to 1×10^{-4} counts/keV/kg/year, the discovery sensitivity (the value of $T^{0\nu}_{1/2}$ providing a 50% chance of detecting a signal above the background with a significance greater than 3σ) is projected to reach $T^{0\nu}_{1/2} \sim 4.5 \times 10^{26}$ years. In the light neutrino exchange scenario, the most commonly considered model for the 0νDBD, this sensitivity corresponds to probing the effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ down to 18 – 31 meV . The parameter space characterized by the inverse neutrino mass ordering, in the effective Majorana neutrino mass and the lightest neutrino mass, is expected to be extensively explored by the experiment. Overall, AMoRE-II is positioned to make significant contributions to the global search for 0νDBD, alongside other leading experiments, and to achieve competitive sensitivities that could potentially lead to the discovery of this rare process.

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