Status of the AMoRE experiment

Hyon-Suk Jo
(on behalf of the AMoRE Collaboration)
Center for Underground Physics, Institute for Basic Science, Daejeon 34047, Korea
E-mail: hyonsuk@ibs.re.kr

Abstract. The goal of the Advanced Mo-based Rare process Experiment (AMoRE) is to search for neutrinoless double beta decay of $^{100}$Mo using low-temperature detectors consisting of molybdenum-based scintillating crystals read out via metallic magnetic calorimeters. Simultaneous measurements of heat and light signals are performed at mK temperatures, which are reached by using a dilution refrigerator. A pilot experiment, named AMoRE-Pilot, using five $^{100}$Mo-enriched, $^{48}$Ca-depleted $^{40}$Ca$^{100}$MoO$_4$ crystals with a total mass of about 1.5 kg, has been running in the 700-m-deep YangYang underground Laboratory. The current setup and status of the AMoRE experiment are presented.

1. Introduction
Several neutrino oscillation experiments provided evidence of the non-zero mass of the neutrinos and their mixing. However, their absolute masses and fundamental particle type (Majorana or Dirac) remain unknown. The search for neutrinoless double beta decay ($0
\nu\beta\beta$) could be key in addressing these unresolved issues as its observation would provide constraints on the absolute mass scale of the neutrinos and would demonstrate their Majorana nature (a particle being its own antiparticle).

While the two-neutrino double beta decay process ($2\nu\beta\beta$), i.e. $(Z,A) \rightarrow (Z+2,A)+2e^-+2\bar{\nu}_e$, is an allowed (although rare) nuclear transition in the Standard Model of particle physics, $0\nu\beta\beta$ is a different type of double beta decay where no (anti)neutrinos are emitted, i.e. $(Z,A) \rightarrow (Z+2,A)+2e^-$, thus violating lepton number conservation, and can occur if the neutrino is a massive Majorana particle. Experimentally, while the sum energy spectrum of the two emitted electrons appears as a continuum with the transition energy of the decay, or Q-value, as a maximum in the case of the $2\nu\beta\beta$ decay, it would simply be a peak at the Q-value in the case of the $0\nu\beta\beta$ decay if it exists, with a width only determined by the finite energy resolution of the detector. Thus a high energy resolution is essential to distinguish the potential $0\nu\beta\beta$ peak from the $2\nu\beta\beta$ continuum.

AMoRE (Advanced Mo-based Rare process Experiment) is an international collaboration searching for the $0\nu\beta\beta$ decay of $^{100}$Mo using Mo-based scintillating crystals based on phonon-light measurement at low temperatures. Among the isotope candidates for the search of $0\nu\beta\beta$, $^{100}$Mo presents the advantage of having a high natural abundance of 9.6%. More importantly, it presents a high Q-value of 3034 keV, which places the $0\nu\beta\beta$ energy region of interest above the energy range of $\gamma$-rays from nearly all naturally occurring radioactive isotopes (range ending at 2615 keV) which would be potential backgrounds otherwise. As $0\nu\beta\beta$ is expected to be an extremely rare process, the detection sensitivity should be enhanced by all possible means, e.g.
by increasing the detector mass, reducing and discriminating internal and external background events, and increasing the efficiency and energy resolution of the detector. The details on the AMoRE experiment goals and parameters can be found in Ref. [1].

2. Detector concept
The detector concept for the AMoRE project, as shown in figure 1, is the use of Mo-based scintillation crystals as both source and absorber of $^{100}\text{Mo}$ decay. Each detector module was designed for the simultaneous measurement of heat (phonon) and scintillation-light (photon) signals from the crystal. Metallic magnetic calorimeter (MMC) sensors which demonstrated high energy resolution and fast response time are used to read the signals [2]. A gold film on the bottom of each crystal is used as phonon collector and is connected to a MMC sensor via annealed gold wires. A Ge wafer on top of each crystal is used as absorber for the scintillation light which is confined within the detector module by a light reflector film. The phonons generated in the wafer by the light absorption are collected by gold films and measured by another MMC sensor [3]. See [4] for more details on the AMoRE detector concept and design.

![Detector Concept](image)

Figure 1. (Color online) The detector concept for the AMoRE project is the use of a Mo-based scintillation crystal as both source and detector. Heat and light signals are measured simultaneously by each detector module, which allows a better discrimination of the background from $\alpha$ events as those usually present a lower light/heat production ratio than the $\beta/\gamma$ events.

3. AMoRE-Pilot experiment at Y2L
A pilot experiment, named AMoRE-Pilot, has been operating since August 2015 at the YangYang underground Laboratory (Y2L), located in the northeast of South Korea, in a tunnel of the YangYang pumped-storage power station. The minimum vertical depth of the laboratory from the ground is 700 m. Y2L can be accessed by car through a 2-km-long tunnel. Although several types of Mo-based scintillation crystals have been and are still being tested, $^{40}\text{Ca}^{100}\text{MoO}_4$ has been the type of crystal used in the AMoRE experiment so far. AMoRE-Pilot thus uses five $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals, named SB28, S35, SS68, SE01 and SB29, with masses from about 0.2 kg to 0.4 kg as shown in table 1 and a total mass of about 1.5 kg. In order to increase the mass of $^{100}\text{Mo}$ (and thus the event rate) and minimize the background from $2\nu\beta\beta$ signals of $^{48}\text{Ca}$, enriched $^{100}\text{Mo}$ (above 96%) and calcium depleted in $^{48}\text{Ca}$ (below 0.001%) have been used to grow the $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals.

A new AMoRE-Pilot run is started after an upgrade in the setup. Run-1 and run-2 have been completed and another run will be carried out towards the end of 2016. Operating temperatures as low as 8 mK are reached using a dry dilution refrigerator. Figure 2 shows the rise time of selected phonon signals from one of the five crystals. The larger peak consists of events observed at around 2615 keV (a $\gamma$ peak from $^{208}\text{Tl}$). $\alpha$ events, observed at lower rise time values as they induce faster signals, can be efficiently discriminated from the $\beta/\gamma$ events due to the large difference between their respective mean rise time values. After the end of run-1,
Figure 2. (Color online) Rise time of selected phonon signals from the SE01 crystal (during run-2, at 10 mK). α events can be separated from the β/γ events.

Figure 3. (Color online) FWHM (full width at half maximum) energy resolution at 2615 keV observed for the phonon signals from the S35 crystal at 20 mK during run-2.

the detector modules were upgraded to reduce the vibration at the level of both heat and light detectors, by redesigning and replacing the springs holding the crystals and Ge wafers. The run-2 measurements then confirmed that the energy resolution has much improved overall as shown in table 1 and illustrated in figure 3. The preparation of run-3 with the development of new damping systems and refinement of the setup materials is underway, aiming to reduce the vibration noise coming from the pulse tube refrigerator of the cryostat and to further reduce the external backgrounds.

Table 1. FWHM energy resolution at 2615 keV observed for the phonon signals of the AMoRE-Pilot detectors during run-1 and run-2.

| Crystals   | AMoRE-Pilot run-1 | AMoRE-Pilot run-2 |
|------------|-------------------|-------------------|
| SB28 (~0.20 kg) | 36.8 keV          | 25.0 keV          |
| S35 (~0.25 kg)  | ——                | 16.3 keV          |
| SS68 (~0.35 kg) | 52.6 keV          | 22.5 keV          |
| SE01 (~0.35 kg) | 39.7 keV          | 24.6 keV          |
| SB29 (~0.40 kg) | 42.6 keV          | ——                |

4. AMoRE-I and AMoRE-II experiments

AMoRE-Pilot will be followed by the AMoRE-I and AMoRE-II experiments expected to start in 2017 and 2020, respectively. AMoRE-I, with about 5 kg of $^{40}$Ca$^{100}$MoO$_4$ crystals, will aim at a half-life sensitivity of $2.7 \times 10^{25}$ years and a mass sensitivity of 70–140 meV. The large-scale AMoRE-II experiment will use 200 kg of Mo-based crystals with the decision on the type of crystal still to be made. The aimed half-life and mass sensitivities are $1.1 \times 10^{27}$ years and 12–22 meV, respectively. A new and larger underground laboratory will be built for AMoRE-II.

References
[1] Alenkov V et al (AMoRE Collaboration) 2015 Preprint 1512.05957
[2] Yoon W S et al 2015 Nucl. Instr. Meth. Phys. Res. A 784 143–146
[3] Lee H J et al 2015 Nucl. Instr. Meth. Phys. Res. A 784 508–512
[4] Kim G B et al 2016 IEEE Trans. Nucl. Sci. 63 539–542