J Low Temp Phys
https://doi.org/10.1007/s10909-018-1925-0

Status of the AMoRE Experiment Searching for Neutrinoless Double Beta Decay Using Low-Temperature Detectors

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Received: 6 November 2017 / Accepted: 16 April 2018

Abstract The goal of the Advanced Mo-based Rare process Experiment (AMoRE) is to search for the neutrinoless double beta decay of ^{100}Mo using low-temperature detectors consisting of Mo-based scintillating crystals read out via metallic magnetic calorimeters. Heat and light signals are measured simultaneously at millikelvin temperatures, which are reached using a cryogen-free dilution refrigerator. The AMoRE-Pilot experiment, using six ^{100}Mo-enriched, ^{48}Ca-depleted calcium molybdate crystals with a total mass of about 1.9 kg, has been running in the 700-m-deep Yangyang underground laboratory as the pilot phase of the AMoRE project. Several setup improvements through different runs allowed us to achieve a high energy resolution and an efficient particle discrimination. This article briefly presents the status of the AMoRE-Pilot experiment, as well as the plans for the next, larger-scale, experimental stages.

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Published online: 01 May 2018

Keywords Heat detector · Light detector · Scintillation crystal · Metallic magnetic calorimeter · Neutrinoless double beta decay

1 Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) experiments aim to determine the nature of the neutrino (Dirac or Majorana) and its absolute mass range [1–3]. Among the various ongoing projects, AMoRE (Advanced Mo-based Rare process Experiment) aims to search for the $0\nu\beta\beta$ decay of ^{100}Mo via low-temperature measurements using Mo-based scintillating crystals as both the source and target material of the $0\nu\beta\beta$ decay, and heat and light detectors based on metallic magnetic calorimeters (MMCs) [4]. Using ^{100}Mo, the region of interest of the AMoRE measurements is at the Q-value of 3.034 MeV that is well above most environmental γ-ray lines.

It has been shown that the technique of simultaneously measuring heat (phonon) and light (photon) signals with a setup composed of a scintillating crystal and MMCs offers great advantages in terms of energy resolution and background rejection, with good separation capabilities between α and β/γ particles [5–7]. AMoRE-Pilot, the pilot phase of the AMoRE project, has been running since late 2015 with ^{100}Mo-enriched and ^{48}Ca-depleted $CaMoO_4$ scintillation crystals at the 700-m-deep Yangyang underground laboratory (Y2L) [8], located in the northeast of South Korea. The $CaMoO_4$ crystals were produced by JSC FOMOS-Materials (Russia) using molybdenum enriched in ^{100}Mo (enrichment above 95%) by using a gas centrifugation technique[1]. To avoid an irreducible background effect of two-neutrino double beta ($2\nu\beta\beta$) decays of ^{48}Ca (the Q-value of ^{48}Ca, 4.268 MeV, being larger than that of ^{100}Mo), calcium depleted in ^{48}Ca was produced using an electromagnetic separation method (with a depletion factor of 100 compared to its natural abundance)[2]. The detector setup's temperature can go as low as about 8 mK by using a cryogen-free dilution refrigerator (CFDR). The experiment has been operated at a minimum of 10 mK though to allow the temperature stabilization system, composed of a heater with a feedback system, to provide an operating temperature as stable as possible. A detailed description of the AMoRE-Pilot setup is given in Ref. [9]. Since late 2015, the AMoRE-Pilot experiment had its first four runs with five $CaMoO_4$ scintillating crystals and a sixth crystal was added in Spring 2017 for the fifth run. A setup upgrade of various parts of the experimental setup was performed between each AMoRE-Pilot run.

It became clear from the AMoRE-Pilot run-1 measurements that the mechanical vibration induced by the pulse tube refrigerator (PTR) of the CFDR was significantly affecting the detector performances. Two different vibration damping systems, briefly presented below, were designed and installed in order to reduce the vibration noise level. Along with others, those setup upgrades improved the overall detector performances, in terms of energy resolution and particle discrimination.

1 JSC Production Association Electrochemical plant (Russia)

2 Russian ElectroKhimPribor Integrated Plant (Russia)

2 AMoRE-Pilot Experimental Setup

The detector concept used in the AMoRE project is the simultaneous measurement of heat and light from a Mo-based scintillating crystal using MMC-based low-temperature detectors. MMCs are high-precision temperature sensors offering high sensitivity and fast response while operating at millikelvin temperatures [10,11]. They are thus capable of providing an excellent energy resolution and a good time resolution, which is required to discriminate particles by their signal rise time. The energy deposit of a particle in the crystal generates a temperature increase that can be measured with an MMC as the magnetization of its paramagnetic sensor material varies as a function of the temperature. That magnetization change can then be measured using a superconducting quantum interference device (SQUID). Low-temperature detectors based on MMCs are of particular interest in rare process searches as they can offer high energy and time resolutions, and thus good particle discrimination and efficient background rejection [6,7,12].

For the fabrication of our MMCs, we have been using a dilute concentration of erbium in a gold host (Au:Er) as the paramagnetic sensor material and a meander-shaped superconducting niobium coil [13]. The paramagnetic ions of the sensor material are magnetized by running a persistent current through the MMC's superconducting coil, and a SQUID can then measure the induced current on the coil originating from the temperature change of the paramagnetic sensor material [11,14]. The AMoRE-Pilot detector modules use $CaMoO_4$ scintillating crystals [15,16]. The MMC sensor's temperature sensitivity, and thus the energy resolution achievable, increases significantly at low temperatures as it depends on the heat capacity of the sensor and absorber materials which largely decreases.

Figure 1 presents the detector concept as well as a picture of a fully assembled detector module. Each crystal is supported by a frame made of NOSV copper (Aurubis, Germany). The heat detector is composed of a patterned gold film of 2 cm diameter, evaporated on the bottom of the crystal and thermally coupled via annealed gold wires to an MMC, placed on the copper frame which is used as a heat bath. The light detector is composed of a 2-inch Ge wafer placed on top of the crystal with three gold films thermally coupled to another MMC. The scintillation light from the crystal is collected toward the wafer by using a reflector film (Vikuiti) around the crystal, and generates a temperature increase in the wafer, which is measured by the MMC. Details on the heat and light detectors can be found in Ref. [5,17].

The detector system of AMoRE-Pilot is a tower assembly of six $CaMoO_4$ crystals, each equipped with heat and light detectors, leading to a total of 12 MMC channels. The crystals are of different sizes and their masses vary from 0.2 to 0.4 kg, for a total mass of about 1.9 kg. This detector system has been installed in a dilution refrigerator (CF-81-1400 Maglev, Leiden Cryogenics, Netherlands) capable of achieving temperatures as low as 8 mK, with a cooling power of 1.6 and 19 μW at usual operating temperatures of 10 and 20 mK, respectively.

The cryostat and the detector system are surrounded with a 15-cm-thick shield made of low-radioactivity lead (JL Goslar, Germany) to suppress the radioactive background from external γ-rays. An internal lead shield, made of two layers of 5-cm-thick low-radioactivity lead (Lemer Pax, France) is installed at the bottom of the cryostat's

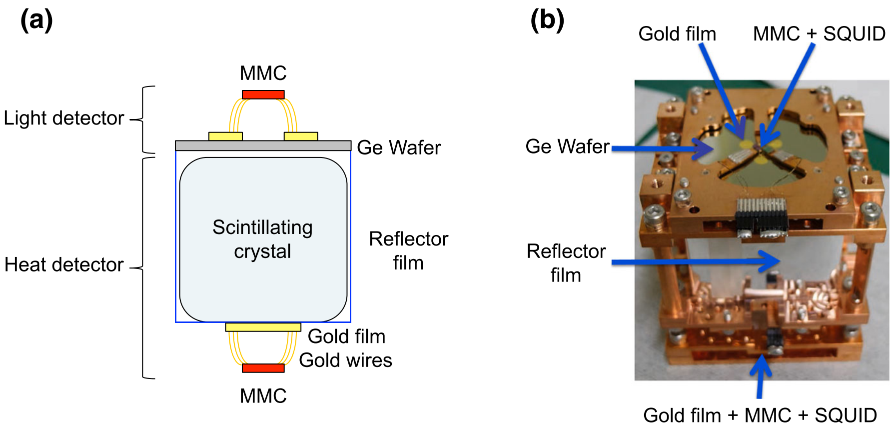

Fig. 1 AMoRE-Pilot detector module. Left: Detector concept. Right: Fully assembled low-temperature detector module including a scintillating crystal, a heat detector (located at the bottom of the module), and a light detector (located at the top) (Color figure online)

mixing chamber (i.e., the 10 mK plate), above the detector tower in order to suppress the background originating from materials composing the CFDR. Finally, a cup-shaped 2-mm-thick superconducting shield made of low-radioactivity lead (Lemer Pax) surrounds the detector tower to shield the MMCs and SQUIDs from external magnetic noise.

As mentioned above, the AMoRE-Pilot run-1 measurements revealed a degradation of the detector performances caused by the mechanical vibration induced by the PTR of the CFDR. A mass-spring-damper (MSD) was designed and installed between the mixing chamber and the detector tower in order to isolate the vibration and thus reduce the resulting noise in the detectors [18]. Annealed copper tapes are used to ensure thermal coupling between the mixing chamber and the detector tower. The MSD has been used in AMoRE-Pilot since run-4. A second vibration damping system, named spring suspended still (SSS), with Eddy current dampers, was built and installed for run-5 [19].

Figure 2 shows a design drawing of the detector tower as well as a picture including the cryostat, the detector tower, and the two vibration damping systems (MSD and SSS).

A cosmic-ray muon veto system composed of ten 5-cm-thick plastic scintillators coupled to a total of 28 2-inch PMTs via light guides was installed around the external lead shield surrounding the cryostat and detector system. The muon counter started recording data at the beginning of run-5 and is to provide essential information for the rejection of muon-induced background events.

3 Measurements

Four AMoRE-Pilot runs were carried out since late 2015. Each run was preceded by an experimental setup upgrade and has resulted in an improvement of the overall detector

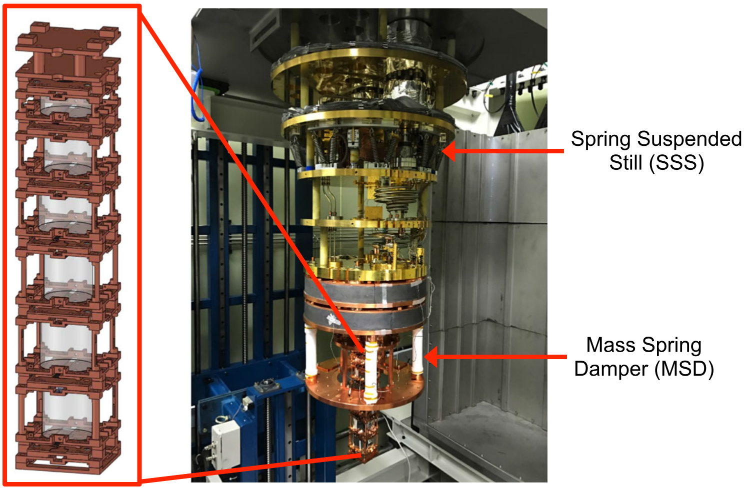

Fig. 2 Detector tower installed in the dilution refrigerator. Left: Design drawing of the detector tower with six modules. Right: Cryostat and shielding structure of the AMoRE-Pilot setup as of Spring 2017. The mass-spring-damper (MSD) connects the detector tower and its superconducting shield (not seen in the picture) to the bottom of the internal lead shield. The second vibration damper, named spring suspended still (SSS), can be seen a few stages above (Color figure online)

performances. The average FWHM (full width at half maximum) energy resolution at 2.615 MeV, over the several detector modules, thus improved from about 43 to 22 keV between run-1 and run-2 thanks to a significant vibration reduction by an improved design of the crystal and wafer holders. A new inner vacuum chamber made of low-radioactivity OFE copper (Aurubis, Germany) was installed and tested in run-3. Then, the installation of the MSD in run-4 allowed us to achieve an average FWHM energy resolution of about 13 keV. With the addition of the SSS, the muon veto system, and a sixth detector module, run-5 is currently ongoing and science data taking started in August 2017. The analysis of the early run-5 data needs to be refined but seems to indicate a further improvement of the energy resolution.

In run-5, the data are currently being acquired in a continuous mode using an 18-bit ADC with a sampling rate of 100 kHz. More details on the AMoRE-Pilot data taking conditions and processing are presented in Ref. [20], while our energy calibration procedure is similar to the ones described in Ref. [6,7].

Following a method already used in Ref. [6,7], 3σ cuts in energy and phonon signal rise time were applied to select 2.615-MeV γ events and the lowest-energy α events in order to estimate the discrimination efficiency between β/γ events and α events. Both γ and α peaks are fitted with Gaussian functions and the extracted mean values and standard deviations are used to estimate the discrimination power which, in this case, is thus defined as $\mathrm{DP}_{\mathrm{RT}} = \frac{|x_\alpha - x_{\beta/\gamma}|}{\sqrt{\sigma_\alpha^2 + \sigma_{\beta/\gamma}^2}}$, where x_α and $x_{\beta/\gamma}$ are the mean values in phonon signal rise time (ranging between 1 ms and 2 ms) for α and β/γ events, respectively, and σ_α and $\sigma_{\beta/\gamma}$ are their standard deviations. The rejection of α-induced events can thus be done via pulse shape discrimination (PSD) using the signal rise time, but it can also be done using the light/heat ratio, i.e., the ratio of scintillation light and heat produced in one event. The discrimination power DP_{LH} is defined in a similar way to DP_{RT} with the Gaussian fits being performed this time on the light/heat ratio distributions of the γ and α events selected using 3σ cuts in energy and light/heat ratio. Therefore, x_{α} and $x_{\beta/\gamma}$ are this time the mean values in light/heat ratio for α and β/γ events, respectively, and σ_{α} and $\sigma_{\beta/\gamma}$ their standard deviations. DP_{LH} depends on the amount of scintillation light produced in the crystal and eventually measured.

The DP values vary from one crystal to another due to the differences in the crystals' mass, optical and crystalline qualities. Therefore, some crystals will provide a better particle separation when using PSD and some others will show better results when using the light/heat ratio. From a preliminary analysis, the first DP results from run-5 are promising, with the DP_{RT} values from PSD (using the rise time) varying from about 6 up to 21, and the DP_{LH} values from light/heat ratio varying from about 10 up to 19. Overall, the best DP value obtained from each detector module ranges from 14 to 21 when combining both DP methods, which results in an excellent particle discrimination.

In terms of schedule, we aim to acquire at least 7 months of science data from the AMoRE-Pilot experiment before upgrading to a larger-scale setup.

4 Next Experimental Phases

Following AMoRE-Pilot, the first larger-scale experiment, AMoRE-I, will be carried out in the same room at Y2L, using the same cryogen-free dilution refrigerator, as the cooling power and cryostat dimensions are sufficient for the AMoRE-I setup. Most, if not all, of the $CaMoO_4$ crystals from AMoRE-Pilot will be utilized in AMoRE-I, with the addition of several more crystals to reach a total number of detector modules that should be from 16 up to 18. While the vast majority of those new crystals will be $CaMoO_4$, we plan to install and use a couple of crystals of another type, such as Li_2MoO_4 or $Na_2Mo_2O_7$. The total crystal mass used in AMoRE-I thus should be at least 5 kg. AMoRE-I is scheduled to begin in 2018 and data taking should last for at least 2 years. As described in [4], the sensitivity of a $0\nu\beta\beta$ experiment depends on many parameters, among which are the total detector mass, measurement time, background level in the region of interest, and the energy resolution. We aim to achieve, from AMoRE-Pilot to AMoRE-I, a reduction of the background level in the region of interest by identifying and reducing the sources of radioactivity in the materials surrounding the detector setup, as well as a further improvement of the overall energy resolution. On top of that, the larger detector mass and longer measurement time in AMoRE-I will contribute to a significant increase in the experimental sensitivity.

The much larger-scale experiment, AMoRE-II, with about 200 kg of crystals, will be carried out in a new underground laboratory in the Jeongseon county, which is in the east part of South Korea. The decision on the type of crystals used in AMoRE-II, will be taken in 2018 while AMoRE-I is running. Among others, the availability and production of high-quality, radiopure isotopically enriched scintillation elements will be one of the important criteria for the choice of the AMoRE-II crystals. A total crystal mass of 200 kg means AMoRE-II should operate about 500 detector modules. Each of those being equipped with light and heat detectors; this represents a total of about 1000 detector channels. The AMoRE project aiming to achieve "zero-background" conditions, further studies and R&D will be performed to push the background level further down. The new underground laboratory is currently being designed and the beginning of the construction is scheduled for Summer 2018. The AMoRE-II experiment requires the design and construction of a tailored cryostat capable of cooling such a massive system to the required millikelvin temperatures, while keeping the level of vibration noise as low as possible. The current goal is to achieve the preparations for AMoRE-II by 2020.

5 Conclusions

AMoRE-Pilot, the pilot experiment of the AMoRE project, has been running since late 2015, with $CaMoO_4$ scintillating crystals and low-temperature heat and light detectors, at the 700-m-deep Y2L facility, at typical operating temperatures of 10 and 20 mK. Four AMoRE-Pilot runs were completed from late 2015 to late 2016 with five $CaMoO_4$ crystals and run-5 is currently in progress with the addition of a sixth crystal in the detector system, a second vibration damping system, as well as a muon veto system to reject muon-induced events in the region of interest. The several setup upgrades throughout the runs significantly improved the overall detector performances in terms of energy resolution and particle discrimination. The preliminary analysis of the ongoing run-5 data shows some promising results. The goal of AMoRE-II is to achieve, with a 5-year exposure, the projected half-life sensitivity of about 1×10^{27} years, that corresponds to an effective Majorana neutrino mass of about 12–22 meV, thus covering the inverted neutrino mass hierarchy region.

Acknowledgements We thank the members of the AMoRE Collaboration. We also thank the Korea Midland Power Co. and Korea Hydro and Nuclear Power Co. for providing the underground space for Y2L. This work was funded by Grant No. IBS-R016-G1.

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