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The AMoRE: Search for Neutrinoless Double Beta Decay in ^{100}Mo

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Abstract

The AMoRE (Advanced Mo-based Rare process Experiment) collaboration is going to use calcium molybdate, $^{40}Ca^{100}MoO_4$ (CMO), crystal scintillators enriched in ^{100}Mo and depleted in ^{48}Ca to search for neutrinoless double-beta ($0\nu\beta\beta$) decay of ^{100}Mo using a technique of cryogenic scintillating bolometers at the underground laboratory in Korea. The collaboration is going to utilize metallic magnetic calorimeters (MMC) as temperature sensors both in heat and light channels of CMO detectors operated at milli-Kelvin temperature. Application of relatively fast MMC sensors provides excellent energy resolution, powerful discrimination of internal alpha particles, effective pulse-shape discrimination of randomly coinciding events of two-neutrino double-beta decay of ^{100}Mo. In its first phase, the AMoRE-10 will use about 10 kg of CMO crystals. As a next step, the AMoRE-200 is going to build about 200 kg detector to reach a half-life sensitivity on the level of 10^{26} years with an aim to explore inverted hierarchy region of the effective Majorana neutrino mass 0.02 - 0.05 eV. Recent progress on the calcium molybdate detectors developments at room and milli-Kelvin temperatures as well as background study based on Monte Carlo simulations will be presented.

Keywords: Double-beta decay, Calcium molybdate crystal scintillator, Cryogenic scintillating bolometer, Radioactive contamination.

1. Introduction

The results of neutrino oscillation experiments have indicated that neutrinos have masses and mix [1]. Nonetheless, there still remain some questions: the absolute mass scale of neutrino and if neutrino is a Dirac or a Majorana particle. The observation of the neutrinoless double-beta ($0\nu\beta\beta$) decays would answer those questions [2].

The AMoRE collaboration will search for $0\nu\beta\beta$ decay of ^{100}Mo by utilizing a scintillation bolometer based on $^{40}Ca^{100}MoO_4$ (CMO) crystal with calcium depleted in ^{48}Ca and molybdenum enriched in ^{100}Mo. Using ^{100}Mo has several advantages, Q-value of 3034 keV for $0\nu\beta\beta$ decays, relatively short theoretical predictions for half-life among other candidate nuclei, large abundance (~10%) and reasonable cost of ^{100}Mo enrichment. Since the two-neutrino double beta ($2\nu\beta\beta$) decay of ^{48}Ca is potential background, a large experiment requires that ^{48}Ca in calcium has to be less than 0.001% level.

In the early phase of the experiment, the collaboration is planning to use CMO crystals ~1 kg with low temperature detectors for search for $0\nu\beta\beta$ decays at the Yangyang underground laboratory with an earth overburden of 700 m in the next year.

2. Production and characterization of CMO crystals

The isotope ^{100}Mo enriched to ~96% in the form of $^{100}MoO_3$ oxide was produced by the JSC Production Association Electrochemical plant in Russia by gas centrifuge technology. The contamination levels for ^{238}U and ^{232}Th in the oxide measured by ICP-MS do not exceed 0.07 ppb and 0.1 ppb, respectively. The 99.96% enrichment of ^{40}Ca with depletion of the ^{48}Ca to the level of $\leq$ 0.001% in the form of calcium oxide pow-

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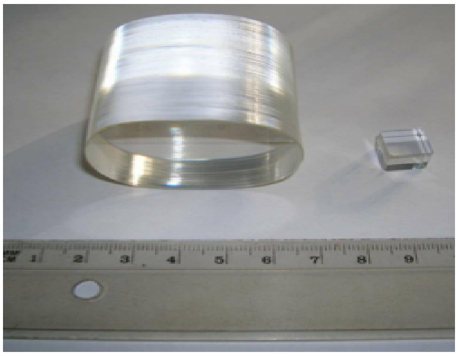

Figure 1: CMO single crystal after double crystallization and annealing in oxygen and cubic cut from the same crystal boule.

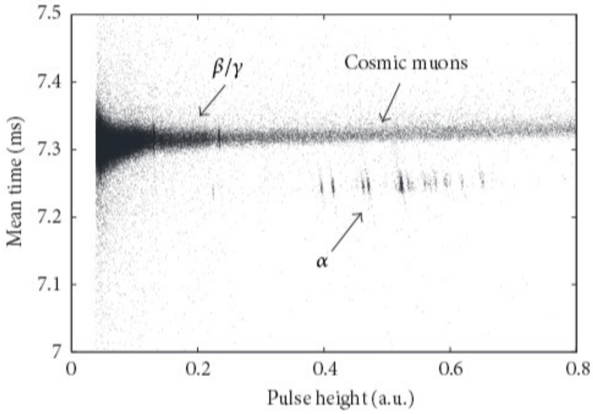

Figure 2: The scatter plot for mean-time vs. pulse height obtained from the background measurement for 95 hours in an overground laboratory. α and β/γ (including cosmic muons) particles are well separated by the mean-time parameter.

der was produced by FSYE Electrochimpribor in Russia, and the concentration of ^{238}U and ^{232}Th in the powder is below 0.2 ppb and 0.8 ppb, respectively.

The method for synthesis of the CMO raw material is co-precipitation reaction. This method has several advantages: the possibility of additional purification of the compounds and better control of the final product stoichiometry.

The CMO crystals have been developed by JSC FOMOS-Materials in Russia and the AMoRE collaboration from a platinum crucible using the Czochralski technique. The transparent CMO crystal with mass of about 0.5 kg and elliptic cylinder form (see Fig. 1) is obtained by the technique of so called double crystallization and annealing procedures.

By using a Cray-500 UV-VIS-NIR spectrometer, the attenuation length and the maximum emission wavelength of CMO crystals were measured to be 90 cm and 520 nm, respectively. The dependences of light output and decay time of a CMO crystal on temperature down to 8 K were measured in [3]. The light outputs of the crystal at room temperature and 7 K are similar within the measurement errors. The decay time constants at room temperature and 7 K are 16.5 μs and 345 μs, respectively.

Radioactive backgrounds for two samples of CMO crystals were measured by using 4π gamma veto system [4] at the Yangyang underground laboratory. By employing a time-amplitude analysis [5] which requires the energies and time difference between primary and secondary signals to select specific fast sequences of decays in the ^{238}U and ^{232}Th chains, the α decay events of ^{214}Po, ^{220}Rn and ^{216}Po were selected. The contaminations by ^{214}Po and by ^{216}Po in the CMO crystals obtained by re-crystallization are preliminary estimated as 0.08 mBq/kg and 0.07 mBq/kg, respectively.

3. Detection technique for $0\nu\beta\beta$ events

The AMoRE intends to use CMO crystal scintillators as cryogenic scintillating bolometers to search for $0\nu\beta\beta$ decays from ^{100}Mo. A thick ultra-pure germanium crystals will be applied as light detectors of scintillation signals from the CMO crystals. The temperature sensor of the CMO crystal is metallic magnetic calorimeter (MMC) operating at sub-Kelvin temperatures. The sensor will measure the heat (phonon) signal both in the CMO and Ge crystals by using the pick-up loop of a SQUID device.

The details of measurement principle and the detector structure with CMO crystals and MMC sensors in form of gold alloy film doped with erbium are in [6, 7]. The detector assembly with MMC sensor operates well in the temperature range of 10 to 50 mK.

In an overground measurement, we demonstrated the full-width-half-maximum energy resolution of 6 to 11 keV for full absorption gamma with calibration sources in the energy range of 511 keV to 2615 keV. The pulse-shape discrimination (PSD) between α and β/γ particles has been studied with the mean-time as a pulse-shape parameter (see the definition of this parameter in [7]) giving the different rise and decay times of two types of particles as shown in Fig. 2. The discrimination power for the PSD is about 7.6σ for the separation of α and β/γ particles. The relatively fast rise-time of the phonon signal with about 1 ms will reduce the pile-up backgrounds such as $2\nu\beta\beta$ decay in the future big-scale experiment which is one of the major background sources in $0\nu\beta\beta$ event searches [8].

4. Background estimations from simulation

In the AMoRE, we studied two types of background: external and internal sources. Intensive simulations using GEANT4 package have been performed for the estimation of each background contribution. The following geometry for the detector was used: one detector cell consists of a cylindrical CMO crystal with diameter of 44 mm and length of 45 mm (mass of 300 g). The crystal is placed in the copper frame of mass of 75 g assembled in periodic structure. The overall simulation geometry is shown in Fig. 3.

The external backgrounds come from environmental (mainly γ rays from rocks) and cosmogenic (mainly due to muons) sources, which can be reduced with passive shielding materials, and copper frames for holding the crystals. The CMO crystals are surrounded by 4 layers of copper can and low activity lead bricks of 15 cm thickness with 50 Bq/kg of ^{210}Pb and muon veto system consisting of scintillator counters. In order to reduce backgrounds from cryostat components, a sunken lead of 15 cm thickness with ultra-low radioactivity is introduced inside the cryostat directly above the crystals with total α activity of $0.01/\mathrm{cm}^2/\mathrm{h}$. Simulation results show that either γ or α backgrounds from the environmental sources and radioactive contaminations in the lead hit the crystals with the deposited energy much below the Q-value, which give negligible contribution. The main background from the copper frame is ^{208}Tl activity in ^{232}Th chain. In the simulation, we used ^{232}Th activity of 3 nBq/kg for the radio pure copper sample in the ILIAS database [9]. The contribution from ^{208}Tl activity is 1.3×10^{-8} counts/keV/kg/y. Although a thick polyethylene shielding to protect from neutron background is under discusion, neutron background can be effectively removed due to excellent PSD discrimination power.

The following internal backgrounds in the crystals were studied: radioactive backgrounds from ^{208}Tl, ^{214}Bi, random coincidences from $2\nu\beta\beta$ decays of ^{100}Mo and other backgrounds such as cosmogenic ^{88}Y, ^{48}Ca in the crystals and ^{214}Bi in copper. The major contribution is coming from $2\nu\beta\beta$ decays of ^{100}Mo, which is expected to be 1.2×10^{-4} counts/keV/kg/y.

We preliminarily estimate the total background to be about 1.6×10^{-4} counts/keV/kg/y. More detailed background study is ongoing.

5. Prospects and conclusions

The AMoRE collaboration is going to use CMO crystals as cryogenic scintillation detectors to search for $0\nu\beta\beta$ from ^{100}Mo. The AMoRE has three phases of planning: AMoRE-pilot with CMO crystals of ~1 kg and AMoRE-10 (-200) with CMO crystals of ~10 (200) kg. Ultimately the AMoRE-200 is going to reach a half-life sensitivity on the level of 10^{26} years with effective Majorana neutrino mass 0.02-0.05 eV.

The new experimental hut including utility for AMoRE-pilot and -10 at Yangyang underground laboratory is almost completed. The AMoRE detector will be installed in a room with a radon mitigation system. The AMoRE-pilot will start to take data in the next year.

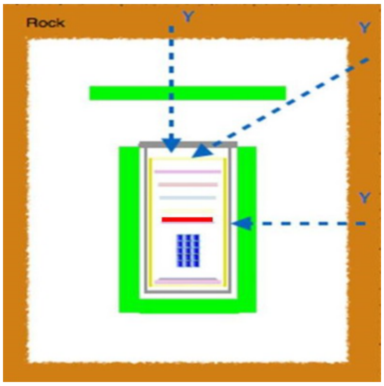

Figure 3: The figure for detector assembly (not to scale). The green (red), yellow and gray colors represent the low (ultra-low) activity lead and copper cans inside the cryostat, respectively. The crystals are shown in blue color.

Acknowledgments

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