AMoRE experiment: a search for neutrinoless double beta decay of $^{100}$Mo isotope with $^{40}$Ca$^{100}$MoO$_4$ cryogenic scintillation detector

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Abstract. AMoRE (Advanced Mo based Rare process Experiment) collaboration is going to use calcium molybdate crystals as cryogenic scintillation detector in a search for neutrinoless DBD of $^{100}$Mo isotope. Simultaneous detection of phonons and light will be used to reject internal background. A FWHM resolution of 0.2% in thephonon channel has been achieved with a 0.5 cm$^3$ crystal. Several $^{40}$Ca$^{100}$MoO$_4$ crystals ($\approx 0.5$ kg) have been developed from enriched $^{100}$Mo and depleted $^{40}$Ca materials. The light yield of these crystals has been shown to be comparable with reference CaMoO$_4$ scintillators for temperatures ranging down to 8 K. The content of dangerous radioisotopes in the crystals is under measurement. The projected sensitivity of the experiment for a 250 kg $\times$ years exposure is $\text{lim } T_{1/2} \approx 3 \times 10^{26}$ years, which corresponds to the effective Majorana neutrino mass $\langle m_\nu \rangle \approx 0.02 \text{ – } 0.06$ eV.
1. Introduction
One of the major achievements in particle physics during the last decade was the discovery of neutrino oscillation, evidencing that neutrinos have non-zero mass. Finding the actual value and establishing whether neutrinos are Dirac or Majorana particles are the next great challenge. This has caused an increase in research activity on neutrinoless double beta decay (0νDBD) of some even-even nuclei.

The new generation of 0νDBD experiments require excellent energy resolution (a few keV), low background within the region of interest (≤ 0.001 events/keV-kg-yr) and a large quantity of the isotope under study (tens and hundreds of kg). A scintillation bolometer based on 40Ca 100MoO4 crystal with calcium depleted in 48Ca and molybdenum enriched in 100Mo is a new tool for 0νDBD experiments with 100Mo.

100Mo is considered as a very promising DBD nucleus due to its high transition energy (Qββ = 3034 keV) and reasonable cost of enrichment due to its production by gas centrifugation. Conversely it is acknowledged that the two-neutrino double beta decay of 48Ca (48Ca is present in natural Ca with an abundance of 0.187%), albeit very rare, will impose unavoidable background, limiting the sensitivity of the experiment to search for 0νDBD with enriched Ca100MoO4 [1]. This background can be eliminated by the use of Ca depleted in 48Ca to the level of ≤ 0.001%.

2. 40Ca 100MoO4 crystal scintillators production
The isotope 100Mo (enriched to 96%) was produced by the JSC Production Association Electrochemical plant (Russia) by gas centrifuge technology. The enriched material supplied in the form of 100MoO3 oxide is very pure with respect to radioactive elements: the results of ICP-MS measurements show that the concentrations of 238U and 232Th in the oxide do not exceed 0.07 ppb and 0.1 ppb, respectively. The calcium carbonate enriched in 40Ca (99.964%) and depleted in the 48Ca isotope by more than two orders of magnitude (≤ 0.001%) was produced by FSUE Electrochimpribor (Russia). The concentration of 238U and 232Th in the powder measured by ICP-MS is below 0.2 ppb and 0.8 ppb, respectively. However γ-spectroscopy analysis of the 40CaCO3 powder demonstrated that specific activity due to 226Ra and progenies are at the level of a few hundreds mBq/kg. Therefore both 40CaCO3 and 100MoO3 were subjected to additional purification.

Commonly used technique for the synthesis of the CaMoO4 raw material (charge) is co-precipitation reaction. This reaction method offers essential advantages: the possibility of additional purification of the starting compounds and better control of the final product stoichiometry.

The 40Ca 100MoO4 crystals have been pulled by JSC FOMOS-Materials (Russia) in air from a platinum crucible by the Czochralski technique. The technology of 40Ca 100MoO4 single crystal production (so called double crystallization procedure, re-crystallization) can be presented as a sequence of the following steps: the charge of 40Ca 100MoO4 in powder form is heated to the melting temperature to convert it to pellets with density similar to the density of crystals. Then the pellets are loaded to a crucible and the raw crystal is pulled. The raw crystals produced in such a way are then loaded into the crucible, melted and the final crystal is pulled. The 40Ca 100MoO4 crystals have mass of ≈ 0.5 kg, and elliptic cylinder form with diameter 49 mm (maximum), and length of the cylindrical part up to 70 mm. The as-grown crystal has strong blue coloration due to oxygen depletion and reduction of Mo6+ ions. This coloration can be removed by extended annealing in an oxygen atmosphere [2]. After this procedure transparent 40Ca 100MoO4 crystals were obtained (Fig.1).
3. Characterization of $^{40}\text{Ca}^{100}\text{MoO}_4$ crystal

The attenuation length of $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals was measured by using a Cary-5000 UV-VIS-NIR spectrophotometer as 90 cm at the wavelength of emission maximum 520 nm.

The dependences of light output and decay time of a $^{40}\text{Ca}^{100}\text{MoO}_4$ sample on temperature down to 8 K were measured [3] with a reference sample of CaMoO$_4$ described in [4]. Throughout the whole examined temperature range the light output of $^{40}\text{Ca}^{100}\text{MoO}_4$ is similar to that of the reference within the error of the measurements. The decay time constants at room temperature and at 8 K are $(16.5\pm0.3)\ \mu s$ and $(345\pm25)\ \mu s$, respectively.

Content of dangerous radioactive impurities ($^{226}\text{Ra}$, $^{208}\text{Tl}$ and $^{214}\text{Bi}$) has been measured in two ways. The initial enriched (depleted) materials, the $^{40}\text{Ca}^{100}\text{MoO}_4$ raw material (charge) and $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals were measured by using a low background HPGe facility [5]. The facility is placed in low background underground laboratory of the Baksan Neutrino Observatory INR RAS. The results of these measurements demonstrated that re-crystallization improves radioactive contamination of calcium molybdate crystals. Reduction factors are $\geq 10$ times for $^{232}\text{Th}$ and $\geq 35$ times for $^{226}\text{Ra}$ ($^{238}\text{U}$ chain).

In addition two samples of $^{40}\text{Ca}^{100}\text{MoO}_4$ scintillators were measured using the $4\pi$ gamma veto system [6] at the Yangyang underground laboratory [7]. For the anti-coincidence with $4\pi$ gamma veto system, we selected signals from $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals without any hit in CsI(Tl) crystal channels. This anti-coincidence reduced about 70% of background. A time-amplitude analysis [8], which exploits the energies and time difference between primary and secondary signals to select specific fast sequences of decays in the $^{238}\text{U}$/$^{232}\text{Th}$ chains, was used to select the $\alpha$ decay events of $^{214}\text{Po}$, $^{220}\text{Rn}$ and $^{216}\text{Po}$. The preliminary results show that the contamination by $^{214}\text{Po}$ (daughter of $^{214}\text{Bi}$, in equilibrium with $^{228}\text{Ra}$ from $^{238}\text{U}$ family) and by $^{216}\text{Po}$ (in equilibrium with $^{228}\text{Th}$ from $^{232}\text{Th}$ family) in the $^{40}\text{Ca}^{100}\text{MoO}_4$ crystal obtained by re-crystallization is on the level of 0.08 mBq/kg and 0.07 mBq/kg, respectively.

4. Cryogenic detector development

Cryogenic particle detection measurements with a 2.5 g CaMoO$_4$ sample as an absorber were made in KRISS [9]. A small MMC (Metallic Magnetic Calorimeter) sensor in form of gold alloy doped with 800 ppm of erbium was used to study the detector performances for 5.5 MeV alpha particles and 59.5 keV gamma quanta from a thin layer $^{241}\text{Am}$ source. The change in magnetization caused a change in the magnetic flux inside the pick-up loop of a dc-SQUID. Energy resolutions (full width at half maximum, FWHM) of 1.7 keV (59.5 keV gamma quanta) and 11.2 keV (5.5 MeV alpha particles) were achieved.
A CaMoO$_4$ crystal $\varnothing 40 \times 40 \text{ mm}$ (crystals of such size are considered as to be used in real experiment) with new meander-type MMC as a phonon sensor is now under investigation.

5. Conclusions and prospects

The AMoRE collaboration is going to use $^{40}\text{Ca}{}^{100}\text{MoO}_4$ crystals with a total mass of 100 kg as cryogenic scintillation detector to search for $0\nu\text{DBD}$ of $^{100}\text{Mo}$. Simultaneous detection of phonons and scintillation light will be used to reject backgrounds from internal radioactive contamination of crystals.

Large volume $^{40}\text{Ca}{}^{100}\text{MoO}_4$ crystals (= 0.5 kg) of very high optical quality were developed for the first time for $^{100}\text{Mo}$ 0vDBD search. The scintillation properties and the internal background of several $^{40}\text{Ca}{}^{100}\text{MoO}_4$ crystals were studied. The light yield of $^{40}\text{Ca}{}^{100}\text{MoO}_4$ samples is shown to be comparable with the reference CaMoO$_4$ sample throughout the wide temperature range down to 8 K. Radioactive contamination of $^{40}\text{Ca}{}^{100}\text{MoO}_4$ scintillator (produced by re-crystallization) by $^{226}\text{Ra}$ and of $^{228}\text{Th}$ was estimated to be on the level of 0.08 and 0.07 mBq/kg, respectively.

High energy resolution has been achieved with a 2.5 g crystal for 5.5 MeV $\alpha$ particles and 59.5 keV $\gamma$ quanta (11.2 keV and 1.7 keV, respectively). Projected sensitivity of the AMoRE experiment after 250 kg·yr of data taking was estimated as $\lim T_{1/2} \sim 3 \times 10^{26}$ years, which corresponds to the effective Majorana neutrino mass $\langle m_\nu \rangle \sim 0.02 – 0.06$ eV.

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