LUMINEU: a search for neutrinoless double beta decay based on $ZnMoO_4$ scintillating bolometers

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Abstract.
   The LUMINEU is designed to investigate the possibility to search for neutrinoless double beta decay in ^{100}Mo by means of a large array of scintillating bolometers based on ZnMoO$_4$ crystals enriched in ^{100}Mo. High energy resolution and relatively fast detectors, which are able to measure both the light and the heat generated upon the interaction of a particle in a crystal, are very promising for the recognition and rejection of background events. We present the LUMINEU concepts and the experimental results achieved aboveground and underground with large-mass natural and enriched crystals. The measured energy resolution, the α/β discrimination power and the radioactive internal contamination are all within the specifications for the projected final LUMINEU sensitivity. Simulations and preliminary results confirm that the LUMINEU technology can reach zero background in the region of interest (around 3 MeV) with exposures of the order of hundreds kg×years, setting the bases for a next generation $0\nu2\beta$ decay experiment capable to explore the inverted hierarchy region of the neutrino mass pattern.

1. Introduction

Search for neutrinoless double beta decay ($0\nu2\beta$) is a unique way to probe physics beyond the Standard Model since the process violates the lepton number and requires the neutrino to be a Majorana particle. The goal of the next generation $0\nu2\beta$ experiments is to test the inverted hierarchy of the neutrino mass (the effective Majorana neutrino mass $\langle m_\nu \rangle$ is at the level of a few hundredths of eV). The decay can be mediated by many other effects beyond the Standard Model, like existence of right-handed currents in weak interaction, Nambu-Goldstone bosons (majorons), and many other hypothetical effects [1, 2, 3, 4, 5].

   The isotope ^{100}Mo is one of the most promising 2β nucleus taking into account the high energy of the decay ($Q_{2\beta} = 3034.40(17)$ keV [6]), the comparatively high natural isotopic abundance ($\delta = 9.82(31)\%$ [7]) and the possibility of isotopical separation by centrifugation in an amount of hundreds kg - tons. The recent calculations of nuclear matrix elements [8, 9, 10, 11] give for ^{100}Mo one of the shortest half-life in the range $T_{1/2}^{0\nu2\beta} \approx (0.7 - 1.7) \times 10^{26}$ yr (for the effective Majorana neutrino mass 0.05 eV, assume the value of the axial vector coupling constant $g_A = 1.27$ and using the phase-space factor from [12]).

   Here we report the current status of the LUMINEU project (Luminescent Underground Molybdenum Investigation for NEUtrino mass and nature), aiming at preparing and fabricating of a next generation $0\nu2\beta$ experiment to search for $0\nu2\beta$ decay of ^{100}Mo at the level of the inverted hierarchy of neutrino mass with cryogenic scintillating bolometers based on zinc molybdate (ZnMoO$_4$) crystal scintillators enriched in ^{100}Mo [13].

## 2. Development of ZnMoO$_4$ cryogenic scintillating bolometers

The LUMINEU program requires a deep purification of molybdenum both from radioactive elements and from impurities, which color the ZnMoO$_4$ crystals [14]. A purification using two-

stage sublimation of molybdenum oxide in vacuum and recrystallization from aqueous solutions of ammonium para-molybdate was developed. A batch of LUMINEU crystals with mass of the crystal boules up to 1.5 kg have been successfully grown by the low-thermal-gradient Czochralski technique (LTG Cz), and their optical, luminescent, diamagnetic, thermal and bolometric properties were studied [15]. We have also found that introducing tungsten oxide into the melt for crystal growth at levels of fractions of percent improves the growth of zinc molybdate crystals. The yield of the crystal boules, their shape and overall quality becomes higher as a result of the melt stabilization thanks to the prevention of the formation of an extraneous phase in the synthesized $ZnMoO_4$ compound and in the melt [16].

As a result of the R&D the production cycle provides high quality $ZnMoO_4$ scintillators with a high yield of the crystal boules (more than 80%) and low enough irrecoverable losses of molybdenum (less than 4%). These features are especially important for the production of crystal scintillators from enriched materials. The first zinc molybdate crystal with a mass of 0.17 kg was produced from molybdenum enriched in ^{100}Mo to 99.5% [17]. Investigations of the scintillating bolometers fabricated with two enriched crystals cut from the boule show that the response of these devices meets the requirements of a high-sensitivity double beta decay search based on this technology, as discussed in [18]. As a next step, an enriched $Zn^{100}MoO_4$ crystal with a mass of 1.4 kg was grown for the first time by the LTG Cz method [19, 20].

Several cryogenic scintillating bolometers were fabricated from the produced crystal scintillators for aboveground and underground tests. In the experimental set-ups the $ZnMoO_4$ crystal samples were fixed inside copper holders by using PTFE supporting elements. Each crystal was instrumented with temperature sensors consisting of Neutron Transmutation Doped (NTD) Ge thermistors attached at the crystals by using an epoxy glue. The light detectors were developed from germanium disks and instrumented with NTD sensors [21]. The light detectors were mounted a few mm off the plane faces of the tested crystals surrounded by reflective foil. The detectors with ~ 0.3 kg $ZnMoO_4$ crystals have shown an excellent particle discrimination ability (near 15σ) and a high energy resolution on the level of 9 keV for the gamma quanta of ^{208}Tl with energy 2615 keV (see Figs. 1 and 2 where results of underground measurements in the EDELWEISS set-up at the Modane underground laboratory are presented).
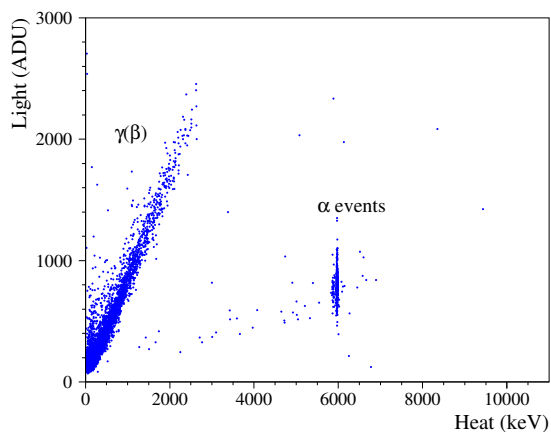
Figure 1. Scatter plot of light versus heat signals accumulated with $ZnMoO_4$ scintillating bolometer with a mass of 334 g over 398 h in the EDELWEISS set-up at the Modane underground laboratory. The β (γ) and α events are clearly separated. The energy calibration used is drawn from the gamma quanta.

Radioactive contamination of $ZnMoO_4$ crystal scintillators is under test in the EDELWEISS set-up at the Modane underground laboratory [22]. Preliminarily the $ZnMoO_4$ crystal scintillators show a very low radioactive contamination (the results of one of the crystals test are presented in Table 1) which is within the specifications for the projected final LUMINEU sensitivity.
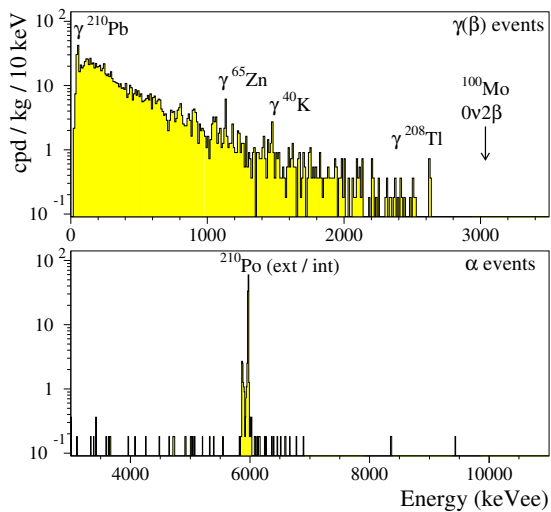
Figure 2. The energy spectra of β and γ events (upper panel) and α events (lower panel) accumulated with $ZnMoO_4$ scintillating bolometer over 398 h in the EDELWEISS set-up at the Modane underground laboratory.

Table 1. Radioactive contamination of $ZnMoO_4$ crystal scintillator with the mass of 334 g measured over 2216 h in the EDELWEISS set-up at the Modane underground laboratory [22].

| Nuclide	Activity (mBq/kg)
^{232}Th	≤ 0.002
^{228}Th	≤ 0.005
^{238}U	≤ 0.002
^{226}Ra	≤ 0.005
^{210}Po	1.27(2)
^{235}U	≤ 0.003
^{190}Pt	0.004(1)

3. Simulation of $Zn^{100}MoO_4$ detectors background

The background conditions of an experiment with $Zn^{100}MoO_4$ scintillating bolometers were estimated with the help of the GEANT4 simulation package. We assume to locate 48 $Zn^{100}MoO_4$ detectors (with a mass ~ 0.5 kg each) in the EDELWEISS set-up at the Modane underground laboratory. We simulated contamination of $Zn^{100}MoO_4$ crystals and the nearest materials to the detectors (copper holders, PTFE clamps, reflective foil) by ^{238}U and ^{232}Th daughters. We have also simulated cosmogenic nuclides in the $Zn^{100}MoO_4$ crystals and the copper holders. The simulated background energy spectrum and its main components are shown in Fig. 3. The preliminary results of the simulations can be found in [20, 23].

The background due to random coincidence of events (especially of $2\nu2\beta$ events [24]) can be reduced to the level of $\approx 10^{-4}$ counts/(yr keV kg) with the help of pulse-shape discrimination [25]. A total background counting rate $\approx 5 \times 10^{-4}$ counts/(yr keV kg) can be reached, which corresponds to 3 counts/(yr ton) in the region of interest (assuming 6 keV window centered at the $0\nu2\beta$ peak position).

4. Conclusions

$ZnMoO_4$ based cryogenic scintillating bolometers, developed in the framework of the LUMINEU project, show excellent performance: a few keV energy resolution and 15σ alpha/beta particle discrimination power at the $Q_{2\beta}$ value of ^{100}Mo. Radioactive contamination of $ZnMoO_4$ crystal
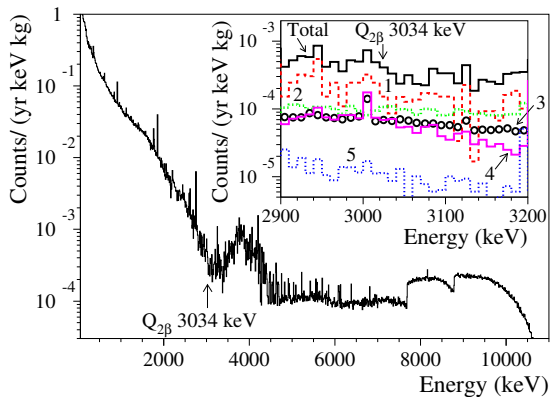
Figure 3. The energy spectra of 48 $Zn^{100}MoO_4$ detectors in EDELWEISS set-up simulated with the help of GEANT4 package. (Inset) The main components of background are shown: (1) surface contamination of $Zn^{100}MoO_4$ crystals, (2) radioactive contamination of the reflecting foil surrounding the crystal, (3) bulk contamination of $Zn^{100}MoO_4$ crystals, (4) contamination of copper holders and (5) PTFE clamps.

scintillators satisfies requirements for a large scale high sensitivity experiment: activities of ^{228}Th and ^{226}Ra are less than 5 μBq/kg. Enriched $Zn^{100}MoO_4$ crystals were grown for the first time by using the LTG Cz technique. The production cycle provided a high yield of the crystal boule ($\approx$ 80% of the initial charge) and an acceptable level of irrecoverable losses of molybdenum ($\approx$ 4%). According to the Monte Carlo simulation a background level of $\sim$ 0.5 counts/(yr keV ton) in the region of interest can be reached in a large detector array. These results pave the way to future sensitive searches based on the LUMINEU technology, capable of exploring the inverted hierarchy region of the neutrino mass pattern. The LUMINEU activity is part of a CUPID, a proposed bolometric tonne-scale experiment to be built as a follow-up of the CUORE experiment and exploiting as much as possible the CUORE infrastructures [26, 27].

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