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LUMINEU: a pilot scintillating bolometer experiment for neutrinoless double beta decay search

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Abstract

The Luminescent Underground Molybdenum Investigation for NEUtrino mass and nature (LUMINEU) aims at preparing the ground for a next-generation neutrinoless double beta decay experiment employing scintillating bolometers: these devices are in fact very promising tools in rare events search, in terms of efficiency, energy resolution and background control. In particular, they can tag alpha events, which are the dominant residual background for double beta decay candidates with a transition energy higher than 2615 keV. LUMINEU's goal is the operation of a pilot detector, consisting of four 400 g $ZnMoO_4$ scintillating bolometers, probing an active ^{100}Mo mass of about 0.7 kg, the energy transition of this isotope being 3034 keV. The enriched material for this setup is available and the experiment is fully funded by ANR in France. This preliminary investigation intends to be feasibility test for a next-generation neutrinoless double beta decay experiment aiming at probing the inverted hierarchy region of the neutrino mass pattern. LUMINEU will help to fix the detailed structure of the single module of this future large-scale experiment. The $ZnMoO_4$ crystals will be grown at the Nikolaev Institute for Inorganic Chemistry in Novosibirsk, Russia. LUMINEU foresees a systematic optimization of the crystal growth parameters, in order to optimize the bolometric performance, the light yield, the α particle rejection factor and the radiopurity of the scintillating bolometers. On this purpose, an aboveground facility was set up at the Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), in Orsay, France. In this contribution, we will describe the LUMINEU program, we will discuss its sensitivity and that one of a future large search based on this technology. We will also present preliminary experimental results achieved in Orsay with scintillating bolometers fabricated employing the first LUMINEU $ZnMoO_4$ crystals, which have been delivered in June 2013.

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Keywords: neutrinoless double beta decay, bolometers, low background

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1. Introduction

The detection of neutrinoless double beta decay (0νDBD) would not only prove lepton number violation, but also that neutrino and antineutrino are the same particle: its study therefore plays a fundamental role in shading light on neutrino physics and several cosmological issues, as the Majorana nature of neutrinos would straightly explain the smallness of neutrino mass and support the leptogenesis scenario. Moreover, a measure of 0νDBD decay rate would give indications on neutrino absolute mass scale and mass hierarchy, the decay rate being proportional to the square effective mass, if it takes place through the so called mass-mechanism [1].

In practice, the challenge consists in measuring a peak in the emitted electrons energy spectrum, at the transition energy Q of the reaction; current best limits on the half-life $T_{1/2}^{0\nu\beta\beta}$ are of the order of 10^{25} years,

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corresponding to an effective neutrino mass $\langle m_\nu \rangle$ of a few hundreds meV, which is compatible with the quasi-degenerate mass pattern. Next-generation experiments goal is to probe the inverted hierarchy region, equivalent to $\langle m_\nu \rangle$ of a few tens meV: their sensitivity should therefore attain the level of $T_{1/2}^{0\nu\beta\beta} \approx 10^{27}$ - 10^{28} years, which requires the study of high isotope mass with high detection efficiency, excellent energy resolution in the energy region of interest (ROI) and ideally ”zero” background (a few counts/year/ton) [2].

Due to the strong Q-value dependence of the decay rate, only nine isotopes are of experimental significance for 0νDBD search, their transition energies being in the 2 - 4 MeV range; furthermore, the choice of a suitable candidate nucleus is constrained by the technical issues of enrichment and compatibility with an effective detection technique. The three candidates ^{82}Se, ^{100}Mo and ^{116}Cd are a good compromise: enrichment of hundreds kilograms is feasible and the 0νDBD Q-value lies above the limit of natural γ radioactivity; in addition, their investigation can be performed with the bolometric technique, which features typical energy resolutions of a few keV in the ROI and high efficiencies. However, the ROI for these isotopes is typically populated by events from α particle energy degradations coming from surface contaminations, as demonstrated by the Cuoricino experience [3]. Besides careful choice and cleaning of materials, events discrimination techniques can effectively suppress this dangerous source of background: the asset of scintillating bolometers.

The purpose of the LUMINEU project is to display the feasibility of a next-generation 0νDBD experiment based on scintillating bolometers, to evaluate its potential and to outline its design: once defined the strategies to properly operate a detector module, the assembly of a large mass experience will just be a matter of economical resources.

2. Methods

Bolometers are calorimetric detectors measuring phonon excitations produced by incoming particles. The interactions occur in an absorber medium equipped with a thermometer to measure the corresponding temperature rise. The choice of absorber’s material and size is fairly flexible, the only constraint being set by the total heat capacity, which determines the detector sensitivity: in order to have fast and large signals with reasonable absorber mass, suitable to 0νDBD purpose, it is convenient to use dielectric diamagnetic materials operated at cryogenic temperatures, a few tens of mK.

Bolometers are a very good option for 0νDBD search for several reasons: their energy resolution is comparable to solid state devices; it is possible to choose among a wide number of proper absorber compounds containing 0νDBD candidate isotopes, so that the source is actually the detector itself and very good efficiencies can be achieved; it is easy to scale-up to large masses by constructing modular experiments. The technique has already been extensively developed in the frame of past and near-future experiments [3, 4]. Nevertheless, in most of cases, no event discrimination is possible just from phonon signals. This drawback can be solved by coupling a scintillating crystal absorber with a proper light detector: at a fixed energy, the ratio of scintillation to phonon excitations (namely the light yield LY) is different for α with respect to events induced by β and γ radiation, so it is possible to discard the dangerous α background from surface contaminations.

The target isotope of the LUMINEU project is ^{100}Mo, which has Q-value of 3034 keV and isotopic abundance of 9.8%; the current best limit on 0νDBD half-life has been set by the NEMO-3 experiment, $T_{1/2}^{0\nu\beta\beta} \geq 10^{24}$ years at 90% C.L. [5]. Zinc molybdate ($ZnMoO_4$) crystals scintillate at low temperature and their successful operation as bolometers was reported for the first time in Ref. [6]; the output light spectrum has a maximum at 625 nm, typical LY_β being of a few keV/MeV. Preliminary crystals (with masses up to $\approx$300 g) operated as scintillating bolometers already showed good event discrimination capability [7]. These results are confirmed by other authors [8]. At cryogenic temperatures, a convenient light detector choice is a thin semiconductor bolometer, opaque to the emitted photons: LUMINEU will employ ultra-pure germanium absorbers read by phonon sensors.

3. The LUMINEU project

The LUMINEU's aim is the development of a demonstrator module of about 0.7 kg of ^{100}Mo, which will be operated in the underground Modane laboratory (LSM) in France, in the EDELWEISS experiment cryostat. The activities are focused on three main axes:

- zinc molybdate crystal production;
- aboveground detector optimization;
- setup of the underground experiment.

Crystal production is performed at the Nikolaev Institute for Inorganic Chemistry in Novosibirsk, Russia, where $ZnMoO_4$ samples are grown by the low-thermal gradient Czochralski method.

In order to reach the requested background rate, special care has to be addressed to crystal radiopurity, required contaminations levels by ^{228}Th and ^{226}Ra being lower than 10 μBq/kg; moreover, the optical properties of the crystals appreciably depend on transition metal impurities, which affect absorption properties, and deep purification of raw materials can significantly improve them [7]. The development of molybdenum purification techniques is fundamental and a complete characterization of the samples is performed [9]; bolometric measurements are important to assess the crystals performances as particle detectors, such as energy resolution, sensitivity and α/β rejection efficiency.

In parallel, detector optimization must be carried on, also in terms of single components characterization: light detectors, phonon sensors, crystal holder structure. In this scope, systematic tests are needed in a convenient setup, possibly aboveground: a dedicated facility was developed at CSNSM (see next section).

As a final step, underground tests are performed at the LSM.

Background simulations allow to predict sensitivities of possible future detector configurations (Table 1) [10]; the LUMINEU pilot experiment corresponds to a four enriched crystal detector module, about 400 g mass each, for a total active mass of 0.7 kg and expected sensitivity comparable to present 0νDBD searches. A total of 10 kg enriched molybdenum is already available.

Number of ≈ 400 g crystals	Total isotope mass [kg]	Half-life sensitivity [10^{25} y]	$m_{\beta\beta}$ sensitivity [meV]
4	0.676	0.53	167-476
40	6.76	4.95	55-156
2000 (nat.)	33.1	15.3	31-89
2000	338	92.5	13-36

Table 1. Calculated sensitivities for a 5-year-livetime, assuming enrichement level of 97% and detection efficiency of 90%. The expected background rate is 4×10^{-4} counts/keV/kg/y. LUMINEU pilot experiment corresponds to the first raw, about 0.7 kg of isotope mass. Material for the production of ≈ 7 kg of ^{100}Mo (2nd raw) is already available.

4. Preliminary tests

The first bunch of crystals produced for LUMINEU were delivered at CSNSM (Orsay, France) in June 2013. Two scintillating bolometers, 55 g and 160 g mass, were assembled: crystal absorbers are 40 mm height cylinders, with diameters of 20 mm and 35 mm respectively. Each crystal is equipped with a Ge Neutron Transmutation Doped (NTD) phonon sensor, whose resistance depends exponentially on temperature, and with a Si heating device for response stabilization. A Ge light detector [11](5 cm diameter, 250 μm thickness), read by a Ge NTD as well, faces the two scintillating absorbers. Mechanical coupling of the absorbers to the copper holder is provided by PTFE pieces, while electrical and thermal links are 25 μm diameter golden wires of several mm length. A reflecting foil surrounds the whole setup, in order to maximize light collection.

The detectors were cooled down at CSNSM, in a dedicated setup for aboveground tests [12], based on a dilution Pulse Tube refrigerator, allowing to reach temperatures down to 10 mK without cryogenic fluids. The heat-sink temperature was stabilized at 18 mK; the thermistors were operated at about 1 mK higher. Energy calibration of the zinc molybdate bolometers was performed thanks to an external ^{232}Th source; the light detector was calibrated with a ^{55}Fe source, emitting 6 keV X-rays, facing the Ge absorber.

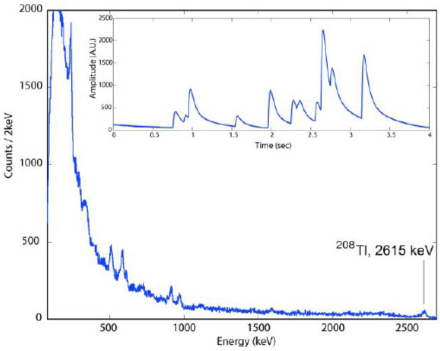

Fig. 1. Energy spectrum of the 160 g bolometer, with the ^{232}Th source. In the inset, typical pile-up effect.

The size of the crystals is marginally compatible with aboveground operation: pile-up is considerable even for background measurements and affects the energy resolution of the detector. Nevertheless, a preliminary complete detector characterization can be performed to obtain sensitivities, relative light yield, quenching factor (QF, i.e. the ratio of α to β LY) and initial hints on crystal radiopurity. The results, summarized in Table 2, are compatible with typical values reported in literature. As regards radiopurity, we will give quantitative estimations in a work in preparation; we can anticipate however that, with the exception of the ^{210}Po line at 5.41 MeV, no internal alpha line emerged in the energy spectrum after about two weeks of data taking.

Crystal mass [g]	Sensitivity [μV/MeV]	Relative light yield [keV/MeV]	QF
55	104	0.98	0.153
160	134	0.96	0.156

Table 2. Performance of the first LUMINEU crystals, operated aboveground in a Pulse Tube refrigerator.

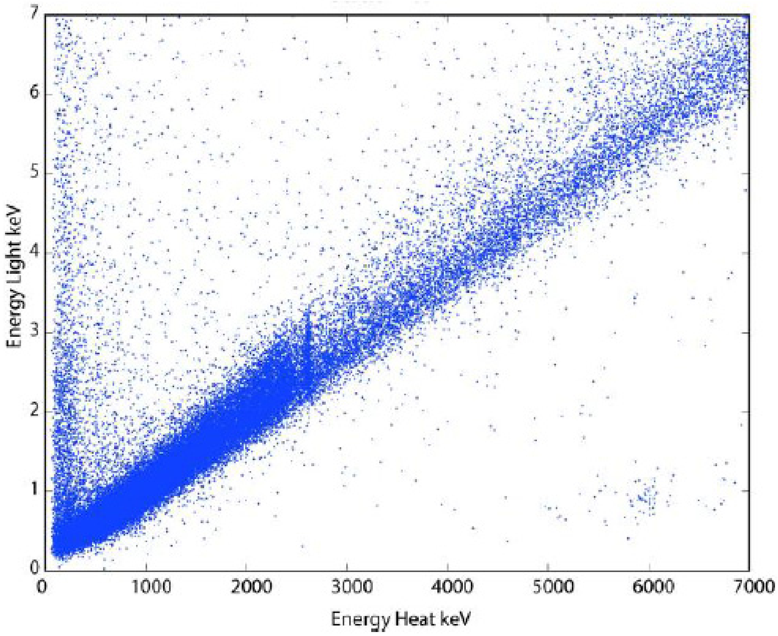

Fig. 2. Plot of coincidence events of heat and scintillation signals, for the 160 g $ZnMoO_4$ crystal operated in the aboveground CSNSM setup, over 81 h. The α band, mainly populated by internal ^{210}Po contaminations, is clearly separated from the γ/β band, including also cosmic rays.

5. Conclusions

LUMINEU will define proper strategies to build a next-generation 0νDBD experiment based on zinc molybdate scintillating bolometers. The operation of a pilot experiment of ≈0.7 kg of ^{100}Mo is foreseen in 2016, at LSM, France.

The first bunch of natural, regular shape crystals has been delivered in June 2013 and two samples of 55 g and 160 g have been tested as bolometric detectors at CSNSM, Orsay, France. The results confirm good event discrimination performances and demonstrate that a preliminary characterization is possible in an aboveground, LHe-free facility.

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