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A neutrinoless double-beta-decay search based on $ZnMoO_4$ and Li_2MoO_4 scintillating bolometers

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Abstract. The LUMINEU project, funded by ANR in France, envisages a high-sensitivity search for neutrinoless double beta decay of ¹⁰⁰Mo with the help of scintillating bolometers based on zinc molybdate $(ZnMoO_4)$ and lithium molybdate (Li_2MoO_4) crystals. The excellent results (obtained in collaboration with the LUCIFER and EDELWEISS research teams) in terms of energy resolution (5-10 keV FWHM in the region of interest), α/β rejection factor (> 99.9%) and intrinsic radiopurity (better than a few $\mu Bq/kg$ for the most harmful nuclides ²²⁸Th and 226 Ra) show that the LUMINEU technology – whose development is part of the program of CUPID, the proposed follow-up to CUORE – is very promising for a next-generation tonne-scale experiment. A 10-kg pilot search is in preparation to confirm these encouraging indications.

1. Introduction

Neutrinoless double-beta $(0\nu\beta\beta)$ decay [1] is a nuclear transition providing a powerful test of lepton number conservation. It is possible for 35 even-even nuclides, but it has never been observed, although it is predicted by many extensions of the Standard Model. Present half-life limits reach values around 10^{26} y [2]. In case of $0\nu\beta\beta$ decay detection, the Majorana nature of neutrino and lepton number violation would be demonstrated. If the process is mediated by the so-called mass mechanism, $0\nu\beta\beta$ decay can fix the absolute neutrino-mass scale and give unvaluable information on the neutrino-mass ordering.

The LUMINEU project is an R&D activity promoting the use of scintillating bolometers based on ZnMoO₄ and Li₂MoO₄ crystals for the investigation of $0\nu\beta\beta$ decay of ¹⁰⁰Mo, a promising candidate featuring high transition energy ($Q_{\beta\beta} = 3034 \text{ keV}$), reasonably high natural isotopic abundance (9.7 %) and viable enrichment technology. The LUMINEU activity is now part of CUPID [3] and aims to prove that the LUMINEU approach is compatible with the CUPID goal. CUPID is a proposed bolometric tonne-scale experiment to be built as a follow-up to CUORE [4]. The results here presented have been achieved by the LUMINEU team in collaboration with LUCIFER [5] for the tests carried out in the Gran Sasso underground laboratory (LNGS) and with EDELWEISS [6] for those performed in the Modane underground laboratory (LSM).

2. Approach, technologies and objectives of LUMINEU

A scintillating bolometer is composed by a main bolometer and an auxiliary one, operated as a light detector. The signals, collected at a temperature below 20 mK, consist of thermal pulses

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both for the light and heat channels. The main bolometer contains the isotope of interest, implementing the "source=detector" approach. Scintillating bolometers feature high energy resolution and efficiency, and excellent rejection of α background, which is dominant for isotopes with a transition energy higher than ~ 2.6 MeV as in the case of ¹⁰⁰Mo. The results presently achieved in LUMINEU, here described, allow us to predict a background rate of the order of 1.5 counts/(tonne × y) [7, 8], with a limiting factor due to random coincidences of the ordinary two-neutrino double-beta decay events [9].

Table 1: Main results from four enriched large modules ("ZMO" and "LMO" stand for ZnMoO₄ and Li₂MoO₄, respectively; "t" and "b" stand for "top" and "bottom", with reference to the sample position in the crystal boule). DP designates the discrimination power as defined in Ref. [8]. All the DP values imply a rejection power > 99.9% with a β selection efficiency > 90%.

Enriched sample	Mass [g]	FWHM @ 2615 keV	Light Yield [keV/MeV]	α/β rejection	$\begin{array}{l} A(^{228}Th) \\ [\mu Bq/kg] \end{array}$	$\begin{array}{l} A(^{226}Ra) \\ [\mu Bq/kg] \end{array}$	$\begin{array}{l} A(^{210}Po)\\ [mBq/kg] \end{array}$
ZMO-t	380	$9 {\rm ~keV}$	1.3	DP=7.8	< 8	14	0.8
ZMO-b	382	$18 \ \mathrm{keV}$	1.2	DP=11	< 21	23	2.4
LMO-t	186	$7 \ \mathrm{keV}$	-	DP=17	< 6	< 6	0.21
LMO-b	204	5 keV	0.8	DP=12	< 6	< 11	0.06

3. Main LUMINEU results

Tests of the LUMINEU detectors are ongoing since 2013 in the cryogenic laboratory of CSNSM (Orsay, France), at LSM (France) and LNGS (Italy). This activity has allowed us to reach remarkable results – listed below – that show the maturity of the LUMINEU technology.

- We have developed a purification-crystallization protocol [10] for the production of high quality crystals implying low irrecoverable losses (< 4%) [11] of the costly enriched molybdenum. Crystal growth is performed at NIIC (Novosibirsk, Russia).
- We have fabricated and operated several detectors from natural and enriched materials [11, 12, 13], optimizing the radiopurity, the energy resolution and the α/β rejection capability.
- We have ascertained that the crystal growth is much easier for Li₂MoO₄ than for ZnMoO₄, providing boules with more regular shapes and less macroscopic defects and inclusions.
- We have performed a dedicated R&D to control the internal ⁴⁰K content in Li₂MoO₄. The present recipe, which includes the use of a selected ultapure Li₂CO₃ powder for the compound synthesis and a double crystallization procedure, allowed us to achieve a harmless ⁴⁰K activity, inferior to 6 mBq/kg.
- The LUMINEU activity has culminated with the production of four enriched large-volume modules (two with ZnMoO₄ and two with Li₂MoO₄ crystals). Enriched molybdenum was provided by the LUMINEU collaborators of ITEP (Moscow, Russia) and KINR (Kyiv, Ukraine). The main achieved results are reported in Table 1. Though ZnMoO₄ is a very promising material as well, Li₂MoO₄ devices have superior performance and radiopurity, and a less pronounced boule-position dependence.

The excellent performance of the enriched Li₂MoO₄ detectors can be appreciated in Fig. 1. From the background measurement, it is possible to extract preliminarily the half-life of the ordinary two-neutrino double-beta decay, with a very simple background model which includes only the internal ⁴⁰K contamination and describes the continuum of the residual background with an exponential function decreasing with energy. The results are 7.5×10^{18} y and 6.7×10^{18} y for the LSM and LNGS data respectively, in good agreement with the accurate NEMO-3 [14] and LUCIFER [15] measurements.

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Figure 1: Spectra obtained with the two enriched Li_2MoO_4 modules. In red, the results achieved by the detector operated at LSM and in blue by that operated in LNGS (line 3 and 4 respectively in Table 1). Left panel: ²³²Th calibration. Right panel: background spectrum. The rate is dominated by the two-neutrino double-beta decay of ¹⁰⁰Mo.

4. Conclusions

The LUMINEU R&D activity has shown that ¹⁰⁰Mo-enriched ZnMoO₄ and Li₂MoO₄ scintillating bolometers are excellent candidates for a next-generation $0\nu\beta\beta$ decay experiment like that proposed in CUPID. The next step (already started) is the assembly and the operation of a medium-scale demonstrator. We have chosen Li₂MoO₄ as main component of this pilot experiment because of its easier production and better performance. The growth of 20 enriched Li₂MoO₄ crystals has started in 2016 in NIIC, containing ~ 3 kg of ¹⁰⁰Mo in total. Additional 20 crystals will be grown in 2017. Simulations using the already achieved results on the single modules show that a 40-crystal demonstrator has a 2 y sensitivity of 1.7×10^{25} y at 90% C.L. corresponding to an upper limit on the Majorana neutrino mass of 70-200 meV. R&D is in progress [16, 17] to bring the background rate due the two-neutrino random-coincidences below 0.1 counts/(tonne × y), as required by a next-generation search.

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