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$ZnMoO_4$: A promising bolometer for neutrinoless double beta decay searches

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ABSTRACT

We investigate the performances of two $ZnMoO_4$ scintillating crystals operated as bolometers, in view of a next generation experiment to search the neutrinoless double beta decay of ^{100}Mo. We present the results of the α vs β/γ discrimination, obtained through the scintillation light as well as through the study of the shape of the thermal signal alone. The separation obtained at the 2615 keV line of ^{208}Tl is 8σ, using the heat-light scatter plot, while it exceeds 20σ using the shape of the thermal pulse alone. The achieved FWHM energy resolution ranges from 2.4 keV (at 238 keV) to 5.7 keV (at 2615 keV). The internal radioactive contaminations of the $ZnMoO_4$ crystals were evaluated through a 407 h background measurement. The obtained limit is <32 µBq/kg for ^{228}Th and ^{226}Ra. These values were used for a Monte Carlo simulation aimed at evaluating the achievable background level of a possible, future array of enriched $Zn^{100}MoO_4$ crystals.

1. Introduction

Double beta decay (DBD) searches became of critical importance after the discovery of neutrino oscillations. Plenty of experiments are now in the construction phase and many others are in R&D phase [1–4]. The main challenges for all the different experimental techniques are the same [5]: (i) increase the active mass, (ii) decrease the background, and (iii) increase the energy resolution.

Thermal bolometers are ideal detectors for this survey: crystals can be grown with a variety of interesting DBD-emitters and multi-kg detectors can be operated with excellent energy resolution [6].

The Cuoricino experiment [7], an array of 62 TeO_2 crystal bolometers, demonstrated not only the power of this technique, but also that the main source of background for these detectors arises from surface contaminations of radioactive α-emitters. α particles, emitted from radioactive contaminations located on the surfaces of the detector or of passive elements facing them, can lose part of their energy in a few µm and deposit the rest in the crystal bolometer. This produces an essentially flat background starting from the Q-value of the decays (several MeV) down to low energies, completely covering, therefore, the region of the $Q_{\beta\beta}$ values. Moreover simulations show that this contribution will largely dominate the expected background of the CUORE experiment [8,9] in the region of interest, since there is no possibility to separate this background from the two DBD electrons. The natural way to discriminate this background is to use a scintillating bolometer [10]. In such a device the simultaneous and independent readout of the heat and of the scintillation light permits to discriminate events due to β/γ, α and neutrons thanks to their different scintillation yield. Moreover, if the crystal is based on a DBD emitter whose transition energy exceeds the 2615 keV γ-line of ^{208}Tl, the environmental background due to natural γ's will decrease abruptly.

^{100}Mo is a very interesting $\beta\beta$-isotope because of its large transition energy $Q_{\beta\beta} = 3034.4$ keV [11] and a considerable natural isotopic abundance $\delta = 9.67\%$ [12]. Several inorganic scintillators containing molybdenum were developed in the last years. $ZnMoO_4$ [13] is an example of crystal recently tested as a cryogenic detector giving very promising results [14].

In this work we present the results obtained with two $ZnMoO_4$ crystals of superior quality with respect to the sample previously studied. This work is focused on the recent observation [15] that

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the thermal signal induced by α and γ/β particles shows a slightly different time development. This feature seems to be explained [16] by the relatively long scintillation decay time (of the order of hundreds of μs) observed in some scintillating crystals (e.g. molybdates). This long decay, combined with an high percentage of non-radiative de-excitation of the scintillation channel, will transfer phonons (i.e. heat) to the crystal. This extremely tiny, but measurable, time dependent phonon release has a different absolute value for isoenergetic α and β/γ particles due to their different scintillation yield. The possibility to have a bolometer in which the α background is identified *without* the need of an additional light detector is particularly appealing since it translates in a simplified set-up.

In Section 2 the experimental set-up is outlined; in Section 3 we describe the α vs β/γ discrimination capability. The evaluation of the internal radioactive contamination of our sample is presented in Section 4, while in Section 5 we present a detailed Monte Carlo simulation of the background performances of a possible future experiment based on a $ZnMoO_4$ crystal array.

Within the Lucifer Project [17], an array of enriched $Zn^{82}Se$ crystals operated as scintillating bolometers, there is also the option of having part of the detectors made of ^{100}Mo enriched crystals. The present work, though based on small size crystal samples, shows the performance that could be reached by a small scale DBD decay experiment based on $Zn^{100}MoO_4$ crystals.

2. Experimental details

High quality $ZnMoO_4$ crystals were developed in the Nikolaev Institute of Inorganic Chemistry (NIIC, Novosibirsk, Russia). Starting material for the crystal growth were High Purity ZnO (produced by Umicore) and MoO_3, synthesized by NIIC. Crystals up to 25 mm in diameter and 60 mm in length were grown by the low-thermal-gradient Czochralski technique in a platinum crucible with a size of $\varnothing$ 40 mm × 100 mm [18].

In this paper we present the result of two separate runs, both carried out in an Oxford 200 $^3He/^4He$ dilution refrigerator located deep underground in the Laboratori Nazionali del Gran Sasso (average depth ≈3650 m w.e. [19]).

The first run was dedicated to the study of the discrimination capability of $ZnMoO_4$ bolometers, while the second one was devoted to the evaluation of the internal contaminations of the sample.

In the first run two different $ZnMoO_4$ crystals were tested in order to study the reproducibility of the background rejection over different samples. The samples were a 27.5 g colourless cylinder ($\varnothing$ 18.5 mm × 22.3 mm) and a 29.9 g slightly orange parallelepiped (28.5 × 18.4 × 13.2 mm^3).

The $ZnMoO_4$ crystals were held by means of four S-shaped PTFE supports fixed to cylindrical Cu columns. They were surrounded (with no direct contact) by a plastic reflecting sheet (3M VM2002). The Light Detector (LD) [20] is constituted by a 36 mm diameter, 1 mm thick pure Ge crystal absorber. The Ge wafer is heated up by the absorbed photons and the temperature variation is proportional to the scintillation signal. The set-up of the detectors is schematized in Fig. 1.

The temperature sensor of the $ZnMoO_4$ crystals is a 3 × 3 × 1 mm^3 Neutron Transmutation Doped (NTD) germanium thermistor, the same used in the Cuoricino experiment. It is thermally coupled to the crystal via 9 glue spots of ≈ 0.6 mm diameter and ≈50 μm height. The temperature sensor of the LD has a smaller volume (3 × 1.5 × 0.4 mm^3) in order to decrease its heat capacity, increasing therefore its thermal signal. A resistor of ≈300 kΩ, realized with a heavily doped meander on a 3.5 mm^3 silicon chip, is attached to each absorber and acts as a heater to stabilize the gain of the bolometer [21,22]. The details of the electronics and the cryogenic facility can be found elsewhere [23–25].

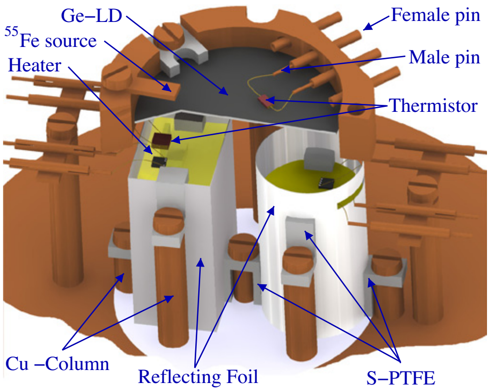

Fig. 1. Set-up of the detectors. The ball-bonded Au wires are crimped into "male" Cu tubes (pins) and inserted into ground-insulated "female" Cu tubes. Custom wires from detectors towards cryostat are not drawn. A section of the light detector is not drawn for a better understanding.

The heat and light pulses, produced by a particle interacting in the absorber and transduced in a voltage pulse by the NTD thermistors, are amplified and fed into a 18 bit NI-6284 PXI ADC unit. The trigger is software generated on each bolometer and when it fires waveforms 0.6 s long, sampled at 2 kHz, are saved on disk. Moreover, when the trigger of a $ZnMoO_4$ crystal fires, the corresponding waveform from the LD is recorded, irrespective of its trigger.

As the main goal of the measurements was to test the discrimination capability of the detectors between α and β/γ events, a $^{238}U/^{234}U$ α source was faced to the crystals, on the opposite side with respect to the LD. The source was covered with a 6 μm thick Mylar film, in order to "smear" the α's energies down to the $Q_{\beta\beta}$ energy region. The γ calibration of the $ZnMoO_4$ crystals is performed through a movable a ^{232}Th source inserted between the Dewar housing the cryostat and the external lead shield. The energy calibration of the LD is achieved thanks to a ^{55}Fe X-ray source, producing two X-rays at 5.9 and 6.5 keV, faced to the LD (see Fig. 1).

In the second run only the best performing bolometer (the cylindrical crystal) was characterized. The α source was removed and the crystal was surrounded by three layers of 12 μm thick ultrapure polyethylene sheets in order to shield the bolometer against the surface contamination of the copper structure. In this measurement the lack of space prevented us from mounting the LD. However this was not a problem, as the previous run convincingly demonstrated that the pulse shape analysis can provide an extremely good α background rejection without the need for the light detection.

2.1. Data analysis

To maximize the signal to noise ratio, the pulse amplitude is estimated by means of an optimum filter technique [26,27]. The filter transfer function is built from the ideal signal shape $s(t)$ and the noise power spectrum $N(\omega)$. $s(t)$ is estimated by averaging a large number of triggered pulses (so that stochastic noise superimposed to each pulse averages to zero) while $N(\omega)$ is computed averaging the power spectra of randomly acquired waveforms not containing pulses. The amplitude of a signal is estimated as the maximum of the filtered pulse. This procedure is applied for the signal on the $ZnMoO_4$ bolometer. The amplitude of the light signal, instead, is estimated from the value of the filtered waveform at a fixed time delay with respect to the signal of the $ZnMoO_4$ bolometer, as described in detail in Ref. [28]. The detector performances are reported in Table 1. The baseline resolution, $FWHM_{base}$, is governed