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A next-generation neutrinoless double beta decay experiment based on $ZnMoO_4$ scintillating bolometers

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ABSTRACT

The search for neutrinoless double β decay probes lepton number conservation with high sensitivity and investigates the neutrino nature and mass scale. Experiments presently in preparation will cover the quasi-degeneracy region of the neutrino mass pattern. Probing the inverted hierarchy region requires improved sensitivities and next-generation experiments, based either on large expansions of the present searches or on new ideas. We examine here a novel technology relying on $ZnMoO_4$ scintillating bolometers, which can provide an experiment with background close to zero in the ton $\times$ year exposure scale. The promising performance of a pilot detector is presented, both in terms of energy resolution and background control. A preliminary study of the sensitivities of future experiments shows that the inverted hierarchy region is within the reach of the technique here proposed. A realistic phased approach program towards a next-generation search is presented and briefly discussed.

1. Introduction and motivations

Neutrinoless double β decay ($0\nu2\beta$) is a hypothetical rare nuclear transition in which an even–even nucleus changes into an isobar by the simultaneous emission of two electrons and nothing else [1]. The observation of this process would imply the violation of the lepton number conservation and definitely new physics beyond the Standard Model, establishing the Majorana nature of neutrinos. If the transition takes place through the mass mechanism, the decay rate is proportional to the square of the effective Majorana mass $m_{\beta\beta}$, that can be determined or at least constrained within the uncertainties of the nuclear matrix elements. This parameter is related to the absolute neutrino mass scale and depends on the three neutrino masses m_1, m_2 and m_3. It is convenient to distinguish three mass patterns: normal hierarchy (NH), where $m_1 < m_2 < m_3$, inverted hierarchy (IH), where $m_3 < m_1 < m_2$, and quasi-degenerate pattern (QD), where the differences between the masses are small with respect to their absolute values. We ignore Nature's choice about the neutrino mass ordering at the moment, but $0\nu2\beta$ has the potential to provide this essential information [1,2], given the relationship between $m_{\beta\beta}$ and the three neutrino masses. In fact, if $m_{\beta\beta}$ is measured to be greater than ≈ 50 meV, the QD pattern holds and an allowed range of m_{min} values can be extracted. On the other hand, if $m_{\beta\beta}$ lies in the range 20–50 meV, the pattern is likely IH. Eventually, if one determined that $m_{\beta\beta} < 10$ meV but non-vanishing (which is unlikely in a foreseeable future), one would conclude that the NH pattern holds. The process $0\nu2\beta$ is important both for the comprehension of fundamental aspects of neutrino physics and for the solution of hot astroparticle and cosmological issues, intimately related to the neutrino mass scale and nature.

The signature for $0\nu2\beta$ consists of a peak located at the Q-value of the transition in a spectrum of the sum of the energy of the two emitted electrons [1]. The current sensitivity to $m_{\beta\beta}$

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is around 0.2–0.5 eV. A much debated claim of evidence in ^{76}Ge corresponds to $m_{\beta\beta} \approx 0.3$ eV [3]. Experiments under commissioning or construction [1] can hardly start to explore the IH region, with sensitivities around 0.1–0.05 eV. In order to deeply analyze it, relevant expansions or improvements of current experiments are needed, or new technologies need to be developed. In this work, we propose to use scintillating bolometers for a frontier $0\nu2\beta$ experiment focused on the study of ^{100}Mo and capable to explore the IH range.

A bolometric detector [4] consists of an energy absorber, in the form of a single crystal, equipped with a temperature sensor. The signal, collected at very low temperatures (typically < 20 mK for large bolometers), consists of a temperature rise of the whole detector determined by a nuclear event. Due to the high energy resolutions and to the wide flexibility in the choice of the detector material, this approach is well tailored to the demands of a sensitive $0\nu2\beta$ experiment, based on the *source = detector* technique [5]. Ultra-pure crystals up to 100–1000 g can be grown with interesting materials, containing appealing candidates. An array of such detectors can be used to achieve total masses of the order of 100–1000 kg, necessary to explore the IH region. The CUORE experiment, under commissioning, applies this technology to the study of the candidate ^{130}Te in arrays of natural TeO_2 bolometers with ≈ 200 kg isotope mass [6].

When the energy absorber in a bolometer scintillates at low temperatures, the simultaneous detection of scintillation light and heat provides a very powerful tool to identify the nature of the interacting particle and therefore to suppress background. In particular, a massive charged particle can be separated from an electron or γ due to the different light yield for the same amount of deposited heat, as proposed more than twenty years ago [7]. In the field of double β decay, the first experimental proof of this concept was achieved in 1992 with a CaF_2 scintillating bolometer, developed as a pilot device for the search for $0\nu2\beta$ in ^{48}Ca [8]. Recently, this approach was proposed to study $0\nu2\beta$ of ^{82}Se (LUCIFER project) with the help of ZnSe crystals [9]. In non-scintillating materials relevant for $0\nu2\beta$, the particle identification can be achieved through the detection of the much weaker Cherenkov light [10,11]. In the current technology, the light is detected by thin dedicated bolometers facing the main one.

Scintillating bolometers containing a double β decay emitter with a Q-value above the 2615 keV ^{208}Tl γ line are very promising devices for a future $0\nu2\beta$ experiment. In fact, the energy region extending above 2615 keV is almost free from γ background due to natural radioactivity, but is dominated by α particles, as the experience brought by Cuoricino and CUORE-R&D clearly shows [12]. Scintillating bolometers can solve this background issue. They offer a reasonable freedom in the choice of the candidate, that can be selected for its high Q-value (such as the here proposed ^{100}Mo, for which $Q = 3034.40(17)$ keV [13]), with the additional advantage that α particles can be recognized and rejected. The performance of the prototype here presented (Section 2) and a detailed background evaluation in a realistic set-up (Section 3) show that an experiment with background close to zero in the ton × year scale exposure is viable with the proposed technique (Section 4).

2. A $ZnMoO_4$ scintillating bolometer prototype

The validation of the approach here discussed has been obtained through the successful operation of a $ZnMoO_4$ scintillating bolometer prototype. $ZnMoO_4$ is an attractive material for the proposed application, as it is an intrinsic scintillator with a high molybdenum content (43% in mass). It forms white tetragonal crystals with a density of 4.3 g/cm^3.

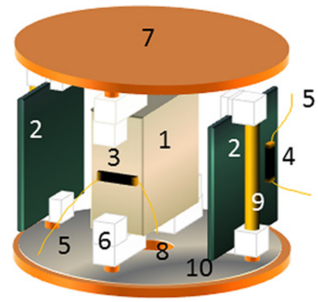

Fig. 1. Schematic view of the detector prototype, after removal of its cylindric Cu container: (1) $ZnMoO_4$ crystal ($\approx 15 \times 15 \times 5$ mm); (2) Square Ge light detectors (15 mm side and 0.5 mm thickness); (3) NTD thermistor glued on the $ZnMoO_4$ crystal; (4) NTD thermistor glued on the Ge slab; (5) ultra-thin gold wires (⊘50 μm) to read out signals form the thermistors; (6) PTFE holder of the $ZnMoO_4$ crystal; (7) Copper support of the detector (acting as heat sink); (8) α source; (9) PTFE/brass support of the Ge light detector; (10) light reflector.

$ZnMoO_4$ crystals of high quality were developed in the Nikolaev Institute of Inorganic Chemistry (Novosibirsk, Russia). The crystal synthetization was preceded by a deep chemical purification of molybdenum (in the form of MoO_3), with the objective to get rid of metal contamination, which may jeopardize the scintillation yield. $ZnMoO_4$ 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 $\oslash 40 \times 100$ mm [14]. Optical characterization of the samples, described in more details in [15], showed a broad emission spectrum under X-ray irradiation, peaking at around 625 nm at 8 K. The optical quality of the crystals resulted largely improved with respect to previous samples.

After these preliminary investigations, a detector prototype was designed, fabricated and cooled down to test its bolometric behaviour and the α/β rejection factor. The tests have been performed aboveground in the cryogenic laboratory of the University of Insubria (Como, Italy) and in the Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (Orsay, France). The realized detector (see Fig. 1) consists of a rectangular $ZnMoO_4$ crystal with a mass of 5.07 g, faced by two light-detecting ultrapure Ge thin slabs. The three bolometers are surrounded by a highly reflective polymeric multilayer foil (Radiant Mirror Film VM2000/VM2002 from 3M). The thermal signals from the $ZnMoO_4$ crystal and the two Ge slabs were read out by three nominally identical sensors, consisting of neutron transmutation doped (NTD) Ge thermistors [16], with a mass of ≈ 10 mg. The thermistor resistances and sensitivities are tuned for an optimal operation in the 20–30 mK range.

In some runs, radioactive sources were placed in the vicinity of the detector for calibration purposes. In particular, a collimated ^{241}Am source, characterized by a main α line at 5.48 MeV and an intense γ line at 59 keV, illuminated the $ZnMoO_4$ crystal at the center of a 15×5 mm face. Two weak ^{55}Fe sources, providing X-rays at 5.9 keV and 6.4 keV, irradiated the external side of each Ge slab.

The detector was operated at various base temperatures — between 25 and 32 mK — in two dilution refrigerators. The typical NTD thermistor resistances at the operation points which provided the best performance were of the order of 1 MΩ, with bias currents ranging between 2 and 5 nA. For the electronic readout, the NTD Ge thermistors were connected to low noise voltage amplifiers [17]. The cryostat in Orsay was equipped with a low-temperature front-end stage. The full waveforms of the signal were acquired and registered, and optimum filtering [18] was applied in order to maximize the detector energy resolution in an off-line analysis.