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CUPID: CUORE Upgrade with Particle IDentification

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Abstract. CUPID is a next generation Double Beta Decay experiment based on scintillating bolometers. The already developed CUORE infrastructure will become the site in which the new detector will be installed. The technology, successfully tested in Laboratory Nazionali del Gran Sasso by CUPID-0 and in Laboratoire Souterrain de Modane by CUPID-Mo, will provide the rejection capability that allows to reduce the background by two orders of magnitude with respect to CUORE one. This result will be achieved using enriched Li_2MoO_4 scintillating bolometers for the study of the ^{100}Mo isotope. The estimated discover sensitivity of CUPID for the effective neutrino Majorana mass is of the order of 20 meV .

1. Introduction

Among the techniques that date a long history in $0\nu2\beta$ search is that of thermal detectors, or bolometers, that today have in the CUORE their most advanced stage. When compared to the other techniques adopted in this field, bolometers stand out for two main features: the high energy resolution (second only to that of Ge diodes) and the granted possibility of a multi-isotope search. CUPID [1] (CUORE Upgrade with Particle IDentification) exploits this latter characteristic: by substituting the TeO_2 crystals used in CUORE [2] with Li_2MoO_4 ones the experiment will turn from a ^{130}Te search to a ^{100}Mo search, from a detector lacking any active background rejection capability to a detector able to identify the interacting particle. Two are the main advantages of this strategy, both contributing to an order of magnitude improved sensitivity: the high $Q_{\beta\beta}$ of ^{100}Mo (3.034 MeV) and the capability of particle identification.

2. From CUORE to CUPID

CUORE searches for ^{130}Te $0\nu2\beta$ with an array of 988 TeO_2 bolometers. The array weights 742 kg (206 kg of ^{130}Te) and is kept at $\sim$10 mK by a specially designed refrigerator. After a delicate and successful commissioning phase CUORE is now working with a 60% live time (physics data). This result marks a milestone in the history of bolometers since for long time their mass scalability was bring into question. Now we know that a ton scale detector is feasible and moreover that the number of read-out channels can be largely increased without compromising the cooling power of the refrigerator. This makes CUPID not only feasible but also scalable to a ton scale experiment. CUPID [1] will be an array of about 1500 scintillating

[1] Collaboration list in [1]

$Li_2{}^{100}MoO_4$ bolometers, the crystals will have a mass of 308 g each and will be grown with ^{100}Mo enriched material. The array, 472 kg in mass (253 kg of ^{100}Mo), will be deployed in the CUORE cryostat substituting the TeO_2 one. The goal is to reach a background counting rate of least 10^{-4} counts/(keV kg y) that corresponds to a 3σ discovery sensitivity of 12-20 meV on the neutrino Majorana mass $m_{\beta\beta}$(in 10 years exposure). This places CUPID in a good competitive position when compared with other next generation experiments, see Fig. 1.

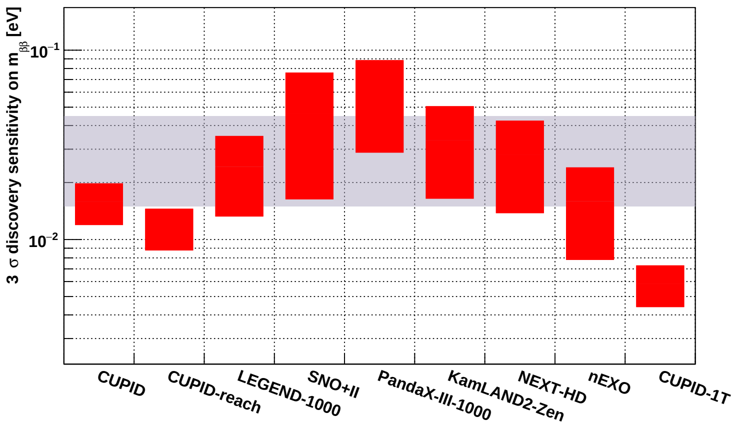

Figure 1. Discovery sensitivity for a selected set of next-generation ton-scale experiments. The grey shaded region corresponds to the parameter region allowed in the Inverted Hierarchy of the neutrino mass. The red error bars show the $m_{\beta\beta}$ values such that an experiment can make at least a 3σ discovery, within the range of the nuclear matrix elements for a given isotope. Parameters of the CUPID detector are discussed in the text. The parameters of the other experiments are taken from Refs. [3, 4, 5]

The big jump in sensitivity, compared to CUORE, is in the background reduction since the isotope mass does not change that much. In CUORE the limiting factor is the background counting rate of about 1.4 10^{-2} c/keV/kg/y in the ROI (^{130}Te transition energy is 2.5275 MeV). This is ascribed to two major components a γ and an α one. The γ contribution is dominated by the ^{208}Tl γ line at 2615 keV, with its multiCompton events that populate the region between the full-energy peak and the Compton-edge, exactly in the ROI. The other major background contribution is due α particles emitted from surface contaminations in ^{238}U, ^{232}Th and their progenies. These loose only a fraction of their total energy in the detector and produce an energy-flat counting rate extending from the full energy down toward the ROI. Both sources have been extensively studied in previous smaller scale TeO_2 experiments like Cuoricino and CUORE-0 [6] and were successfully reduced in CUORE thanks to accurate material selection&cleaning and to a detector design that reduced the amount of inert material between the crystals (a potential source of background) creating a closed packed array. All these solutions were successful, but they are not enough for a next generation experiments. A new strategy was therefore put on the table. An isotope with $Q_{\beta\beta}$ above the 2615 keV ^{208}Tl line makes γ background less relevant (still some contribution can come either from the cascade of the two γ's at 583 and 2615 keV or from a contribution due to ^{208}Tl β particles). Both ^{82}Se and ^{100}Mo match this requirement, moreover both have compounds that can be grown in single dielectric crystals with scintillating properties and scintillating bolometers can efficiently reject α induced events. Consequently the obvious evolution of CUORE is the substitution of the detector with a scintillating bolometer array.

2.1. Scintillating bolometers and CUPID

These devices are scintillating crystal instrumented for a double read-out, see Fig. 2. The phonon channel is fed by the particle energy lost in the Li_2MoO_4 crystal and converted into heat. Its read-out is done with a Ge thermistor specially developed for low temperature operation. Signal amplitude provides a precise measurement of energy, and is almost insensitive to particle type. The photon signal is due to that small fraction of deposited energy that excites scintillation centres; photons are detected by a Ge wafer operated as bolometric light detector. Both crystal scintillation light yield and time development of the scintillation signal are particle dependent, therefore can be used for particle identification.

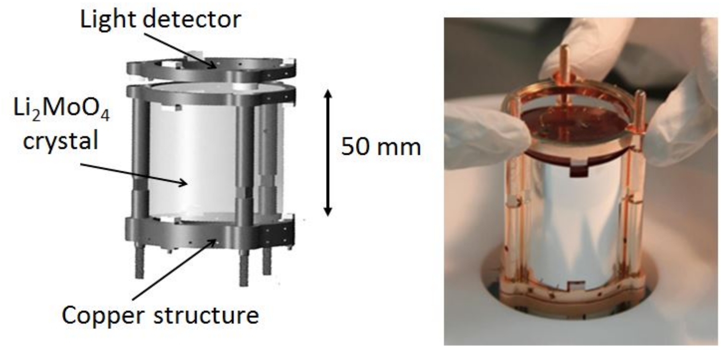

Figure 2. Left: schematic view of the CUPID single module according to the baseline design: a Li_2MoO_4. Right: photo of a CUPID-0 scintillating bolometer, prefiguring the CUPID single-module structure. The reflective foil surrounding the crystal is visible.

This technique is mature and was already adopted in two $0\nu2\beta$ experiments, CUPID-0 [7], using $Zn^{82}Se$ crystals, and CUPID-Mo [8], using $Li_2^{100}MoO_4$ crystals (see also articles in these proceedings). CUPID-0, performed in the underground Laboratory of Gran Sasso, was the first $0\nu2\beta$ experiment using scintillating bolometers, taking advantage of the excellent scintillation yield of ZnSe. Besides the competitive result on ^{82}Se half-life its importance for CUPID is twofold. First it proved that, even if on small scale, scintillating bolometers can be operated in stable conditions for long time. Second it gave detailed information concerning background composition. CUPID-0 gave the first direct prove that the flat background observed by CUORE is really due to energy-degraded α particles and allowed for the first time to look beyond this background thanks to its α rejection capability [9]. Unfortunately, ZnSe crystals are not easy to grow which translates in a moderate reproducibility and energy resolution that is 3-4 times worse than in TeO_2, in addition to a non-negligible internal contamination. Li_2MoO_4 on the contrary is easily grown in large highly-radiopure crystals with energy resolution comparable with CUORE [10]. Despite Li_2MoO_4 light yield is lower than that of ZnSe, its α rejection capability is by far compatible with CUPID requirements. CUPID-Mo, presently in operation at the Modane Underground Laboratory, have extensively tested the characteristics of $Li_2{}^{100}MoO_4$ scintillating bolometers, not only confirming the excellent energy resolution and α rejection power at a 20-module scale, but providing also clear indications on the extremely low bulk contamination achievable with these crystals.

3. CUPID design and background model

CUPID will use $Li_2{}^{100}MoO_4$ crystals, the baseline design assumes a cylindrical shape of the crystal that will be surrounded by a reflective foil. The crystal size is chosen in order to limit the intrinsic background due to $2\nu2\beta$ pile-up. Indeed, given the fast $2\nu2\beta$ decay time of $7.1\,10^{18}$ yr for molybdenum and the generally slow response time of bolometers, accidental pile-up of $2\nu2\beta$ events can contribute to the rate in the ROI at a detectable level, thus becoming a limiting factor for the sensitivity of the experiment.

The background counting rate expected in CUPID can be projected in a conservative data-driven approach. The hypotheses are the following (focusing only on relevant sources):

- a FWHM energy resolution of 5 keV at $Q_{\beta\beta}$ (CUPID-Mo detectors have a 7 keV resolution but in an optimized set-up this can be much improved)
- a light yield for γ/β particles of 0.74 keV and an α quenching of 0.209 (on the average what is measured in CUPID-Mo);
- $Li_2{}^{100}MoO_4$ bulk contaminations fully compatible to those measured by CUPID-Mo;
- $Li_2{}^{100}MoO_4$ surface contaminations identical to CUORE ones (crystal surface treatment will be done using the same materials selected for CUORE);
- a holder design and materials identical to that used in CUPID-0 (we use therefore CUPID-0 result for material contaminations);
- a background from the CUORE infrastructure defined on the basis of the preliminary results of CUORE background model;
- a $2\nu2\beta$ background based on the status-of-the-art technology of scintillating bolometers.

The result is a background counting rate of 10^{-4} counts/(keV kg y) dominated by the $2\nu2\beta$ pile-up . This is the background rate assumed in Fig 1 and labeled 'CUPID', it is extremely conservative. Since CUPID will start its construction within more than two years form now, it is very likely that some significant improvement especially on $2\nu2\beta$ induced background will be obtained. 'CUPID-reach' is the configuration of the experiment presented in Fig 1 that refers to a background rate of $2\,10^{-5}$ counts/(keV kg y).

4. Conclusions

CUPID is the natural evolution of CUORE. The mere substitution of the TeO_2 detector array with an array of $Li_2{}^{100}MoO_4$ scintillating bolometers, built using the present technology, implies the achievement of a ten times better sensitivity on the neutrino Majorana mass, almost covering the IH region. The cost of the experiment will be modest, when compared with its competitors, but the real strength of CUPID is that it does not imply a change in the mass scale of the experiment with all the related challenges and unknown. The timeline, the cost, the organization of the construction, assembly and commissioning will be basically a reproduction of what we have already done in CUORE. Finally, CUPID sensitivity here discussed is limited by the background counting rate and there are clear indications that improvements are possible, The increase in mass itself, achieving the 1 ton size, is an open option.

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