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$0\nu\beta\beta$ decay: the CUPID-0 experiment

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Abstract. CUPID-0 is an array of $24 \text{ Zn}^{82}\text{Se}$ scintillating bolometers used to search for the $0\nu\beta\beta$ decay of ^{82}Se . It is the first large mass $0\nu\beta\beta$ experiment exploiting a double read-out technique: the phonon signal to accurately measure particle energies and the light signal to reject the α -induced background. Its success might open the road to a next generation project of ton mass scale, CUPID. The array is in operation at Laboratori Nazionali del Gran Sasso since the beginning of 2017, in this paper we present the preliminary results obtained with an exposure of 10.45 kg·y.

1. Introduction

The search for $0\nu\beta\beta$ decay is challenging experimentalists since about half a century [1]. It is today commonly accepted that the key features of a ton-scale next generation experiment are isotopic enrichment and active background rejection. In the case of phonon detectors these two requirements can be simultaneously matched by the use of “scintillating bolometers” [2, 3]. This



technique dates back to the 90es but its application to $0\nu\beta\beta$ decay is recent, CUPID-0 is the first kg-scale $0\nu\beta\beta$ experiment ever realized. It is today in operation at Laboratori Nazionali del Gran Sasso (LNGS), L'Aquila, Italy.

The detector is an array of 26 ZnSe crystals, 24 made of ^{82}Se enriched material. Its design exploits a successful experience in operating TeO_2 bolometers arrays [4, 5, 6] and several years of R&D activities dedicated to the development of ZnSe enriched detectors [7, 8, 9].

The main physics goal is the investigation of $0\nu\beta\beta$ decay in ^{82}Se , signature of the decay is a monochromatic line, equivalent to an energy deposition of 2998 keV in the crystal (the ^{82}Se Q-value [10]). Exploiting the particle discrimination capability of the detector, events with a similar energy deposition but produced by α particles can be rejected with high efficiency. If successful, CUPID-0 would open the way for a CUORE Upgrade with Particle Identification (CUPID) [11].

2. The array

CUPID-0 array includes 26 ZnSe scintillating-bolometers and 31 Ge light detectors. 24 out of the 26 ZnSe crystals are made with 96% ^{82}Se enriched material. The total mass of Zn^{82}Se is 9.65 kg (corresponding to 5.28 kg of ^{82}Se) while the two natural crystals sum to 0.85 kg (corresponding to 40 g of ^{82}Se).

The ZnSe cylindrical single-crystals are instrumented to read-out the phonon signal produced by particle traversing their volume (with a design almost identical to that of TeO_2 bolometers). Disk shaped Ge wafers are used to read out the scintillation light emitted by the ZnSe crystals. These light detectors (LD) are operated as bolometers, they use a phonon sensor and a read-out chain that is very similar to the one serving the ZnSe bolometers but – thanks to the very small volume and hence the low heat capacity – are sensitive to energy depositions as low as few tens of eV.

The double read-out allows a precise measurement of particle energy deposition (using the phonon signal) and the discrimination of particles having different light yields (using the light signal). Indeed, while the the phonon signal is dependent only on the amount of energy deposited in the ZnSe bolometer, the scintillation photon production depends on the particle ionization properties. The result is a light signal with amplitudes and shapes that depend on the kind of interacting particle. Either the ratio between the light and the phonon signals or the shape of the light signal itself can be effectively used to discriminate highly ionizing particles like β/γ 's (including $0\nu\beta\beta$ generated β s) from α 's and nuclear recoils.

In CUPID-0, crystals are organized in 5 columns that hung from a copper disk (the detector support plate) mechanically secured to the cold finger of the dilution refrigerator through an anti-vibration suspension system. In each column, the ZnSe crystals are stacked one over the other being separated by a LD. In this way each ZnSe bolometer is viewed by two LD's. A reflective foil surrounds the lateral part of the ZnSe cylinders to improve light collection.

All the materials used in the construction of the array (mainly made of PTFE¹ and NOSV² copper) were selected for their low radioactive contamination in Th and U. Assembly procedures followed very strict protocols in order to avoid recontaminations. The array stands, at about 10 mK, in the inner vacuum chamber of the Oxford Instrument dilution refrigerator formerly used by Cuoricino [4] and CUORE-0 [5], the same shielding system used in these experiment serves now CUPID-0 (details on cryostat and shield design and contamination can be found [12]).

¹ PolyTetraFluoroEthylene.

² A special copper alloy suitable for cryogenic use produced by Aurubis company.

3. Commissioning and operation

Commissioning started in October 2016 with an optimization of the vibrational and cryogenic configurations of the refrigerator. Following, the electronic read-out and DAQ systems were optimized. The first physics run started at the beginning of 2017, it resulted characterized by large instabilities of the cryogenic system therefore requiring an “ad hoc” tuning of the signal processing algorithms which is still not perfectly satisfactory. The following run started only after a further optimisation of the system that fixed most of the instability problems.

Here we report the results collected in these two runs, totalling an exposure of 1.46 kg·y on enriched ZnSe crystals. One out of the two natural crystals and two enriched ones had poor performances and are excluded from the analysis. These results are really preliminary, in particular for the above mentioned reasons the first physics run will be likely excluded from the final data-release.

4. Preliminary results of CUPID-0

The phonon signal, used for energy measurement, shows a noise figure corresponding to a 0.4 keV FWHM, mainly dominated by vibrational noise. We observe a worsening of the energy resolution with increasing energy, likely due to crystal quality. In the ^{232}Th calibration, we measure an average FWHM of ~ 25 keV for the 2615 keV peak due to ^{208}Tl . The FWHM extrapolated at the ^{82}Se Q-value is ~ 28 keV. A study for a better description of the peak shape (here simply represented with a gaussian function) is under-way and may lead to slightly different FWHM values.

As already done for a small test array operated in 2015 [9], we verified that the most efficient and reliable way to discriminate between β/γ and α particles relies on the shape of the LD signal (ascribed to the different characteristic time associated to the scintillation light emitted by ZnSe crystals when excited by β/γ or α particles).

The processing-chain applies to triggered events a set of cuts consisting in:

- (i) a single-hit cut that removes events where more than one ZnSe crystal triggered. These are either spurious pulses or radioactivity induced signals.
- (ii) pulse shape cuts that reject pulses deformed by noise and pile-up (since the algorithm used to evaluate pulse amplitude could fail).
- (iii) a cut based on the shape of the light signal and used to reject α induced events.

The energy spectrum of events surviving the first two cuts is shown in figure 1 in gray, those surviving also the third cut are shown in blue.

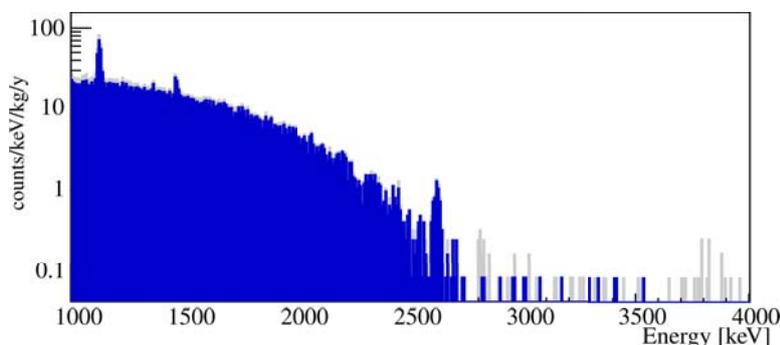


Figure 1. Energy spectrum of single-hit events surviving pulse shape cuts (gray) and superimposed that of events surviving also the α rejection cut (blue).

The spectrum is clearly dominated by the $2\nu\beta\beta$ decay of ^{82}Se . Visible peaks are the lines of ^{40}K at 1460 keV and that of ^{208}Tl at 2615 keV, both due to natural radioactivity. The line at 1115 keV is ascribed to ^{65}Zn , a short lived isotope produced in ZnSe by cosmogenic activation. At the right of the 2615 keV line, the counting rate is dramatically reduced.

Between 2.8 and 3.2 MeV the counting rate is $(52 \pm 9) \cdot 10^{-3}$ cts/(keV·kg·y) on the gray spectrum and is reduced to $(15 \pm 5) \cdot 10^{-3}$ cts/(keV·kg·y) in the blue one (i.e after α particle rejection). In this region we observe an α peak (at about 2.8 MeV) and an α continuum (gray events) plus few β/γ events (blue events) that appear to form a flat continuum. Most of the residual β/γ events are removed applying a delayed coincidence cut. This is optimized to remove what we think is the major source of these counts: β or $\beta + \gamma$ events from ^{208}Tl decay. We use the α particle emitted by ^{208}Tl precursor, ^{212}Bi , to tag and remove events that are likely due to this decay chain. Between 2.8 and 3.2 MeV only three events survive this cut (see figure 2) therefore the counting rate is in the range $[1.8 - 8.6] \cdot 10^{-3}$ cts/(keV·kg·y) (Poisson 68% C.L. interval).

The probability that a $0\nu\beta\beta$ event is accidentally removed from the final spectrum by one of the above mentioned cuts is $\sim 85\%$ (however we are working on an improvement of the efficiency of the cuts and very likely we can approach a better than 90% efficiency). Finally the probability of a full containment of both the two electrons emitted in a $0\nu\beta\beta$ decay is $\sim 80\%$ (in the residual 20% cases at least one of the two electrons escape the source crystal that consequently records an event below the Q-value).

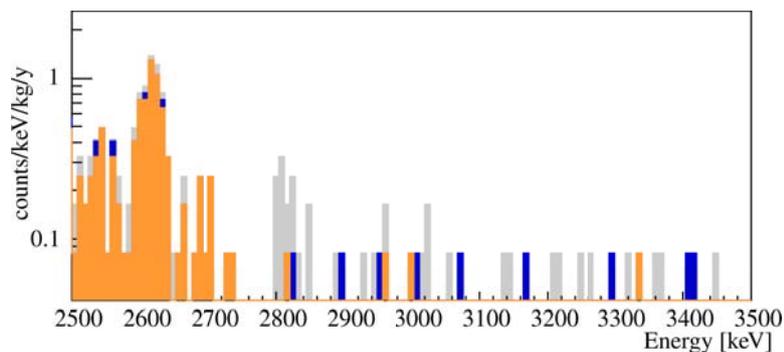


Figure 2. Detailed view near the $0\nu\beta\beta$ region of the energy spectrum of figure 1. Events surviving the delayed coincidence cut are shown in yellow. The $0\nu\beta\beta$ decay peak should appear at 2998 keV.

5. Conclusions

CUPID-0 started the physics run in early 2017, it is expected to run at least for 1 y of live-time to prove the potentialities of the scintillating bolometers technology. The high number of emitters will allow to reach a remarkable sensitivity on the ^{82}Se $0\nu\beta\beta$ decay. Preliminary result on the background counting rate near the region of interest indicate the achievement of an extremely low background.

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