Final results of the CUPID-0 Phase I experiment

N Casali[1,*], O Azzolini[2], J W Beeman[3], F Bellini[1,4], M Beretta[5,6], M Biassoni[6], C Brofferio[5,6], C Bucci[7], S Capelli[5,6], L Cardani[1], P Carniti[5,6], D Chiesa[5,6], M Clemenza[5,6], O Cremonesi[6], A Cruciani[1], I Dafinei[1], S Di Domizio[8,9], F Ferroni[1,10], L Gironi[5,6], A Giuliani[11,12], P Gorla[7], C Gotti[5,6], G Keppel[2], M Martinez[1,4], S Nagorny[7,10], M Nastasi[5,6], S Nisi[7], C Nones[13], D Orlandi[7], L Pagnanini[5,6], M Pallavicini[8,9], L Pattavina[7], M Pavan[5,6], G Pessina[6], V Pettinacci[1,4], S Pirro[7], S Pozzi[5,6], E Previtali[5,6], A Puiu[5], C Rusconi[7,14], K Schäffner[7,10], C Tomei[1], M Vignati[1] and A S Zolotarova[13]

[1] INFN, Sezione di Roma, P.le Aldo Moro 2, 00185, Roma, Italy
[2] INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro (Pd) - Italy
[3] Lawrence Berkeley National Laboratory , Berkeley, California 94720, USA
[4] Dipartimento di Fisica, Sapienza Università di Roma, P.le Aldo Moro 2, 00185, Roma, Italy
[5] Dipartimento di Fisica, Università di Milano Bicocca, I-20126 Milano - Italy
[6] INFN Sezione di Milano - Bicocca, I-20126 Milano - Italy
[7] INFN Laboratori Nazionali del Gran Sasso, I-67100 Assergi (AQ) - Italy
[8] INFN Sezione di Genova, I-16146 Genova - Italy
[9] Dipartimento di Fisica, Università di Genova, I-16146 Genova - Italy
[10] Gran Sasso Science Institute, 67100, L'Aquila - Italy
[11] CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Universitè Paris-Saclay, 91405 Orsay, France
[12] DISAT, Università dell'Insubria, 22100 Como, Italy
[13] IRFU, CEA, Universit*é* Paris-Saclay, F-91191 Gif-sur-Yvette, France

E-mail: `nicola.casali@gmail.com`

Abstract.
A convincing observation of neutrino-less double beta decay (0νDBD) relies on the possibility of operating high-energy resolution detectors in background-free conditions. Scintillating cryogenic calorimeters are one of the most promising tools to fulfill the requirements for a next-generation experiment. Several steps have been taken to demonstrate the maturity of this technique, starting form the successful experience of CUPID-0. The CUPID-0 experiment collected almost 10 kg y of exposure, running 26 Zn^{82}Se crystals during two years of continuous detector operation. The complete rejection of the dominant α background was demonstrated, measuring the lowest counting rate in the region of interest for this technique. Furthermore, the most stringent limit on the ^{82}Se 0νDBD was established. In this contribution we present the final results of CUPID-0 phase-I, including a detailed model of the background and the measurement of the 2νDBD half-life.

1. Introduction

The neutrino-less double beta decay [1] (0νDBD) is the most sensitive process able to unveil the Majorana nature of neutrino [2]. Furthermore, its observation would be an incontrovertible evidence of the non conservation of the lepton number. Finally, many theoretical models [3] explaining the matter antimatter asymmetry occurred in the early universe require the Majorana nature of neutrinos. For all these reasons, there is an increasing interest in the search for this process exploiting several technologies [4, 5, 6, 7, 8]. Despite the experimental effort the 0νDBD was never observed: the current limits on its half-life are of the order of 10^{25}-10^{26} yr, depending on the isotope. Next generation experiments aim to achieve a sensitivity on the half-life of the process of the order of 10^{27} yr improving their current technologies [9]. First proposed by Fiorini and Niinikoski [10], in the last years cryogenic calorimeters proved to be among the most promising techniques for 0νDBD search. Furthermore, the particle identification capability offered by the dual read-out of heat and light allows a strong reduction of the background in the energy region of interest. Indeed, thanks to the dual read-out of a scintillating cryogenic calorimeter, as proposed by Pirro [11], the background can be dramatically reduced disentangle the β/γ interactions from the α ones. The CUPID-0 detector is the first medium scale demonstrator of such technique.

2. CUPID-0

Assembled at the and of 2016, CUPID-0 was cooled-down in the Underground Laboratory of Gran Sasso at the beginning of 2017.

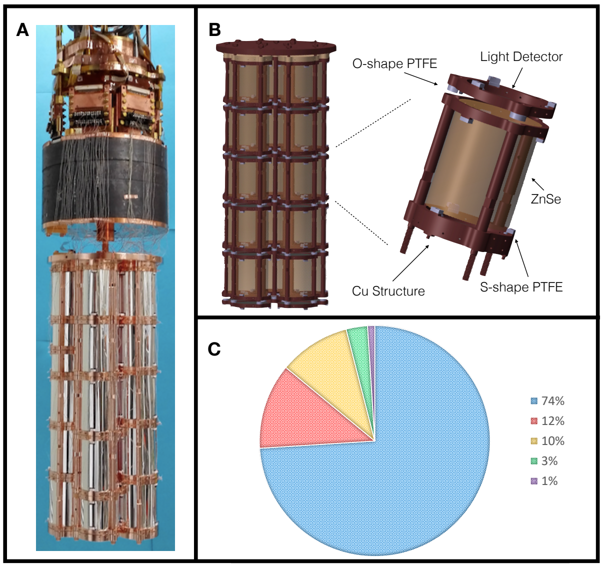

Figure 1. A: The CUPID-0 detector anchored to the dilution refrigerator located in the Hall A of Underground Laboratory of Gran Sasso. B: Detector and single module design. C: Duty cycle of CUPID-0 in the phase-I data taking: 74% - physics data; 12% - system maintenance; 10% - ^{232}Th energy calibration; 3% - ^{56}Co energy calibration; 1% - AmBe source.

The detector is composed by 26 ZnSe scintillating calorimeters (24 enriched in ^{82}Se at 95% level and the remaining two natural) each one surrounded by a VIKUITI reflective foil and monitored by two light detectors consisting in Ge slabs operated as cryogenic calorimeters (see Fig 1 A and B). The details on the detector construction and commissioning can be found in Ref. [12]. In Fig. 1 C the duty-cycle of the detector in the first phase data taking (from June 2017 to December 2018) is showed. The data collected are divided in 9 data sets each one characterized by its own energy resolution, event selection efficiency and exposure. At both beginning and end of each data set, energy calibration runs are performed exploiting ^{232}Th γ source. The evaluation of the detector performances as well as the analysis technique used are described in details in Ref. [13, 14, 15]. The total exposure collect in the 9 data sets results 9.95 kg y of $Zn^{82}Se$, corresponding to 3.88×10^{25} ^{82}Se atoms yr.

3. Physics results

As detailed in Ref. [13] we applied three types of events selection cuts to the data acquired: the first one rejecting no particle-like events (electronic noise, spikes, pile-up events, etc), the second one rejecting the alpha particle interactions, and the final one rejecting the β/γ interactions coming from internal contaminations of ^{208}Tl tagging the α decay of its mother (^{212}Bi). The corresponding three energy spectra are shown in Fig. 2 left. The 0νDBD of ^{82}Se is expected

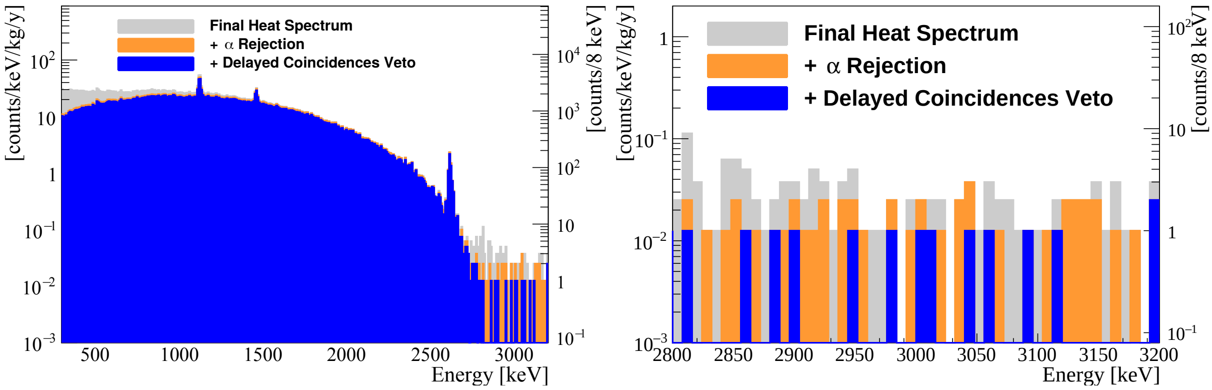

Figure 2. Energy spectra corresponding to 9.95 kg y of $Zn^{82}Se$ exposure in two energy windows. The grey histogram is the spectrum obtained with the selection on $Zn^{82}Se$ thermal pulses. The filled orange histogram includes the α rejection through the LD pulse shape. The filled blue histogram is the final spectrum after the rejection of the delayed coincidences with ^{212}Bi events.

as a mono-energetic peak at the Q-value of the reaction (2997.9$\pm$0.3 keV [16]). Therefore, we selected a symmetric energy region around the Q-value (see Fig. 2 right) to evaluate the background index in the energy region of interest. In this energy region 14 events survived all the cuts. This corresponds to a background index of $(3.5^{+1.0}_{-0.9}) \times 10^{-3}$ counts/(keV kg yr), the lowest achieved by a cryogenic calorimeter experiment [17]. Then, since we found no evidence of 0νDBD, we put a Bayesian lower limit on the ^{82}Se half-life of $T^{0\nu}_{1/2} > 3.5 \times 10^{24}$ yr at 90% C.I. [17].

In order to understand the sources of the residual background we developed a detailed background model able to accurately reproduce the collected data [18]. Thanks to this model, along with the high signal-to-noise of the acquired two neutrino double beta decay (2νDBD) spectrum, we performed the most precise measurements of the 2νDBD half-life of ^{82}Se [20]. Furthermore studing the shape of 2νDBD we also set an upper limits on the Lorentz violating term in such nuclear transition [19] and established which nuclear model better reproduces the collected data (see Ref. [20] for more details).

Finally, the background model allowed to recognize that the main contribution in the ROI is due to μ interactions: $(1.53\pm0.13\ \text{stat}\pm0.25\ \text{syst})\times10^{-3}$ counts/(keV kg yr). The contaminations of the crystals dominate the residual one.

4. Conclusions and future perspectives

The CUPID-0 detector, the first demonstrator of the scintillating calorimeter technique, have concluded at the end of 2018 the first phase of data taking collecting an exposure of 9.95 kg y of $Zn^{82}Se$. The results concerning the most stringent limits on the ^{82}Se 0νDBD both on excited and ground states of ^{82}Kr are published respectively in Ref [21] and [17]. Concerning the 2νDBD we collected the energy spectrum with the best signal-to-noise ratio reported in literature. This allowed to measure the ^{82}Se 2νDBD half-life with unprecedented precision [20], and to accurately study the possible spectrum distortion caused by a Lorentz violating term in nuclear transition [20] or by the nuclear model describing the transition [20]. In order to assess the individual contributions to the measured background, at the beginning of 2019 we upgraded the CUPID-0 detector by installing a muon veto and removing the reflecting foil that prevents the analysis of coincidences of surface events among crystals. In such a way, we plan to improve the capability of recognizing the sources of the β/γ background measured by CUPID-0. Measuring residual background contributions with such a high sensitivity will be of crucial importance in anticipation of the next-generation CUPID experiment [22]. The phase II data taking began in June 2019 and it is smoothly ongoing.

5. Acknowledgment

This work was supported by the European Research Council (FP7/2007-2013), Contract No. 247115 and by Istituto Nazionale di Fisica Nucleare.

References

[1] W. H. Furry, Phys.Rev.Lett. **56**, 1184 (1936).
[2] J. Schechter, J. W. F Valle, Phys. Rev. D **25**, 2951 (1982). DOI 10.1103/PhysRevD.25.2951.
[3] S. Dell'Oro *et al.*, Adv. High Energy Phys. **2016**, 2162659 (2016). DOI 10.1155/2016/2162659
[4] J. B. Albert *et al.* [EXO Collaboration], Phys. Rev. Lett. **120** no.7, 072701 (2018). DOI 10.1103/PhysRevLett.120.072701.
[5] [KamLAND-Zen Collaboration], Phys. Rev. Lett. **117** no.8, 082503 (2016), Addendum: [Phys. Rev. Lett. **117** no.10, 109903(E) (2016)]. DOI 10.1103/PhysRevLett.117.109903, DOI 10.1103/PhysRevLett.117.082503.
[6] C. E. Aalseth *et al.* [Majorana Collaboration],Phys. Rev. Lett. **120** no.13, 132502 (2018). DOI 10.1103/PhysRevLett.120.132502.
[7] C. Alduino *et al.* [CUORE Collaboration], Phys. Rev. Lett. **120** no.13, 132501 (2018). DOI 10.1103/PhysRevLett.120.132501.
[8] M. Agostini *et al.* [GERDA Collaboration], Phys. Rev. Lett. **120** no.13, 132503 (2018). DOI 10.1103/PhysRevLett.120.132503.
[9] O. Cremonesi and M. Pavan, Adv. High Energy Phys. **2014** 951432 (2014). DOI 10.1155/2014/951432.
[10] E. Fiorini and T.O. Niinikoski, Nucl. Instr. and Methods in Physics Research A **224**, 83 (1984).
[11] S. Pirro, *et al.*, Phys. Atom. Nucl. **69**, 2109 (2006). DOI 10.1134/S1063778806120155.
[12] O. Azzolini *et al.* [CUPID Collaboration], Eur. Phys. J. C **78** 428 (2018). DOI 10.1140/epjc/s10052-018-5896-8.
[13] O. Azzolini *et al.*, Eur. Phys. J. C **78** no.9, 734 (2018). DOI 10.1140/epjc/s10052-018-6202-5
[14] M. Beretta *et al.*, arXiv:1901.10434 [physics.ins-det].
[15] C. Alduino *et al.* [CUORE Collaboration], Phys. Rev. C **93** no.4, 045503 (2016). DOI 10.1103/PhysRevC.93.045503
[16] D.L. Lincoln *et al.*, Phys.Rev.Lett. **110**, 012501 (2013). DOI 10.1103/Phys. Rev. Lett.110.012501.
[17] O. Azzolini *et al.* [CUPID Collaboration], Phys. Rev. Lett. **123**, no. 3, 032501 (2019). DOI 10.1103/PhysRevLett.123.032501
[18] O. Azzolini *et al.* [CUPID Collaboration], Eur. Phys. J. C **79**, no. 7, 583 (2019). DOI 10.1140/epjc/s10052-019-7078-8
[19] O. Azzolini *et al.* [CUPID Collaboration], Phys. Rev. D **100**, 092002 (2019). DOI 10.1103/PhysRevD.100.092002
[20] O. Azzolini *et al.*, submitted to Phys. Rev. Lett. arXiv:1909.03397 [nucl-ex].
[21] O. Azzolini *et al.* [CUPID Collaboration], Eur. Phys. J. C **78**, no. 11, 888 (2018). DOI 10.1140/epjc/s10052-018-6340-9
[22] W. R. Armstrong *et al.* [CUPID Collaboration], arXiv:1907.09376 [physics.ins-det].