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Communication

Result on the Neutrinoless Double Beta Decay Search of ^{82}Se with the CUPID-0 Experiment

Fabio Bellini [1,2,*], Oscar Azzolini [3], Maria Teresa Barrera [3], Jeffrey Beeman [4], Mattia Beretta [5,6], Matteo Biassoni [6], Chiara Brofferio [5,6], Carlo Bucci [7], Lucia Canonica [8], Silvia Capelli [5,6], Laura Cardani [2], Paolo Carniti [5,6], Nicola Casali [2], Lorenzo Cassina [5,6], Massimiliano Clemenza [5,6], Oliverio Cremonesi [6], Angelo Cruciani [2], Antonio D'Addabbo [7,9], Ioan Dafinei [2], Sergio Di Domizio [10,11], Fernando Ferroni [2,9], Luca Gironi [5,6], Andrea Giuliani [12,13], Paolo Gorla [7], Claudio Gotti [5,6], Giorgio Keppel [3], Maria Martinez [14], Silvio Morganti [2], Sergei Nagorny [4], Massimiliano Nastasi [5,6], Stefano Nisi [7], Claudia Nones [15], Donato Orlandi [7], Lorenzo Pagnanini [5,6], Marco Pallavicini [9,10], Vincenzo Palmieri [4,†], Luca Pattavina [8,16], Maura Pavan [5,6], Gianluigi Pessina [6], Valerio Pettinacci [2], Stefano Pirro [7], Stefano Pozzi [5,6], Ezio Previtali [6], Andrei Puiu [5,6], Claudia Rusconi [7,17], Karoline Schäffner [7,9], Claudia Tomei [2], Marco Vignati [2] and Anastasia Zolotarova [15]

1. Dipartimento di Fisica, Sapienza Università di Roma, P.le Aldo Moro 2, 00185 Roma, Italy
2. INFN, Sezione di Roma, P.le Aldo Moro 2, 00185 Roma, Italy; laura.cardani@roma1.infn.it (L.C.); nicola.casali@roma1.infn.it (N.C.); angelo.cruciani@roma1.infn.it (A.C.); ioan.dafinei@roma1.infn.it (I.D.); fernando.ferroni@roma1.infn.it (F.F.); silvio.morganti@roma1.infn.it (S.M.); valerio.pettinacci@lngs.infn.it (V.P.); claudia.tomei@roma1.infn.it (V.T.); marco.vignati@roma1.infn.it (M.V.)
3. INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro (Pd), Italy; oscar.azzolini@lnl.infn.it (O.A.); barrera@lnl.infn.it (M.T.-B.); giorgio.keppel@lnl.infn.it (G.K.)
4. Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA; beeman@lbl.gov (J.W.B.); nagorny@lngs.infn.it (S.N.); Vincenzo.Palmieri@lnl.infn.it (V.P.)
5. Dipartimento di Fisica, Università di Milano Bicocca, I-20126 Milano, Italy; mattia.beretta@mib.infn.it (M.B.); chiara.brofferio@mib.infn.it (C.B.); silvia.capelli@mib.infn.it (S.C.); paolo.carniti@mib.infn.it (P.C.); lorenzo.cassina@mib.infn.it (L.C.); massimiliano.clemenza@mib.infn.it (M.C.); luca.gironi@mib.infn.it (L.G.); claudio.gotti@mib.infn.it (C.G.); massimiliano.nastasi@mib.infn.it (M.N.); lorenzo.pagnanini@mib.infn.it (L.P.); maura.pavan@mib.infn.it (M.P.); stefano.pozzi@mib.infn.it (S.P.); andrei.puiu@mib.infn.it (A.P.)
6. INFN Sezione di Milano Bicocca, I-20126 Milano, Italy; matteo.biassoni@mib.infn.it (M.B.); oliviero.cremonesi@mib.infn.it (O.C.); gianluigi.pessina@mib.infn.it (G.P.); ezio.previtali@mib.infn.it (E.P.)
7. INFN Laboratori Nazionali del Gran Sasso, I-67100 Assergi (AQ), Italy; carlo.bucci@lngs.infn.it (C.B.); antonio.daddabbo@lngs.infn.it (A.D.); paolo.gorla@lngs.infn.it (P.G.); stefano.nisi@lngs.infn.it (S.N.); donato.orlandi@lngs.infn.it (D.O.); stefano.pirro@lngs.infn.it (S.P.); claudia.rusconi@mib.infn.it (C.R.); karoline.schaeffner@lngs.infn.it (K.S.)
8. Physik Department, Technische Universität München, D85748 Garching, D-80805 München, Germany; lucia.canonica@lngs.infn.it
9. Gran Sasso Science Institute, 67100 L'Aquila, Italy; luca.pattavina@lngs.infn.it
10. Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy; sergio.didomizio@ge.infn.it (S.D.D.); marco.pallavicini@mib.infn.it (M.P.)
11. INFN Sezione di Genova, I-16146 Genova, Italy
12. CNRS/CSNSM, Centre de Sciences Nucléaires et de Sciences de la Matière, 91405 Orsay, France; andrea.giuliani@csnsm.in2p3.fr
13. DISAT, Università dell'Insubria, 22100 Como, Italy
14. Fundacion ARAID and U. Zaragoza, C/ Pedro Cerbuna 12, 50009 Zaragoza, Spain; maria.martinez@roma1.infn.it
15. IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France; claudia.nones@cea.fr
16. Max-Planck-Institut für Physik, D-80805 München, Germany
17. Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA; anastasiia.zolotarova@cea.fr

* Correspondence: fabio.bellini@roma1.infn.it

† Deceased.

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Abstract: CUPID-0 is the first large array of scintillating $Zn^{82}Se$ cryogenic calorimeters (bolometers) implementing particle identification for the search of the neutrinoless double beta decay ($0\nu\beta\beta$). The detector consists of 24 enriched $Zn^{82}Se$ bolometers for a total ^{82}Se mass of 5.28 kg and it has been taking data in the underground LNGS (Italy) since March 2017. In this article we show how the dual read-out provides a powerful tool for the α particles rejection. The simultaneous use of the heat and light information allows us to reduce the background down to $(3.2^{+1.3}_{-1.1})\times10^{-3}$counts/(keV kg year), an unprecedented level for cryogenic calorimeters. In a total exposure of 5.46 kg year $Zn^{82}Se$ we set the most stringent limit on the $0\nu\beta\beta$ decay ^{82}Se half-life $T^{0\nu}_{1/2} > 4.0 \times 10^{24}$ year at 90% C.I.

Keywords: neutrinoless double beta decay; $Zn^{82}Se$ scintillating cryogenic calorimeters; Majorana neutrino

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1. Introduction

The neutrinoless double beta deca $0\nu\beta\beta$ [1] is a transition, in which a nucleus (A, Z) decays into its isobar (A, Z + 2) with the simultaneous emission of two electrons. Both the parent and the daughter nucleus must be more bound than the intermediate one (A, Z + 1) in order to avoid the occurrence of the sequence of two single beta decays. Such a condition, due to the pairing term, is fulfilled in nature for 35 even-even nuclei [2]. This process violates the lepton number by two units; it's not allowed by the Standard Model of interactions but it's envisaged in many of its extensions in which neutrinos are their own antiparticles [2]. Its discovery would establish unambiguously the nature of neutrinos as Majorana fermions [3]. In the standard paradigma [2,4] the decay is mediated only by the exchange of three virtual light neutrinos between two charged weak interaction vertices. The chirality mismatch imposed by the V-A structure of the ElectroWeak theory leads to an amplitude proportional to a linear combination of the three neutrino masses. Their squared mass differences are known from neutrino oscillation experiments $\Delta m^2_{12} = m^2_{\nu_2} - m^2_{\nu_1} \sim 7 \times 10^{-5}\text{eV}^2$, $\Delta m^2_{23} = m^2_{\nu_3} - m^2_{\nu_2} \sim 2 \times 10^{-3}\text{eV}^2$ [4–6] and their sum is constrained to be less than 0.66 eV at 95% C.L. from cosmological observations but the absolute scale is still unknown [4–6]. Three possible orderings are therefore conceivable: normal hierarchy (NH), in which $m_{\nu1} < m_{\nu2} < m_{\nu3}$, inverted hierarchy (IH) where $m_{\nu3} < m_{\nu1} < m_{\nu2}$, and the quasi-degenerate hierarchy (QD), for which masses differences are tiny compared to their absolute values.

At present, no $0\nu\beta\beta$ evidence has been found and actual limits on the decay half-life, in the range of (10^{24}–10^{26}) years [5–13], are probing the QD region. The main signature of the $0\nu\beta\beta$ decay is a peak in the sum energy spectrum of the electrons at the Q-value of the reaction which must be resolved over a continuous background [5]. In order to completely explore the IH region ($\tau \approx 10^{27-28}$ years), new technologies must be developed, able to reduce the specific background close to zero at the ton $\times$ year exposure scale in combination with a sensitive mass of hundreds of kg of isotope and a FWHM energy resolution better than 0.5% [5,14].

Cryogenic calorimeters (usually called bolometers) play an important role in this field of research [15,16] and in this contribution we review the most recent results obtained by the CUPID-0 experiment.

2. The Detector

A bolometer [17,18] is a single crystal calorimeter operating at $\sim$10 mK in which the temperature increase, following an energy release inside the crystal itself, is picked-up by a highly sensitive thermometer. This technology allows us to embed the $0\nu\beta\beta$ source in the detector itself and it exhibits excellent energy resolution and very high detection efficiency. One-Ton scale detectors composed of a thousand bolometers could be successfully operated as demonstrated by the CUORE experiment [11,19]. The CUORE sensitivity is limited by the residual background generated by energy-degraded α particles emitted by surface contaminations of the detector material. To suppress α particles the CUPID-0 experiment makes use of scintillating bolometers [20–22] in which a small fraction of the released energy is converted into scintillating light. The light escapes the crystal and it is absorbed by a thin bolometer working as light detector. The dual read-out allows us to identify the particle type because α particles have a different light yield and scintillation time-development compared to iso-energetic electrons [23–27].

The CUPID-0 detector is an array of $Zn^{82}Se$ bolometers, enriched in ^{82}Se at $\sim$95% [28–30]. The isotope under study for the $0\nu\beta\beta$ decay is ^{82}Se with a $Q_{\beta\beta}$= 2997.9 $\pm$ 0.3 keV [31], well above the energy of the most intense natural high-energy $^{208}Tl\gamma$ line at 2615 keV. The $2\nu\beta\beta$ decay of ^{82}Se, allowed by the Standard Model, has a life time $\tau_{1/2}$ = (9.39 $\pm$ 0.17(stat) $\pm$ 0.58(syst))$\times 10^{19}$ year [32] longer enough to reduce to a negligible level the background induced by the pile-up of two $2\nu\beta\beta$ events in the region of interest. The array consists of 24 $Zn^{82}Se$ crystals for a total mass of 9.65 kg, corresponding to 5.13 kg of ^{82}Se and two natural ZnSe crystals (40 g of ^{82}Se mass) not used in the analysis. The number of ^{82}Se nuclei under investigation is (3.41 $\pm$ 0.03) $\times$ 10^{25} excluding two crystals featuring poor performances. Each $Zn^{82}Se$ is held in a copper frame by means of small PTFE supports and surrounded by a 3 M Vikuiti plastic reflector to enhance the light collection. The light detector (LD) is a 170-µm-thick Ge disk [33] working as a bolometer. One side of the LD is coated with a SiO 60-nm-thick layer to enhance light absorption [34].

Both the LD and Zn^{82} are equipped with an NTD -Ge thermistor sensor [35], acting as temperature-voltage transducer, and a Si Joule heater [36], which periodically injects a fixed amount of energy to equalise the bolometer gain [37,38].

The signal, amplified and filtered by a six-pole anti-aliasing active Bessel [39–44], is recorded by an 18 bit ADC board operating at 1(2) kSPS for the $Zn^{82}Se$ (LD). The detector is anchored to the mixing chamber of an Oxford 1000 $^3He/^4He$ dilution refrigerator [45] operating at a temperature of about 10 mK and located in Hall A of the Laboratori Nazionali del Gran Sasso (average depth $\sim$3650 m water equivalent [46]).

The CUPID-0 detector cool down began in January 2017 and, after a period of commissioning it reached stable data taking beginning in May 2017. Here we report the analysis obtained with an a $Zn^{82}Se$ exposure of 5.46 kg year. The results of the first 3.44 kg year data have been published in Ref. [47].

3. Data Analysis and Results

We acquire the complete data stream for both the $Zn^{82}Se$ and the light detector. For the ZnSe, we implement a derivative software trigger while pulses produced by the Joule heater are flagged by the data acquisition system. The waveform is analysed 4 s after the trigger and 1 s before (baseline).

We use the optimum filter algorithm [48,49] to infer the pulse amplitude and the shape parameters. The amplitude is corrected for any shift in thermal gain using the reference pulse injected by the heater every 400 s [37] and the baseline to estimate the detector temperature. We find the amplitude-energy conversion using the most intense γ lines produced by a ^{232}Th source [47,50].

We discard events on the $Zn^{82}Se$ inconsistent with the filter signal template and events on different bolometers if they occur within 20 ms since they are most likely induced by multiple Compton γ's.

The LD signal amplitude and shape is estimated applying the optimum filter at a fixed time delay compared to the $Zn^{82}Se$ heat signal as detailed in Ref. [51]. We build a light shape parameter [27] and we optimize the selection in order to have a unitary efficiency while rejecting the α background and shown in Figure 1. Finally we suppress the background induced by the internal $^{208}Tl\beta/\beta + \gamma$ decay to ^{212}Pb ($\tau_{1/2}$ = 3.01 min) tagging the ^{212}Bi (^{208}Tl mother) which α decays with a Q_α = 6207 keV. If the contamination is close to the surface and the α escapes the crystal, only part of the energy of the parent decay is collected. We therefore require the α particle to be in the energy range 2.0–6.5 MeV.

The resulting background index in the region of interest 2800–3200 keV, after the whole selection, results to be BI = $(3.2^{+1.3}_{-1.1}) \times 10^{-3}$counts/(keV kg year).

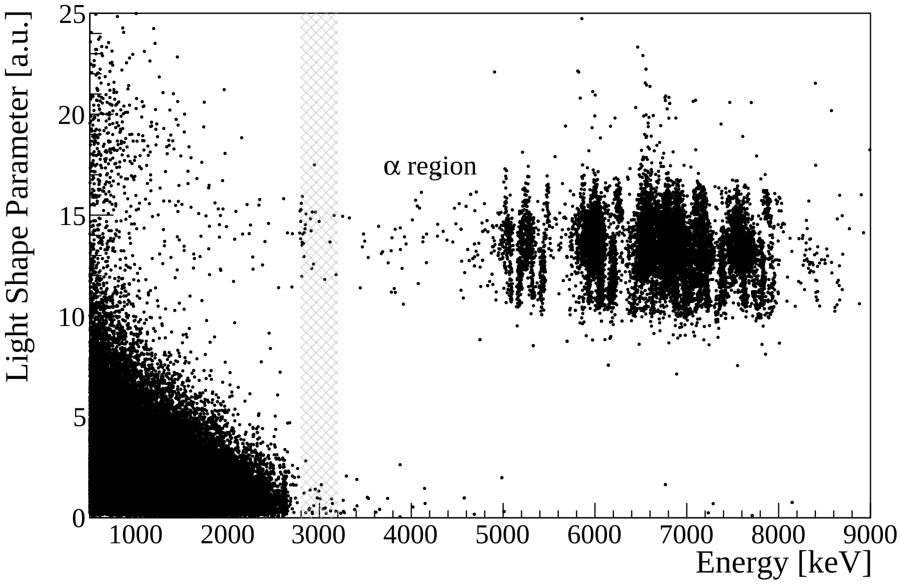

Figure 1. Light shape parameter as a function of the energy released in the ZnSe (all crystals). The dashed vertical band region identifies the 400 keV region centered around the ^{82}Se $Q_{\beta\beta}$ used for the $0\nu\beta\beta$ analysis and for the background evaluation. The α events are concentrated in the right upper region while β/γ events populate the left lower corner. The Figure is adapted from Ref. [50].

The total efficiency on the signal $0\nu\beta\beta$ candidate is (75 $\pm$ 2)%. It comprises the selection efficiency, evaluated on the most prominent peak in the physics spectrum [52], the ^{65}Zn and the $0\nu\beta\beta$ containment efficiency estimated via GEANT4 simulation. No signal events were found and we set a 90% credibile interval Bayesian lower limit on the ^{82}Se half life $T^{0\nu}_{1/2} > 4.0 \times 10^{24}$ year. Details of the analysis and the procedure used to compute the upper limit can be found in Ref. [47,50].

4. Conclusions

CUPID-0 demonstrates that a large array of enriched scintillating bolometers can be successfully operated. The simultaneous readout of the heat and light signals allows us to reject the α induced background and reach the lowest background level ever achieved with bolometric experiments: $(3.2^{+1.3}_{-1.1}) \times 10^{-3}$counts/(keV kg year). This represents a key milestone for the next generation of tonne-scale experiments. In a total exposure of 5.46 kg year Zn^{82}Se we set the most stringent limit on the neutrinoless double beta decay ^{82}Se half-life $T^{0\nu}_{1/2} > 4.0 \times 10^{24}$ year at 90% C.I. The data taking is on going and new results will be released in Spring 2019.

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