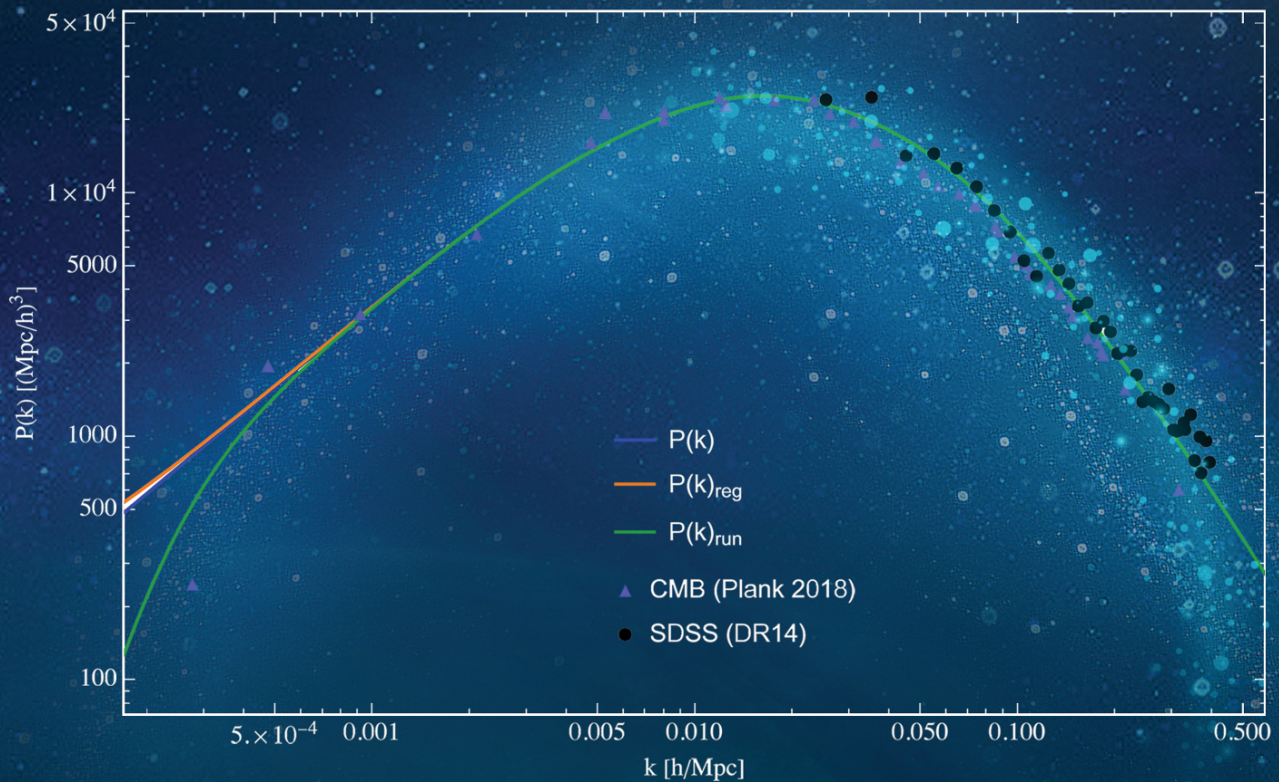


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Result on the Neutrinoless Double Beta Decay Search of ^{82}Se with the CUPID-0 Experiment

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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 $(3.2^{+1.3}_{-1.1}) \times 10^{-3}$ 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 $T_{1/2}^{0\nu} > 4.0 \times 10^{24}$ year at 90% C.I.

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

PACS: 07.20.Mc; 23.40.-s; 21.10.Tg; 14.60.Pq; 27.60.+j

1. Introduction

The neutrinoless double beta decay $0\nu\beta\beta$ [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 paradigm [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 $\Delta m_{12}^2 = m_{\nu_2}^2 - m_{\nu_1}^2 \sim 7 \times 10^{-5} \text{eV}^2$, $\Delta m_{23}^2 = m_{\nu_3}^2 - m_{\nu_2}^2 \sim 2 \times 10^{-3} \text{eV}^2$ [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 $m_{\nu_1} < m_{\nu_2} < m_{\nu_3}$, inverted hierarchy (IH) where $m_{\nu_3} < m_{\nu_1} < m_{\nu_2}$, 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 ~ 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 $^{208}\text{Tl}\gamma$ line at 2615 keV. The $2\nu\beta\beta$ decay of ^{82}Se , allowed by the Standard Model, has a life time $\tau_{1/2} = (9.39 \pm 0.17(\text{stat}) \pm 0.58(\text{syst})) \times 10^{19}$ 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}Se 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 $^3\text{He}/^4\text{He}$ 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 ~ 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 $^{208}\text{Tl}\beta/\beta + \gamma$ decay to ^{212}Pb ($\tau_{1/2} = 3.01$ min) tagging the ^{212}Bi (^{208}Tl mother) which α decays with a $Q_{\alpha} = 6207$ 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 $BI = (3.2^{+1.3}_{-1.1}) \times 10^{-3} \text{ counts}/(\text{keV kg year})$.

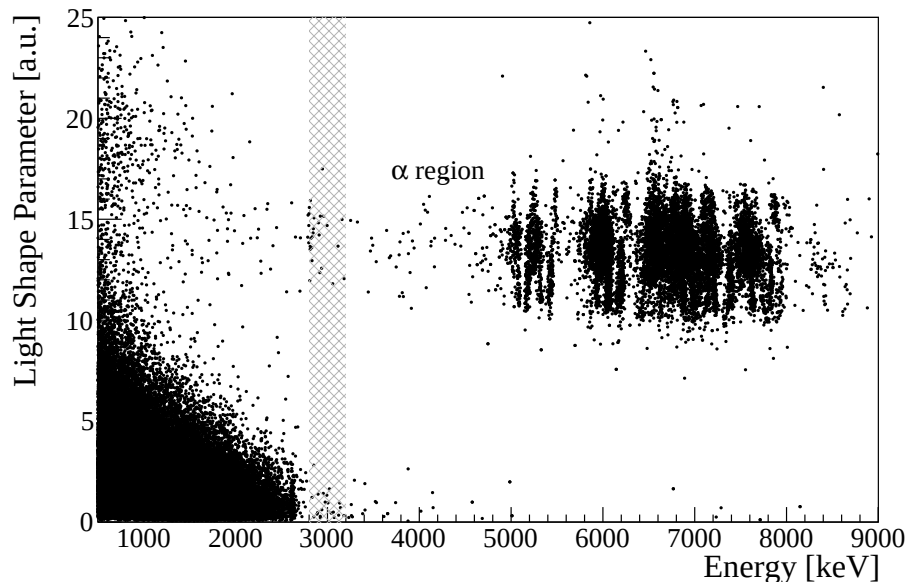


Figure 1. Light shape parameter as a function of the energy released in the ZnSe (all crystals). The dashed vertical band region identifies the 400 keV region centered around the ^{82}Se $Q_{\beta\beta}$ used for the $0\nu\beta\beta$ analysis and for the background evaluation. The α events are concentrated 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% credible interval Bayesian lower limit on the ^{82}Se half life $T_{1/2}^{0\nu} > 4.0 \times 10^{24}$ 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: $(3.2^{+1.3}_{-1.1}) \times 10^{-3} \text{ counts}/(\text{keV kg year})$. 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 $T_{1/2}^{0\nu} > 4.0 \times 10^{24}$ year at 90% C.I. The data taking is on going and new results will be released in Spring 2019.

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