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PROCEEDINGS OF SCIENCE

# Latest results from CUPID-0

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**G. Fantini,**[1,2,*] **O. Azzolini,**[3] **J.W. Beeman,**[4] **F. Bellini,**[1,2] **M. Beretta,**[5,6,a] **M.Biassoni,**[6] **C.Brofferio,**[5,6] **C.Bucci,**[7] **S.Capelli,**[5,6] **V.Caracciolo,**[7,b] **L. Cardani,**[2] **P. Carniti,**[5,6] **N. Casali,**[2] **E. Celi,**[7,11] **D. Chiesa,**[5,6] **M. Clemenza,**[5,6] **I. Colantoni,**[2,8] **O. Cremonesi,**[6] **A. Cruciani,**[2] **A. D'Addabbo,**[7] **I. Dafinei,**[2] **S. Di Domizio,**[9,10] **V. Dompè,**[1,2] **F. Ferroni,**[2,11] **L. Gironi,**[5,6] **A. Giuliani,**[12] **P. Gorla,**[7] **C. Gotti,**[6] **G. Keppel,**[3] **J. Kotila,**[13,14,15] **M. Martinez,**[1,2,c] **S. Nagorny,**[7,d] **M. Nastasi,**[5,6] **S. Nisi,**[7] **C. Nones,**[16] **D. Orlandi,**[7] **L. Pagnanini,**[11,17,7] **M. Pallavicini,**[9,10] **L. Pattavina,**[7,e] **M. Pavan,**[5,6] **G. Pessina,**[6] **V. Pettinacci,**[2] **S. Pirro,**[7] **S. Pozzi,**[5,6] **E. Previtali,**[5,7] **A. Puiu,**[7,11] **A. Ressa,**[1,2] **C. Rusconi,**[7,18] **K. Schäffner,**[7,f] **C. Tomei,**[2] **M. Vignati**[1,2] **and A. S. Zolotarova**[16]

[1] *Università di Roma La Sapienza, P.le A. Moro, 5, Rome, Italy*
[2] *INFN, Sezione di Roma, P.le Aldo Moro 2, 00185, Roma, Italy*
[3] *INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro (Pd) - Italy*
[4] *Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[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] *Consiglio Nazionale delle Ricerche, Istituto di Nanotecnologia, c/o Dip. Fisica, Sapienza Università di Roma, 00185, Rome, Italy*
[9] *Dipartimento di Fisica, Università di Genova, I-16146 Genova - Italy*
[10] *INFN Sezione di Genova, I-16146 Genova - Italy*
[11] *Gran Sasso Science Institute, 67100, L'Aquila - Italy*
[12] *CNRS/CSNSM, Centre de Sciences Nucleaires et de Sciences de la Matière, 91405 Orsay, France*
[13] *University of Jyväskylä, Department of Physics, P. O. Box 35 (YFL), FI-40014, Finland*
[14] *Finnish Institute for Educational Research, P.O.Box 35 FI-40014 University of Jyväskylä - Finland*
[15] *Center for Theoretical Physics, Sloane Physics Laboratory, Yale University, New Haven, Connecticut 06520-8120 - USA*
[16] *IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[17] *Department of Physics and Engineering Physics Astronomy, Queen's University Kingston, Ontario, K7L 3N6 Kingston, Canada*
[18] *Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208 - USA*
[a] *Present address: Department of Physics, University of California, Berkeley, CA 94720, USA*
[b] *Present address: Dipartimento di Fisica, Università di Roma Tor Vergata, I-00133, Rome, Italy*

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[*] Speaker

https://pos.sissa.it/

[c] *Present address: Centro de Astropartículas y Física de Altas Energías, Universidad de Zaragoza, and ARAID, Fundación Agencia Aragonesa para la Investigación y el Desarrollo, Gobierno de Aragón, Zaragoza 50018, Spain*

[d] *Present address: Department of Physics  Engineering Physics Astronomy, Queen's University Kingston, Ontario, K7L 3N6 Kingston, Canada*

[e] *Present address: Physik-Department and Excellence Cluster Origins, Technische Universität München, 85747 Garching, Germany*

[f] *Present address: Max-Planck-Institut für Physik, 80805 München - Germany*

*E-mail:* guido.fantini@uniroma1.it

CUPID-0 is a pilot experiment in scintillating cryogenic calorimetry for the search of neutrino-less double beta decay. 26 ZnSe crystals were operated continuously in the first project phase (March 2017 - December 2018), demonstrating unprecedented low levels of background in the region of interest at the Q-value of $^{82}$Se. From this successful experience comes a demonstration of full alpha to beta/gamma background separation, the most stringent limits on the $^{82}$Se neutrino-less double beta decay, as well as the most precise measurement of the $^{82}$Se half-life. After a detector upgrade, CUPID-0 began its second and last phase (June 2019 - February 2020). We present the latest results on the neutrino-less double beta decay of $^{82}$Se with the full isotope exposure of 8.82 kg × yr. We set a lower bound to the ground state half life $T_{1/2}(^{82}\mathrm{Se}) > 4.6 \times 10^{24}$ yr (90% C.I.). We review the most recent results from a Bayesian search for spectral distortions to the $^{82}$Se double-beta decay spectrum due to exotic decay modes.

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## 1. Introduction

Neutrino-less double beta decay ($0\nu\beta\beta$) is a possible beyond Standard Model decay mode, where a nucleus decays into its isobar $(A, Z) \longrightarrow (A, Z+2) + 2e^-$ emitting two electrons in the final state. If observed, it would imply lepton number violation and that neutrinos are massive Majorana particles [1, 2]. The Standard Model counterpart of the same nuclear transition ($2\nu\beta\beta$) was observed in several nuclei among which $^{82}$Se, $^{100}$Mo, $^{130}$Te, whereas the most sensitive experiments were able to exclude $0\nu\beta\beta$ setting limits on its half life at the level of $10^{25} - 10^{26}$ yr. In $0\nu\beta\beta$ decay the sum energy spectrum of the emitted electrons is a sharp peak at $Q_{\beta\beta}$, the reaction Q-value, as opposed to a continuum in the Standard Model $2\nu\beta\beta$ decay mode.

Next generation experiments are being developed to reach the $10^{27}$ yr floor in half life sensitivity, with an unprecedented effort in mass and background reduction. One of the technologies deployed for such studies is cryogenic calorimetry. Dielectric and diamagnetic crystals, where the source is embedded in the detector, are cooled down to $\sim$ 10 mK temperature and equipped with temperature sensors such as neutron transmutation doped (NTD) Ge thermistors to detect the temperature rise due to nuclear decays within the crystal lattice. The CUORE experiment is the largest experiment using this technique, currently taking data at the INFN Laboratori Nazionali del Gran Sasso, Italy is a tonne scale cryogenic calorimeter array of $TeO_2$ crystals able to achieve a 0.3% energy resolution at $Q_{\beta\beta}$ and a background in the region of interest of the order of 10 counts/(keV × tonne × yr) [3–8].

CUPID (CUORE Upgrade with Particle Identification) is a proposed upgrade foreseen to run in the same cryogenic infrastructure, where an array of $Li_2MoO_4$ crystals with > 95% enrichment in $^{100}$Mo will be operated. The main upgrade with respect to the previous generation is the particle identification capability, via dual readout of the heat and scintillation light signals. CUPID will be able to disentangle $\alpha$ from $\beta/\gamma$ decay events, tearing the background index down to 0.1 counts/(keV × tonne × yr) in the region of interest [9–11].

## 2. The CUPID-0 experiment

The CUPID-0 detector is a demonstrator for the next-generation CUPID detector, based on previous experience from LUCIFER [12] and LUMINEU [13]. It demonstrated the particle discrimination capability achievable with scintillating cryogenic bolometers. The CUPID-0 detector array is a tower of 26 ZnSe crystals, 24 of which had a 95% enrichment in $^{82}$Se and 2 were produced out of natural components. In between each pair of ZnSe bolometers, a Ge circular light detector was placed. Such Ge disks act as bolometers on their own, and are read out with separate NTD thermistors. The simultaneous detection of a heat energy deposition and light from the top and bottom Ge detectors allows to identify $\alpha$ particles, which make up for the dominant contribution of the background in the region of interest of CUORE. Each ZnSe detector was wrapped in a Vikuiti$^{\mathrm{TM}}$ foil to increase the light collection. In this way CUPID-0 was able to achieve a background index as low as 1 counts/(keV × tonne × yr). The CUPID-0 detector was placed in a dedicated facility in the Laboratori Nazionali del Gran Sasso of INFN, and its data taking ended in 2020. The first data taking campaing, which is referred to as phase-I, corresponds to 5.29 kg × yr of $^{82}$Se exposure. A second set of data was acquired without the reflecting foil, to efficiently tag surface $\alpha$ events that would otherwise be absorbed and escape a coincidence analysis. Moreover an additional copper shield and muon veto were installed.

## 3. Results

The latest results from the CUPID-0 experiment on the search for $0\nu\beta\beta$ decay come from an analysis of a 8.82 kg × yr $^{82}$Se exposure, coming from phase I + II of data taking. The energy resolution at the $Q_{\beta\beta}$ of $^{82}$Se was evaluated as $\Delta E = (20.05 \pm 0.34)$ keV, and the background index was evaluated as $(3.5 \pm 1.0)$ counts/(keV × tonne × yr) for the phase I data and $(5.5 \pm 1.0)$ counts/(keV × tonne × yr) for phase II. We found no evidence for a signal, and could set a bayesian upper limit of $\mathrm{T}_{1/2} > 4.6 \times 10^{24}$ yr at 90% C.I. corresponding to $m_{\beta\beta} = (263 - 545)$ meV in the hypothesis of light Majorana neutrino exchange [14, 15].

At the time of writing much effort is being put into modelling the data from both phases of the CUPID-0 experiments, but results are available just from phase I [16]. The approach is to produce a minimal set of Geant-4 based Monte Carlo simulations of the single-hit and double-hit coincident spectra of energy releases, and fit the activities simultaneously to four 1-dimensional binned spectra: single site $\beta/\gamma$, single site $\alpha$, double site single energy, double site sum energy. The dominant contribution in the low energy region < 2.5 MeV is due to the continuous $2\nu\beta\beta$ decay spectrum of $^{82}$Se. The CUPID-0 experiment was able to measure the half life of $^{82}$Se with outstanding precision as $\mathrm{T}_{1/2} = \left[8.60 \pm 0.03(\mathrm{stat.})^{+0.19}_{-0.13}(\mathrm{syst.})\right] \times 10^{19}$ yr [17]. High statistics and signal purity can be used to disentangle tiny spectral shape differences in $2\nu\beta\beta$ events, and CUPID-0 provided evidence for Single State Dominance of $2\nu\beta\beta$ transition in $^{82}$Se over Higher State Dominance [17].

Many other beyond Standard Model scenarios predict a distortion in the $2\nu\beta\beta$ spectrum of $^{82}$Se decay. The high statistics and excellent signal purity of the CUPID-0 sample can provide sensitivity to such models. The introduction of a consistent quantum gravity theory predicts new physics at the Planck scale, that has a low energy counterpart in the Standard Model Extension as Lorentz-violating operators. CUPID-0 was able to set the first upper limit on the isotropic components of the Lorentz violating coefficient from a cryogenic bolometer, of $\mathring{a}^{(3)}_{of} < 4.1 \times 10^{-6}$ GeV [18].

Several new physiscs models predict the existence of a Majoron-like particle coupled to the neutrino in $0\nu\beta\beta$ decay. The experimental signature of different Majoron emitting channels is a modified phase space as

$$\frac{d\Gamma_{0\nu\beta\beta\chi_0}}{dE} \sim (Q_{\beta\beta} - E)^n \tag{1}$$

where $E$ is the sum energy of the emitted electrons. We investigated single Majoron emission modes $0\nu\beta\beta\chi$ with $n = 1, 2, 3$ and double Majoron emission $0\nu\beta\beta\chi\chi$ with $n = 3, 7$ finding no evidence of beyond Standard Model physics in any channel. We set a Bayesian lower limit (90% credibility interval) on the half-life of $1.2 \times 10^{23}$ yr in the case of $n = 1$, $3.8 \times 10^{22}$ yr for $n = 2$, $1.4 \times 10^{22}$ yr for $n = 3$ and $2.2 \times 10^{21}$ yr for $n = 7$. These are the best limits on the $0\nu\beta\beta\chi$ half-life of $^{82}$Se, and demonstrate the potential of the CUPID-0 technology in this field [19].

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