Colloquia: EuNPC 2018

Results from the CUORE experiment

N. Moggi[27][4](*), D. Q. Adams[1], C. Alduino[1], K. Alfonso[2],
F. T. Avignone III[1], O. Azzolini[3], G. Bari[4], F. Bellini[5][6],
G. Benato[7], A. Bersani[8], M. Biassoni[9], A. Branca[10][11],
C. Brofferio[12][9], C. Bucci[13], A. Caminata[8], A. Campani[14][8],
L. Canonica[15][13], X. G. Cao[16], S. Capelli[12][9],
L. Cappelli[13][7][17], L. Cardani[6], P. Carniti[12][9], N. Casali[6],
L. Cassina[12][9], D. Chiesa[12][9], N. Chott[1], M. Clemenza[12][9],
S. Copello[18][13], C. Cosmelli[5][6], O. Cremonesi[9], R. J. Creswick[1],
J. S. Cushman[19], A. D'Addabbo[13], D. D'Aguanno[13][20], I. Dafinei[6],
C. J. Davis[19], S. Dell'Oro[21], M. M. Deninno[4], S. Di Domizio[8][8],
V. Dompè[13][18], A. Drobizhev[7][17], D. Q. Fang[16], G. Fantini[13][18],
M. Faverzani[12][9], E. Ferri[12][9], F. Ferroni[5][6], E. Fiorini[9][12],
M. A. Franceschi[22], S. J. Freedman[17][7], Z. Fu[15],
B. K. Fujikawa[17], A. Giachero[12][9], L. Gironi[12][9], A. Giuliani[23],
P. Gorla[13], C. Gotti[12][9], J. Gruszko[15], T. D. Gutierrez[24],
K. Han[25], K. M. Heeger[19], R. Hennings-Yeomans[7][17], R. G. Huang[7],
H. Z. Huang[2], J. Johnston[15], G. Keppel[3], Yu. G. Kolomensky[7][17],
A. Leder[15], C. Ligi[22], Y. G. Ma[16], L. Marini[7][17], M. Martinez[5][6][26],
R. H. Maruyama[19], Y. Mei[17], S. Morganti[6], S. S. Nagorny[13][18],
T. Napolitano[22], M. Nastasi[12][9], C. Nones[28], E. B. Norman[29][30],
V. Novati[23], A. Nucciotti[12][9], I. Nutini[13][18], T. O'Donnell[21],
J. L. Ouellet[15], C. E. Pagliarone[13][20], M. Pallavicini[14][8],
L. Pattavina[13], M. Pavan[12][9], G. Pessina[9], C. Pira[3], S. Pirro[13],
S. Pozzi[12][9], E. Previtali[9], A. Puiu[12][9], C. Rosenfeld[1],
C. Rusconi[1][13], M. Sakai[2], S. Sangiorgio[29], D. Santone[13][31],
B. Schmidt[17], N. D. Scielzo[29], V. Singh[7], M. Sisti[12][9], D. Speller[19],
L. Taffarello[10], F. Terranova[12][9], C. Tomei[6], M. Vignati[6],
S. L. Wagaarachchi[7][17], B. S. Wang[29][30], H. W. Wang[16],
B. Welliver[17], J. Wilson[1], K. Wilson[1], L. A. Winslow[15], T. Wise[19][32],
L. Zanotti[12][9], G. Q. Zhang[16], S. Zimmermann[33] and S. Zucchelli[27][4]

[1] *Department of Physics and Astronomy, University of South Carolina - Columbia, SC 29208, USA*
[2] *Department of Physics and Astronomy, University of California - Los Angeles, CA 90095, USA*
[3] *INFN, Laboratori Nazionali di Legnaro - Legnaro (Padova) I-35020, Italy*
[4] *INFN, Sezione di Bologna - Bologna I-40127, Italy*
[5] *Dipartimento di Fisica, Sapienza Università di Roma - Roma I-00185, Italy*
[6] *INFN, Sezione di Roma - Roma I-00185, Italy*
[7] *Department of Physics, University of California - Berkeley, CA 94720, USA*

(*) E-mail: niccolo.moggi@bo.infn.it

(^{8}) *INFN, Sezione di Genova - Genova I-16146, Italy*
(^{9}) *INFN, Sezione di Milano Bicocca - Milano I-20126, Italy*
(^{10}) *INFN, Sezione di Padova - Padova I-35131, Italy*
(^{11}) *Dipartimento di Fisica e Astronomia, Università di Padova - I-35131 Padova, Italy*
(^{12}) *Dipartimento di Fisica, Università di Milano-Bicocca - Milano I-20126, Italy*
(^{13}) *INFN, Laboratori Nazionali del Gran Sasso - Assergi (L'Aquila) I-67100, Italy*
(^{14}) *Dipartimento di Fisica, Università di Genova - Genova I-16146, Italy*
(^{15}) *Massachusetts Institute of Technology - Cambridge, MA 02139, USA*
(^{16}) *Shanghai Institute of Applied Physics, Chinese Academy of Sciences - Shanghai 201800, China*
(^{17}) *Nuclear Science Division, Lawrence Berkeley National Laboratory - Berkeley, CA 94720, USA*
(^{18}) *INFN, Gran Sasso Science Institute - L'Aquila I-67100, Italy*
(^{19}) *Wright Laboratory, Department of Physics, Yale University - New Haven, CT 06520, USA*

(^{20}) *Dipartimento di Ingegneria Civile e Meccanica, Università degli Studi di Cassino e del Lazio Meridionale - Cassino I-03043, Italy*
(^{21}) *Center for Neutrino Physics, Virginia Polytechnic Institute and State University - Blacksburg, Virginia 24061, USA*
(^{22}) *INFN, Laboratori Nazionali di Frascati - Frascati (Roma) I-00044, Italy*
(^{23}) *CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay - 91405 Orsay, France*
(^{24}) *Physics Department, California Polytechnic State University - San Luis Obispo, CA 93407, USA*
(^{25}) *INPAC and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai Laboratory for Particle Physics and Cosmology - Shanghai 200240, China*
(^{26}) *Laboratorio de Fisica Nuclear y Astroparticulas, Universidad de Zaragoza - Zaragoza 50009, Spain*
(^{27}) *Dipartimento di Fisica e Astronomia, Alma Mater Studiorum, Università di Bologna - Bologna I-40127, Italy*
(^{28}) *Service de Physique des Particules, CEA / Saclay - 91191 Gif-sur-Yvette, France*
(^{29}) *Lawrence Livermore National Laboratory - Livermore, CA 94550, USA*
(^{30}) *Department of Nuclear Engineering, University of California - Berkeley, CA 94720, USA*
(^{31}) *Dipartimento di Scienze Fisiche e Chimiche, Università dell'Aquila - L'Aquila I-67100, Italy*
(^{32}) *Department of Physics, University of Wisconsin - Madison, WI 53706, USA*
(^{33}) *Engineering Division, Lawrence Berkeley National Laboratory - Berkeley, CA 94720, USA*

Summary. — The Cryogenic Underground Observatory for Rare Events (CUORE) is the first bolometric experiment searching for neutrinoless double beta decay that has been able to reach the 1-ton scale. In this talk we present the neutrinoless doube beta decay results of CUORE from examining a total TeO_2 exposure of 86.3 kg yr, characterized by an effective energy resolution of 7.7 keV FWHM and a background in the region of interest of 0.014 counts/(keV kg yr). In this physics run, CUORE placed a lower limit on the decay half-life of $^{130}Te > 1.3 \times 10^{25}$ yr (90% C.L.). We then discuss the additional improvements in the detector performance achieved in 2018 and the latest update on the evaluation of the background budget.

1. – The CUORE experiment

The *Cryogenic Underground Observatory for Rare Events* (CUORE [1]) is an experiment focused on the search for the neutrinoless double beta decay ($0\nu\beta\beta$), a lepton number violating process $(Z, A) \rightarrow (Z+2, A) + 2e^-$ with emission of (only) two electrons in the final state. Such process may be regarded as one of the most sensitive probes to physics beyond the Standard Model. The experimental signature is given by a peak in the spectrum of the summed electron energy at Q-value ($Q_{\beta\beta}$) of the isotope.

CUORE is based on the cryogenic bolometric technique: the energy released by the final state electrons is converted into lattice vibrations of an absorbing crystal inducing a temperature rise. The $0\nu\beta\beta$ emitter is ^{130}Te with $Q_{\beta\beta}$=2527.5 keV and isotopic abundance $\simeq$34%. The detector is composed of 988 cubic crystals of TeO$_2$ operated as independent bolometers that act both as source and detector. This approach gives a high signal efficiency ($\sim$90%) and excellent energy resolution. The total mass is 742 kg, or 206 kg of ^{130}Te. Each crystal is glued to a neutron transmutation doped thermistor to read the energy deposition. The bolometers are arranged in 19 copper structures (towers) of 13 floors each (the copper serving also as heath bath) and cooled down to $\sim$10 mK inside a dilution-refrigerator custom made cryostat.

The sensitivity may be expressed as $\propto \sqrt{M \cdot t / b \cdot \Delta E}$, where M is the total mass, t the time exposure, b the background in counts/(kg·keV·y) and ΔE the energy resolution. The expected sensitivity in 5 years is Te$^{0\nu}_{1/2}$ >9× 10^{25} y [2].

The underground location at L.N.G.S. (3600 m water equivalent depth) and passive shields both outside and inside the cryostat reduce the environmental radioactivity. Great efforts have been made to meet the strict radiopurity requirements of all the parts used to build the cryostat and the detector [3], including: careful selection of all materials, dedicated cleaning procedures, assembly and temporary storage in N$_2$ atmosphere.

The assembly of the detector was completed in summer 2016 followed by the installation inside the cryostat and cooldown. Base temperature was reached in January 2017. Overall 984/988 bolometers are operational. After a commissioning and optimisation period, two datasets were collected during summer 2017 for a total of 86.3 kg ·y of TeO$_2$ or 24.0 kg·y of ^{130}Te. These datasets are characterised by an exposure weighted energy resolution of 7.7±0.5 keV FWHM [4].
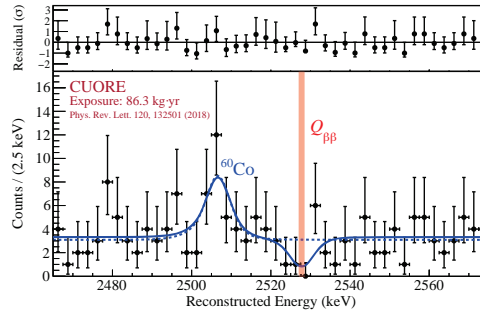

Fig. 1. – The best-fit model in the ROI. The normalized residuals of this model and the binned data are shown in the top panel. The vertical band is centered at $Q_{\beta\beta}$; the width of the band reflects the systematic uncertainty on the reconstructed energy.
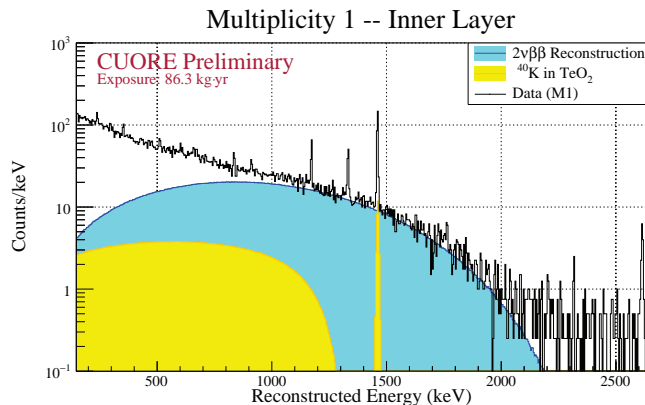
Fig. 2. – The $2\nu\beta\beta$ spectrum overlaid to the full physical spectrum. Only $M1$ events are used. For illustrative purposes the spectrum has been converted to 1keV binning with no uncertainty shown, and $2\nu\beta\beta$ and ^{40}K to smooth continua.

2. – Results

The energy-calibrated spectrum is obtained using six γ lines of the ^{232}Th decay chain from the calibration runs that bracket each dataset. The high statistics ^{208}Tl 2615 keV line is used also to characterise the energy resolution performance. Data quality cuts are then applied: events with energy deposit in more than one bolometer are rejected and a pulse shape consistent with signal-like events is required. The final spectrum shows no evidence of $0\nu\beta\beta$ decay. An unbinned extended maximum likelihood fit is performed in the range 2465-2575 keV (fig.1) to extract a limit on the half-life. The fit function include a signal peak at $Q_{\beta\beta}$m a peak at 2506 keV (^{60}Co) and a dataset-dependent flat background. Assuming zero signal, the 90% C.L. limit is $Te^{0\nu}_{1/2}$ >1.3×10^{25} y [4]. By combining this with Cuoricino and CUORE-0 results [5] we obtain $Te^{0\nu}_{1/2}$ >1.5× 10^{25} y which is the most stringent result to date. Interpreted as a limit on the Majorana mass this results may be expressed as $m_{\beta\beta}$ <110-520 eV at 90% C.L. depending on the nuclear matrix element used and assuming $g_A = 1.27$.

The fit yields a background index of 0.0014±0.002 counts/(kg·keV·y) at $Q_{\beta\beta}$ (average over datasets). Both energy resolution and background index improve in the second dataset. More improvements are expected with the understanding of the new cryostat performance and the implementation of all the data quality cuts. In order to understand the observed spectrum a background model was developed where all possible background sources are simulated following the method used in CUORE-0 [6]. About 60 parameters represent the source types, contamination levels and detector locations. Much information may be extracted directly from the CUORE data by splitting events into different type of spectra. "Multiplicity 1" ($M1$) contains events where energy os deposited in a single bolometer, "Multiplicity 2" ($M2$) events where the energy is shared between two bolometers and $M2sum$ events where energy of the $M2$ events is summed. $M1$ mostly contains signal, $M2$ and $M2sum$ mostly background. $M1$ may be further split geometrically into spectra from inner bolometers (more shielded) and outer bolometers (more exposed to external contaminations). By fitting the simulated spectra to the observed data all major features of the physical spectrum are reproduced. The dominant

component of $M1$ in the region 1-2 MeV is due to the $2\nu\beta\beta$ decay of ^{130}Te (fig.2). Its contribution may be disentangled from other backgrounds and the half-life evaluated to be $T_{1/2}^{2\nu}$=(7.9±0.1$_{stat.}$±0.2$_{syst.}$)× 10^{20} y, consistent with previous measurements [7] and most precise to date.

Besides its potential also for dark matter searches and other $\beta\beta$ decays, CUORE will continue to be one of the most sensitive searches for $0\nu\beta\beta$ over the coming years.

REFERENCES

[1] ARDITO R. *et al.*, *arxiv:hep-ex/0501010*
[2] ALDUINO C. *et al.*, *Eur. Phys. J. C*, **77** (2017) 532.
[3] ALDUINO C. *et al.*, *J. Instrum.*, **11** (2016) P07009.
[4] ALDUINO C. *et al.*, *Phys. Rev. Lett.*, **120** (2018) 132501.
[5] ALFONSO K. *et al.*, *Phys. Rev. Lett.*, **115** (2015) 102502.
[6] ALDUINO C. *et al.*, *Eur. Phys. J. C*, **77** (2017) 543.
[7] ALDUINO C. *et al.*, *Eur. Phys. J. C*, **77** (2017) 13.