STATUS OF THE CUORE AND CUORE-0 EXPERIMENT AT GRAN SASSO

F. BELLINI
Sapienza Università di Roma and INFN Roma, P.le Aldo Moro 5, 00185, Italy

CUORE is a 741 kg array of TeO_2 bolometers for the search of neutrinoless double beta decay in ^{130}Te. The detector is being constructed at the Laboratori Nazionali del Gran Sasso, Italy, where it will start taking data in 2015. If the target background of 0.01 counts/(keV kg y) will be reached, in 5 years of data taking CUORE will have an half life sensitivity of about 10^{26} y. CUORE-0 is a smaller experiment constructed to test and demonstrate the performances expected for CUORE. The detector is a single tower of 52 CUORE-like bolometers that started taking data in spring 2013. The status and perspectives of CUORE are discussed and the first CUORE-0 data are presented.

1 Introduction

The study of neutrino properties is one of the fundamental challenges in particle physics nowadays. Fifty years of investigations established that neutrinos are massive but the absolute mass scale has not yet been measured. Moreover its true nature is still unknown: is the neutrino a Dirac particle like all the elementary fermions or a Majorana particle thus coinciding with its own antiparticle? The only way to probe the neutrino nature is through the observation of Neutrinoless Double Beta Decay ($0\nu\beta\beta$), a very rare spontaneous nuclear transition in which a nucleus (A, Z) decays into nucleus (A,Z+2) with the emission of two electrons and no neutrinos. Observation of $0\nu\beta\beta$ would establish unambiguously the Majorana nature of the neutrino. CUORE-0 [1] is a cryogenic detector that uses an array of TeO_2 bolometers to search for $0\nu\beta\beta$ in the ^{130}Te of the bolometers themselves. ^{130}Te is an attractive isotope for a $0\nu\beta\beta$ search because of its relatively high Q-value at 2528 keV [2] and its very high natural isotopic abundance at 34.2%. CUORE-0 also serves as a technical prototype for CUORE [3,4] (Cryogenic Underground Observatory of Rare Events) which will consist of 19 towers identical to the single CUORE-0 tower. CUORE-0 is the first tower produced on the CUORE assembly line, and its successful commissioning represents a major milestone towards CUORE. CUORE is in the advanced stages of detector construction and is scheduled to begin data taking in 2015.

2 The CUORE-0 detector

CUORE-0 [1] is composed by 52 TeO_2 crystals arranged in a 13 planes single tower and housed in the cryostat situated in the Hall A of Laboratori Nazionali del Gran Sasso (LNGS) of INFN. Crystals are held, by means of polytetrafluoroethylene (PTFE) pieces, inside a copper frame that acts as thermal bath to cool the bolometers to a base temperature of 13-15 mK. Each crystal weighs 750 g, which results in a total detector mass of 39 kg (11 kg of ^{130}Te) and is instrumented with a single neutron transmutation doped (NTD) germanium thermistor[5] for the signal readout The typical signal amplitude $\Delta T/\Delta E$ is 10 - 20 μ K/MeV. A silicon Joule heater[8] is also glued to the crystal for the offline correction of thermal gain drift caused by temperature variation of the individual bolometer. Crystals were manufactured by the Shangai Institute of Ceramics following a strict radio purity control protocol [6] to limit bulk and surface contaminations introduced in crystal production and sent to LNGS by sea to minimise cosmogenic activation. A few crystals from each batch were instrumented as bolometers for characterization tests. The ^{238}U (^{232}Th) bulk contamination was measured to be less than 6.7×10^{-7} Bq/kg (8.4×10^{-7} Bq/kg) at 90 % C.L. The surface contamination was found to be less than 8.9×10^{-9} Bq/cm^2 (2.0×10^{-9} Bq/cm^2) at 90 % C.L. The detector assembly procedure was designed to minimize the recontamination of clean components. Tower assembly took place in a dedicated class 1000 clean room and, to prevent radon contamination, all steps were performed under nitrogen atmosphere inside glove boxes. All tools used inside the glove boxes were cleaned and certified for radiopurity. The assembled tower was enclosed in a copper thermal shield and mounted in the cryostat that was used for CUORICINO [9,10]. CUORE-0 also uses the same external lead shield, borated-polyethylene neutron shield, Faraday cage and electronic of its predecessor [11]. The signals are amplified, filtered by 6-pole active Bessel filter [12] and then fed into an 18-bit National Instrument PXI analog-to-digital converter (ADC). The filter cutoff and the ADC sampling frequency are set to 12 Hz and 125 Hz, respectively. The trigger is software generated on each bolometer. When it fires, one second of data preceding the trigger and the 4 seconds following are saved to disk. In addition to the signal triggers, each bolometer is pulsed periodically at 300 s intervals with a fixed and known energy through the heater. Random noise events are also acquired. The energy calibration is performed before and after each subset of runs, which lasts about a month, by exposing the array to two thoriated tungsten wires (50 Bq activity) inserted in immediate vicinity of the refrigerator.

3 CUORE-0 data analysis and performances

CUORE-0 data analysis chain comprises: matched filter amplitude evaluation [13,14], gain correction [8], energy calibration, pulse shape analysis and time coincidence analysis among the bolometers. Noisy time periods due to cryogenic or electronic instabilities are rejected. The shape of the pulse is used to discard pile-up events. Since 86% of $0\nu\beta\beta$ events are fully contained in a single crystal, single site events are selected applying a 100 ms anti-coincidence window around each event.

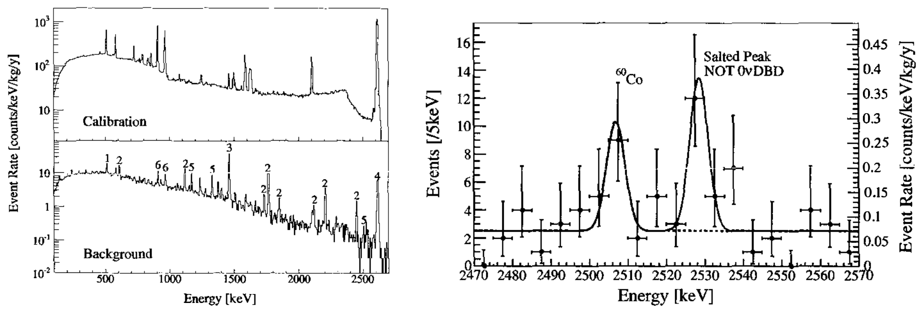

Figure 1 – Left: CUORE-0 calibration (top panel) and background spectrum (bottom panel). γ-ray peaks from known radioactive sources in the background spectrum are labeled as follows: (1) e^+e^- annihilation; (2) ^{214}Bi; (3) ^{40}K; (4) ^{208}Tl; (5) ^{60}Co; and (6) ^{228}Ac. Right: blinded $0\nu\beta\beta$ energy region of interest. The peak at 2506 keV is due to the sum of the two γs from Co. The peak at 2528 keV is the salted $0\nu\beta\beta$ peak.

Cut efficiencies are evaluated on the 2615 keV ^{208}Tl γ line, except for the anti-coincidence cut, for which the 1461 keV γ line from ^{40}K is used. Taking into account the trigger and

$0\nu\beta\beta$ confinement efficiency an overall detection efficiency $80.4 \pm 1.9\%$ is achieved. The calibration is performed for each channel using a third order polynomial function with zero intercept. The left panel in Fig.1 shows the energy spectrum obtained using the ^{232}Th calibration source and the background spectrum for the sum of all channels corresponding to an exposure of 7.1 kg y (2.0 kg y of 130 Te).^{208}Tl,^{40}K and ^{60}Co γ peaks are attributed to contamination in the cryostat, while the ^{214}Bi ones are attributed to ^{222}Rn in the air around the cryostat during the initial runs. The energy resolution in the ROI, defined as the FWHM of 2615 keV γ ray peak is determined by a fit to the summed background spectrum of all channels and found to be 5.7 keV. The $0\nu\beta\beta$ region is blinded. Our blinding procedure is a form of data salting, where we randomly exchange a blinded fraction of events within ± 10 keV of the 2615 keV γ ray peak with events within ± 10 keV of the $0\nu\beta\beta$ Q-value. The exchange probability varies between 1 and 3% and is randomized run by run. Since the number of 2615 keV γ ray events is much larger than that of possible $0\nu\beta\beta$ events, the blinding algorithm produces an artificial peak around the $0\nu\beta\beta$ value and blinds the real $0\nu\beta\beta$ rate of ^{130}Te. This method of blinding the data preserves the integrity of the possible $0\nu\beta\beta$ events while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuities in the spectrum. The energy spectrum in the $0\nu\beta\beta$ ROI in shown in Fig.1 (right). The spectrum is fitted with two gaussians, centred at the nominal ^{60}Co sum peak and $0\nu\beta\beta$ peak and with FWHM fixed to 5.7 keV. The flat background rate in the ROI is measured to be 0.071 ± 0.011 counts/(keV kg y). The two major sources of background are degraded α particles from surface contamination on the copper and crystals and Compton scattered 2615 keV γ rays that originate from the cryostat. Degraded α particles with a decay energy of 4 to 8 MeV may deposit part of their energy in the $0\nu\beta\beta$ ROI. These α events form a continuous energy spectrum extending from their decay energy to well below $0\nu\beta\beta$ region. The α background rate in the ROI is estimated by counting events in the "α flat continuum region", which is defined to be from 2.7 to 3.9 MeV excluding the ^{190}Pt peak region from 3.1 to 3.4 MeV. This energy range is above almost all naturally occurring γ rays, in particular the 2615 keV γ rays from ^{208}Tl decay. Left plot of Fig.2 shows the α background energy spectrum of CUORE-0 (shaded red) and Cuoricino (black). The measured α background rate for CUORE-0 is 0.019 ± 0.002 counts/(keV kg y), which improves on the Cuoricino result (0.110 ± 0.001 counts/(keV kg y)) by a factor of 6. The γ background in the ROI is consistent with the one observed in CUORICINO, which took data in the same cryostat.

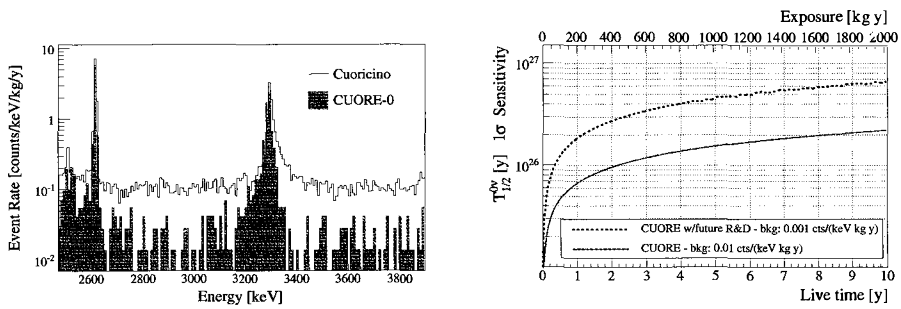

Figure 2 – Left: background spectrum of CUORE-0 (red with shades) and Cuoricino (black) in the α region. The peak at 3.2 MeV is due to Pt contamination in the crystals. Right: CUORE 1σ sensitivity to the half-life of $0\nu\beta\beta$ decay of ^{130}Te assuming an energy resolution of 5 keV FWHM. The solid green line shows the sensitivity for the target background rate of 0.01 counts/(keV kg y), while the dashed blue line shows a speculative future scenario in which the background is ten times lower

4 CUORE

CUORE will be made of 19 CUORE-0 like towers (Fig.3 left) housed in a single custom made dilution refrigerator (Fig.3 right). The single tower assembly process is the same as CUORE-0 and is divided in 4 main steps: gluing of thermistors and heaters to crystals, assembly of instrumented crystals into a tower, attachment of readout cables, wire bonding of the chips to the readout cables. All the steps are performed in glove boxes under nitrogen atmosphere to prevent radon contamination. The gluing of semiconductor chips to crystals is performed by a semi-automated robotic system to achieve precise and uniform results. A matrix of uniform Araldite Rapid bicomponent epoxy glue spots is dispensed by a cartesian robot on an upturned chip placed on a precision positioning device. A crystal is fetched by a robotic arm and placed on a cradle above the chips separated by a distance of 50 μm. The chip-equipped crystals are then assembled into a tower with 500 ultraclean copper pieces and PTFE spacers. The tower is built one floor at a time, descending into a dedicated storage garage as it grows in size.

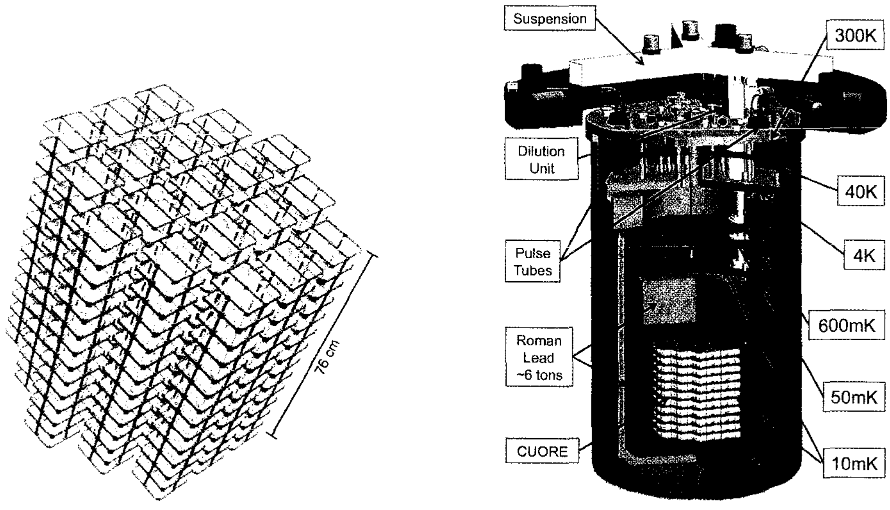

Figure 3 – The CUORE array(left) and the CUORE cryostat (right) with major components highlighted.

Once a tower is built, two sets of flexible printed circuit board (PCB) cables on opposite sides are glued to a rigid copper backing using Araldite standard bicomponent epoxy. The cables are made of wire traces etched from copper sheet on polyethylene naphthalate (PEN) substrate. They are 2.4 m long to provide electrical connections from the bottom floor of the tower up to the cryostat's mixing-chamber plate. The readout traces terminate in bonding pads located on horizontal arms extending from either side of the readout cables at each tower floor. The last step is to connect the crystals' chips to the PCB cable traces with 25 μm gold wires. This is accomplished using a modified Westbond 7700E manual wire bonder which has been oriented vertically and mounted on motor-driven rails to enable precise horizontal motion. Each gold wire is first ball bonded to a chip pad and then wedge bonded to a copper pad, and then the wedge bond is reinforced with a security ball bond. Two wires are bonded for each electrical connection to provide redundancy. After bonding work on a tower is complete, protective copper covers are installed over the PC. Completed towers are stored in nitrogen-flushed canisters to await future installation in the cryostat. CUORE tower assembly started in January 2013 and is expected to end Summer 2014. Given its large detector mass and its excellent energy resolution

CUORE will be one of the most sensitive $0\nu\beta\beta$ decay experiments. The CUORE sensitivity [15] is shown in the right plot of Fig.2 assuming an energy resolution of 5 keV FWHM and target background rate of 0.01 counts/(keV kg y) (green line). In 5 years of live time CUORE will reach a 1σ (90% C.L.) sensitivity of 1.6×10^{26}y, (9.5×10^{25} y) on the half-life of $0\nu\beta\beta$ decay of ^{130}Te.

References

1. C. Aguirre, et al., submitted to *Eur. Phys. J. C* http://arxiv.org/abs/1402.0922
2. M. Redshaw, B. J. Mount, E. G. Myers, F. T. Avignone, *Phys. Rev. Lett.* **102**, 212502 (2009)
3. C. Arnaboldi, et al., *Nucl. Instrum. Methods* A **518**, 775 (2004)
4. D. Artusa, et al., submitted to *Adv.High Energy Phys.* http://arxiv.org/abs/1402.6072
5. K. M. Itoh, et al., *Appl. Phys. Lett.* **64** 2121 1994
6. C. Arnaboldi, et al., *J. Cryst. Growth* **312** 2999 2010
7. F. Alessandria, et al., *Astropart. Phys.* **35** 839 2012
8. A. Alessandrello, et al.,*Nucl. Instrum. Methods* A **412**, 454 (1998)
9. C. Arnaboldi, et al., *Phys. Rev. C* **78** 035502 2008
10. E. Andreotti, et al. *Astropart. Phys* **34** 822 2011
11. C. Arnaboldi, et al., *Nucl. Instrum. Methods* A **520**, 578 (2004).
12. C. Arnaboldi, et al., *Nucl. Instrum. Methods* A **617**, 327 (2010)
13. V. Radeka, N. Karlovac, *Nucl. Instrum. Methods* **52**, 86 (1967)
14. E. Gatti, P. F. Manfredi, *Riv. Nuovo Cimento* **9** 1 1986
15. F. Alessandria, et al., submitted to *Astropart. Phys* http://arxiv.org/abs/1109.0494