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Status of CUORE Experiment and latest results from CUORE-0

C. Pagliarone(1)(2)(*), C. Alduino(3), K. Alfonso(4), D. R. Artusa(3)(1), F. T. Avignone III(3), O. Azzolini(5), T. I. Banks(6)(7), G. Bari(8), J. W. Beeman(9), F. Bellini(10)(11), A. Bersani(12), M. Biassoni(13)(14), C. Brofferio(13)(14), C. Bucci(1), A. Camacho(5), A. Caminata(12), L. Canonica(1), X. G. Cao(15), S. Capelli(13)(14), L. Cappelli(1), L. Carbone(14), L. Cardani(10)(11), P. Carniti(13)(14), N. Casali(10)(11), L. Cassina(13)(14), D. Chiesa(13)(14), N. Chott(3), M. Clemenza(13)(14), S. Copello(16)(12), C. Cosmelli(10)(11), O. Cremonesi(14), R. J. Creswick(3), J. S. Cushman(17), I. Dafinei(11), C. J. Davis(17), S. Dell'Oro(1)(18), M. M. Deninno(8), S. Di Domizio(16)(12), M. L. Di Vacri(1)(19), A. Drobizhev(6)(7), D. Q. Fang(15), M. Faverzani(13)(14), G. Fernandes(16)(12), E. Ferri(14), F. Ferroni(10)(11), E. Fiorini(14)(13), M. A. Franceschi(20), S. J. Freedman(7)(6), B. K. Fujikawa(7), A. Giachero(14), L. Gironi(13)(14), A. Giuliani(21), L. Gladstone(22), P. Gorla(1), C. Gotti(13)(14), T. D. Gutierrez(23), E. E. Haller(9)(24), K. Han(25)(17), E. Hansen(22)(4), K. M. Heeger(17), R. Hennings-Yeomans(6)(7), K. P. Hickerson(4), H. Z. Huang(4), R. Kadel(26), G. Keppel(5), Yu. G. Kolomensky(6)(26)(7), A. Leder(22), C. Ligi(20), K. E. Lim(17), X. Liu(4), Y. G. Ma(15), M. Maino(13)(14), L. Marini(16)(12), M. Martinez(10)(11)(27), R. H. Maruyama(17), Y. Mei(7), N. Moggi(28)(8), S. Morganti(11), P. J. Mosteiro(11), T. Napolitano(20), C. Nones(29), E. B. Norman(30)(31), A. Nucciotti(13)(14), T. O'Donnell(6)(7), F. Orio(11), J. L. Ouellet(22)(6)(7), M. Pallavicini(16)(12), V. Palmieri(5), L. Pattavina(1), M. Pavan(13)(14), G. Pessina(14), V. Pettinacci(11), G. Piperno(10)(11), C. Pira(5), S. Pirro(1), S. Pozzi(13)(14), E. Previtali(14), C. Rosenfeld(3), C. Rusconi(14), E. Sala(13)(14), S. Sangiorgio(30), D. Santone(1)(19), N. D. Scielzo(30), V. Singh,(6), M. Sisti(13)(14), A. R. Smith(7), L. Taffarello(32), M. Tenconi(21), F. Terranova(13)(14), C. Tomei(11), S. Trentalange(4), G. Ventura(33)(34), M. Vignati(11), S. L. Wagaarachchi(6)(7), B. S. Wang(30)(31), H. W. Wang(15), J. Wilson(3), L. A. Winslow(22), T. Wise(17)(35), A. Woodcraft(36), L. Zanotti(13)(14), G. Q. Zhang(15), B. X. Zhu(4), S. Zimmermann(37) and S. Zucchelli(38)(8)

(1) *INFN, Laboratori Nazionali del Gran Sasso - Assergi (L'Aquila) I-67010, Italy*

(2) *Dipartimento di Ingegneria Civile e Meccanica, Università degli Studi di Cassino e del Lazio Meridionale - Cassino I-03043, Italy*

(3) *Department of Physics and Astronomy, University of South Carolina - Columbia, SC 29208, USA*

(4) *Department of Physics and Astronomy, University of California - Los Angeles, CA 90095, USA*

(*) On behalf of the CUORE Collaboration. E-mail: `carmine.pagliarone@lngs.infn.it`.

(5) *INFN, Laboratori Nazionali di Legnaro - Legnaro (Padova) I-35020, Italy*
(6) *Department of Physics, University of California - Berkeley, CA 94720, USA*
(7) *Nuclear Science Division, Lawrence Berkeley National Laboratory - Berkeley, CA 94720, USA*
(8) *INFN, Sezione di Bologna - Bologna I-40127, Italy*
(9) *Materials Science Division, Lawrence Berkeley National Laboratory - Berkeley, CA 94720, USA*
(10) *Dipartimento di Fisica, Sapienza Università di Roma - Roma I-00185, Italy*
(11) *INFN, Sezione di Roma - Roma I-00185, Italy*
(12) *INFN, Sezione di Genova - Genova I-16146, Italy*
(13) *Dipartimento di Fisica, Università di Milano-Bicocca - Milano I-20126, Italy*
(14) *INFN, Sezione di Milano Bicocca - Milano I-20126, Italy*
(15) *Shanghai Institute of Applied Physics, Chinese Academy of Sciences - Shanghai 201800, China*
(16) *Dipartimento di Fisica, Università di Genova - Genova I-16146, Italy*
(17) *Department of Physics, Yale University - New Haven, CT 06520, USA*
(18) *INFN, Gran Sasso Science Institute - L'Aquila I-67100, Italy*
(19) *Dipartimento di Scienze Fisiche e Chimiche, Università dell'Aquila - L'Aquila I-67100, Italy*
(20) *INFN, Laboratori Nazionali di Frascati - Frascati (Roma) I-00044, Italy*
(21) *CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay - 91405 Orsay, France*
(22) *Massachusetts Institute of Technology - Cambridge, MA 02139, USA*
(23) *Physics Department, California Polytechnic State University - San Luis Obispo, CA 93407, USA*
(24) *Department of Materials Science and Engineering, University of California - Berkeley, CA 94720, USA*
(25) *Department of Physics and Astronomy, Shanghai Jiao Tong University - Shanghai 200240, China*
(26) *Physics Division, Lawrence Berkeley National Laboratory - Berkeley, CA 94720, USA*
(27) *Laboratorio de Fisica Nuclear y Astroparticulas, Universidad de Zaragoza - Zaragoza 50009, Spain*
(28) *Dipartimento di Scienze per la Qualità della Vita, Alma Mater Studiorum, Università di Bologna - Rimini I-47921, Italy*
(29) *Service de Physique des Particules, CEA / Saclay - 91191 Gif-sur-Yvette, France*
(30) *Lawrence Livermore National Laboratory - Livermore, CA 94550, USA*
(31) *Department of Nuclear Engineering, University of California - Berkeley, CA 94720, USA*
(32) *INFN, Sezione di Padova - Padova I-35131, Italy*
(33) *Dipartimento di Fisica, Università di Firenze - Firenze I-50125, Italy*
(34) *INFN, Sezione di Firenze - Firenze I-50125, Italy*
(35) *Department of Physics, University of Wisconsin - Madison, WI 53706, USA*
(36) *SUPA, Institute for Astronomy, University of Edinburgh - Blackford Hill, Edinburgh EH9 3HJ, UK*
(37) *Engineering Division, Lawrence Berkeley National Laboratory - Berkeley, CA 94720, USA*

(38) *Dipartimento di Fisica e Astronomia, Alma Mater Studiorum, Università di Bologna Bologna I-40127, Italy*

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Summary. — Neutrinoless Double Beta Decay ($0\nu\beta\beta$) is a rare nuclear transition that if it occurs at all it will be very important for the exploration of the inverted hierarchy region of the neutrino mass pattern. The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment that aims to search for such a transition in ^{130}Te together with other rare processes. In the present paper we will describe the basic features of CUORE Experiment, the status of the experiment as well as the latest results obtained from CUORE-0 detector, a smaller scale experiment constructed to test and demonstrate the expected performances of CUORE.

1. – Introduction

As far as we know, neutrinos are the lightest known particles in the Universe, in fact they are several orders of magnitude lighter than all other known fermions [1]. Because of their lightness, no experiment has directly observed their masses. Evidence for non-zero mass comes from oscillations experiments with solar, reactor, accelerator and atmospheric neutrinos [1]. One goal of many neutrino experiments and theoretical models is to explain the observed neutrino masses and mixing patterns, and to relate them to the well known charged lepton masses and possibly to the quark masses and mixings. For this reason, to explain the neutrino mass hierarchy (MH) is of a crucial importance. Among the different experimental approaches, one way to determine neutrino MH is to search for neutrinoless double beta decay ($0\nu\beta\beta$) decay. As matter of fact the rate for such a process is proportional to the square of the effective Majorana mass [2]. Double beta decay consists in the simultaneous β decay of two neutrons inside a nucleus. In the Standard Model of Particle Physics (SM) the decay $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ is a second order process. Experimentally, these kinds of nuclear decays have been observed in a dozen of isotopes and their life-time measured to range between 7×10^{18} and 2×10^{24} yr. Several theories beyond the SM (BSM) predict the existence of $0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2\,e^-$. The observation of such a process, that violates the Lepton Number conservation by two units ($\Delta L = 2$), would also demonstrate the Majorana nature of neutrinos at the same time. In fig. 1 we show the Feynman diagram for this process together with the comparison between the SM double beta decay energy spectrum *versus* the $0\nu\beta\beta$ decay. As one can observe, this represents the best signature for investigating the existence of such a process [3, 4].

2. – The CUORE Experiment

The CUORE Experiment will exploit the bolometric technique [5] to search for neutrinoless double beta decay. The experiment consists of a close-packed array of 19 towers, each containing 52 TeO_2 crystals, of dimensions $5 \times 5 \times 5\,\mathrm{cm}^3$ (see fig. 1) and 750 g each, for a total mass of 741 kg of TeO_2, corresponding to a total mass of 204 kg of ^{130}Te (the natural isotope abundance is 34%). The 988 TeO_2 crystals, operated as bolometers, will serve as source as well as detector at the same time and they will be cooled inside a large cryostat down to 10 mK or less. Due to their small heat capacity at this low temperature

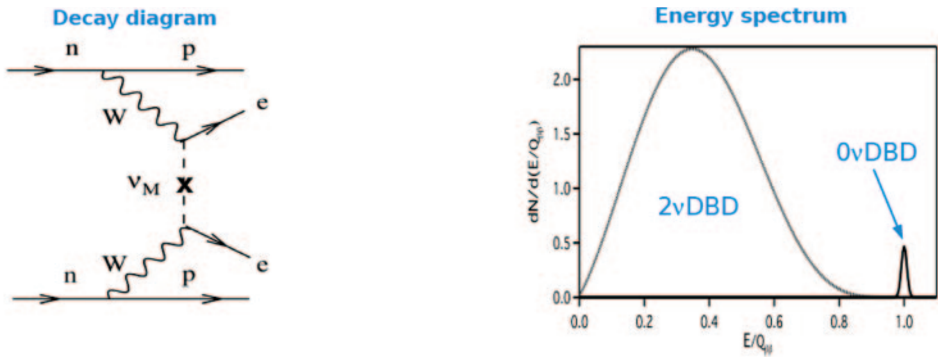

Fig. 1. – Left: Feymann diagram for a neutrinoless double beta decay. Right: a typical energy spectrum $E/Q_{\beta\beta}$ for the SM double beta decay and for the $0\nu\beta\beta$ decay.

the crystals act as highly sensitive calorimeters, converting the relatively small energies deposited by single interacting particles into measurable rises in temperature.

CUORE is located in Italy, in the Hall A of the Laboratori Nazionali del Gran Sasso (LNGS) of the Istituto Nazionale di Fisica Nucleare (INFN) at a depth of about 3500 m.w.e. under the Gran Sasso mountain. The half-life $0\nu\beta\beta$ decay of ^{130}Te can be determined from the number of observed events. CUORE aims, at 1σ C.L., to reach a sensitivity on the half-life of $T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) = 1.6 \times 10^{26}$ yr in 5 years of data taking. The improvements in the radio-purity of materials and the detector shielding will lead to an expected background level for CUORE of 0.01 counts/keV/kg/yr in the signal region around the Q-value of ^{130} Te (2527.5 keV). CUORE experimental design was built off of Cuoricino and was validated by CUORE-0 experiment. Cuoricino was an array of 62 $\mathrm{TeO_2}$ bolometers (for a total mass of 40.7 kg) which collected data at LNGS from 2003 to 2008. By operating 58 crystals of natural $\mathrm{TeO_2}$ and 4 enriched $\mathrm{TeO_2}$ crystals, containing approximately 11 kg of ^{130}Te in total, with a total exposure of 19.75 kg/yr, Cuoricino set a limit of $T_{1/2}^{0\nu\beta\beta} > 2.8 \times 10^{24}$ yr (90% C.L.) on the $0\nu\beta\beta$ half-life of ^{130} Tes.

3. – The CUORE Cryogenic System

The CUORE detector (see fig. 2) is housed in a dedicated cryostat and cooled to ~ 10 mK by a pulse-tube-assisted (PT) dilution refrigerator (DR) [6]. Cryostat cooling down to 4 K is provided by 5 two-stage Cryomech PT415 Pulse Tubes, with nominal cooling power of 40 W at 45 K and 1.5 W at 4.2 K each. PTs have been chosen mainly to avoid liquid cryogens refills and improving the experiment duty cycle. The baseline temperature is finally reached using a modified DRSCF3000 continuous-cycle Dilution Refrigerator made by the Leiden Cryogenics. The DR has a nominal cooling power of 3 mW at 120 mK and 5 μW at 12 mK. The lowest temperature that the DR is able to reach is around 5 mK. To shield the detector from environmental radioactivity and radioactive contaminations of the dilution refrigerator, several layers of lead will be used both inside and outside the cryostat, with Roman lead constituting the innermost layer. The Roman lead used in CUORE comes from Roman bricks that had remained on the seabed with the ship that transported them in the sea for about two millennia, during which time the albeit low original radioactivity of one of the radionuclides, ^{210}Pb, decreased by approximately 100000 times.

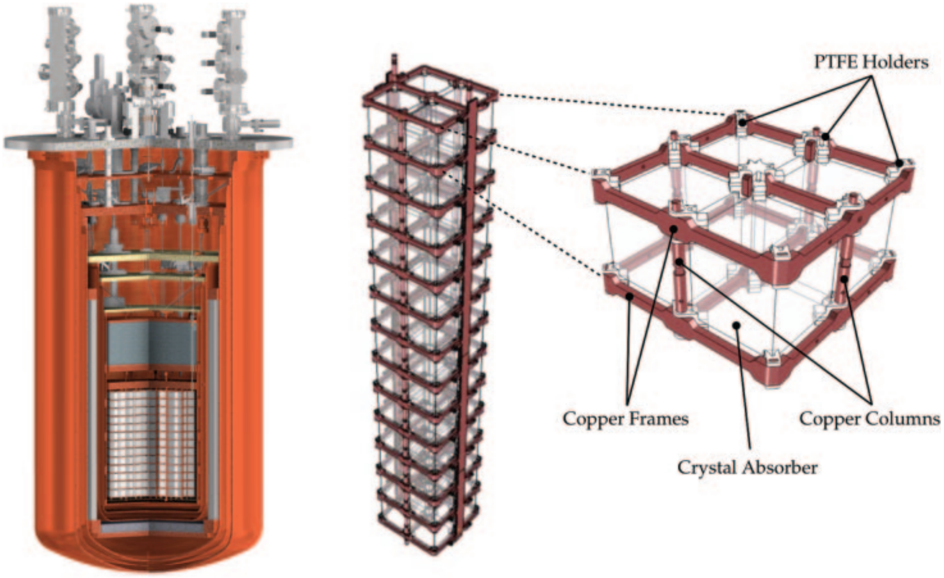

Fig. 2. – Left: schematic overview of the full CUORE Experiment. Right: layout of CUORE tower. CUORE has 19 towers containing 52 bolometers each for a total of 988 detectors.

3˙1. *The CUORE cryostat.* – The CUORE cryostat is the only one of its kind in the world, in terms of dimensions, mass and extreme temperatures reached as well as for the selected materials and building techniques intended to guarantee very low levels of radioactivity. During a run (called run 1.3) in the summer of 2014 the CUORE cryostat set a world record by cooling a copper vessel of 1 m^3 and weight of approximately 400 kg to a temperature of ~ 6 mK. It was the first time that an experiment cooled this much mass and volume to such a low temperature. The temperature remained stable (± 0.15 mK) during all the 15 days in which the test was performed [7, 8]. The cryostat is a custom apparatus consisting of six coaxial nested copper vessels, related top plates, a cryogen free cooling system with five pulse tubes (PTs), a very powerful dilution refrigerator, and a fast cooling system (FCS) for pre-cooling. The 6 thermal shields are at temperatures of 300 K, 40 K, 4 K, 600 mK, 50 mK and 10 mK, respectively. Two of these shields are vacuum chambers: the 300 K shield referred to as the Outer Vacuum Chamber (OVC) and the 4 K, referred to as the Inner Vacuum Chamber (IVC). A thermal radiation shield, between the OVC and the IVC chambers, is maintained at a temperature of about 40 K by the PTs. Because of the risk of radioactive contamination, only 10 layers of specially selected Multilayer Insulation (MLI) cover the 40 K shield and the IVC shield.

3˙2. *CUORE Fast Cooling System.* – The five CUORE Pulse Tubes alone are not able to cool down the whole CUORE Cryostat, lead shields and bolometric crystals to a temperature of 4 K in an acceptable time. For this reason, in addition to PTs, a Fast Cooling System (FCS) has been designed and constructed for a quick pre-cooling of CUORE Inner Vacuum Chamber (IVC) from room temperature to less than 20–30 K in about 10 days. In spite of other CUORE cooling systems (PTs and DR), that are Cryogenic-Fluid-Free Refrigerators, the FCS uses helium to reach the goal of speeding up the cooling process. CUORE FCS can be schematically described as an external vessel

(Fast Cooling Unit, FCU) with two main heat exchangers inside (a third one is outside the FCU), three CRYOMECH AL600 Single Stage Gifford-McMahon Cryo-coolers (each with a cooling power of about 600 W at 77 K), a helium blower, double-walled pipes, a gas handling system and an automated FC Control System. The Helium gas, moved by a blower, is progressively cooled down. It first enters an external heat exchanger, called HEX0, then the FCU cryostat through a second heat exchanger called HEX1 and finally it passes to the third cooling stage (the coldest), where it reaches the desired temperature by means of the three GM Cryocoolers thermally linked to the third heat exchanger (HEX2). Thus, it exits the FCU to enter the CUORE cryostat to cool down the entire IVC volume (copper, lead shields and crystal towers). The gas is then extracted from CUORE and recirculated inside the FCU by means of the external blower. During run 4, one of the CUORE commissioning runs (started in November 2015), CUORE cryostat was cooled down from a temperature of 300 K to 4 K in about 16 days.

3˙3. *CUORE Cryogenic Slow Control System.* – In order to avoid any risk to the apparatus, to the crystals and to be able to safely run the Cryogenic systems, pressures, temperatures, DR, PTs, FCS, vacuum pumps, compressors, etc. need to be constantly monitored and remotely and automatically controlled by a dedicated slow control system. This system is called the CUORE-Cryogeny Monitor and Control System (CMCS), and consists of several components which directly monitor and control the cryogenic systems and a custom LabVIEW-based software package to coordinate the systems in real-time. The CMCS also provides all the stored cryogenic information to a separate Slow Monitoring database, which collects and archives data from several CUORE systems. A Slow Monitoring website displays this data through its graphical plotting interface, making it possible for anyone in the collaboration to follow the status of the apparatus.

4. – Status of CUORE commissioning

The commissioning of the CUORE cryostat was successfully concluded in March 2016. All the tests done so far show that the measurements are in good agreement with expectation and the subsystems work properly. During run 4, the cryostat worked stably, keeping a base temperature of 6.3 mK for about 70 days, with the full load apart from the detector itself. A minitower, a test tower with only 8 crystals, was installed and operated for the purpose of studying the performances of the crystals, for debugging the DAQ and o9ther systems as well as for analysing the cryogenic performance of the cryostat. The results were rather encouraging. The installation of the towers inside the CUORE cryostat is expected to end at some point during the summer 2016. After this phase, CUORE will start the cool down and then move into the next phase towards the first physics run.

5. – Latest CUORE-0 results

In order to test and demonstrate the performance of the upcoming CUORE experiment, a smaller scale setup (CUORE-0) was built. The CUORE-0 experiment was done using 52 TeO_2 bolometers, 750 g each, arranged in 13 layers, constructed following the CUORE experiment protocols. CUORE-0 was in fact the first tower produced using the CUORE assembly line [9]. This tower was operated in a standalone mode, collecting data from from March 2013 to March 2015 and was located in Hall A of LNGS, hosted in the same cryostat that was previously used for Cuoricino. In March 2015 the

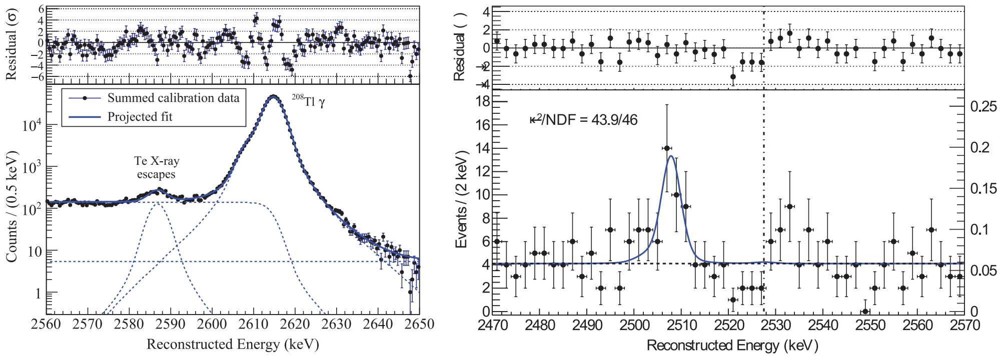

Fig. 3. – Left Bottom: Calibration data in the region around the 2615 keV ^{208}Tl γ-ray line, integrated over all bolometers in the entire statistic. The blue line is the projection of the UEML fit to data. Right bottom: the best-fit model from the UEML fit (solid blue line) overlaid on the spectrum of $0\nu\beta\beta$ decay candidates in CUORE-0 (data points); the peak at ~ 2507 keV is attributed to ^{60}Co; the dotted black line shows the continuum background component of the best-fit model. On the top of both the plots there are the normalised residuals of the best-fit model and the binned data. The vertical dot-dashed black line indicates the position of $Q_{\beta\beta}$.

data-taking was concluded as the sensitivity of the previous Cuoricino Experiment was surpassed. Cuoricino set a lower limit, at 90% C.L., on $0\nu\beta\beta$ decays, of 2.8×10^{24} yr that means an upper limit on the neutrino effective Majorana mass between 300 and 710 MeV considering the theoretical and systematic uncertainties [10].

5˙1. *Detector performances.* – CUORE-0 energy resolution has been evaluated using calibration data collected while the detector was exposed to a thoriated tungsten wire source. In this way we calibrated each bolometer using the known gamma lines from ^{232}Th chain. We used the high-statistics 2615 keV ^{208}Tl line to establish the detector response to a monoenergetic deposit near the ROI. Figure 3 shows the unbinned extended Maximum Likelihood (UEML) fit to the calibration data. In addition to a double-Gaussian lineshape for each bolometer dataset, the fit function includes terms to model a multi scatter Compton continuum, a ~ 30 keV Te X-ray escape peak, and a continuum background. The FWHM of the projected fit is 4.8 keV. This demonstrates that the CUORE goal of 5 keV can be reached. We also evaluated the continuum event rate between 2700 keV and 3900 keV, to estimate the surface-alpha background reduction. We measured this to be 0.016 ± 0.001 c/keV/kg/yr, a ~ 7 fold reduction relative to Cuoricino. Based on Monte Carlo simulations, considering the reduced surface-background and the radiopurity of materials selected for the new CUORE cryostat, we conclude that the target ROI background level for CUORE, 0.01 c/keV/kg/yr, can be achieved.

5˙2. *Result on the search for $0\nu\beta\beta$ in ^{130}Te.* – The performed analysis finds no evidence for $0\nu\beta\beta$ of ^{130}Te and sets a 90% C.L. Bayesian upper limit on the decay rate using a uniform prior distribution ($\pi(\Gamma_{0\nu}) = 1$ for $\Gamma_{0\nu} \geq 0$) at $\Gamma_{0\nu} < 0.25 \times 10^{-24}\,\mathrm{yr}^{-1}$ or $T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{24}$ yr (statistical uncertainties only). Including the systematic uncertainties (due to modelling of the lineshape, the calibration uncertainties, the parametrization of the background in the ROI and the UEML fit) 90% C.L. limits are $\Gamma_{0\nu} < 0.26 \times 10^{-24}\,\mathrm{yr}^{-1}$ or $T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{24}$ yr. These results were then combined with Cuoricino data analysis and limits. The combined 90% C.L. limit is $T_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24}$ yr, which is the most stringent limit ever obtained so far. Using different Nuclear Matrix Element (NME) models, this result was translated as a limit on the effective Majorana neutrino mass: $m_{\beta\beta} < 270$–650 meV. For further details see fig. 3.

6. – Conclusions

The CUORE cryostat commissioning was finished in March 2016. All the tests done so far show that the measurements are in good agreement with expectations and the subsystems work properly [11]. The installation of the towers, inside the CUORE cryostat, is expected to end at some point during summer 2016. Just after this phase CUORE is expected to start the cool down and to move into the next phase towards the first physics run. In summary the CUORE-0 experiment found no evidence for $0\nu\beta\beta$ decays of ^{130} Te. The achieved result, combined with Cuoricino analysis gave us the most stringent limit on such a process. Because of the lower background, improved energy resolution and a higher data-taking efficiency, CUORE-0 has been able to surpass the sensitivity of Cuoricino in half of the runtime.

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