CUORICINO: final results

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Abstract. CUORICINO, the predecessor experiment of CUORE, was operated in Gran Sasso National Laboratories in Italy and demonstrated the feasibility of CUORE. The CUORICINO detector was an array of large cubic TeO$_2$ crystals summing up to the total mass of 40.7 kg. CUORICINO stopped the data taking in middle 2008. We present the CUORICINO detector performances and final experimental results in double beta decay, on ground and excited states of $^{130}$Te and on $^{120}$Te, together with the total data analysis that is of fundamental interest in the prediction of the expected CUORE background.

1. Introduction

Double beta decay [1] is a rare spontaneous process in which a nucleus changes its atomic number by two units. It is believed that this decay can occur in two modes. In the two neutrino mode ($2\nu$DBD) two electrons and two anti-neutrinos are emitted. In the neutrinoless mode ($0\nu$DBD) only two electrons are emitted. Even if very rare, $2\nu$DBD is allowed by the Standard Model and has been observed on several nuclei (half lives are of the order of $10^{21}$ y). In contrast, $0\nu$DBD violates the lepton number conservation by two units: it is forbidden in the Standard Model and, apart from a controversial claim, has never been observed (half life lower limits range from $10^{21}$ to $10^{25}$ y). The existence of this process would imply that the neutrino is a Majorana particle [2]. Assuming that $0\nu$DBD proceeds through the exchange of a light Majorana neutrino, the decay rate can be written as $\Gamma^{0\nu} = ln(2) F_N m_{\beta\beta}^2/m_e^2$. $F_N$, the nuclear factor of merit, embeds the phase space factor and the nuclear matrix element for the transition, $m_e$ is the electron mass and $m_{\beta\beta}$ is the effective Majorana mass, a combination of the neutrino mixing matrix elements and of the neutrino masses. Thus, knowing the value of $F_N$, the measurement of $\Gamma^{0\nu}$ would also provide information on the absolute scale of neutrino masses and on the mass hierarchy.

In a calorimetric detector, $0\nu$DBD would produce a monochromatic line in the energy spectrum at the Q-value of the decay, because all the final-state energy would be deposited by the two decay electrons. However the extremely low rate of the decay make its detection extremely challenging. For this reason $0\nu$DBD experiments require a large source mass, low background, and good energy resolution.

CUORICINO was a cryogenic array of TeO$_2$ bolometers designed to search for $0\nu$DBD of $^{130}$Te. It operated underground at the Laboratori Nazionali del Gran Sasso, Italy, from 2003 to 2008. $^{130}$Te is a good candidate for a $0\nu$DBD search: it has a high natural isotopic abundance (33.8%), and the Q-value (2527.5 keV [3, 4, 5]) is above most of the environmental gamma radioactivity. In the following the principal aspects of CUORICINO are reviewed and the final results of the experiment for several double beta decay modes and Te isotopes are presented.
2. The CUORICINO detector

CUORICINO was composed of 62 TeO$_2$ bolometers maintained at a temperature of 10 mK by a dilution refrigerator. A bolometer [6] detects an energy release as a temperature rise of an absorber crystal. The thermal pulse is converted to an electric signal by mean of a sensor coupled to the absorber. CUORICINO used TeO$_2$ crystals as absorbers, and Neutron Transmutation Doped (NTD) Germanium thermistors as sensors. The experiment had a total TeO$_2$ mass of 40.7 kg (11.3 kg of $^{130}$Te). The bolometers were arranged in a tower of 13 floors. Eleven floors consisted of four $5 \times 5 \times 5$ cm$^3$ crystals, each weighting 790 g, and two floors were made of nine $3 \times 3 \times 6$ cm$^3$ crystals, each weighting 330 g. Four of the small crystals were enriched, two in $^{128}$Te (i.a. 82%) and two in $^{130}$Te (i.a. 75%). All other detectors had natural isotopic abundances.

The crystals were held in a copper structure which acted also as a thermal bath. Each crystal was mechanically coupled to the copper frames by small Teflon supports that constituted the thermal conductance towards the heat bath. A NTD sensor, polarized with a constant current, was glued on each absorber. NTD signals passed through a readout chain composed of an amplification stage and an anti-aliasing filter. Signals exceeding the trigger threshold were sampled by a 18-bit ADC and saved to disk. Each bolometer also had a Silicon heater attached on it which was used to periodically inject a fixed amount of energy in the crystals. The resulting pulses of heat, almost identical to those induced by particle interactions, were used for offline gain correction.

The detectors, and all the materials surrounding them, underwent strict radiopurity checks. Background events produced by environmental radioactivity were suppressed by two lead shields. A 20 cm thick commercial lead shield surrounded the cryostat. A 1 cm shield, made of low activity lead ($A < 4$ mBq/kg in $^{210}$Pb) and kept at a temperature of 600 mK, protected the detectors from the contaminations of the cryostat itself. The external lead shield was surrounded by 20 cm of borated polyethylene to reduce neutron backgrounds. The cryostat was enclosed in a Faraday cage and the environment was maintained in nitrogen overpressure to avoid contamination from the radon in the air. A complete description of the experiment can be found in [7].

3. CUORICINO results

CUORICINO ended in 2008 after more than five years of data taking. In this period the experiment accumulated a statistics of 19.75 kg·y of $^{130}$Te exposure. A monthly calibration of the bolometers was performed by inserting a $^{202}$Th source between the cryostat and the external lead shield. The energy resolution was estimated for each bolometer and calibration measurement from the $^{208}$Tl peak at 2615 keV, and the average FWHM values were 6.3 keV, 9.9 keV and 13.9 keV for the big, small natural and small enriched crystals respectively.

3.1. $^{130}$Te Neutrinoless double beta decay to the ground state of $^{130}$Xe

The CUORICINO energy spectrum around the 0νDBD Q-value, obtained by operating all the bolometers in anti-coincidence, is shown in Figure 1. The peak at 2505 keV is produced by the sum energy of the 1173 keV and 1332 keV gammas emitted in the $\beta$-decay of $^{60}$Co, a contaminant in the cryostat materials. The flat background around the Q-value was of 0.17 counts/(keV·kg·y). The spectrum was fitted using a maximum likelihood procedure that resulted in an event rate compatible with zero: $\Gamma^{0\nu} = (-0.2 \pm 1.4 \text{ (stat)} \pm 0.3 \text{ (syst)}) \text{ y}^{-1}$. The half life lower limit was extracted with a Bayesian approach, using a flat prior in the physical region, yielding $T_{1/2}^{0\nu}(^{130}\text{Te}) > 2.8 \times 10^{25}$ y at 90% C.L. [8]. Using nuclear matrix elements from several authors, this result translates into an upper limit on $m_{\beta\beta}$ in the range $(0.3\pm0.7)$ eV.

A detailed study of the CUORICINO data revealed that the background in the signal region is the sum of three main contributions: degraded $\alpha$ particles originating from the copper surrounding the detectors (≈50%), $^{208}$Tl multi-Compton events from a $^{232}$Th contamination in...
Figure 1. CUORICINO spectrum in the 0νDBD region. The peak at ≈2505 keV is produced by the sum energy of the 1173 keV and 1332 keV photons emitted in 60Co β-decay. Black dots represent the data; blue line is the best fit curve; green and red lines represent the peak amplitude corresponding respectively to the 68% and 90% C.L. half life lower limits.

the cryostat shields (∼30%) and degraded α particles from the crystal surfaces (∼10%). These background sources were further investigated with Monte Carlo simulations and dedicated test measurements. It was found that the last two contributions can be lowered below the CUORE background goal, 0.01 counts/(keV·kg·y), with improvements in the shielding and in the crystal cleaning procedures. In contrast, tests on copper contaminations resulted in an upper limit on the background that is lower than the value measured in CUORICINO, but still between two and four times above the CUORE goal.

3.2. 130Te double beta decay to the first 0+ excited state of 130Xe

130Te can decay to the first 0+ excited state of 130Xe, producing two electrons (and two anti-neutrinos in 2νDBD) with a total energy of 734 keV. Compared to the decay to the ground state, this process has a lower transition rate because the available phase space is smaller. However, the decay is accompanied by the emission of de-excitation photons. The modular structure of CUORICINO offered the possibility of performing a coincidence-based analysis that could reduce the background to a level sufficient to render this decay mode observable. In 86% of the cases two photons with energies of 536 keV and 1257 keV are emitted. For each decay mode (0νDBD and 2νDBD) three coincidence scenarios were considered:

(i) both γ’s escape the original crystal and are completely absorbed in two distinct crystals;
(ii) the 536 keV γ is trapped in the original crystal with the electrons, the 1257 keV γ is absorbed in another crystal;
(iii) the 1257 keV γ is trapped in the original crystal with the electrons, the 536 keV γ is absorbed in another crystal.

While in 0νDBD all the hits give rise to monochromatic lines in the energy spectrum, in 2νDBD a broad spectrum is produced in the crystal originating the decay, because the anti-neutrinos escape undetected. Efficiencies, evaluated with Monte Carlo simulations, were in the range (0.4%÷2.3%), depending on the decay mode considered and the energy deposition scenario. After applying the event selection criteria to the CUORICINO data, no evidence for a signal was found in the energy spectra. For each decay mode the half life lower limit was extracted by combining the result from the three scenarios, yielding $T_{1/2}^{2ν} > 1.3 \times 10^{23}$ y (90% C.L.) and $T_{1/2}^{0ν} > 9.4 \times 10^{23}$ y (90% C.L.) [9]. These new limits represent an improvement of almost two orders of magnitude with respect to previous publications.

3.3. 120Te β+/EC double beta decay

CUORICINO contained 1.43×10^{23} nuclei of 120Te, whose natural abundance is 0.096%. 120Te can undergo β+/EC double beta decay, $^{120}\text{Te} \rightarrow ^{120}\text{Sn} + e^+ (+2\nu)$. In CUORICINO this process can be studied using a coincidence-based analysis, because the two gammas emitted in positron
annihilation can escape the the crystal in which they originated and be absorbed by other detectors. The following scenarios were considered:

(i) both $\gamma$’s escape the original crystal, but only one of them is detected;
(ii) both $\gamma$’s escape the original crystal and are detected in two other crystals;
(iii) one $\gamma$ is trapped in the original crystal, the other $\gamma$ is absorbed in another crystal.

The above scenarios assume that the kinetic energy of the positron ($K$) and the binding energy of the captured electron ($E_b$) are detected in the crystal where the decay occurred. In the neutrinoless decay mode the positron has a fixed energy $K_{\text{max}}$ and these two contributions always sum up to $E_0 = K_{\text{max}} + E_b = 693$ keV. In the two neutrino decay mode the positron kinetic energy has a continuous distribution between $E_b$ and $K_{\text{max}}$ ($E_b = 30.5$ keV if the capture proceeds through the K-shell). Detection efficiencies, evaluated with Monte Carlo simulations, were in the range from 0.4% to 6.2%, depending on the energy deposition scenario considered.

After applying the event selection criteria to the CUORICINO data, no evidence for a signal was found in the energy spectra. For each decay mode the half life lower limit was extracted by combining the results from the three scenarios, yielding $T_{1/2}^{0\nu} > 7.6 \times 10^{19}$ y (90% C.L.), and $T_{1/2}^{2\nu} > 9.4 \times 10^{20}$ y (90% C.L.) [10]. These results improve the existing limits by almost three orders of magnitude (four in the case of the $0\nu$ decay mode).

3.4. Muon-induced backgrounds

During the last three months of operation of CUORICINO, the detector was surrounded by several plastic scintillators for the purpose of investigating the effect of muon-induced events in the bolometers’ counting rate. The study consisted in looking at bolometric signals in coincidence with triggers from the scintillators. It demonstrated that by operating the bolometers in anti-coincidence (a standard procedure in $0\nu$DBD analysis, see Sec. 3.1), the muon-induced background rate was compatible with the rate of accidental coincidences. This resulted in an upper limit for the muon-induced background of 0.0021 counts/(keV·kg·y) at 95% C.L. in the region around the Te-130 Q-value [11].

4. Low energy threshold trigger

Dark matter candidates are expected to produce a signal in TeO$_2$ at energies below $\sim 30$ keV. Thanks to its large mass and low background, CUORE could be sensitive to these signals. For this purpose a trigger and a pulse shape discrimination parameter with high rejection power at low energy were developed and tested on two real bolometers [12]. The new algorithm is based on the matched filter technique and, compared to the standard trigger used in double beta decay search, should enable a lowering of the energy threshold from few tens of keV to few keV.

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