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# Search for Neutrinoless Double-Beta Decay of $^{130}\text{Te}$ with CUORE-0

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We report the results of a search for neutrinoless double-beta decay in a 9.8 kg-yr exposure of  $^{130}\text{Te}$  using a bolometric detector array, CUORE-0. The characteristic detector energy resolution and background level in the region of interest are  $5.1 \pm 0.3$  keV FWHM and  $0.058 \pm 0.004$  (stat.)  $\pm 0.002$  (syst.) counts/(keV·kg·yr), respectively. The median 90 % C.L. lower-limit sensitivity of the experiment is  $2.9 \times 10^{24}$  yr and surpasses the sensitivity of previous searches. We find no evidence for neutrinoless double-beta decay of  $^{130}\text{Te}$  and place a Bayesian lower bound on the decay half-life,  $T_{1/2}^{0\nu} > 2.7 \times 10^{24}$  yr at 90 % C.L. Combining CUORE-0 data with the 19.75 kg-yr exposure of  $^{130}\text{Te}$  from the Cuoricino experiment we obtain  $T_{1/2}^{0\nu} > 4.0 \times 10^{24}$  yr at 90 % C.L. (Bayesian), the most stringent limit to date on this half-life. Using a range of nuclear matrix element estimates we interpret this as a limit on the effective Majorana neutrino mass,  $m_{\beta\beta} < 270 - 760$  meV.

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Neutrinoless double-beta ( $0\nu\beta\beta$ ) decay is a hypothesized lepton-number-violating process [1] that has never been decisively observed. Its discovery would demonstrate that lepton number is not a symmetry of nature, establish that neutrinos are Majorana fermions, possibly constrain the absolute neutrino mass scale, and provide corroborating evidence for theories that leptons played a role in creating the matter-antimatter asymmetry in the universe [2]. The clear potential for fundamental impact has motivated intense experimental effort to search for this decay [3–6].

The Cryogenic Underground Observatory for Rare Events (CUORE) [7, 8], now in the final stages of construction at the Laboratori Nazionali del Gran Sasso (LNGS), promises to be one of the most sensitive upcoming  $0\nu\beta\beta$  decay searches. The detector exploits the bolometric technique [9, 10] in  $5 \times 5 \times 5$  cm<sup>3</sup> natTeO<sub>2</sub>

crystals, whereby the tiny heat capacity attained by a crystal at  $\sim 10$  mK results in a measurable increase of its temperature when it absorbs energy. The sought-after signature of  $0\nu\beta\beta$  decay is a peak in the measured energy spectrum at the transition energy ( $Q_{\beta\beta}$ ), which for  $^{130}\text{Te}$  is  $2527.518 \pm 0.013$  keV [11]. CUORE will consist of 19 towers each containing 52 crystals; CUORE-0 is a single such tower built using the low-background assembly techniques developed for CUORE [12]. The 52 TeO<sub>2</sub> crystals [13] are held in an ultra-pure copper frame by polytetrafluoroethylene (PTFE) supports and arranged in 13 floors, with 4 crystals per floor. Each crystal is instrumented with a neutron-transmutation-doped Ge thermistor [14] to record thermal pulses and a silicon resistor (“heater”) to generate reference pulses [15]. The tower is deployed in Hall A of LNGS and exploits the cryogenic system, shielding configuration, and front-end electronics from a predecessor experiment, Cuoricino [16–18].

CUORE-0 represents the state of the art for large-mass, low-background, ultra-low-temperature bolometer arrays. As well as being a competitive  $0\nu\beta\beta$  decay search, it has validated the ultraclean assembly techniques and radiopurity of materials for the upcoming CUORE experiment. Technical details can be found in [12, 13, 19–21]; we focus here on the first physics results from CUORE-0.

The data were collected in month-long blocks called *datasets* during two campaigns which ran from March 2013 to August 2013 and from November 2013 to March 2015. For approximately three days at the beginning and end of each dataset, we calibrated the detector by placing thoriated wires next to the outer vessel of the cryostat. Data collected between calibrations, denoted *physics data*, are used for the  $0\nu\beta\beta$  decay search.

Each thermistor voltage is continuously acquired at a rate of 125 Hz, however one bolometer is not read out due to a failed thermistor wire-bond during construction. Events are identified using a software trigger with a threshold of between 30 keV and 120 keV, depending on the channel. Typical particle-induced pulses have rise and decay times of 0.05 s and 0.2 s, respectively and amplitudes of  $\sim 0.3$   $\mu\text{V}/\text{keV}$  before amplification. Once triggered, we analyze a 5-s-long window consisting of 1 s before and 4 s after the trigger. The pre-trigger voltage establishes the bolometer temperature before the event; the

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pulse amplitude, determined from the remaining waveform, establishes the energy. Every 300 s, each heater is excited with a stable current to generate reference pulses which are flagged in the data. In addition, noise waveforms are collected on all bolometers every 200 s.

In this analysis we have applied two parallel pulse-filtering techniques, denoted optimal filter (OF) and decorrelated optimal filter (DOF), as well as two thermal gain stabilization (TGS) techniques, denoted heater-TGS and calibration-TGS. The filters exploit the distinct frequency characteristics of particle-induced vs. noise pulses to optimize energy resolution [22]. TGS corrects for small changes in the energy-to-amplitude response of the bolometer and readout chain; the monoenergetic heater pulses provide the input for heater-TGS. Both OF and heater-TGS were used for Cuoricino [18]. We developed DOF to reduce correlated noise between adjacent crystals; this class of noise predominantly affects the upper floors of the tower closest to cryostat noise sources [23, 24]. To recover data from two of the bolometers that have non-functioning heaters and from periods when temperature drifts in a bolometer exceeded the linear dynamic range of the heater-TGS, we developed a new method, calibration-TGS, using the 2615 keV  $^{208}\text{Tl}$  calibration line. To successfully apply calibration-TGS to physics data, we routinely monitor electronic parameters that can affect the bolometer response between calibrations (e.g., drifts in DC offset or amplifier gain). Where possible we utilize both TGS methods for all bolometers resulting in up to four stabilized pulse-amplitude estimators for each event (OF and DOF, with heater- and calibration-TGS).

To convert these to energy, we correlate prominent peaks in the stabilized-amplitude spectra collected in calibration runs with gamma lines of known energy between 511 keV and 2615 keV (see Fig. 1). We fit a quadratic function with zero intercept to the peak-mean vs. known-energy points to determine a separate calibration function for each stabilized-amplitude estimator of each bolometer-dataset; we then apply these to the physics data. Following this the physics data in the region of interest (ROI) for  $0\nu\beta\beta$  decay are *blinded* to avoid biasing the subsequent analysis. The blinding procedure [25] produces an unphysically intense, artificial peak at  $Q_{\beta\beta}$ .

We select the best-performing energy estimator for each bolometer-dataset to optimize sensitivity to  $0\nu\beta\beta$  decay (quantified by the ratio of energy resolution of the 2615 keV calibration line to the physics data exposure). While the combination of OF with heater-TGS was the default choice, combinations involving DOF and calibration-TGS — which are more robust against low-frequency common-mode noise and long-term temperature drifts, respectively — were selected where their out-performance of the default was statistically significant. The fractions of exposure using OF with calibration-TGS, DOF with heater-TGS, and DOF with calibration-TGS are: 21%, 12%, and 8%, respectively. The new anal-

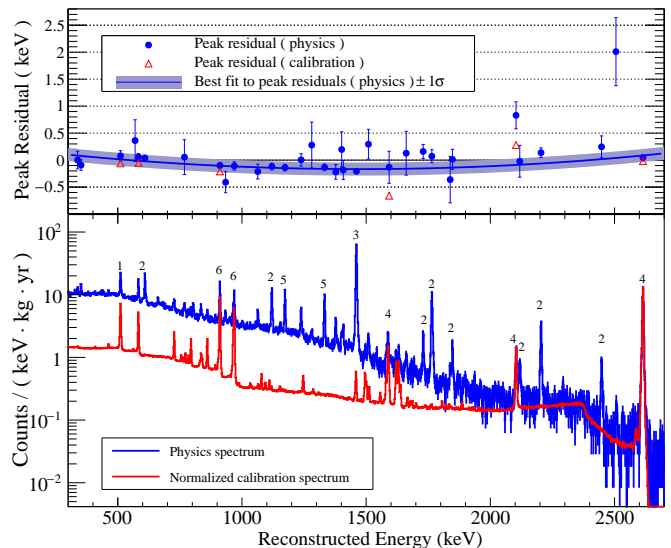


FIG. 1. Bottom: Energy spectra measured in calibration (red) and physics (blue) data. The calibration spectrum is normalized relative to the physics spectrum at 2615 keV. The labeled lines are identified as follows: (1)  $e^+e^-$  annihilation, (2)  $^{214}\text{Bi}$ , (3)  $^{40}\text{K}$ , (4)  $^{208}\text{Tl}$ , (5)  $^{60}\text{Co}$ , and (6)  $^{228}\text{Ac}$ . Top: The data points are the residuals of the best-fit reconstructed peak energy and expected peak-energy (fit - expected) for physics data (blue) and calibration data (red). The blue line and shaded band are the best-fit function to the physics peak residuals and the  $1\sigma$  fit uncertainty.

ysis techniques result in a 4% improvement in energy resolution and a 12% increase in usable exposure.

We select  $0\nu\beta\beta$  decay candidates in the physics data according to the conditions below. First, we discard low-quality data (e.g., periods of cryostat instability or known equipment malfunction), reducing the total exposure by 7%. To allow a bolometer time to equilibrate after each event (pileup rejection) we require that the times since the previous event and until the next event on the same bolometer are greater than 3.1 s and 4.0 s, respectively. To reject noisy pulses which can contribute to background we require each waveform to be consistent with a waveform template, constructed for each bolometer-dataset from calibration data around the 2615 keV  $^{208}\text{Tl}$  peak. Six pulse-shape parameters characterize the waveforms and the criteria for acceptance are tuned simultaneously on a set of prominent peaks in the physics data — ranging from 146 keV to 2615 keV — to maximize the signal sensitivity at each peak. The sensitivity is quantified by the ratio of signal accepted to square root of the background accepted, where the signal sample is drawn from events that populate each peak and the background is drawn from nearby off-peak events. For this tuning we use a randomly selected fraction of the data corresponding to half the exposure and exclude the ROI. Finally, to reduce background from radiation that deposits energy in multiple crystals, such as  $\alpha$  decays at crystal surfaces or

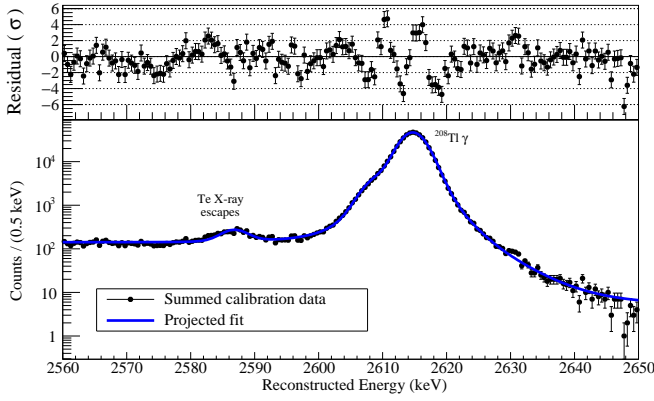


FIG. 2. Bottom: Calibration data in the region around the 2615 keV  $^{208}\text{Tl}$   $\gamma$ -ray line, integrated over all bolometer-datasets. The solid blue line is the projection of the UEML fit described in the main text. In addition to a double-gaussian lineshape for each bolometer-dataset, the fit function includes terms to model a multiscatter Compton continuum, a  $\sim 30$  keV Te X-ray escape peak, and a continuum background. Top: Normalized residuals of the data and the best-fit model.

multiple Compton scattering, we reject an event if there is another event in the tower within  $\pm 5$  ms (anticoincidence).

The selection efficiencies are evaluated using the fraction of exposure not utilized for their optimization, and averaged over all bolometer-datasets. The trigger efficiency is estimated from the fraction of heater excitations that produce an event trigger; we also exploit the heater events to measure the energy reconstruction efficiency (i.e., the probability for a monoenergetic pulse to reconstruct correctly). The combined trigger and reconstruction efficiency is  $(98.529 \pm 0.004)\%$ . The combined efficiency of the pileup and pulse-shape selection, estimated from the fraction of 2615 keV  $^{208}\text{Tl}$  events in physics data that pass this selection, is  $(93.7 \pm 0.7)\%$ . The anticoincidence efficiency has two components: the probability for a  $0\nu\beta\beta$  decay event to be fully contained in a single crystal, and the probability for it to survive accidental coincidences. We estimate the former to be  $(88.4 \pm 0.09)\%$  using a Geant4 simulation [26, 27], while the latter we determine to be  $(99.64 \pm 0.10)\%$  using the 1461 keV  $\gamma$ -ray line from  $^{40}\text{K}$ . The total selection efficiency is  $(81.3 \pm 0.6)\%$ .

We use the high-statistics 2615 keV  $^{208}\text{Tl}$  line in calibration data to establish the detector response to a monoenergetic deposit (lineshape) near the ROI. The data exhibit a non-gaussian lineshape characterized by a primary peak and a secondary peak whose mean is lower in energy by  $\sim 0.3\%$  and whose amplitude is typically  $\sim 5\%$  of the primary peak. The physical origin of this structure is still under investigation. We studied several lineshapes, including double- and triple-gaussian models; while the latter perform well at the  $^{208}\text{Tl}$  line, we adopt the double-gaussian lineshape as it is the simplest model that reproduces the detector response over the broad-

est range of energies. We quantify the systematic uncertainty associated with this choice below.

We parametrize the lineshape  $\rho$  for each bolometer-dataset  $(b, d)$  as:  $\rho_{b,d} = \rho(\mu_{b,d}, \sigma_{b,d}, \delta_{b,d}, \eta_{b,d})$ . For each  $(b, d)$  pair,  $\mu_{b,d}$  is the mean of the primary peak,  $\delta_{b,d}$  is the ratio of the means of the secondary and primary peaks,  $\sigma_{b,d}$  is the common gaussian width of both peaks, and  $\eta_{b,d}$  is the fractional intensity of the secondary peak. We estimate these parameter values with a simultaneous, unbinned extended maximum likelihood (UEML) fit to calibration data. Fig. 2 shows the fit result. In what follows we denote the best-fit lineshape parameters of the  $^{208}\text{Tl}$  calibration line as  $\hat{\mu}_{b,d}$ ,  $\hat{\sigma}_{b,d}$ ,  $\hat{\delta}_{b,d}$ , and  $\hat{\eta}_{b,d}$ ; we characterize these parameters in the context of the physics data below.

We apply this lineshape in a series of UEML fits to peaks of well-known energy between 511 keV and 2615 keV in the physics data (Fig.1). For a peak of known energy  $E$ ,  $\mu_{b,d}(E)$  is allowed to vary around the expected calibrated energy via a global free parameter  $\Delta\mu(E)$ . To account for energy dependence of the resolution and a possible systematic difference in resolution between calibration vs. physics data we vary the  $\sigma_{b,d}$  relative to  $\hat{\sigma}_{b,d}$  via a global scaling parameter  $\alpha_\sigma(E)$ . For the  $\delta_{b,d}$  we scale the corresponding  $\hat{\delta}_{b,d}$  by the ratio of  $E$  to 2615 keV; we fix the  $\eta_{b,d}$  to the corresponding  $\hat{\eta}_{b,d}$ .

The energy residual parameter,  $\Delta\mu(E)$ , at each peak is plotted in Fig. 1. A prominent outlier is the peak attributed to  $^{60}\text{Co}$  double-gamma events which reconstructs at  $2507.6 \pm 0.7$  keV,  $1.9 \pm 0.7$  keV higher than the established value [28]; a shift of  $0.84 \pm 0.22$  keV is also observed for the single escape peak of the  $^{208}\text{Tl}$  2615 keV gamma at 2104 keV. Calibration data taken with a  $^{60}\text{Co}$  source confirm the double-gamma events reconstruct at higher energy, in agreement with our physics data. Monte Carlo simulations show the double-gamma energy deposit in a bolometer is significantly less localized than the other single-gamma lines studied. We aim to clarify if this could be responsible for the shift in response with further studies. We note that the double escape peak of the  $^{208}\text{Tl}$  2615 keV line ( $E \simeq 1593$  keV) reconstructs within  $0.13 \pm 0.30$  keV of the expected value. Since the interaction topology of the  $e^+e^-$  pair is similar to that expected from  $0\nu\beta\beta$  decay we assume that  $0\nu\beta\beta$  decay events would reconstruct according to the calibrated energy scale.

We determine the calibration offset at  $Q_{\beta\beta}$  from a parabolic fit to the physics-peak residuals in Fig. 1, excluding the  $^{60}\text{Co}$  double-gamma and  $^{208}\text{Tl}$  single-escape lines as outliers. We adopt the standard deviation of the parabolic fit residuals as a systematic uncertainty. The result is  $\Delta\mu(Q_{\beta\beta}) = 0.05 \pm 0.05(\text{stat.}) \pm 0.12(\text{syst.})$  keV. Similarly, fitting the resolution-scaling parameter data with a linear function we find  $\alpha_\sigma(Q_{\beta\beta}) = 1.05 \pm 0.05$ . As a characteristic value of the detector resolution for physics data in the ROI we quote the exposure-weighted harmonic mean of the FWHM values of the  $\rho_{b,d}$  evaluated with  $\sigma_{b,d}(Q_{\beta\beta}) = 1.05 \times \hat{\sigma}_{b,d}$ :  $5.1 \pm 0.3$  keV. The

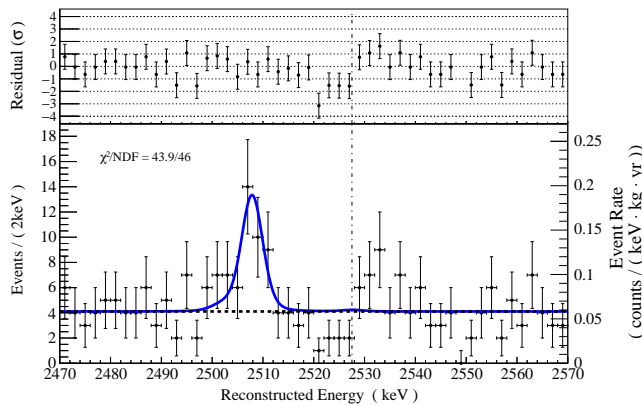


FIG. 3. Bottom: Energy spectrum of  $0\nu\beta\beta$  decay candidates in CUORE-0 (data points) and the best-fit model from the UEML analysis (solid blue line). The peak at  $\sim 2507$  keV is attributed to  $^{60}\text{Co}$ ; the dotted black line shows the continuum background component of the best-fit model. Top: The normalized residuals of the best-fit model and the binned data. The vertical dot-dashed black line indicates the position of  $Q_{\beta\beta}$ .

RMS of the exposure-weighted FWHM values is 2.9 keV.

After unblinding the ROI by removing the artificial peak, we determine the yield of  $0\nu\beta\beta$  decay events from a simultaneous UEML fit [29] in the energy region 2470–2570 keV (Fig. 3). The fit has three components: a posited signal peak at  $Q_{\beta\beta}$ , a peak at  $\sim 2507$  keV from  $^{60}\text{Co}$  double-gammas, and a smooth continuum background attributed to multiscatter Compton events from  $^{208}\text{Tl}$  and surface decays [30]. We model both peaks using the established lineshape. For  $0\nu\beta\beta$  decay, the  $\mu_{b,d}(Q_{\beta\beta})$  are fixed at the expected position (i.e.,  $87.00 \text{ keV} + \Delta\mu(Q_{\beta\beta})$  below  $\hat{\mu}_{b,d}$ , where  $87.00 \text{ keV}$  is the nominal energy difference between  $Q_{\beta\beta}$  and the  $^{208}\text{Tl}$  line), the  $\sigma_{b,d}$  are fixed to be  $1.05 \times \hat{\sigma}_{b,d}$ , the  $\delta_{b,d}$  and  $\eta_{d,b}$  are fixed to their best-fit calibration values, and the  $0\nu\beta\beta$  decay rate ( $\Gamma_{0\nu}$ ) is treated as a global free parameter. The  $^{60}\text{Co}$  peak is treated in a similar way except that a global free parameter is added to the expected  $\mu_{b,d}$  to accommodate the anomalous double-gamma reconstruction. Furthermore, the  $^{60}\text{Co}$  yield, although a free parameter, is constrained to follow the  $^{60}\text{Co}$  half-life [28] since  $^{60}\text{Co}$  was cosmogenically produced above ground but is not replenished under ground at LNGS. Within the limited statistics the continuum background can be modeled using a simple slowly-varying function. We use a zeroth-order polynomial as the default choice but also consider first- and second-order functions.

The ROI contains 233 candidate events from a total  $\text{TeO}_2$  exposure of 35.2 kg·yr, or 9.8 kg·yr of  $^{130}\text{Te}$  considering the natural isotopic abundance of 34.167% [31]. The result of the UEML fit is shown in Fig. 3. The best-fit value of the  $0\nu\beta\beta$  decay rate is  $\Gamma_{0\nu} = 0.01 \pm 0.12 \text{ (stat.)} \pm 0.01 \text{ (syst.)} \times 10^{-24} \text{ yr}^{-1}$  and the profile likelihood for  $\Gamma_{0\nu}$  is shown in Fig. 4. The

best-fit value of the background index in the ROI is  $0.058 \pm 0.004 \text{ (stat.)} \pm 0.002 \text{ (syst.) counts/(keV·kg·yr)}$ .

We evaluate the goodness-of-fit by comparing the value of the binned  $\chi^2$  in Fig. 3 (43.9 for 46 d.o.f.) with the distribution from a large set of pseudo-experiments with 233 Poisson-distributed events in each, and generated with the best-fit values of all parameters. We find that 90% of such experiments return a value of  $\chi^2 > 43.9$ . The data are also compatible with this set of pseudo-experiments according to the Kolmogorov-Smirnov metric. Finally, for each of the positive and negative fluctuations about the best-fit function we evaluated the significance by comparing the likelihood of our best-fit model to the likelihood from an UEML fit in which the fluctuation was modeled with a signal peak. For one d.o.f, the most negative (positive) fluctuation has a probability of 0.5% (3%). The probability to realize the largest observed fluctuation anywhere in the 100-keV ROI is  $\sim 10\%$ .

We find no evidence for  $0\nu\beta\beta$  of  $^{130}\text{Te}$  and set 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  $\Gamma_{0\nu} < 0.25 \times 10^{-24} \text{ yr}^{-1}$  or  $T_{1/2}^{0\nu} > 2.7 \times 10^{24} \text{ yr}$  (statistical uncertainties only). The median 90% C.L. lower-limit sensitivity for  $T_{1/2}^{0\nu}$  is  $2.9 \times 10^{24} \text{ yr}$ . The probability to obtain a more stringent limit than the one reported above is 54.7%. Including the systematic uncertainties which are described below, the 90% C.L. limits are  $\Gamma_{0\nu} < 0.25 \times 10^{-24} \text{ yr}^{-1}$  or  $T_{1/2}^{0\nu} > 2.7 \times 10^{24} \text{ yr}$ .

To estimate systematic uncertainties we perform a large number of pseudo-experiments with zero and non-zero signal. We find that our UEML analysis has negligible bias on  $\Gamma_{0\nu}$ . To estimate the systematic error from the lineshape choice we repeat the analysis of each pseudo-experiment with single-gaussian and triple-gaussian lineshapes and study the deviation of the best-fit decay rate from the posited decay rate as a function of posited decay rate. We also propagate the 5% uncertainty on  $\alpha_\sigma(Q_{\beta\beta})$ , the 0.12 keV energy scale uncertainty and the choice of zeroth-, first-, or second-order polynomial for the continuum background using this technique. The resultant systematic uncertainties are summarized in Table I.

TABLE I. Systematic uncertainties on  $\Gamma_{0\nu}$  in the limit of zero signal (Additive) and as a percentage of nonzero signal (Scaling).

	Additive ( $10^{-24} \text{ yr}^{-1}$ )	Scaling (%)
Lineshape	0.007	1.3
Energy resolution	0.006	2.3
Fit bias	0.006	0.15
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Selection efficiency	0.7%	

We combine our data with an existing 19.75 kg·yr



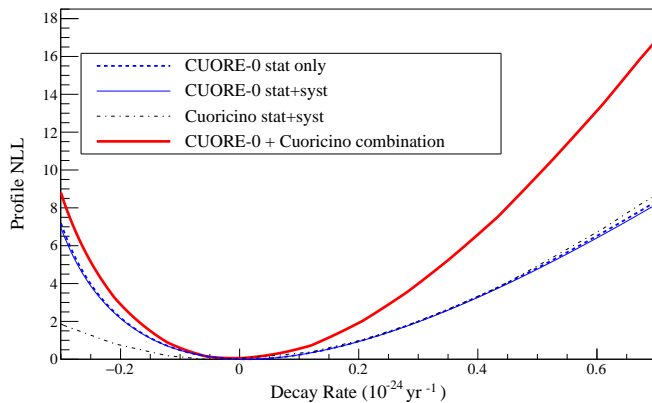


FIG. 4. Profile negative log-likelihood (NLL) curves for CUORE-0, Cuoricino [16–18], and their combination.

exposure of  $^{130}\text{Te}$  from the Cuoricino experiment [18]. The exposure-weighted mean and RMS FWHM energy resolution of the Cuoricino detectors was 6.9 keV and 2.9 keV, respectively, and the ROI background index was  $0.169 \pm 0.006$  counts/(keV·kg·yr). We report the profile likelihoods in Fig. 4. The combined Bayesian 90% C.L. limit is  $T_{1/2}^{0\nu} > 4.0 \times 10^{24}$  yr which is the most stringent limit to date on this quantity. For comparison, the 90% C.L. frequentist limits [32] are  $T_{1/2}^{0\nu} > 2.8 \times 10^{24}$  yr for CUORE-0 only, and  $T_{1/2}^{0\nu} > 4.1 \times 10^{24}$  yr for the combination with Cuoricino.

We interpret our Bayesian combined limit in the context of models for  $0\nu\beta\beta$  decay mediated by light Majorana neutrino exchange using the phase space factors from Ref. [33], the most recent nuclear matrix element (NME) calculations for a broad range of models available in the literature [34–38], and adopting the value of

$g_A \simeq 1.27$  for the axial coupling constant. The resulting range for the 90% C.L. upper limit on the effective Majorana mass is  $m_{\beta\beta} < 270\text{--}650$  meV; for ease of comparison with limits reported for other isotopes in the field this range excludes Ref. [39]. If we include the latter NME calculation the range extends to  $m_{\beta\beta} < 270\text{--}760$  meV.

In summary, CUORE-0 finds no evidence for  $0\nu\beta\beta$  decay of  $^{130}\text{Te}$  and, when combined with the Cuoricino exposure, provides the most stringent limit to date on this important process. Benefiting in particular from lower background, improved energy resolution, and higher data-taking efficiency, the experiment has surpassed the sensitivity of Cuoricino in approximately half the runtime.

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