High sensitivity neutrinoless double-beta decay search with one tonne-year of CUORE data

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Despite being the feeblest and lightest of the known particles, the neutrino is one of the most abundant particles in the Universe and has played a crucial role in its evolution. Within standard cosmological models, most of the neutrinos were produced in the Big Bang and completely decoupled from matter after the first second. During that short time it is possible that through the process
of Leptogenesis neutrinos helped to produce the matter/anti-matter asymmetry that sets the stage for all of the structures that we see in the universe today. However, these theories generally require the condition that the neutrino is a so-called Majorana particle, acting as its own anti-particle. The search for the extremely rare neutrinoless double-beta (0νββ) decay is currently the most practical way to address this question. Here we present the results of the first tonne-year exposure search for 0νββ decay of 130Te with CUORE. With a median half-life exclusion sensitivity of 2.8 × 1025 yr, this is the most sensitive search for 0νββ decay in 130Te to date. We find no evidence for 0νββ decay and set a lower bound of $T_{1/2}^{0νββ} > 2.2 \times 10^{25}$ yr at a 90% credibility interval. CUORE is the largest, coldest solid-state detector operating below 100 mK in the world. The achievement of 1 tonne-year of exposure demonstrates the long-term reliability and potential of cryogenic technology at this scale, with wide ranging applications to next generation rare event searches, dark matter searches, and even large-scale quantum computing.

I. INTRODUCTION

Our understanding of the neutrino has a long history, but it remains incomplete and evolving. The neutrino was proposed by Wolfgang Pauli in 1930, and first observed by Clyde Cowan and Frederic Reines in 1957. In 1937 Ettore Majorana developed a theory in which neutrinos are their own anti-particles, and in 1939 Wendel Furry suggested testing Majorana’s theory with a neutrinoless version of Maria Goeppert-Mayer’s double-β (2νββ) decay. In 1968, Ray Davis measured the flux of neutrinos from the sun, and set off a controversy when he reported about 1/3 as many as predicted by the Standard Solar Model of John Bahcall and his colleagues. In 1958, Bruno Pontecorvo predicted the oscillation between different neutrino families. In the Standard Model, neutrinos come in three “flavors” corresponding to their charged lepton cousins: electrons, muons and tau particles. In 1998, data from the Super-Kamiokande detector in Japan demonstrated that neutrinos produced in the atmosphere by cosmic rays do oscillate between flavors; this showed for the first time that they do have mass. In 2001, the mystery of the missing 8B solar neutrinos was laid to rest by the Sudbury Neutrino Observatory experiment (SNO). Even with this long line of developments, the absolute mass scale of neutrinos is still unknown, and the question of whether or not neutrinos are Majorana particles is also still a mystery. For a detailed history see Bilenky and the references therein [1].

The question of neutrino mass is important in cosmology due to its effects on the cosmological mass distribution and the possibility of massive neutrinos constituting a part of dark matter [2]. The neutrino is also unique in that it is the only fundamental particle that is capable of being a Majorana particle. A discovery that neutrinos have a Majorana nature would shed light on the nature of being a Majorana particle. A discovery that neutrinos have a Majorana nature would shed light on the nature of dark matter [2]. The neutrino is also unique in that it is the only fundamental particle that is capable of being a Majorana particle. A discovery that neutrinos are their own anti-particles, and in 1939 Wendel Furry suggested testing Majorana’s theory with a neutrinoless version of Maria Goeppert-Mayer’s double-β (2νββ) decay. In 1968, Ray Davis measured the flux of neutrinos from the sun, and set off a controversy when he reported about 1/3 as many as predicted by the Standard Solar Model of John Bahcall and his colleagues. In 1958, Bruno Pontecorvo predicted the oscillation between different neutrino families. In the Standard Model, neutrinos come in three “flavors” corresponding to their charged lepton cousins: electrons, muons and tau particles. In 1998, data from the Super-Kamiokande detector in Japan demonstrated that neutrinos produced in the atmosphere by cosmic rays do oscillate between flavors; this showed for the first time that they do have mass. In 2001, the mystery of the missing 8B solar neutrinos was laid to rest by the Sudbury Neutrino Observatory experiment (SNO). Even with this long line of developments, the absolute mass scale of neutrinos is still unknown, and the question of whether or not neutrinos are Majorana particles is also still a mystery. For a detailed history see Bilenky and the references therein [1].

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II. THE CUORE EXPERIMENT

CUORE represents the culmination of a long chain of cryogenic calorimetric experiments based on TeO2 and covering almost thirty years of 0νββ research [14]. It searches for the 0νββ decay of 130Te, which benefits from both a high natural isotopic abundance of
FIG. 1. The CUORE detector. Left: Rendering of the CUORE detector, showing the close-packed array of 988 TeO$_2$ calorimeters arranged in a cylindrical matrix of 19 identical towers. Center: The CUORE detector assembled and installed in the CUORE cryostat inside the CUORE cleanroom. The plastic ring was used during assembly for radon protection, but was removed before the cryostat was closed. Right: View of a single CUORE tower, showing the top floor hosting 4 TeO$_2$ crystals.

(34.167 ± 0.002)% [15], allowing for cost-effective use of natural tellurium, and a large energy release of $Q_{\beta\beta} = (2527.515 \pm 0.013)$ keV [16], placing the region of interest (ROI) above most natural gamma-emitting radioactive backgrounds. The CUORE detector is a close-packed array of 988 extremely pure $^{nat}$TeO$_2$ crystals [17] operated as cryogenic calorimeters [18] at a temperature of about 10 mK. They are arranged in a cylindrical matrix of 19 identical copper-framed towers (see Fig. 1). Each tower hosts 52 $5 \times 5 \times 5$ cm$^3$ crystals divided into 13 floors of 4 crystals. Each crystal has a mass of 750 g, corresponding to a total mass of 742 kg of TeO$_2$ containing 206 kg of $^{130}$Te.

The CUORE detector array is cooled to cryogenic temperatures by means of a multistage cryogen-free cryostat, uniquely designed for this application [19] and equipped with 5 cryogen-free pulse tube cryocoolers, which allows us to maintain a high duty-cycle by avoiding the need to stop data-taking for cryogen refills (a schematic of the cryostat is shown in Fig. 2). To mitigate possible degradation in energy resolution due to physical vibrations, the detector is mechanically decoupled from the cryostat by a custom detector suspension system, and the cryocoolers are actively driven with relative phases tuned to achieve vibration cancellation [20]. The total mass of $\sim$17 tonnes with 12.7 tonnes cooled to 4 K or below, along with a cooling power of $>3\mu$W and experimental volume of $\sim$1 m$^3$ at 10 mK, make the CUORE cryostat the largest, most powerful dilution refrigerator system in operation and the coldest cubic meter in the known universe [21].

With the calorimetric technique, a crystal converts the energy deposited by a particle interaction inside it into a measurable rise in temperature. Each crystal is instrumented with a neutron-transmutation-doped germanium thermistor (NTD) [22] to record thermal pulses and convert them into electric signals, as well as a silicon-based heater [23] to inject reference pulses with fixed energy for thermal gain stabilization (TGS) [24] (see Fig. 3). At CUORE’s operating temperatures, a TeO$_2$ crystal’s specific heat [25] yields a temperature increase of $\sim$100 $\mu$K/MeV, which the NTD converts into a voltage change of $\sim$100 $\mu$V/MeV [26]. Since each crystal contains the isotope of interest, $^{130}$Te, a $0\nu\beta\beta$ decay will deposit its energy directly into one of the crystals, leading to this measurable increase in temperature. Any energy depositions from other sources serve as a background for our $0\nu\beta\beta$ search.

Several steps are taken to protect CUORE from outside backgrounds that could obscure a $0\nu\beta\beta$ signal. CUORE is located at the underground Laboratori Nazionali del Gran Sasso (LNGS) of INFN in Italy, in a tunnel under a rock overburden equivalent to about 3,600 meters of water. This overburden shields CUORE from hadronic cosmic rays and reduces the muon flux at the experiment by about six orders of magnitude [28]. To suppress the $\gamma$ backgrounds originating from the environment outside the cryostat, two lead shields are integrated in the cryogenic volume: a 30-cm thick shield at $\sim$50 mK ($\sim$2 tonnes) and a 6-cm thick lateral and bottom shield at $\sim$4 K ($\sim$5 tonnes). The latter is made of $^{210}$Pb-depleted ($\lesssim$0.7 mBq kg$^{-1}$) ancient lead recovered from a Roman shipwreck [29], and is shown in Fig. 4. Additional shielding from $\gamma$ rays and neutrons is provided by an external 25-cm thick lead shield surrounded by borated polyethylene panels. Furthermore, strict radio-purity material selection criteria and cleaning procedures were applied to all of the structures facing the detector [30].

Despite the technical complexity associated with operating such a large cryostat, CUORE has been able to successfully and stably operate 984 out of its 988 calorimeters over several years, cementing its place as the only successful tonne-scale cryogenic calorimetric experiment
FIG. 2. Rendering of the CUORE cryostat with thermal stages, cooling and shielding elements highlighted. The cryogenic infrastructure consists of 6 nested vessels, the innermost of which contains the experimental volume. The different stages are identified by their nominal temperatures: 300 K, 40 K, 4 K, 800 mK or Still, 50 mK or Heat Exchanger and ∼10 mK or Mixing Chamber. The 300K and the 4K vessels are vacuum-tight and define two vacuum volumes called the Outer Vacuum Chamber (OVC) and the Inner Vacuum Chamber (IVC), respectively. The two lead shields to suppress external γbackground in the IVC are shown. The CUORE detector is attached to the Tower Support Plate placed right below the Top Lead. Cooling is provided through three different systems: the so-called fast cooling system, which is active in the initial stage of a cooldown, the pulse tube refrigerators that cool the 40 K and the 4 K plates, and the 3He/4He dilution unit that maintains the detector at base temperature [19].

not only in the field of 0νββ decay, but in general. Even under the lockdown conditions of a global pandemic, the experiment was able to continue collecting data with almost no human intervention, allowing for the nearly continuous accumulation of exposure shown in Fig. 5.

III. DATA ANALYSIS

The ultimate goal of our analysis chain is to convert the measurable temperature changes of our calorimeters into an energy spectrum of events, which will allow us to look for evidence of 0νββ decay in the ROI. To start, the voltage across the thermistor of each calorimeter is amplified, filtered through a 6-pole Bessel anti-aliasing filter, and continuously digitized with a sampling frequency of 1 kHz [26, 31]. During data acquisition periods, we save continuous detector waveforms that are later digitally re-triggered offline. For each triggered pulse, we analyze a 10-s window consisting of 3 s before and 7 s after the trigger time. The pre-trigger voltage serves as a proxy for the crystal temperature before a particle interaction, while we use the pulse amplitude to extract the energy released in the crystal.

We group our data into datasets covering one to two months each, bookended by calibrations at the beginning and at the end. We use the data between calibration periods for the 0νββ decay search and refer to them collectively as physics data. The calibration was performed with internal 232Th sources [32] for the first three datasets, an external 232Th source for the fourth, and external mixed 232Th–60Co sources for the rest of them, with consecutive datasets sharing their intermediate calibrations.

In this analysis, we use a low threshold trigger based on the optimum filter (OF) technique [33, 34]. This technique maximizes the signal-to-noise ratio by exploiting the distinct shapes of the stochastic noise power spectrum and the particle-induced signal spectrum. We build the OF transfer function for each calorimeter in each dataset and then extract the amplitude of each triggered pulse from the maximum of the filtered waveform.

Since the gain of a calorimeter depends on its operating temperature, we apply one of two algorithms offline to correct for any slow time variation in the operating temperature of our detector that could otherwise spoil the energy resolution [35, 36]. The first uses monenergetic heater pulses (heater-TGS), while the second exploits pulses induced by γ rays from the 2615 keV 208Tl calibration line (calibration-TGS). We employ the second method for the calorimeters with non functioning or unstable heaters in each dataset. For crystals in which both stabilization procedures can be employed, we compare the resulting energy spectra and select the method that optimizes the energy resolution at the 2615 keV 208Tl peak in calibration.

We calibrate each calorimeter over a single dataset by measuring the stabilized amplitude of the most intense γ lines in the calibration data. We fit the reconstructed peak positions against their energies using a second order-polynomial with zero intercept [36].

We apply a simple salting procedure to blind our data in the ROI, shifting a random portion of events around the 208Tl γ peak at 2615 keV in physics data down to the 130Te Q-value around 2527 keV and vice versa. Since fully absorbed 208Tl γ events induce responses in our detectors similar to those expected from 0νββ decays, this produces an artificial peak at Qβββ with the shape of a true signal peak. The analysis is tuned on the blinded data, and we reverse the salting to unblind the data once the analysis procedure is finalized.
FIG. 3. Left: CUORE calorimeters. The TeO$_2$ crystal plays the role of the absorber when a particle releases energy, and to measure its temperature increase we use NTD Ge thermistors, whose resistance has a steep dependence on the temperature. The thermal link between the crystal and the heat bath (the copper holders) is provided by the golden bonding wires and the PTFE supports [27]. The silicon heater we employ for thermal gain stabilization is also highlighted. Right: simplified calorimeter thermal model. The detector is modeled as a single object with heat capacity $C$ coupled to the heat bath (with constant temperature $T_0$) through the thermal conductance $G$. A sensor for signal readout is attached to the absorber.

To select 0$\nu$\beta\beta decay candidate events we apply the following selection criteria. First, we remove periods of time with unusually high noise levels or where the processing failed, corresponding to a $\sim 5\%$ loss in exposure. We also exclude any calorimeters in each dataset with a full width at half maximum (FWHM) $> 19$ keV at the 2615 keV calibration line, yielding a further $\sim 3\%$ loss in exposure and $\sim 0.5\%$ loss in sensitivity. Next, from Monte Carlo (MC) simulations we expect that the large majority of 0$\nu$\beta\beta decay events ($\sim 88\%$) release all of their energy into a single crystal [37]. We thus enforce an anti-coincidence veto by excluding any events that occur within a $\pm 5$ms time window of another triggered event with energy $> 40$ keV in a separate crystal. Finally, we use a pulse shape discrimination (PSD) procedure to eliminate pileup events, defined as events with more than one distinct energy deposit within the same time window, and other non-physical pulses that survived basic data quality cuts.

In this analysis, we employ a new technique for this pulse shape discrimination. We adopt a principal component analysis (PCA) based method similar to the one previously used in CUPID-Mo [38], which we detail in Methods. Compared to the PSD techniques used in our previous analyses, PCA achieves higher signal efficiency while maintaining similar background rejection capabilities. The effects of the PSD cut in both physics and calibration data are shown in Fig. 6.

The signal detection efficiency for a 0$\nu$\beta\beta decay is a product of several contributions: the containment efficiency, the reconstruction efficiency, the anti-coincidence (AC) efficiency, and the PSD efficiency. The first term is the probability that the full energy of the decay is contained in a single crystal, obtained through MC simulations. The reconstruction efficiency is the probability that a signal event is triggered, has the energy properly reconstructed, and is not rejected because of basic quality cuts. This is evaluated using heater events that we inject, which are a good approximation of signal-like events but are also externally flagged. Given the large statistics of heater events, the reconstruction efficiency is evaluated for each calorimeter in a dataset separately and is then averaged over the entire dataset. The anti-coincidence efficiency is the probability that a signal event is not incorrectly vetoed due to an accidental coincidence between two independent events. This is extracted by looking at the survival probability of fully absorbed $\gamma$ events at 1460 keV from electron capture decays of $^{40}$K, which should be uncorrelated with any other events. Due to the low overall event rate in physics data, this efficiency is calculated as an average term for the entire dataset.

Lastly, the PSD efficiency is obtained as the average survival probability of events in the $^{60}$Co, $^{40}$K, and $^{208}$Tl $\gamma$ peaks that already passed the base cuts and anti-coincidence cut. In principle, the PSD efficiency could be different for each calorimeter, but given the limited statistics in physics data we evaluate it over the full dataset. To account for any possible variation between individual calorimeters, we compare the PSD efficiency obtained by directly summing their individual spectra and counting the events at the $\gamma$ peaks before and after the PSD cut with that extracted from an exposure-weighted sum of the calorimeters’ spectra. We find a $\pm 0.3\%$ discrepancy between them, and include this as a global systematic uncertainty in the 0$\nu$\beta\beta fit.

The detector response function to a mono-energetic peak near $Q_{\beta\beta}$ is extracted for each calorimeter in each dataset by fitting the high-statistics 2615 keV $^{208}$Tl line in calibration data [11]. We model it empirically as a superposition of three Gaussians with the same width to account for a slightly non-Gaussian behavior [39, 40]. Thus, the normalized response function of each calorimeter-
FIG. 4. Lateral view of the roman lead shield integrated in the cryogenic volume to suppress external $\gamma$ background [29].

dataset pair is completely defined by 6 parameters: the relative intensities of the sub-peaks, the position of the means and the common peak width. We obtain an exposure-weighted average FWHM of $(7.78 \pm 0.03)$ keV at the 2615 keV calibration line in this analysis.

To account for possible discrepancies in the detector response between physics and calibration data, we fit the most prominent $\gamma$ lines in physics data with the lineshape function extracted at the $^{208}$Tl line in calibration, letting both the peak position and the energy resolution vary. In order to measure and correct for any residual bias in the energy calibration procedure, we then parameterize the energy calibration bias, defined as the difference between the reconstructed and the true peak position, as a quadratic function of energy. The energy resolution is also expected to be energy dependent, and we parameterize the observed trend as a linear function of energy [36]. We interpolate both functions to $Q_{\beta\beta}$ and we obtain an exposure-weighted harmonic mean FWHM of $(7.8 \pm 0.5)$ keV and an energy bias of $<0.7$ keV at $Q_{\beta\beta}$. A summary of all of the relevant quantities for the $0\nu\beta\beta$ decay analysis is given in Table I.

FIG. 5. Exposure accumulation for CUORE since it first began taking data, along with the amount of data unblinded in this analysis. Data collection was paused for periods of time in 2017 and 2018 for cryogenic maintenance, but since the beginning of 2019 CUORE has operated stably and has been collecting data with almost no interruptions. The cuts leading to the small loss in exposure shown are detailed in the Data Analysis section.

| Number of datasets | 15 |
|-------------------|----|
| TeO$_2$ exposure  | 1038.4 kg $\cdot$ yr |
| FWHM at 2615 keV in calibration data | 7.78(3) keV |
| FWHM at $Q_{\beta\beta}$ in physics data | 7.8(5) keV |
| Total analysis efficiency | 92.4(2)\% |
| Reconstruction efficiency | 96.418(2)\% |
| Anticoincidence efficiency | 99.3(1)\% |
| PSD efficiency | 96.4(2)\% |
| Containment efficiency | 88.35(9)\% [36] |

IV. RESULTS

The CUORE physics spectrum around $Q_{\beta\beta}$ after all selection cuts is shown in Fig. 7, along with our final fit result. The ROI is taken from 2490 keV to 2575 keV. The closest expected structure to $Q_{\beta\beta}$ is the sum peak at 2505.7 keV due to $^{60}$Co decays where both the 1173.2 keV and 1332.5 keV de-excitation $\gamma$ rays are fully absorbed in the same crystal. In addition, we expect background events from the trace amounts of environmental radiation that were not eliminated by our shielding and material purification procedures. Roughly 90\% of these events come from degraded $\alpha$ particles, where a portion of the $\alpha$ decay energy is deposited in some part of the support structures and the rest is deposited in a calorimeter, while the other 10\% are largely multi-Compton scattered 2615 keV $\gamma$ rays from $^{208}$Tl decays [37, 41].

We perform an unbinned Bayesian fit combined over all calorimeters and datasets, imposing a uniform prior on
non-negative $0\nu\beta\beta$ rates. We find no evidence for $0\nu\beta\beta$ decay, measuring a best fit rate of $\Gamma_{0\nu} = (0.9 \pm 1.4) \times 10^{-26}$ yr$^{-1}$ and setting a limit on the $^{130}\text{Te}$ $0\nu\beta\beta$ half-life of $T_{1/2}^{0\nu} > 2.2 \times 10^{25}$ yr with a 90% credibility interval (CI). We also calculate a Frequentist limit of $T_{1/2}^{0\nu} > 2.6 \times 10^{25}$ yr at 90% confidence. Our systematic uncertainties have a total effect of 0.8% on both the global mode of $\Gamma_{0\nu}$ and our limit on $T_{1/2}^{0\nu}$. Details for both the Bayesian and Frequentist approaches as well as the systematic effects are described in Methods.

Repeating the fit without the $0\nu\beta\beta$ decay contribution, we measure an average background index (BI) of $(1.49 \pm 0.04) \times 10^{-2}$ counts / (keV kg yr) at $Q_{\beta\beta}$. If we assume no signal is present, our median exclusion sensitivity with this data release is $T_{1/2}^{0\nu} > 2.8 \times 10^{25}$ yr (90% CI). The probability of obtaining a stronger limit than our result of $2.2 \times 10^{25}$ yr is 72%, putting us well within the range of expected outcomes.

Assuming $0\nu\beta\beta$ decay is mediated by the exchange of a light Majorana neutrino, our limit on the $^{130}\text{Te}$ $0\nu\beta\beta$ decay half-life corresponds to an upper limit of 90-305 meV on the effective Majorana mass $m_{\beta\beta}$, with the spread coming from different nuclear matrix element calculations currently available in the literature [42–48].

V. DISCUSSION

We note that this analysis presents a weaker limit than our previous result [12]. This is well within the range of expected outcomes due to statistical fluctuations in the
FIG. 7. Top: ROI spectrum with the best-fit curve (solid red) and the best-fit curve with the $0\nu\beta\beta$ decay component fixed to the 90% CI limit (dashed blue), as well as the fit without the $0\nu\beta\beta$ component (dashed green). Bottom: The corresponding marginalized posterior probability distribution of $\Gamma_{0\nu}$ with all the systematics included. The shaded region corresponds to the 90% credibility interval.

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APPENDIX A: Optimum trigger and analysis threshold

In order to study low energy events, we digitally trigger our raw data waveforms. Each pulse transfer function is matched to the signal shape so that frequency components with low SNR are suppressed. A trigger is fired if the amplitude of a signal exceeds a fixed multiple of the filtered noise RMS of each calorimeter in each dataset.
As a figure of merit for the quality of energy thresholds obtained with our trigger procedure, we use the point of 90% trigger efficiency. This is evaluated by adding fake pulses with increasing energy on noise events with a software procedure. Compared to the previous method, it has the advantage that any physics run acquired under standard conditions can be employed, and thresholds can be monitored along the data-taking. On the other hand, it relies on the assumption that real pulses are similar to the average pulse we use to simulate particle events. We identify the stabilized amplitude corresponding to the energy we want to inject from the calibration function. Then, we compute the raw event amplitude using the stabilization function. For each calorimeter and energy we evaluate the detection efficiency as the ratio of the number of detected signal events over the number of events generated. We perform a fit with the error function and invert it to evaluate the energy corresponding to the 90% trigger efficiency. The distribution of the energy thresholds at 90% efficiency is shown in Fig. 8.

We set a common analysis threshold of 40 keV to guarantee that our trigger efficiency is above 90% for the majority (97%) of our detectors while also being low enough to reliably remove multi-Compton events from the ROI with the anti-coincidence cut. Our improved ability to detect low-energy events using this OT method also increases the efficiency with which we can reconstruct events that release energy in more than one calorimeter, improving our background reconstruction ability [49, 53].

APPENDIX B: Principal Component Analysis for PSD

In this analysis we use a new algorithm based on principal component analysis (PCA) for pulse shape discrimination. The method has previously been detailed for CUPID-Mo [38], and has been adapted for usage in CUORE. This technique replaces the algorithm employed in previous CUORE results that was based on 6 pulse shape variables [36]. We found that performing a PCA decomposition on signal-like events pulled from γ calibration peaks in CUORE calorimeters usually yields a leading component that is similar to an average pulse, and that using just this leading component captures > 99% of the variance between pulses. We choose to treat the average pulse of each calorimeter in a dataset as if it were the leading PCA component, normalizing it like a PCA eigenvector. We can then project any event from the same channel onto this vector and attempt to reconstruct the 10-second waveform using only this leading component. For any waveform \( x \) and leading PCA component \( w \) with length \( n \), we define the reconstruction error as

\[
RE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x - (x \cdot w_i))^2} \tag{B1}
\]

This reconstruction error metric measures how well an event waveform can be reconstructed using only the average pulse treated as a leading PCA component. Events that deviate from the typical expected shape of a signal waveform are poorly reconstructed and have a high reconstruction error, allowing us to reject them. We normalize the reconstruction errors as a second order polynomial function of energy on a calorimeter-dataset basis (see Fig. 9), and then cut on these normalized values by optimizing a figure of merit for signal efficiency over expected background in the \( Q_{\beta\beta} \) ROI. Using this PCA-based method, we obtain an overall efficiency of (96.4 ± 0.2)% compared to the (94.0 ± 0.2)% from the pulse shape analysis used in our previous results, as well as a 50% reduction in the PSD systematic uncertainty from 0.6% to 0.3%.

APPENDIX C: Statistical 0νββ analysis

We employ an unbinned Bayesian fit on the combined data using the BAT software package [54]. The model parameters are the 0νββ decay rate (\( \Gamma_{0ν} \)), a linearly sloped background, and the \( ^{60}\text{Co} \) sum peak amplitude. The \( \Gamma_{0ν} \) and \( ^{60}\text{Co} \) rates are common to all datasets, with the \( ^{60}\text{Co} \) rate scaled by a preset dataset-dependent factor to account for its expected decay over time. The base background index expressed in terms of counts / (keV·kg·yr) is dataset-dependent, while the linear slope to the background is shared among all datasets since any structure to the shape of the background should not vary between datasets. The \( \Gamma_{0ν} \), \( ^{60}\text{Co} \) rate, and background index parameters are all given uniform priors constrained to non-negative values, while the linear slope to the background has a uniform prior allowing both positive and negative values.

In addition to these statistical parameters, we consider the systematic effects induced by the uncertainty on the energy bias and energy resolution, the value of \( Q_{\beta\beta} \), the
FIG. 9. Left: example of a normalization fit of the PCA reconstruction error vs energy for a single calorimeter. The 2nd order polynomial fit is drawn in red, and each point corresponds to an event in the calorimeter that passed other base cuts. Right: two example pulses from this calorimeter, along with their locations in the left scatter plot. The actual pulse is drawn in black, and the attempted reconstruction using the PCA-based method of PSD is drawn in red. Pulse a) deviates from the expected shape of a good pulse in this calorimeter and is rejected by the PSD, while pulse b) conforms to the expected response and is accepted by the PSD.

FIG. 10. 90% exclusion limits from an ensemble of $10^4$ pseudo-experiments assuming no $0\nu\beta\beta$ signal, with background rates obtained from a background-only fit to our current data. Each possible exclusion limit is obtained by performing on one of the pseudo-experiments the same Bayesian fit that we apply to the actual data.

A list of the systematics and priors is reported in Table II. The efficiencies and the isotopic abundance are multiplicative effects on our expected signal, so their impact is reported as a relative effect on $\Gamma_{0\nu}$. In contrast, the uncertainties on $Q_{\beta\beta}$, the energy bias, and the resolution scaling are additive effects that do not scale with the signal rate. Therefore, we report their absolute effects on $\Gamma_{0\nu}$. The dominant effect is due to the uncertainty on the energy bias and resolution scaling in physics data. We account for possible correlations between the nuisance parameters by including all of them in the fit simultaneously.

To determine our expected $0\nu\beta\beta$ exclusion sensitivity with this analysis procedure, we generated a set of 10000 pseudo-experiments with only the $^{60}$Co and linear background components, split into 15 datasets with exposure and background rates obtained from the background-only fits to our actual data. We fit each of these experiments with the same signal plus background model that we use on real data, obtaining the exclusion sensitivity shown in Fig. 10.

natural isotopic abundance of $^{130}$Te, and the analysis, containment, and PSD efficiencies. We evaluate their separate effects on the $0\nu\beta\beta$ rate by adding nuisance parameters to the fit one at a time and studying both the variation of $\Gamma_{0\nu}$ at the posterior global mode $\hat{\Gamma}_{0\nu}$, and the resulting effect on the marginalized 90% CI limit on $\Gamma_{0\nu}$.
TABLE II. Systematics affecting the $0\nu\beta\beta$ decay analysis. The total analysis efficiency is the product of all the efficiencies listed in Table I except containment. The analysis efficiency II refers to the additional systematic uncertainty on the PSD efficiency described in the text. The first 4 systematics are multiplicative effects and their impacts are presented as percentages. The last 2 are additive systematics, for which we cite their absolute effect on the signal $\Gamma_{0\nu}$. We report the variation induced on the marginalized 90% CI limit (third column) and the effect they have at the posterior global mode $\hat{\Gamma}_{0\nu}$ (last column).

| Systematic                      | Prior           | Effect on the Marginalized $\Gamma_{0\nu}$ Limit | Effect on $\hat{\Gamma}_{0\nu}$ |
|---------------------------------|-----------------|-------------------------------------------------|---------------------------------|
| Total analysis efficiency I     | Gaussian        | 0.2%                                            | < 0.1%                          |
| Analysis efficiency II          | Gaussian        | 0.3%                                            | < 0.1%                          |
| Containment efficiency          | Gaussian        | 0.2%                                            | < 0.1%                          |
| Isotopic abundance              | Gaussian        | 0.2%                                            | < 0.1%                          |
| $Q_{\beta\beta}$                | Gaussian        | < $0.1 \cdot 10^{-27}$ yr$^{-1}$                | $< 0.1 \cdot 10^{-27}$ yr$^{-1}$|
| Energy bias and Resolution scaling | Multivariate  | $0.2 \cdot 10^{-27}$ yr$^{-1}$                 | $0.1 \cdot 10^{-27}$ yr$^{-1}$  |

Our Frequentist limit is determined using the Rolke method. We use the same fit procedure as in the Bayesian approach and consider the resulting profiled likelihood function $\mathcal{L}$ for $\Gamma_{0\nu}$. We can then extract a 90% confidence interval on $\Gamma_{0\nu}$ by treating $-2\log \mathcal{L}$ as approximately a $\chi^2$ distribution with one degree of freedom, with our lower limit on $T_{1/2}$ coming from the corresponding upper edge of this confidence interval on $\Gamma_{0\nu}$.

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