Experiment	Energy resolution FWHM(KeV)	B_index($* \, 10^{-3}$)	M_norm
CUORE	7.8	8.51	134.7
CUPID-Baseline	5	$1.47 * 10^{-3}$	2012.0
CUPID-1T	5	$7.4 * 10^{-4}$	7953.4
GERDA	~	$3.77 * 10^{-1}$	145.4
LEGEND-1000	2.5	$1.1 * 10^{-3}$	12380
EXO-200	150	$2.6 * 10^{-1}$	9.247
nEXO	46	$8.3 * 10^{-4}$	4531
KamLAND-Zen	9.89(Phase1) 11.07(Phase2)	$6.8 * 10^{-2}$ $2.4 * 10^{-2}$	1.445 8.1

$$\boxed{T_{1/2}^{0\nu\beta\beta} = \ln 2 \cdot \frac{N_A}{M_{\text{isotope}}} \cdot \frac{M \cdot \epsilon\eta \cdot t}{\alpha \cdot \sqrt{b}}}$$

$$\rightarrow$$

$$\boxed{\left(\frac{T_{1/2}^{0\nu\beta\beta} \cdot \alpha}{\ln 2 \cdot N_A} \right)^2 = \frac{M_{\text{norm}}}{B_{\text{I}}}}$$

$$\nearrow \quad \boxed{B_{\text{I}} = \frac{b}{(M\epsilon\eta \cdot t / M_{\text{isotope}}) \cdot \text{ROI}}}$$

$$\searrow \quad \boxed{M_{\text{norm}} = \frac{M\epsilon\eta \cdot t}{\text{ROI} \cdot M_{\text{isotope}}}}$$

https://iopscience.iop.org/article/10.1088/1742-6596/606/1/012006

Regular calibration runs were taken on a weekly basis, using a ^{228}Th source, in order to determine the energy scale of the individual detectors. The energy shift between successive calibrations is less than 1 keV at $Q_{\beta\beta}$. This is due to gain drifts of the readout chain [10]. The mean exposure-weighted energy resolutions for the GERDA detectors are $\boxed{4.8 \pm 0.2\,\mathrm{keV}}$ for the semi-coaxial detectors and $\boxed{3.2 \pm 0.2\,\mathrm{keV}}$ for the BEGe detectors.

a lower limit of $T_{1/2} > 1.5 \times 10^{26}$ yr at 90% C.L. is set. Phase I and Phase II data together give a total exposure of 127.2 kg yr, which corresponds to (1.288 ± 0.018) kmol yr of ^{76}Ge in the active volume. The combined analysis has also a best fit for null signal strength, and provides a half-life limit of

$$T_{1/2} > \boxed{1.8 \times 10^{26}} \text{ yr at 90\% C.L.} \qquad (4)$$

Phase I of GERDA collected 23.5 kg yr of exposure (= total germanium mass × live time) between November 2011 and September 2013, with an average background index B of $\boxed{11 \times 10^{-3}\,\mathrm{counts/(keV\,kg\,yr)}}$ at $Q_{\beta\beta}$ [18]. Phase II of GERDA started in December 2015, after a major upgrade [15] with additional germanium detectors of superior per-

GERDA achieved an unprecedentedly low background in Phase II, as derived from the fit, of $\boxed{B = 5.2^{+1.6}_{-1.3} \times}$ 10^{-4} counts/(keV kg yr), and met the design goal of background-free performance: the mean background expected in the signal region ($Q_{\beta\beta} \pm 2\sigma$) is 0.3 counts.

The statistical analysis is carried out also within a Bayesian framework. The one-dimensional posterior probability density function $P(S|data)$ of the signal strength is derived by

Data set	$\mathcal{E}$ (kg yr)	$\langle\epsilon\rangle$	Background	BI[a]	Counts
Without PSD					
Golden	17.9	0.688 ± 0.031	76	18 ± 2	5
Silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
With PSD					
Golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
Silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

[a]In units of 10^{-3} counts/(keV kg yr).

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.111.122503

	Dec 2015–May 2018		July 2018–Nov 2019		
	Coaxial	BEGe	Coaxial	BEGe	Inverted coaxial
Number of detectors	7	30	6	30	5
Total mass	15.6 kg	20 kg	14.6 kg	20 kg	9.6 kg
Exposure $\mathcal{E}$	28.6 kg yr	31.5 kg yr	13.2 kg yr	21.9 kg yr	8.5 kg yr
Energy resolution at $Q_{\beta\beta}$ (FWHM)	(3.6 ± 0.2) keV	(2.9 ± 0.3) keV	(4.9 ± 1.4) keV	(2.6 ± 0.2) keV	(2.9 ± 0.1) keV
$0\nu\beta\beta$ decay detection efficiency ϵ:	(46.2 ± 5.2)%	(60.5 ± 3.3)%	(47.2 ± 5.1)%	(61.1 ± 3.9)%	(66.0 ± 1.8)%
Electron containment	(91.4 ± 1.9)%	(89.7 ± 0.5)%	(92.0 ± 0.3)%	(89.3 ± 0.6)%	(91.8 ± 0.5)%
^{76}Ge enrichment	(86.6 ± 2.1)%	(88.0 ± 1.3)%	(86.8 ± 2.1)%	(88.0 ± 1.3)%	(87.8 ± 0.4)%
Active volume	(86.1 ± 5.8)%	(88.7 ± 2.2)%	(87.1 ± 5.8)%	(88.7 ± 2.1)%	(92.7 ± 1.2)%
Liquid argon veto	(97.7 ± 0.1)%			(98.2 ± 0.1)%	
Pulse shape discrimination	(69.1 ± 5.6)%	(88.2 ± 3.4)%	(68.8 ± 4.1)%	(89.0 ± 4.1)%	(90.0 ± 1.8)%

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.125.252502

Detector Array (GERDA) experiment on the search for the $0\nu\beta\beta$ decay of ^{76}Ge are presented. GERDA used high-purity germanium detectors made out of material isotopically enriched in ^{76}Ge to $\boxed{\sim 87\%}$ [14,15]: this approach maximizes the detection efficiency as source and detector coincide. The outstanding energy resolution of germanium

$$\mathrm{M}_{norm} = \left(\frac{17.9 * 0619 * 10^3}{76 * (\frac{4.8}{2.355} * 4)} + \frac{1.3 * 0.619 * 10^3}{76 * (\frac{4.8}{2.355} * 4)} + \frac{2.4 * 0.663 * 10^3}{76 * (\frac{3.2}{2.355} * 4)} + \right.$$

$$\left. \frac{28.6 * 0.462 * 10^3}{76 * (\frac{3.6}{2.355} * 4)} + \frac{31.5 * 0.605 * 10^3}{76 * (\frac{2.9}{2.355} * 4)} + \frac{13.2 * 0.472 * 10^3}{76 * (\frac{4.9}{2.355} * 4)} + \frac{21.9 * 0.611 * 10^3}{76 * (\frac{2.6}{2.355} * 4)} + \frac{8.5 * 0.66 * 10^3}{76 * (\frac{2.9}{2.355} * 4)}\right) * 0.87(enriched) = 145.4$$

$$\mathrm{B}_{norm} = \frac{1.1 * 10^{-2} * 76}{1000 * 0.87 * 0.62} * \frac{23.5}{127.2} + \frac{5.2 * 10^{-4} * 76}{1000 * 0.87 * 0.56} * \frac{103.7}{127.2} = 3.77 * 10^{-4}$$

(GERDA)

https://arxiv.org/pdf/2107.11462.pdf

Germanium Experiment for Neutrinoless $\beta\beta$ Decay. This internationa
to answer one of the highest priority questions in fundamental physics.
Ge detectors enriched to more than 90% in the ^{76}Ge isotope of interest o
active shield at a deep underground laboratory. The experiment is design

TABLE IV. Experimental parameters in the LEGEND-1000 discovery potential and background projections.

Parameter	**Value**
Performance Parameters	
$0\nu\beta\beta$ decay isotope	^{76}Ge
$Q_{\beta\beta}$	2039 keV
Total mass	1000 kg
Energy resolution at $Q_{\beta\beta}$	2.5 keV FWHM
Overall signal acceptance[a]	0.69
Live time goal	10 yr
Total exposure goal	10 t yr
Background goal	$< 1 \times 10^{-5}$ cts/(keV kg yr)
	< 0.025 cts/(FWHM t yr)
$T^{0\nu}_{1/2}$	1.3×10^{28} yr (99.7% CL discovery)
	1.6×10^{28} yr (90% CL sensitivity)
$m_{\beta\beta}$	9.4–21.4 meV (99.7% CL discovery)
	8.5–19.4 meV (90% CL sensitivity)
Physics Parameters	
$M_{0\nu}$	2.66–6.04 [28, 37]
$G_{0\nu}$	2.363×10^{-15} /yr [22]
g_A	1.2724

[a] Includes an average 91% ^{76}Ge enrichment, 92% active volume, 92% containment efficiency, and 90% analysis cuts. An additional factor of 95% is necessary for the fraction of events in a $\pm 2\sigma$ optimal region of interest in a counting-based analysis. See Sect. V.C.3 for details.

$$\mathrm{M}_{norm} = \frac{10 * 10^6 * 0.69 * 1}{76 * 2.5 * 4/2.355(ROI)} = 21380$$

$$\mathrm{B}_{norm} = \frac{1 * 10^{-5} * 76}{1000 * 0.69 * 1} = 11 * 10^{-7}$$

(LEGEND-1000)

This search is based on data acquired between May 2017 and December 2020 and includes a reanalysis of the data already published [11, 12]. With a total TeO_2 exposure of $1038.4\ \mathrm{kg \cdot yr}$, this represents a threefold increase in exposure over our previous result and the largest amount of data ever collected with a cryogenic solid-state detector. This result serves as proof that cryogenic technology can be operated with the scale and low radioactivity needed not only for future generation $0\nu\beta\beta$ searches, but also for other rare event searches and even quantum computing applications [13].

TABLE I. Summary of exposure-weighted average detector performance parameters and efficiencies. The containment efficiency is evaluated from MC simulations.

Number of datasets	15
TeO_2 exposure	1038.4 kg· 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]

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 ($0\nu\beta\beta$) decay is currently the most practical way to address this question. Here we present the results of the first tonne-year exposure search for $0\nu\beta\beta$ decay of ^{130}Te with CUORE. With a median half-life exclusion sensitivity of 2.8×10^{25} yr, this is the most sensitive search for $0\nu\beta\beta$ decay in ^{130}Te to date. We find no evidence for $0\nu\beta\beta$ decay and set a lower bound of $T_{1/2}^{0\nu} > 2.2 \times 10^{25}$ 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.

are described in Methods.

Repeating the fit without the $0\nu\beta\beta$ decay contribution, we measure an average background index (BI) of $(1.49 \pm 0.04) \cdot 10^{-2}$ counts / (keV kg yr) at $Q_{\beta\beta}$. If we assume no signal is present, our median exclusion sensitivity with this data release is $T_{1/2}^{0\nu} > 2.8 \cdot 10^{25}$ yr (90%

https://arxiv.org/pdf/2104.06906.pdf

https://journals.aps.org/prc/pdf/10.1103/PhysRevC.93.045503

$$\mathrm{B}_{norm} = \frac{1.49 * 10^{-2} * \ (130 + 16 * 2)}{1000 * 0.924 * 0.341 * 0.8835} = 8.51 * 10^{-3}$$

$$\mathrm{M}_{norm} = \frac{1038400 * 0.924 * 0.341 * 0.8835}{(130 + 16 * 2) * \frac{7.8}{2.355} * 4(ROI)} = 134.7$$

CUORE

satisfies the CUPID requirements.

In its baseline design, CUPID will consist of an array of 1534 Li_2MoO_4 crystals, grown from molybdenum enriched at $\geq 95\%$ in ^{100}Mo. The single-crystal mass will be approximately 308 g, corresponding to a total ^{100}Mo mass of about 253 kg. CUPID will be housed in the present cryogenic facility of CUORE, located in the Laboratori Nazionali del Gran Sasso of INFN, Italy, and will benefit from its infrastructure and operation procedures (see Sec. 3). The expected background index (BI) is about

Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

https://arxiv.org/pdf/1907.09376.pdf

$$\mathrm{B}_{norm} = \frac{10^{-4} * 100}{1000 * 0.79 * 0.9 * 0.95} = 1.47 * 10^{-5}$$

$$\mathrm{M}_{norm} = \frac{253 * 1000 * 0.79 * 0.9 * 10 * 0.95}{5 * 4/2.355(ROI) * 100} = 2012$$

CUPID-Baseline

$$\mathrm{B}_{norm} = \frac{5 * 10^{-6} * 100}{1000 * 0.79 * 0.9 * 0.95} = 7.4 * 10^{-7}$$

$$\mathrm{M}_{norm} = \frac{1000 * 1000 * 0.79 * 0.9 * 10 * 0.95}{5 * 4/2.355(ROI) * 100} = 7953.4$$

CUPID-1T

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analyses, the signal detection efficiency has been raised from 80.8% to 96.4 ± 3.0%, and the energy resolution of the detector at the Q value of ^{136}Xe $0\nu\beta\beta$ has been improved from $\sigma/E = 1.23\%$ to 1.15 ± 0.02% with the upgraded detector. Accounting for the new data, the median 90% confidence level $0\nu\beta\beta$ half-life sensitivity for this analysis is 5.0×10^{25} yr with a total ^{136}Xe exposure of 234.1 kg yr. No statistically significant evidence for $0\nu\beta\beta$ is observed, leading to a lower limit on the $0\nu\beta\beta$ half-life of 3.5×10^{25} yr at the 90% confidence level

$0\nu\beta\beta$ detection efficiency has been raised to 97.8 ± 3.0% (96.4 ± 3.0%) in Phase I (Phase II) from 82.4 ± 3.0% (80.8 ± 2.9%) [8] by relaxing two selection criteria. First

10 mm away from the cylindrical PTFE reflector, as well as the cathode and the V-wire planes. This FV contains $3.31 \cdot 10^{26}$ atoms of ^{136}Xe, with an equivalent mass of 74.7 kg. While the incomplete xy-matched energy deposits may fall outside the FV, this effect is determined by detector simulations to have a negligible effect on the estimated detection efficiency due to the energy require-

sitivities in the range $10^{25} - 10^{26}$ yr at 90% confidence level (CL). Exploiting the advantages of a liquid xenon (LXe) cylindrical time projection chamber (TPC) filled with LXe enriched to 80.6% in ^{136}Xe [13], EXO-200 [14] achieved a sensitivity of $3.7 \cdot 10^{25}$ yr with the most recent $0\nu\beta\beta$ search [8], while the most sensitive search to date for the same isotope reached $5.6 \cdot 10^{25}$ yr [9]. Here we report on a search with similar sensitivity to the previous

In Dec. 2018, EXO-200 completed data taking with the upgraded detector ("Phase II", May 2016 to Dec. 2018), after collecting an exposure similar to that of its first run ("Phase I", Sept. 2011 to Feb. 2014). This letter reports a search for $0\nu\beta\beta$ using the full EXO-200 dataset, which after data quality cuts [13] totals 1181.3 d of livetime. This represents approximately a 25% increase in exposure relative to the previous search [8] that already included nearly half of the Phase II dataset. In addition to

$$\mathrm{B}_{norm} = \frac{1.5 * 10^{-3} * 136}{1000 * 0.97 * 0.806} = 2.61 * 10^{-4}$$

https://arxiv.org/pdf/1906.02723.pdf

$$\mathrm{M}_{norm} = \frac{74.7 * 1000 * 0.97 * 0.806 * 3.23}{150(ROI) * 136} = 9.247$$

EXO-200

- !NESTBugFound
- FWHM = [2435 keV – 2481 keV] (0.8% sigma)
- light ¡ 1.077*charge+313 && light¿0.597*charge-216
- DNNvalue ¿ 0.85

$$T_{1/2} = \frac{M_{fid}\ N_A\ f\ T_{live}\ \epsilon}{M_A\ N_{0\nu}}\ \ln(2) \tag{15}$$

where $M_{fid} = 3281\,\mathrm{kg}$ is the mass of LXe inside the fiducial volume, $M_A = 0.1358\,\mathrm{kg/mol}$ is the average atomic mass of the enriched LXe, $f = 0.9$ is the enrichment fraction, $\epsilon = 0.96$ is the signal detection efficiency, T_{live} is the livetime in years, and $N_A = 6.02$ atoms/mol is Avogadro's constant.

At this stage, we consider two different models of nEXO: one in which the copper components are made from standard Aurubis copper, and one in which the copper components are made from electroformed copper (which has much lower radioactivity). These are denoted D-023 and D-024 in the Material Database, respectively. We report the sensitivity for each in the left-hand column in Table XVII.

$$\mathrm{B}_{norm} = \frac{5.3 * 10^{-6} * 136}{1000 * 0.96 * 0.9} = 8.34 * 10^{-7}$$

$$\mathrm{M}_{norm} = \frac{3281 * 1000 * 0.96 * 0.9 * 10}{46(\mathrm{ROI}) * 136} = 4531$$

nEXO

We present results from the first phase of the KamLAND-Zen double-beta decay experiment, corresponding to an exposure of 89.5 kg yr of ^{136}Xe. We obtain a lower limit for the neutrinoless double-beta decay half-life of $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr at 90% C.L. The combined results from KamLAND-Zen and EXO-200 give $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr at 90% C.L., which corresponds to a Majorana neutrino mass

$\sigma \sim 15$ cm$/\sqrt{E\text{ (MeV)}}$, and the energy resolution is $\sigma = (6.6 \pm 0.3)\%/\sqrt{E\text{ (MeV)}}$.

KamLAND-Zen result [2]. The hypothesis that backgrounds from ^{88}Y, ^{208}Bi, and ^{60}Co are absent marginally increases the limit to $T^{0\nu}_{1/2} > 2.0 \times 10^{25}$ yr (90% C.L.). A Monte Carlo simulation of an ensemble of experiments based on the best-fit background spectrum indicates a sensitivity [7] of 1.0×10^{25} yr. The chance of obtaining

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.110.062502

$$\mathrm{M}_{norm} = \frac{89.5 * 1000 * 0.9077 * 0.999}{136 * (0.042 * 2458 * 4)(\mathrm{ROI})} = 1.445$$

$$\mathrm{B}_{norm} = \frac{2 * 10^{-4} * 136}{1000 * 0.9077 * 0.999} = 6.8 * 10^{-5}$$

KamLAND-Zen Phase I

outer LS, which is corrected in the detector simulation, while the nonlinearities for both the LS regions are consistent. The observed energy resolution is $\sigma \sim 7.3\%/\sqrt{E(\mathrm{MeV})}$,

(1,2,4-trimethylbenzene) by volume, 2.29 g/liter of the fluor PPO (2,5-diphenyloxazole), and $(2.91 \pm 0.04)\%$ by weight of isotopically enriched xenon gas. The isotopic abundances in the enriched xenon were measured by a residual gas analyzer to be $(90.77 \pm 0.08)\%$ ^{136}Xe, $(8.96 \pm 0.02)\%$ ^{134}Xe. Other xenon isotopes have negligible

radius, together with the best-fit background composition and the 90% C.L. upper limit for $0\nu\beta\beta$ decays. Combining the results, we obtain a 90% C.L. upper limit of < 2.4 (kton day)$^{-1}$, or $T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr (90% C.L.). We find that a fit including potential backgrounds from ^{88}Y, ^{208}Bi, and ^{60}Co [3] does not change the obtained limit. A MC of an ensemble of experiments assuming the best-fit background spectrum without a $0\nu\beta\beta$ signal indicates a sensitivity of 5.6×10^{25} yr, and the probability of obtaining

started the second science run (phase II), and found a reduction of ^{110m}Ag by more than a factor of 10. We report on the analysis of the complete phase-II data set, collected between December 11, 2013 and October 27, 2015. The total live time is 534.5 days after muon spallation cuts, discussed later. This corresponds to an exposure of 504 kg yr of ^{136}Xe with the whole Xe-LS volume.

Following the end of phase II, we performed a detector calibration campaign using radioactive sources deployed at various positions along the central axis of the IB. The event position reconstruction—determined from the scintillation

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.117.082503

$$\mathrm{M}_{norm} = \frac{504 * 1000 * 0.999}{136 * (0.0465 * 2458 * 4)(\mathrm{ROI})} = 8.1$$

$$\mathrm{B}_{norm} = \frac{1.6 * 10^{-4} * 136}{1000 * 0.907 * 0.999} = 2.4 * 10^{-5}$$

KamLAND-Zen Phase II