Search for Majorana neutrinos with the first two years of EXO–200 data

The EXO–200 Collaboration*

Many extensions of the standard model of particle physics suggest that neutrinos should be Majorana-type fermions—that is, that neutrinos are their own anti-particles—but this assumption is difficult to confirm. Observation of neutrinoless double-$\beta$ decay ($0\nu\beta\beta$), a spontaneous transition that may occur in several candidate nuclei, would verify the Majorana nature of the neutrino and constrain the absolute scale of the neutrino mass spectrum. Recent searches carried out with $^{76}\text{Ge}$ (the GERDA experiment) and $^{136}\text{Xe}$ (the KamLAND-Zen and EXO (Enriched Xenon Observatory)-200 experiments) have established the lifetime of this decay to be longer than $10^{25}$ years, corresponding to a limit on the neutrino mass of 0.2–0.4 electronvolts. Here we report new results from EXO–200 based on a large $^{136}\text{Xe}$ exposure that represents an almost fourfold increase from our earlier published data sets. We have improved the detector resolution and revised the data analysis. The half-life sensitivity we obtain is $1.9 \times 10^{25}$ years, an improvement by a factor of 2.7 on previous EXO–200 results. We find no statistically significant evidence for $0\nu\beta\beta$ decay and set a half-life limit of $1.1 \times 10^{25}$ years at the 90 per cent confidence level. The high sensitivity holds promise for further running of the EXO–200 detector and future $0\nu\beta\beta$ decay searches with an improved Xe-based experiment, nEXO.

Majorana fermions, a class of neutral spin-1/2 particles described by two-component spinors, have been an element of quantum field theory since its inception. Electrons and other spin-1/2 elementary particles with distinct antiparticles are, however, described by four-component Dirac spinors. Majorana quasiparticles may have been observed in condensed matter systems where neutrality is achieved through the collective action of electrons and holes. Among the known elementary particles, only neutrinos are Majorana fermion candidates, owing to their intrinsic neutrality. Confirmation of this property would imply the non-conservation of lepton number, an additive quantum number that, unlike charge or colour, is not related to any known gauge symmetry. As yet, lepton number has been empirically found to be conserved. Neutrinos are also remarkable for their small, yet finite, masses that are generally difficult to explain, but arise naturally in many extensions of the standard model of particle physics. A generic consequence of many such extensions is that neutrinos should be of the Majorana variety.

The most sensitive probe for Majorana neutrinos is a nuclear process known as neutrinoless double-$\beta$ decay ($0\nu\beta\beta$), whereby a nucleus decays by emitting two electrons and nothing else, while changing its charge by two units. A related double-$\beta$ decay process, known as two-neutrino double-$\beta$ decay ($2\nu\beta\beta$), is allowed by the standard model and has been observed in many nuclei, $^{136}\text{Xe}$ among them. It provides, however, no direct information on the Majorana/Dirac question. The exotic $0\nu\beta\beta$ can be distinguished from the $2\nu\beta\beta$ by measuring the sum energy of the two electrons that is peaked at the $Q$-value for the former and is a continuum for the latter. The $Q$-value is the mass difference between the mother and daughter nuclei. We refer to this region around the $Q$-value as the $0\nu\beta\beta$ region of interest (ROI). The half-life of the $0\nu\beta\beta$ is related to the effective Majorana neutrino mass ($m_{\nu\beta\beta}$) by a phase space factor and a nuclear matrix element. Hence observation of the $0\nu\beta\beta$ decay would demonstrate lepton number violation and measure the neutrino mass scale ($m_{\nu\beta\beta}$), at least to within the theoretical uncertainty of the nuclear matrix elements.

Recent sensitive searches for $0\nu\beta\beta$ have been carried out in $^{76}\text{Ge}$ (GERDA) and $^{136}\text{Xe}$ (KamLAND-Zen and EXO–200). These experiments have set limits on the Majorana neutrino mass of $\sim 0.2–0.4$ eV, and have cast doubt on an earlier claim of observation. In this Letter we report new $0\nu\beta\beta$ search results from the EXO–200 experiment based on about two years of data.

The EXO–200 detector

EXO–200 has been described in detail elsewhere. Briefly, the detector is a cylindrical liquid xenon (LXe) time projection chamber (TPC), roughly 40 cm in diameter and 44 cm in length. Two drift regions are separated in the centre by a cathode. The LXe is enriched to 80.6% in $^{136}\text{Xe}$, the $0\nu\beta\beta$ candidate ($Q = 2.457.83 \pm 0.37$ keV; ref. 16). The TPC provides $X–Y–Z$ coordinate and energy measurements of ionization deposits in the LXe by simultaneously collecting the scintillation light and the charge. Charge deposits spatially separated by about 1 cm or more are individually observed and the position accuracy for isolated deposits is a few millimetres. Avalanche photodiodes (APDs) measure the scintillation light. Small radioactive sources can be positioned at standard positions near the TPC to calibrate the detector and monitor its stability.

The TPC is shielded from environmental radioactivity on all sides by ~50 cm of HFE-7000 cryofluid (HFE) maintained at ~167 K inside a vacuum-insulated copper cryostat. Further shielding is provided by at least 25 cm of lead in all directions. The entire assembly is housed in a clean-room located underground at a depth of 1.585 ± 0.016 metres water equivalent (a measure of the effective shielding accounting for variations in the overhead rock) at the Waste Isolation Pilot Plant near Carlsbad (New Mexico). Four of the six sides of the clean-room are instrumented with plastic scintillator panels (‘muon-veto panels’) recording the passage of cosmic ray muons. An extensive materials screening campaign was employed to minimize the radioactive background produced by the detector components.

Data analysis and methodology

The data analysis methods in this work follow closely those presented in detail elsewhere. Events in the detector are classified as single-site

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(SS) or multi-site (MS) according to the number of detected charge deposits. $0\nu\beta\beta$ events are predominantly SS whereas $\gamma$ backgrounds are mostly MS. For each event, the energy is determined as a linear combination of charge and scintillation, while a ‘standoff distance’ is defined as the distance between a charge deposit and the closest material that is not LXe, other than the cathode. To search for $0\nu\beta\beta$, a binned maximum-likelihood fit is performed simultaneously over the SS and MS events using probability density functions (PDFs) in energy and standoff distance, generated using a Geant4-based Monte Carlo simulation (MC). The energy range 980–9,800 keV is used. The ‘low-background data set’ (physics data) is obtained after applying event selection cuts. With respect to ref. 9, the current analysis additionally includes: (1) improved signal processing for the scintillation waveforms resulting in lower noise; (2) $^{226}$Ra source calibration data; (3) an expanded fiducial volume; (4) the estimation of systematic errors related to the $0\nu\beta\beta$ ROI; and (5) updated background and systematic studies relevant to the $0\nu\beta\beta$ search.

The data set presented here (Run 2) combines Run 2a (already used for refs 9 and 13, 22 September 2011 to 15 April 2012) and Runs 2b and 2c (16 April 2012 to 1 September 2013). After removing periods of poor data quality and calibration runs, the total amount of low-background data for this analysis is 477.60 ± 0.01 days, a 3.8-fold increase from previous EXO-200 publications. The primary tool used for understanding data quality and calibration runs, the total amount of low-background data set, while maintaining systematic uncertainties at an acceptable level.

The energy resolution of the detector is dominated by electronic noise in the scintillation readout and exhibits variations over time due to changes in this noise. We apply a de-noising algorithm to the scintillation signals during post-processing, improving the detector resolution and reducing its time dependence. This algorithm attempts to find the optimal combination of APD waveforms to determine the amount of scintillation light for each event, taking into account the measured electronic noise of each APD channel as well as the position of each charge deposition in the detector. Figure 1 shows the resolution with and without de-noising.

We define an effective, time-independent energy resolution function $\sigma(E) = \sigma_{\text{dec}} + bE + cE^2$. Here $\sigma_{\text{dec}}$, $b$ and $c$ are 20.8 keV, 0.628 keV$^{1/2}$ and 1.10 $\times$ 10$^{-3}$ (25.8 keV, 0.602 keV$^{1/2}$ and 4.04 $\times$ 10$^{-3}$) for SS (MS), determined by a maximum-likelihood fit to calibration data taken during Run 2. This function is folded with the energy distributions derived from the simulation to create the PDFs used in final fits. The effective resolution ($\sigma/E$) for SS (MS) at the $0\nu\beta\beta$ Q-value is 1.53 ± 0.06% (1.65 ± 0.05%).

The fiducial volume is larger than in ref. 9 to maximize the sensitive mass while maintaining systematic uncertainties at an acceptable level. Events in the fiducial volume are required to have 182 mm $>|Z|>10$ mm (where $Z=0$ is the cathode plane) and are contained in a hexagon with 162 mm aperture. This represents a $^{136}$Xe mass of 76.5 kg, corresponding to 3.39 $\times$ 10$^{20}$ atoms of $^{136}$Xe and, with the quoted live-time, results in an exposure of 100 kg yr (736 mol yr).

Investigation and determination of systematic errors

The main systematic uncertainties relevant to the search for $0\nu\beta\beta$ are related to signal efficiency, location of the $0\nu\beta\beta$ ROI within the spectrum, and estimation of the background in the ROI.

Figure 1 | Effect of de-noising on the energy resolution, $\sigma/E$. Shown is the resolution for SS events at the 2,615-keV $^{208}$Tl full-absorption peak (with and without de-noising) and propagated to the $0\nu\beta\beta$ Q-value (with de-noising). The variation with time (shown on x axis) is caused by changes in the noise of the APD front-end electronics. The horizontal dashed line shows the effective Q-value SS energy resolution used for the data set (1.53%). MS resolution (not shown) exhibits similar behaviour. Error bars, ±1 s.d.

Figure 2 | Comparison of energy and standoff distance distributions of a $^{226}$Ra calibration source for SS events in simulation and data. Energy (main panel) and standoff distance (inset), both in normalized counts, are shown for data (black points) and simulation (blue line). The calibration source is at a position near the cathode outside the TPC. Error bars, ±1 s.d.
Discrepancies in the shapes of energy and standoff distance distributions between data and simulation affect the estimation of the background in the 0νββ ROI. To quantify this effect, we calculate skewing functions based on the small discrepancies observed in source calibration studies. We distort the background PDFs with the skewing functions and use these to produce a set of ‘toy’ MC data sets, which are then fitted to un-skewed PDFs. The change in the 0νββ ROI background is 9.2%, which we take as systematic error.

In the rate comparison studies (2), we combine the total number of selected events in data and simulation as (data – MC)/data for several source positions. The error-weighted average of the results is calculated using the fiducial volume in this analysis as well as that in ref. 9. The difference between these values is 1.7%, which we combine with the underlying fiducial volume uncertainty (also 1.7%; ref. 9) conservatively assuming full correlation to produce a total error on the detector efficiency of 3.4%.

To address (3), the ratio of the number of SS events to the total number of events, SS/(SS + MS), is compared between data and simulation for three sources in Fig. 3. The general behaviour is largely independent of the underlying spectral shape. We choose to assign a single systematic uncertainty to the SS/(SS + MS) ratio of 9.6%, calculated from the weighted average of the maximum deviations observed for the 228Th, 60Co and 226Ra (data from the latter available after June 2013) sources at several different source locations in each calibration campaign.

Event selection requires an event to be fully reconstructed in all three coordinates (X, Y and Z). We compare the relative efficiency of this requirement for 2νββ from MC to the measured relative efficiency derived from the background-subtracted low-background energy spectrum. Here, we define the relative efficiency as the ratio of the number of events passing the entire set of selection requirements to the number passing the set not including the full-reconstruction requirement. The relative efficiency from simulation changes modestly across the 2νββ energy range (>99% to 90%) from 980 keV to 2,450 keV) and similar behaviour is seen in data. The average deviation between simulation and data over the 2νββ spectrum (7.8%) is taken as a systematic error on the efficiency.

The uncertainty on the location of the ROI in the spectrum is dominated by a possible energy-scale difference between β-like events in the LXe (for example, 0νββ) and γ-like events (including most backgrounds and the sources used for the primary energy calibration). We define the ‘β-scale’ as $E_B = E_{\gamma}$, where $E_{\gamma}$ is the energy for both $E_B$ and B is a measured constant. We determine the β-scale by fitting to the 2νββ-decay-dominated low-background data and find $B = 0.999 \pm 0.002$.

Several cross-checks were performed to search for energy dependence in the β-scale. The above fits were performed using different energy thresholds and with different background PDFs produced using the skewing functions discussed earlier. We also fitted the low-background data assuming a linear energy dependence (for example, $p_0 + p_1 E$) for $B$. In all cases the results are consistent with the original fit, providing no evidence for energy dependence of the β-scale. The estimate of the β-scale is also robust against a different choice of 2νββ spectral shape.

To investigate the dependence of the ROI background estimate on the completeness of the model used to fit the data, we derive PDFs from different source locations and introduce them separately into the default background model used in the fit. The relative change of the estimated ROI background is then determined. The three background PDFs considered in this study are 238U in the HFE and inner cryostat, and 60Co in the copper source guide tube. These were chosen because the initial source location affects relative amplitudes and spectral features in the ROI, that is, the 214Bi (2,448 keV) and 60Co sum peak. This study indicates a total possible deviation of 5.7% for the expected background counts in the ROI.

The residual time dependence of the energy resolution (Fig. 1) can introduce additional counts in the ROI from the 2,615-keV 208Tl peak. This was estimated to affect the ROI background counts by ±1.5%.

A summary of the 0νββ signal efficiency and associated uncertainty is presented in Table 1. Table 2 summarizes the uncertainties on the estimation of background in the ROI. These errors are explicitly included as input to the final fit to the low-background data. Items not listed in the tables, such as the β-scale and the SS/MS ratios, still contribute to the total systematic error on the 0νββ signal as they are propagated to the final result by the maximum-likelihood fit to the low-background data.

Neutrons arising from cosmic-ray muons or radioactive decays in the salt surrounding the laboratory may contribute background to the 0νββ ROI via neutron capture or spallation processes. The contribution in the ROI is expected to arise primarily from neutron-capture γ’s in the LXe and surrounding materials (for example, capture on 65Cu and 66Cu in the copper components, and on 136Xe in the LXe). A simulation using a simplified experimental geometry and employing the FLUKA22,23 and SOURCES24 software packages is used to generate,

Table 1 | 0νββ signal efficiency and associated systematic errors

| Source                              | Signal efficiency (%) | Error (%) |
|-------------------------------------|-----------------------|-----------|
| Summary from ref. 9                 | 93.1                  | 0.9       |
| Partial reconstruction              | 90.9                  | 7.8       |
| Fiducial volume/rate agreement      | NA                    | 3.4       |
| Total                               | 84.6                  | 8.6       |

1Partial reconstruction refers to the requirement that all events be fully reconstructed in X, Y and Z. The summary for event selection from ref. 9 includes all efficiencies and related errors except fiducial volume and partial reconstruction, which have been recalculated in this work for 0νββ. NA, not applicable.

Table 2 | Systematic errors on background determination in the ROI

| Source                              | Error (%) |
|-------------------------------------|-----------|
| Background shape distortion         | 9.2       |
| Background model                    | 5.7       |
| Energy resolution variation         | 1.5       |
| Total                               | 10.9      |

These errors arise from incorrect modeling of the background shape (‘Background shape distortion’), incorrect or incomplete background model (‘Background model’) and the residual variation of the energy resolution over time (‘Energy resolution variation’; see, for example, Fig. 1).
track and thermalize neutrons. The resulting neutron capture rates are used as input to the Geant4-based20 EXO-200 simulation package9, with the respective n-capture γ-spectra produced on the basis of ENSDF information20 for the given nuclides. The produced PDFs are used in fits to the low-background data. Good shape agreement is found between these PDFs and data coincident with muon-veto-panel events.

Results

The fit to the low-background data minimizes the negative log-likelihood function constructed using a signal and background model composed of PDFs from simulation. A profile-likelihood scan is performed to search for a 0νββ signal.

The PDFs chosen for the low-background fit model are those used in ref. 9 plus a 'far-source'232Th PDF, a137Xe PDF and neutron-capture-related PDFs, including136Xe neutron capture in the LXe,1H neutron-capture in the HFE, and63Cu,65Cu neutron capture in Cu components (LXe vessel, inner and outer cryostats). The far-source232Th PDF allows for background contributions from Th in materials far from the TPC, for example in the HFE and in the copper cryostat. (Remote238U is included in the fit model via222Rn, simulated in the air between the cryostat and Pb shield.) We combine the neutron-capture-related PDFs to form one PDF, allowing the relative rates of the component PDFs to float within 20% of their simulation-estimated values. The total rate of this summed PDF is allowed to float unconstrained.

We constrain the single-site fractions, SS/(SS + MS), of all components to be within 9.6% of their value calculated from simulation. An additional 90% correlation between single-site fractions of γ components is introduced into the likelihood function, owing to the consistent behaviour observed in these parameters in calibration studies (for example, Fig. 3). The overall normalization is allowed to float within the estimated systematic errors (8.6%). The background-PDF amplitudes within the ROI are also allowed to vary within their estimated systematic errors (10.9%). The β-scale is not allowed to float during the fit, but is manually profiled while performing the profile-likelihood scan for 0νββ.

The final step before performing the fit was the unmasking of livetime around the SS ROI. However, before unmasking the full data set, we investigated backgrounds associated with Xe feeds, irregular occurrences in which additional Xe gas is introduced into the purification circulation loop. (These Xe feeds occurred 10 times over the run period

Figure 4 | Fit results projected in energy. a, b. Main panels show SS (a) and MS (b) events, as counts versus energy, with a zoom-in (inset) around the ROI: 2,250–2,600 keV (2,100–2,700 keV) for SS (MS); the bin size is 14 keV, and data points are shown in black. Lower panels in a and b show residuals between data and best fit normalized to the Poisson error, ignoring bins with 0 events. The green (blue) shaded regions in the lower panels represent ±1σ (±2σ) deviations. The 7 (18) events between 4,000 and 9,800 keV in the SS (MS) spectrum have been collected into an overflow bin for presentation here. The vertical (red) lines in the SS spectra indicate the ±2σ ROI. The result of the simultaneous fit to the standoff distance is not shown here. Several background model components (including Rn,135Xe and137Xe, n-capture,232Th (far), Vessel, 0νββ and 2νββ, all described further in the text) are indicated in the main panel of b to show their relative contributions to the spectra. Error bars on data points, ±1 s.d.
and are known to temporarily elevate, for example, Rn levels in the detector.) The live-time in the two-week periods following the 10 feed events were unmasked first to search for increased background levels in the ROI. No evidence for such an increase was found and the unmasking of the remaining live-time proceeded.

The results of the maximum-likelihood fit are presented in Fig. 4. The measured $2\nu\beta\beta$ decay rate is consistent with ref. 9. From the best-fit model, the estimate of the background in the $0\nu\beta\beta\pm2\sigma$ ROI is 31.1 ± 1.8 (stat.) ± 3.3 (sys.) counts, or (1.7 ± 0.2) × 10$^{-3}$ keV$^{-1}$ kg$^{-1}$ yr$^{-1}$ normalized to the total Xe exposure (123.7 kg yr). Both this and the ±1σ value (also (1.7 ± 0.2) × 10$^{-3}$ keV$^{-1}$ kg$^{-1}$ yr$^{-1}$) are consistent with previous results, 1.5 ± 0.1 (1.4 ± 0.1) with the same units in the ±1σ (±2σ) ROI$^{15}$. The dominant backgrounds arise from $^{232}$Th (16.0 counts), $^{238}$U (8.1 counts) and $^{137}$Xe (7.0 counts). This amount of $^{137}$Xe is consistent with estimates from studies of the activation of $^{136}$Xe in muon-veto-tagged data. The total number of events seen in this region is 39. The best-fit value of $0\nu\beta\beta$ counts is 9.9, consistent with the null hypothesis at 1.2σ as calculated using toy MC studies. The corresponding profile-likelihood scan of this parameter is shown in Fig. 5.

A number of cross-checks were performed on the result. No event reconstruction anomalies were found after hand-scanning all events in the ROI. The time-between-events distribution of the ROI events is consistent with a constant-rate process and the standoff distance distribution of events in data is consistent with the best-fit model. Additional backgrounds were considered that could contribute events to the ROI. In particular, we tested for $^{110m}$Ag and $^{89}$Y because of their possible association with the measurement in ref. 12, and found that both produce a distinct high-multiplicity signature in EXO-200 (SS/MS) ~5–10%. Separate fits including each of these PDFs contributed the following counts to the ±2σ ROI: $N_{^110mAg}=0.04\pm0.02$ and $N_{^{89}Y}=0.02\pm0.01$. Finally, we were able to exclude any significant effect on the ROI background from $^{214}$Bi external to the Pb shield—for example, from $^{238}$U in the surrounding salt.

Discussion

In summary, we report a 90% confidence level lower limit on the $0\nu\beta\beta$ half-life of 1.1 × 10$^{25}$ yr. With the nuclear matrix elements of refs 26–29 and the phase space factor from ref. 21, this corresponds to an upper limit on the Majorana neutrino mass of 190–450 meV. Using the three flavour fit of ref. 30 (also M. Tortola and J. Valle, personal communication), we further use this range of effective mass limits to construct a constraint on the mass $m_{\nu_{\beta\beta}}$ of the lightest neutrino mass eigenstate, assuming the most disadvantageous combination of CP phases. This corresponds to $m_{\nu_{\beta\beta}} < 0.69–1.63$ eV, in the case where neutrinos are Majorana particles.

The results reported here supersede those of ref. 13, owing to the increased exposure and improved analysis. The limit presented is however not as strong as the limit from ref. 13, consistent with expected statistical fluctuations in the data. An appropriate metric to characterize the improvement of the experiment independent of such fluctuations is the ‘sensitivity’, defined as the median expected 90% confidence level half-life limit assuming the background estimated from the maximum-likelihood fit and the absence of a $0\nu\beta\beta$ signal. We calculate this metric using an ensemble of limits determined from Monte Carlo pseudo-experiments and find the EXO-200 sensitivity to be 1.9 × 10$^{25}$ yr, representing an improvement by a factor of 2.7 over ref. 13.

In Fig. 6 we compare the $0\nu\beta\beta$ sensitivity and half-life limits from the GERDA, KamLAND-Zen and EXO-200 experiments. Also shown is the positive observation claim in $^{76}$Ge from ref. 14. The results of the present analysis are inconsistent with the central value of this claim at 90% confidence level for two of the four considered nuclear matrix element calculations, namely, GCM$^{26}$ and NSM$^{27}$.

The first two years of EXO-200 data demonstrate the power of a large and homogeneous LXe TPC in the search for $0\nu\beta\beta$. Simulations of the nEXO experiment, a proposed 5,000-kg LXe TPC based on the EXO-200 design, show that the state-of-the-art background measured in EXO-200 can be further improved by finer charge readout pitch (to improve the SS/MS discrimination) and by lower electronic noise in the scintillation channel. In addition, Xe self-shielding will become more powerful in larger detectors, where the $\gamma$ attenuation length at energies near the Q-value becomes small with respect to the linear size of the LXe vessel. This advantage only applies to monolithic, homogeneous detectors.

![Figure 5](https://example.com/figure5.png)

**Figure 5 | Profile likelihood, $\lambda$, for $0\nu\beta\beta$ counts.** The horizontal dashed lines represent the 1σ and 90% confidence levels assuming the validity of Wilks’ theorem$^{23–25}$, intersecting the profile curve at (3.1, 18) and 24 $0\nu\beta\beta$ counts, respectively. From toy Monte Carlo studies, the best-fit value is consistent with the null hypothesis at 1.2σ.

![Figure 6](https://example.com/figure6.png)

**Figure 6 | Comparison with recent results from $^{136}$Xe and $^{76}$Ge $0\nu\beta\beta$ experiments.** Sensitivity (orthogonal lines) and limits (arrows) from GERDA and KamLAND-Zen are from refs 11 and 12, respectively. The diagonal lines are derived from several recent nuclear matrix element calculations and the phase-space factor from ref. 21, included to allow comparison between results from the two nuclei: GCM$^{26}$, NSM$^{27}$, IBM-2$^{28}$ and RQRP$^{29}$. Tick marks along these lines indicate the associated effective neutrino mass in eV. The claimed observation in $^{76}$Ge (KK&K; ref. 14) is shown as a shaded grey band (CL, confidence level). The previous EXO-200 limit and sensitivity from ref. 13 were 1.6 × 10$^{25}$ yr and 0.7 × 10$^{25}$ yr, respectively.
