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Neutrinoless Double Beta Decay

Joshua Albert[*]
Author Indiana University
E-mail: joalbert@indiana.edu

Here we review the status of experimental searches for neutrinoless double beta decay ($0\nu\beta\beta$). Measurements of this hypothetical decay could determine the Dirac/Majorana nature of neutrinos, and possibly their absolute mass. Thus far, only limits on this process have been set. The status of current-generation and next-generation experiments is reported, with an emphasis on the diverse techniques which can be used to search for this rare process.

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[*]Speaker.

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1. Introduction

1.1 The State of Neutrino Knowledge

While neutrinos have been a part of the Standard Model since the Model's formulation, the way in which they fit is not exactly clear. We know neutrinos are spin-1/2 fermions which only interact via the weak interaction (and gravity). All observed neutrinos are left-handed, and all observed anti-neutrinos are right-handed. From oscillation experiments, we have learned that they have a small but non-zero mass, that there are 3 mass and flavor eigenstates, connected through a mixing matrix, and that all 3 real mixing angles are non-zero. The three neutrino flavors, e, μ, and τ, correspond to the three known charged leptons.

If we ignore clearly Beyond Standard Model (BSM) phenomena (such as a fourth neutrino which is sterile), there are four major questions remaining about how neutrinos behave. The first is the mass ordering. The neutrino mass squared differences are known from oscillation experiments, and we know that there is a small mass splitting and a large mass splitting, but whether the small mass splitting is between the lighter two neutrinos or the heavier two is unknown. The ordering in which the lighter two neutrinos have the smaller mass splitting is known as the normal ordering, or normal hierarchy. This "normal" refers to how this splitting would be similar to that of the masses of the charged leptons e, μ, and τ . The other possibility is known as inverted ordering or inverted hierarchy.

The second question is that of the absolute neutrino mass. There are upper limits on the absolute neutrino mass, set by careful measurement of β decay spectra, but no measurement. Cosmology experiments offer some model-dependent estimates and limits on the neutrino mass, and, in the future, tritium β decay measurements may be capable of measuring the small absolute mass.

The third question is that of CP-violation. It is possible that neutrinos and anti-neutrinos may oscillate differently, and this difference is parameterized by a cp-violating phase in the mixing matrix. Finally, there is the question of whether neutrinos and anti-neutrinos are actually distinct particles, or the same particle, with different helicities.

Neutrino helicity was first measured in 1958 by Goldhaber *et al.* [1], and all neutrinos appear to be left-handed. All anti-neutrinos appear as right-handed. As neutrinos are very light (their mass energy is much less than their kinetic energy in all neutrino detections, so they are always highly relativistic), their helicity and chirality are very closely coupled. The weak interaction is maximally CP-violating, so left-handed neutrinos would only be allowed to couple to electrons, and right-handed anti-neutrinos would only be allowed to couple to positrons. The lack of neutrino charge opens the possibility that neutrinos and anti-neutrinos could be the same particles with different helicities. Fundamentally distinct neutrinos and anti-neutrinos are termed “Dirac”, and particles where the only distinction is spin are termed “Majorana”. These fit into the Standard Model Lagrangian in different ways, and have different possible mechanisms to acquire neutrino mass (the lightness of which is puzzling to theorists).

The first and the third of these questions can be answered using long-baseline neutrino oscillation experiments. The second and fourth cannot. However, if neutrinos are Majorana particles, a process called neutrinoless double beta decay must exist, and, if it could be measured, the second and fourth questions would be answered.

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1.2 Double Beta Decay

Double beta decay is a second order weak interaction which occurs for certain even-even nuclei. In these cases, ordinary beta decay ($n \to p + e^- + \overline{\nu}_e$) is forbidden or highly suppressed, typically because the daughter nucleus is heavier than the initial one. However, double beta decay ($2n \to 2p + 2e^- + 2\overline{\nu}_e$) could still be allowed, and in fact has been observed for several nuclei and is predicted in others.

In addition to this two-neutrino double beta decay ($2\nu\beta\beta$), there is also a theoretical process, zero-neutrino double beta decay ($0\nu\beta\beta$), which must exist if neutrinos are massive (we know they are) and Majorana. This process ($2n \to 2p + 2e^-$) violates lepton number conservation, and so is of particular interest, as no other known process can do that. Assuming the universe began with a lepton number of zero, some lepton-number violating process must exist. The main experimental signature of this process, which distinguishes it from $2\nu\beta\beta$, is that the entire Q-value of the decay is carried away with the electrons. A plot of the sum of electron kinetic energies for $2\nu\beta\beta$ and $0\nu\beta\beta$ is shown in Figure 1.

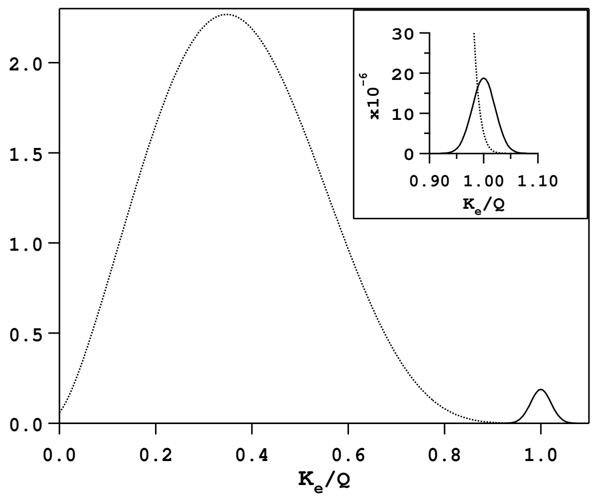

Figure 1: Illustration of the $2\nu\beta\beta$ (dotted) and $0\nu\beta\beta$ (solid) spectra. The x-axis is sum of electron kinetic energies, and the y-axis is an arbitrary normalization. A 5% energy resolution has been convoluted in, and the ratio of normalizations for these two curves is not to scale, though the upper right inset shows the $0\nu\beta\beta$ spectrum at a more realistic scale relative to $2\nu\beta\beta$. From reference [2].

Due to the rarity of this decay (half lives of at least $\sim 10^{25}$ years), experiments are typically designed to have very low backgrounds, so just a few $0\nu\beta\beta$ decays could be a valid signal. To achieve this requires an extremely clean (radiopure) detector, as radioactive decays are typically the primary background; an underground laboratory, to reduce the effect of cosmic rays; good energy resolution, to ensure that the $2\nu\beta\beta$ spectrum can be clearly distinguished from the $0\nu\beta\beta$ line; and additional techniques, beyond just energy, to distinguish $0\nu\beta\beta$ decays from background processes. Additionally, a large quantity of the candidate isotope is required. The cost, availability, enrichability, and Q-value of these candidate isotopes vary considerably, and no single isotope stands out as the obvious choice.

Searches for $0\nu\beta\beta$ are often compared to searches for dark matter weakly interacting massive particles (WIMPs), as the detectors are similar, but with different optimizations. Searches for $0\nu\beta\beta$ decays involve a focus on electron recoils near ~ 2 MeV. Background reduction requires extensive shielding against γ rays, and extremely strict radiopurity requirements to avoid backgrounds from primordial radionuclides. The signal of WIMPs would be a low energy nuclear recoil, so detectors are optimized for low thresholds, with a focus around ~ 100 keV. Penetrating γ rays are well above this energy, so less γ shielding is needed, but the shield must be effective against neutrons. The less stringent radiopurity requirements and lack of isotopic enrichment means that dark matter experiments can iterate more quickly from one generation to the next. Given these different optimizations, we are not yet at a point where it is economical to design a single experiment which can excel in both types of searches.

The half life for $0\nu\beta\beta$ is inversely related to the square of the neutrino mass by

$$\frac{1}{t_{1/2}^{0\nu}} = G^{0\nu}\left|M^{0\nu}\right|^2 m_{\beta\beta}^2, \tag{1.1}$$

where

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} m_i U_{ei}^2\right| \tag{1.2}$$

defines the Majorana neutrino mass. This Majorana mass ($m_{\beta\beta}$) is a function of the mixing matrix terms, and, due to complex phase factors, may be smaller than the actual lightest neutrino mass eigenstate. The other terms in the expression include a phase space factor $G^{0\nu}$, and a matrix element $M^{0\nu}$. This matrix element must be computed separately for each isotope, and there are considerable theoretical uncertainties on it. Because of this, half life limits are typically converted to a limit on $m_{\beta\beta}$ which includes a range between the extreme matrix elements from a variety of computational techniques. Comparisons between limits from experiments using different isotopes are complicated by this, but these systematic uncertainties should decrease in the future with advances in computational nuclear physics.

While the simplest $0\nu\beta\beta$ model is mediated by light neutrino exchange, various BSM theories may introduce other processes which, on the surface, look like standard $0\nu\beta\beta$. Detailed measurement of the angular distributions of the daughter electrons may help distinguish between models to an extent, but it would be very difficult to rule out these other mechanisms, many of which involve contributions from supersymmetric particles. Regardless of the exact mechanism, all models of $0\nu\beta\beta$ require Majorana neutrinos and lepton number non-conservation.

2. Experimental Searches

The potential of a $0\nu\beta\beta$ experiment can be estimated with three metrics. First is sensitivity (the most commonly cited), which is a measure of what limits can be set on $m_{\beta\beta}$, assuming the $0\nu\beta\beta$ rate is zero. Second is discovery potential, which is a measure of the smallest $m_{\beta\beta}$ for which a 3σ or 5σ observation could be made. Discovery potential generally requires a stronger background understanding (understanding the origin of all backgrounds and having measured constraints on them), while sensitivity is usually optimized by minimizing backgrounds in general. Finally, there is the issue of cost and feasibility. This last one is difficult to quantify, but very

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important. Most tonne-scale $0\nu\beta\beta$ experiments are being designed to have sensitivity to $m_{\beta\beta}$ to cover all possible inverted hierarchy neutrino masses, but the costs of building these experiments, and the certainty that they will perform as designed, are not yet known, and likely vary considerably between proposals.

What follows is an incomplete list of current and proposed $0\nu\beta\beta$ experiments. Emphasis has been placed on explaining the diverse design choices, and experimental results, rather than projected sensitivities.

2.1 EXO-200/nEXO

The EXO-200 (Enriched Xenon Observatory) experiment is a liquid xenon time projection chamber (TPC) utilizing ~ 175 kg of enriched xenon (80% ^{136}Xe) to search for $0\nu\beta\beta$. It is presently located underground at the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA. The experiment has been taking data since 2011. The planned next-generation experiment, nEXO, would use 5 tonnes of enriched xenon and be located deeper underground, likely at SNOlab.

The strengths of these programs lie in the detailed interaction information from the TPCs, as well as the monolithic nature of the xenon volume. The TPC works by putting a uniform electric field (374 V/cm for phase I, 2011-2014) over the liquid xenon. When charged particles move through the xenon, they produce prompt scintillation light and a cloud of freed electrons. The scintillation light is immediately detected (by avalanche photodiodes (APDs) in EXO-200, by silicon photomultipliers (SiPMs) in nEXO), and the freed electrons will drift to the crossed wireplanes at the detector anode where this ionization signal will be detected. By combining the induction and collection signals at the anode with the time for the ionization cloud to drift to the anode, the 3D position of all charge clusters can be determined. Additionally, if multiple separate charge depositions occur (as is common for Compton scatters from γ rays), they can be resolved individually, with a position resolution of $\sim$1 cm. The energy of the events are reconstructed through a linear combination of the detected scintillation and ionization signals, with energy resolution of $\sim$1.53% for phase I data.

As a noble gas, xenon can be highly purified through the use of a heated getter, so the xenon volume is almost entirely free of radioactive contaminants. The xenon is a dense high-Z material, so it shields itself from γ rays originating externally quite effectively. The TPC vessel was constructed out of copper (chosen for its radiopurity). It is surrounded by a clean cryogenic fluid (HFE), a copper cryostat, and a lead shield. The clean room where the detector is located is also surrounded on 4 sides by scintillating muon veto panels to identify and reject cosmogenic backgrounds. A diagram of the detector setup is shown in Figure 2. All components located within the lead shield were screened by radioassay and selected for radiopurity [3].

Signal/background discrimination is achieved in several ways, beyond simple calorimetry. The ratio of the scintillation and ionization signals gives information about the dE/dx of the ionizing particle, allowing for excellent discrimination between α decays and depositions from β or γ rays. The multiplicity of charge depositions is used to split the data into single-site (SS) and multi-site (MS) events, where SS events are more likely from β decays (mainly $2\nu\beta\beta$), and MS events are more likely from γ Compton scatter events. This provides $\sim 5:1$ rejection of γs at the $0\nu\beta\beta$ Q-value, and allows for better identification of background sources. Interaction positions are also

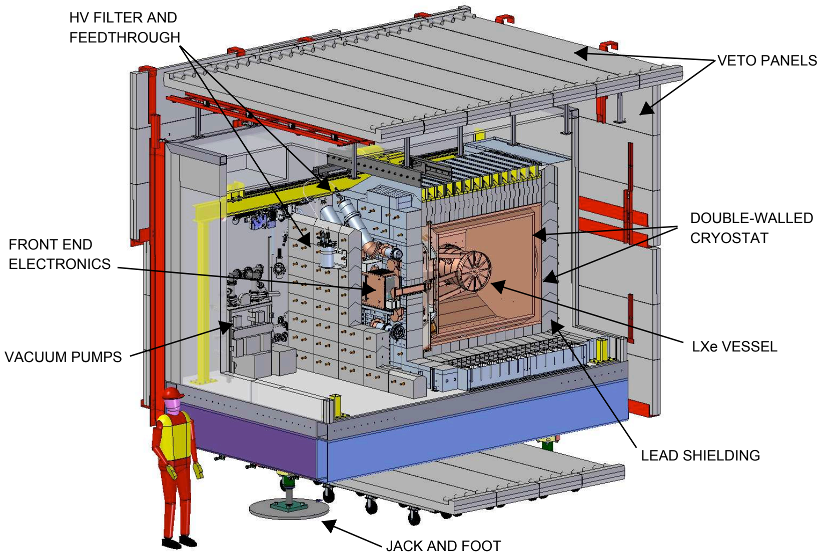

Figure 2: A rendering of the EXO-200 detector and surrounding systems. From reference [3].

fit, discriminating between backgrounds originating from outside the TPC and inside, and time correlations between signals can be used to identify decay chains

The energy spectra after the fit to data from the most recent $0\nu\beta\beta$ analysis from EXO-200 is shown in Figure 3. Based on the fit, the primary backgrounds (SS signals near the $0\nu\beta\beta$ Q-value) come from γ rays emitted from decays in the ^{232}Th and ^{238}U (also ^{222}Rn) chains. These are due to contamination in the TPC vessel and in more distant shielding. An additional 20% comes from beta decay of cosmogenic ^{137}Xe. The analysis set a limit of $t_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}$ years, corresponding to $m_{\beta\beta} < 190 - 450$ meV. The limit is slightly worse than the sensitivity ($t_{1/2}^{0\nu\beta\beta} > 1.9 \times 10^{25}$ years), due to an upward fluctuation in background counts near the Q-value.

After a ~ 2 year hiatus due to underground access issues, EXO-200 is now taking data again. Upgraded electronics, new analysis techniques, and a radon reduction system are expected to improve the physics reach of EXO-200 for this new run (called phase II). While this is proceeding, research and design work is ongoing for nEXO.

The nEXO experiment will build on the strengths of EXO-200. It is being designed to have a giant, monolithic active volume of pure xenon. The detector center will be at least 7 γ attenuation lengths from the TPC wall, making the center of the detector nearly free of external γ backgrounds. See Figures 4 and 5. Improved self-shielding, continued emphasis on radiopurity, deeper underground location, improved energy and spatial resolution, and larger mass should allow for nEXO to have sensitivity through the inverted hierarchy of neutrino masses. Additionally, research efforts are ongoing for barium tagging technology, which would allow for spectroscopic identification of daughter barium ions. This is not strictly part of the nEXO collaboration plan, but, if demonstrated successfully, would allow for a reduction of all backgrounds except $2\nu\beta\beta$ to virtually zero.

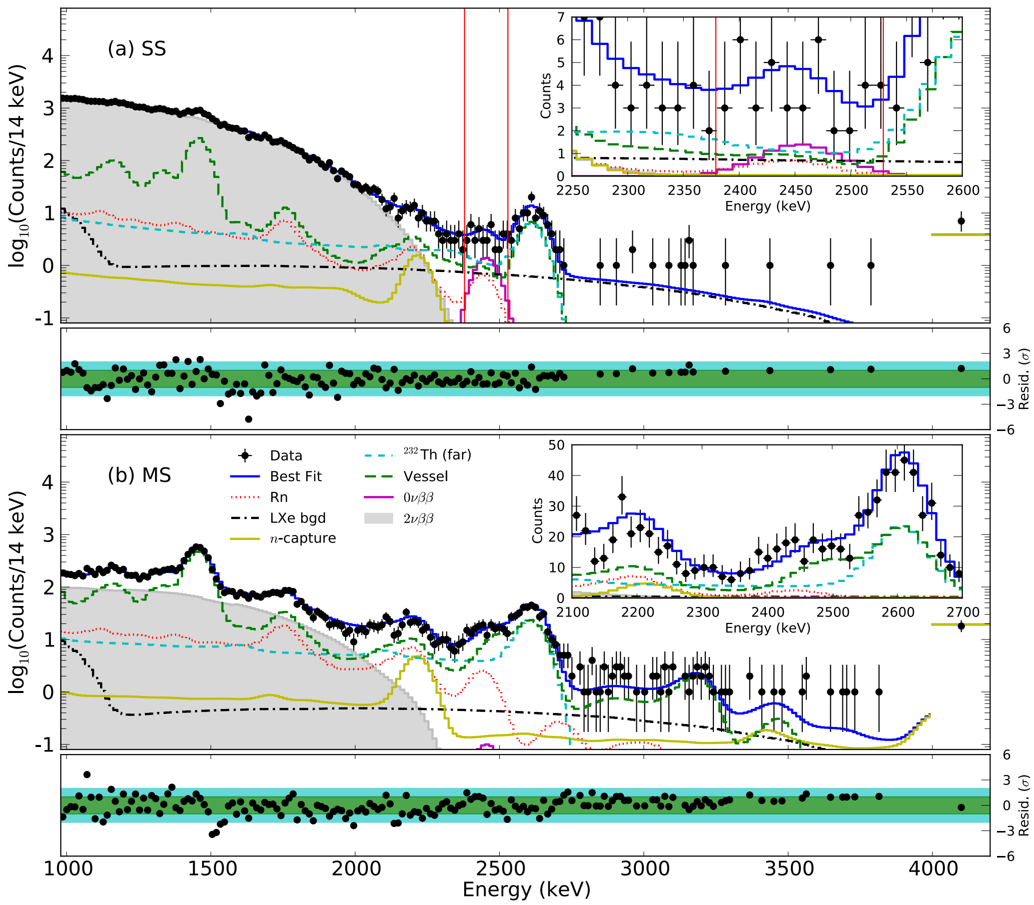

Figure 3: Final fit to EXO-200 data with 477.6 days livetime. Single-site (SS) data is shown in the upper panel, and multi-site (MS) data in the lower one. The fitted PDFs for signal and various backgrounds are also shown. The fit to data was performed simultaneously in energy and standoff distance (a function of event position) for SS and MS data. The signal for $0\nu\beta\beta$ would be a sharp peak in SS data at the Q-value of 2458 keV. See reference [4] for more details.

2.2 KamLAND-Zen

The KamLAND experiment (which successfully studied reactor neutrino oscillations [5]) has been repurposed by adding a balloon to the middle containing ^{136}Xe dissolved in liquid scintillator. The xenon balloon (inner balloon, IB, 1.5 m radius) is surrounded by a larger balloon filled with pure scintillator (6.5 m radius), which is surrounded by a mineral oil buffer volume (9 m radius) on the outside of which the PMTs are mounted. The liquid scintillator has been very highly purified through vacuum distillation, yielding a very large, very clean volume which can also serve as an active veto. Within the 6.5 m radius scintillator balloon, the only non-scintillating region is the 25 μm thick IB.

KamLAND-Zen began data taking in 2011, though the initial data taking was hampered by contamination by an unexpected background, which the KamLAND-Zen collaboration has determined to be decay of ^{110m}Ag, an isotope released by the Fukushima nuclear accident in 2011.

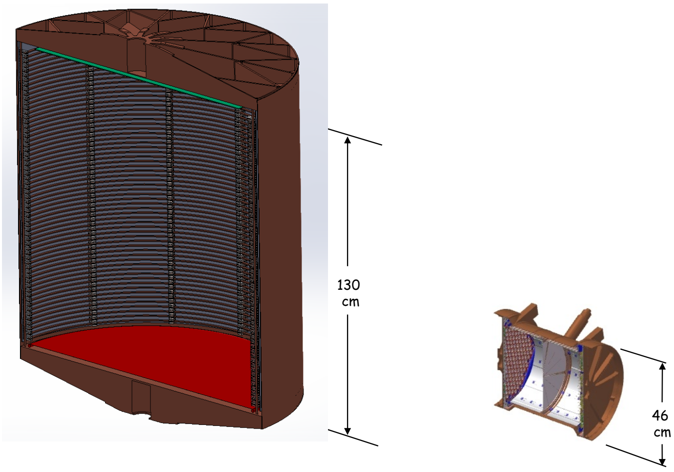

Figure 4: Renderings of the EXO-200 TPC (right) and nEXO TPC (left), to scale. Note that the nEXO design removes the central cathode to increase the size of the monolithic xenon volume.

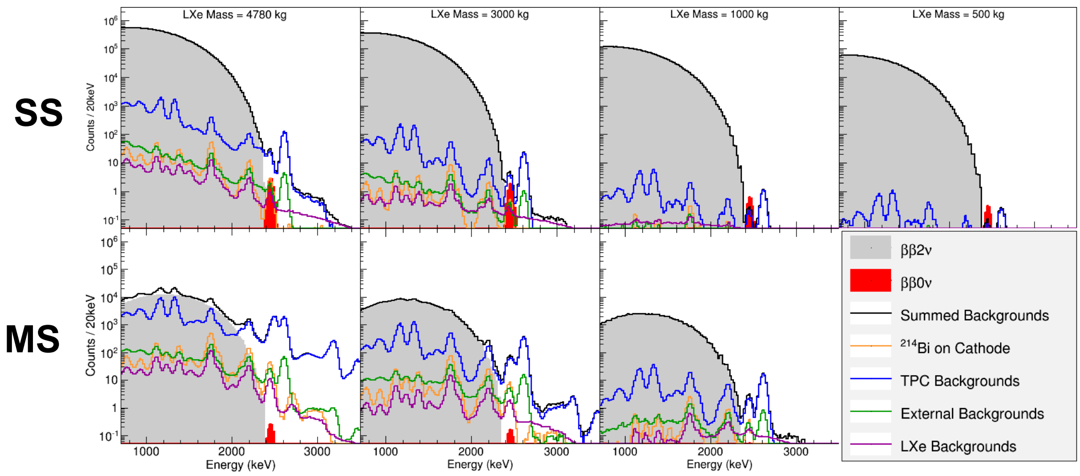

Figure 5: Simulation of nEXO signal and backgrounds, corresponding to 5 years simulated data with $t_{1/2}^{0\nu\beta\beta} = 6.6 \times 10^{27}$ years. Upper panels are SS events, and lower panels are MS events. Each column corresponds to a listed xenon mass, where the data comes from a cylindrical volume of that mass in the center of the detector. Thus, the right-most plot shows nearly no backgrounds near the Q-value for the 500 kg of xenon furthest from any non-xenon masses. This demonstrates how the outer xenon is very useful for identifying and constraining backgrounds, while the inner xenon is nearly background-free.

Following a purification campaign, a new run with 534.5 days of live-time (phase II) and 380 kg of 90% $^{\mathrm{enr}}$Xe was performed. The ^{110m}Ag background had been significantly reduced by the purification campaign, and decreased significantly over the course of the phase II data taking. For the second half of the phase II data, $2\nu\beta\beta$ was the leading background near the $0\nu\beta\beta$ Q-value, followed by ^{10}C from muon spallation and ^{214}Bi (from the ^{238}U series) decays from the IB. Energy and event position data from the most recent publication [6] are shown in Figure 6. Using a fit based on event position, energy, and time, after significant cuts to remove spallation products, a limit of $t_{1/2}^{0\nu\beta\beta} > 1.07 \times 10^{26}$ years was set, with a sensitivity of $t_{1/2}^{0\nu\beta\beta} > 5.6 \times 10^{25}$ years. The limit corresponds to Majorana neutrino mass of $m_{\beta\beta} < (65-165)$ meV at the 90% CL. This is presently the strongest limit on this mass of any $0\nu\beta\beta$ experiment. For more information on this analysis, see reference [6].

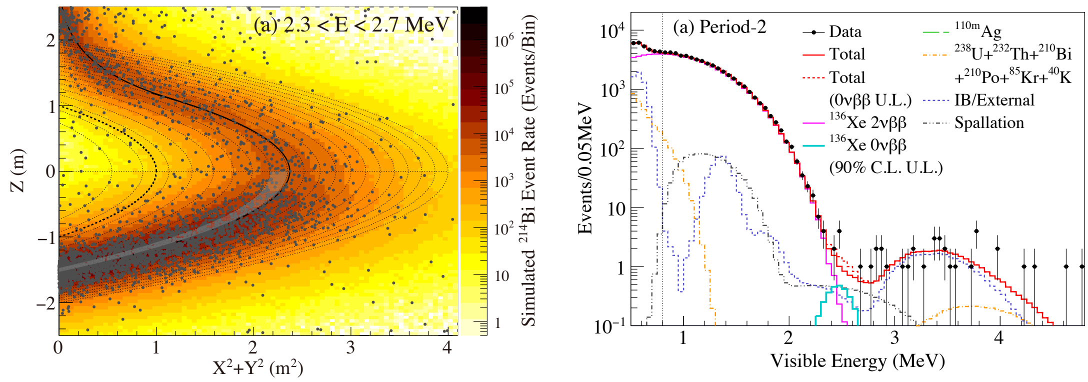

Figure 6: Plots of phase II KamLAND-Zen data. On the left, the positions of signal candidate events (energy between 2.3 and 2.7 MeV) are plotted as a function of position. Simulated ^{214}Bi event rates are included as a color scale. The IB is indicated by the solid black line, and the inner 1 m sphere is indicated by a thick dotted line. Thin dotted lines indicate position bins used in fitting. On the right, the energy of period 2 (the second half of phase II) events within the inner 1 m radius are shown, along with fitted backgrounds. From reference [6].

As seen in Figure 6, position reconstruction allows for regions of low backgrounds to be isolated, leading to stronger limits on $0\nu\beta\beta$. This is another example of how a large monolithic active volume can be valuable for $0\nu\beta\beta$ experiments. The main weaknesses of the KamLAND-Zen approach are the lack of multiplicity discrimination (to reject γ backgrounds) and relatively poor energy resolution (4.5% at the Q-value for their most recent data). There are plans for future runs with KamLAND-Zen to use a larger, cleaner balloon with more xenon, and to improve the energy resolution with higher quantum efficiency PMTs, a new liquid scintillator, and reflective cones. An imaging system to provide multiplicity discrimination is also being developed. The target sensitivity for this future upgraded detector (known as KamLAND2-Zen) is $m_{\beta\beta} < 20$ meV.

2.3 Germanium Experiments

There are presently two major experimental efforts, MAJORANA and GERDA, searching for $0\nu\beta\beta$ using ^{76}Ge. This isotope has been popular for $0\nu\beta\beta$ searches because high purity germanium detectors are a mature technology with excellent energy resolution ($\sim 0.06\%$). The two projects differ in shielding techniques and some other design choices.

The GERDA (GERmanium Detector Array) experiment is located underground at Gran Sasso National Laboratory (LGNS) in Italy and features 35 kg of instrumented enriched germanium crystal detectors. The detectors are shielded within a liquid argon volume. Phase I of the experiment (2011-2013) used the argon as a passive shield and for cooling, though phase II (ongoing) uses instrumented argon to serve as an active veto. The phase I analysis resulted in limits of

$t_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{25}$ years and $m_{\beta\beta} < 0.2 - 0.4$ eV. In addition to excellent energy resolution, the shape of the signal pulses can be used to discriminate between single-site (β-like) and multi-site (γ-like) events. The phase I GERDA energy spectrum and an example of pulse shape discrimination are shown in Figure 7.

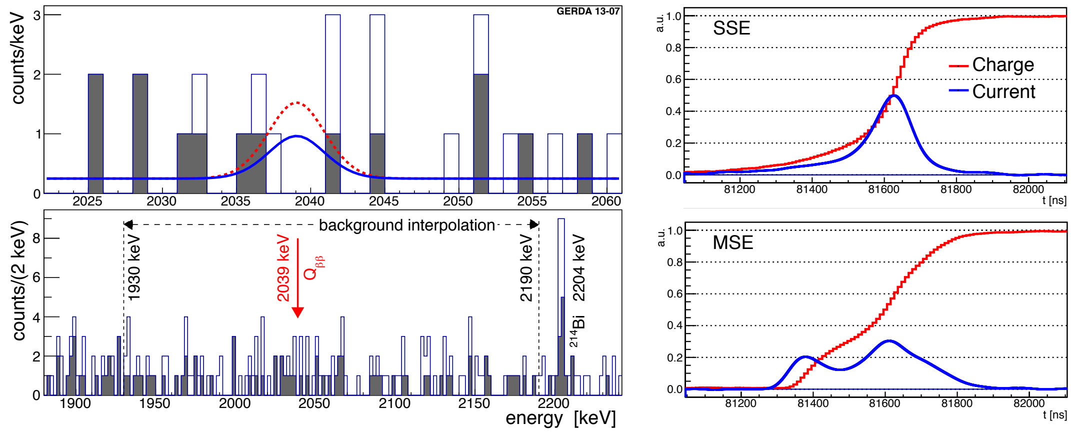

Figure 7: Plots of GERDA phase I data. On the left is the energy spectrum. Upper panel is zoomed in near the Q-value. The filled (open) histogram represents events passing (failing) the pulse shape discrimination cuts. On the upper panel, expectations for the $0\nu\beta\beta$ signal are shown corresponding to half lives of $t_{1/2}^{0\nu\beta\beta} > 1.19 \times 10^{25}$ years (red dashed) and $t_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{25}$ years (blue solid). From reference [7]. The right panel shows candidate pulse traces for single-site and multi-site events. From reference [8].

The MAJORANA collaboration has an experiment, the MAJORANA Demonstrator (MJD), which is presently taking data with with 30 kg ^{enr}Ge underground with at the Homestake mine in South Dakota, USA [9]. A major difference between MJD and GERDA is the choice of shielding. MJD uses ultra-pure copper, electroformed underground, for its innermost shielding. Results from the experiment will be released in the future.

The two collaborations plan to merge for the next-generation detector, and will use the best features of each detector in the design for the tonne scale future experiment. The size of germanium crystals will not change, but the mass will be scaled up by adding more modules of crystals similar to those used in GERDA and MJD.

2.4 CUORE

CUORE (Cryogenic Underground Observatory for Rare Events) is an experiment which will use a cryogenic Te_2O crystal bolometer to search for $0\nu\beta\beta$ in ^{130}Te. At very low temperatures, the heat capacity of crystals such as Te_2O is proportional to the temperature to the third power, so near absolute zero (CUORE is designed to operate below 10 mK), a small energy deposition can produce a large change in temperature. CUORE utilizes neutron transmission doped germanium thermistors affixed to the Te_2O crystals to measure these temperature changes, and in doing so, can make a calorimetric measurement of total energy deposited in a decay with excellent energy resolution (0.085% at the ^{130}Te Q-value).

The Te_2O crystals do not require enrichment, as the natural abundance of ^{130}Te is 34%. CUORE has been proceeding in a staged program, starting with CUORICINO (2003-2008), continuing to CUORE-0 (2013-2015) and leading to the full CUORE experiment, which is expected to start taking data in 2016. CUORE will have 740 kg Te_2O (206 kg ^{130}Te) [10], arranged in 19 towers of 52 crystals each (CUORE-0 utilized a single such tower). The combined CUORICINO and CUORE results yield limits of $t_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24}$ years and $m_{\beta\beta} < 270 - 760$ meV [11].

The biggest challenge for future bolometric searches for $0\nu\beta\beta$ is a lack of a second detection channel which could be used to discriminate between α and β decays. There is now a research campaign called Cuore Upgrade with PID (CUPID) investigating different crystals which may produce a usable Cherenkov or scintillation signal in addition to the phonons. If successfully developed, a new crystal technology could be used with the existing CUORE cryostat for an improved future $0\nu\beta\beta$ search. Crystals using $0\nu\beta\beta$ isotopes with Q-values above 2615 keV (the highest prominent γ line from primordial radioisotopes) are of particular interest.

2.5 Other Experiments

Neutrino Ettore Majorana Observatory (NEMO) [12] is a project to search for $0\nu\beta\beta$ using foils of source materials and magnetized tracking volumes on either side. The tracking can give good background discrimination, and many different isotopes can be easily tested with the same detector, but the use of foils means that the detector size is quite large for the same source mass as other experiments. NEMO-3 produced measurements of $2\nu\beta\beta$ with several isotopes, and the SuperNEMO demonstrator is currently in commissioning with ~ 5 kg ^{82}Se. If the demonstrator is successful, a full-scale SuperNEMO may be built, with ~ 100 kg ^{82}Se.

SNO+ [13] is a repurposing of the Sudbury Neutrino Observatory (SNO) detector for $0\nu\beta\beta$. A central acrylic tank in the SNO detector will be filled with liquid scintillator loaded with tellurium. The energy resolution ($\sim 4.5\%$) will be poor relative to most competing technologies, but future upgrades, similar to those planned for KamLAND-Zen, may help. As tellurium can be used without enrichment, it should be possible to scale up to large ^{130}Te masses at modest cost. The detector is presently preparing for a water fill, to be followed by a fill with scintillator, and then loaded scintillator.

Neutrino Experiment with a Xenon Time projection chamber (NEXT) [14] is a high-pressure (15 bar) gas TPC experiment being developed. The big advantages of a gas TPC over a liquid one are improved energy resolution ($\sim$0.4%) and longer particle tracks. This can make it possible to observe the Bragg peak of each β, providing a strong topological discriminator against γ Compton scatters, single β decay, and most other backgrounds. An example of this from MC simulation is shown in Figure 8. Scaling up to large masses while maintaining low backgrounds will be a challenge. The NEXT collaboration is presently working on a 10 kg detector, with plans for a 100 kg detector to follow.

3. Conclusions

This review has only covered experiments running or soon-to-run with large quantities of $0\nu\beta\beta$ candidate isotopes. Many other projects are underway exploring other isotopes or techniques on smaller scales, and other large projects exist in the early conceptual stages. The field of $0\nu\beta\beta$

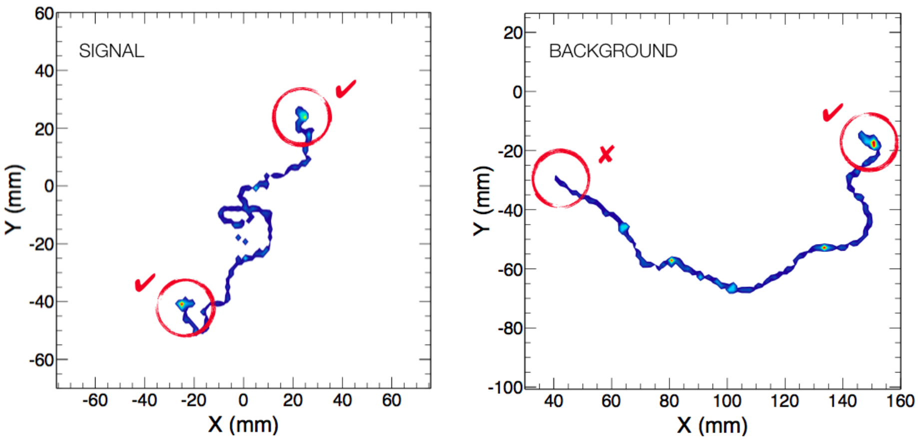

Figure 8: Simulated data for a NEXT-like gas TPC. The left panel shows a ^{136}Xe $0\nu\beta\beta$ decay, and the right panel shows a single electron background event of similar energy from a γ scatter. Identification of the Bragg peak from each β can be a powerful discriminator. From reference [14].

searches will be changing as experimental costs for next generation tonne-scale experiments will grow to the point where only a few such experiments will be supported globally. It is possible that these experiments may result in proof that neutrinos are Majorana, or, if the neutrino mass can be limited (by direct measurement or determination that the hierarchy is inverted), may result in exclusion of Majorana neutrinos. It also possible that only limits will be set. Regardless of the outcome, multiple experiments will be needed to verify results, and impressive advances in low background techniques will be made along the way.

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