Neutrinoless double beta decay experiments

M C Chen
Department of Physics, Queen’s University, Kingston, Ontario K7L 3N6, Canada
E-mail: mchen@queensu.ca

Abstract. Understanding the charge conjugation nature and the absolute mass scale of neutrinos will lead to valuable insights into physics beyond the Standard Model. Both of these aspects can be probed by the observation of neutrinoless double beta decay. The experimental search for neutrinoless double beta decay is thus an important, next step in neutrino physics. Several experiments have recently started taking data and several more are under construction. The sensitivity of upcoming double beta decay experiments will begin to probe neutrino masses as would be suggested by the inverted neutrino mass hierarchy. A summary of the capabilities and status of several double beta decay experiments was presented at NuPhys 2013.

1. Introduction
Double beta decay is the decay of a nucleus in which two neutrons change into two protons, with two outgoing electrons and two antineutrinos being emitted. This process was first proposed by Goeppert-Meyer in 1935. This second-order weak decay, which will be referred to as $2\nu\beta\beta$ decay in this summary, is quite rare involving half-lives of the order $10^{20}$ years or more. After Majorana proposed in 1937 that neutrinos could be their own antiparticles (we now call particles with this charge-conjugation nature “Majorana” fermions, as opposed to “Dirac” fermions), Furry pointed out in 1939 that double beta decay might proceed without neutrino emission. As illustrated in Fig. 1, the process essentially involves one of the antineutrinos emitted in the decay being absorbed as a neutrino by the other transforming nucleon. It is clear that neutrinoless double beta decay ($0\nu\beta\beta$ decay) can occur if and only if neutrinos are Majorana particles.

One observes from the diagram for the process (and an understanding of the weak interaction) that the helicity of the neutrino has to “flip” in order for it to be absorbed. Consequently, the transition amplitude for $0\nu\beta\beta$ must be related to the wrong-handed component of the neutrino propagator, and thus proportional to $m_\nu/E_\nu$. More precisely, the amplitude for this process involves all three neutrino masses and the PMNS mixing matrix components $U_{ei}^2$, since there are two vertices involving the neutrino propagator and electrons in Fig. 1. We define:

$$|\sum_i m_i U_{ei}^2| \equiv \langle m_{\beta\beta} \rangle \quad (1)$$

where the value $\langle m_{\beta\beta} \rangle$ is the known as the effective Majorana neutrino mass for double beta decay. As the decay rate for neutrinoless double beta decay depends on the amplitude squared, it will be proportional to $\langle m_{\beta\beta} \rangle^2$. It is important to note that the amplitude is the coherent sum of complex-valued $U_{ei}$ elements of the PMNS matrix, including the so-called “Majorana phases.” The consequence of this summation is the possibility of cancellations in the amplitude; Fig. 2 from [1] illustrates this possible effect in the allowed regions that dip down to small values.
Figure 1. Diagram for neutrinoless double beta decay. It can be seen that the process requires neutrinos to be Majorana fermions. The helicity flip is also depicted.

Figure 2. Possible values for the effective Majorana neutrino mass implied by neutrino oscillation data, from [1].

Fig. 2, the best-fit neutrino oscillation parameters (mixing angles and mass-squared differences) were used with ranges $\pm 2\sigma$ for $\theta_{13}$, $\delta=0$, $\pm 1\sigma$ for all other relevant oscillation parameters, and all Majorana phases $\alpha$ from $[0,\pi]$. Blue and green allowed regions (for the inverted and the normal neutrino mass hierarchies, respectively) have CP-conserving Majorana phases, whereas the red allowed regions include at least one of $\alpha_{21}, \alpha_{31}, (\alpha_{31}-\alpha_{21})$ CP-violating.

The full expression for the decay rate for $0\nu\beta\beta$ is:

$$[T_{1/2}]^{-1} = G_{0\nu} \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} |M_{0\nu}|^2 \tag{2}$$

where $G_{0\nu}$ is the phase space integral (that can be calculated precisely) and $|M_{0\nu}|$ is the nuclear matrix element (NME) for which substantial uncertainties exist in the calculations [2].

There are 35 naturally-occurring isotopes that can undergo double beta decay. Table 1 lists all of the double beta decaying isotopes with Q-value greater than 2 MeV. In general, a larger Q-value is desirable for phase space, detectability and for background considerations. Except for $^{96}$Zr and $^{110}$Pd, there has been recent and active R&D directed at using each of these isotopes in a double beta decay experiment. In this list of isotopes are all of the main candidates for current and upcoming experiments.

When considering the question of whether there is a favoured isotope for double beta decay, given Equation 2, the candidate with the largest phase space and NME product would be preferred. Different nuclear models yield different calculated NMEs and there are the large uncertainties in the NME calculations that must be taken into account. On the other hand, it has been noted by [3] that a plot of specific phase space versus the geometric mean of NME calculations (for the isotopes listed in Table 1), shows a possible anti-correlation in those two quantities. While there is no obvious reason why this should be true, there is likewise no obvious reason to discount this empirical observation. If true, it would suggest that there is no theoretically favoured isotope, as far as predicted decay rate is concerned. A double beta decay experiment would select their preferred isotope solely from experimental considerations.

2. General experimental considerations and common features
In the next generation of neutrinoless double beta decay experiments, three experimental aspects can be considered to be requirements. Double beta decay experiments must have a large quantity
Table 1. Double beta decaying isotopes with Q-value greater than 2 MeV, sorted from highest decay energy to lowest. Values are from the NNDC website (accessed in 04/2014).

| isotope | Q-value [MeV] | natural abundance [%] |
|---------|---------------|-----------------------|
| $^{48}$Ca | 4.27          | 0.187                 |
| $^{150}$Nd | 3.37          | 5.6                   |
| $^{96}$Zr | 3.35          | 2.8                   |
| $^{100}$Mo | 3.03          | 9.8                   |
| $^{82}$Se | 3.00          | 8.7                   |
| $^{116}$Cd | 2.81          | 7.5                   |
| $^{130}$Te | 2.53          | 34.1                  |
| $^{136}$Xe | 2.46          | 8.86                  |
| $^{124}$Sn | 2.29          | 5.8                   |
| $^{76}$Ge | 2.04          | 7.73                  |
| $^{110}$Pd | 2.02          | 11.7                  |

of isotope, good energy resolution and very low background levels in the region of interest. There is a variety of experimental approaches for double beta decay currently being pursued and each have relative strengths and weaknesses with respect to these three considerations.

Here, I choose to highlight one of the requirements: very low backgrounds. All of the next-generation experiments have worked extensively on background reduction and rejection. Backgrounds from natural radioactivity (including the usual suspects such as U and Th) are not the only concern. Cosmogenic backgrounds will become more and more important to control as the sensitivity of double beta decay experiments improves, and other background levels are reduced. Background rejection techniques will also need to be exploited. Examples of such techniques include: pulse-shape analysis in Ge diodes to determine an event’s spatial topology; track identification of the two beta electrons as a way to strongly reject backgrounds; and using delayed coincidence event signatures (such as the well-known $^{214}$Bi-Po). Ultimately it is the amount of isotope and the background level in the energy region of interest that directly determine the sensitivity of a neutrinoless double beta decay experiment.

Section 3 will survey the features, status and results from currently running experiments. I will also report on the future plans of these experiments. Section 4 will summarize the features and status of experiments currently under construction.

3. Currently running experiments

3.1. CANDLES

CANDLES III [4] is taking data in the Kamioka Lab. The experiment uses 96 CaF$_2$ scintillating crystals (305 kg, with 0.187% $^{48}$Ca) immersed in liquid scintillator that serves as a veto. The transparent tank, crystals and photomultiplier tubes (PMTs) are in a water tank for shielding. With a Q-value of 4.27 MeV for $^{48}$Ca, the highest of all isotopes, CANDLES is less prone to natural radioactivity backgrounds (that are at lower energies). The expected neutrino mass sensitivity of CANDLES III is 0.5 eV. For the next incarnation of the detector, the enrichment of $^{48}$Ca is needed and is being developed.

3.2. KamLAND-Zen

KamLAND is a liquid scintillator neutrino detector. By deploying a mini-balloon in the detector, they are able to put xenon-loaded scintillator inside the balloon in order to conduct a neutrinoless
double beta decay search with $^{136}$Xe. 320 kg of 90% enriched $^{136}$Xe is in the experiment and a total amount of 615 kg is in hand [5]. The main features of KamLAND-Zen, as the double beta search experiment is called, is that a massive quantity of isotope can be deployed in a low-background environment. The xenon-loaded scintillator can also be purified and the mini-balloon replaced with relatively low cost.

![Figure 3.](image)

**Figure 3.** From [6] half-life limits from KamLAND-Zen and EXO-200 compared to the measured half-life claim in [7].

Results from the first phase of KamLAND-Zen [6] include a lower limit on the $0\nu\beta\beta$ half-life of $T_{1/2} > 1.9 \times 10^{25}$ yr, corresponding to an upper limit of $\langle m_{\beta\beta} \rangle < 120$-250 meV, (including the NME model uncertainty). Fig. 3 from [6] shows the half-life limits of KamLAND-Zen and EXO-200, compared to the measured half-life in $^{76}$Ge claimed in [7]. The diagonal lines in Fig. 3 correspond to different nuclear theory methods for calculating the NMEs needed to convert half-life limits to effective Majorana neutrino mass; the values shown along the lines are the neutrino masses (in eV). Fig. 4 shows the spectrum. Backgrounds at $Q_{\beta\beta}$ where the $0\nu\beta\beta$ peak is expected include $^{110m}$Ag. Observations of the rate of this background over time and comparisons to the half-life of $^{110m}$Ag support this conclusion. It is possible that this background was cosmogenic, introduced during the delivery of the xenon.

KamLAND-Zen has completed purifying the xenon and the liquid scintillator in 2013. Data taking has resumed with lower $^{110m}$Ag (also lower from decay). A 600 kg deployment with a clean mini-balloon is being planned. There is R&D towards an improved detector with high QE PMTs, higher light yield liquid scintillator and adding light concentrators. Other future possibilities include operating the detector with pressurized xenon (for a higher loading concentration) and R&D toward a scintillating film for the mini-balloon (for background rejection).

### 3.3. EXO-200

EXO-200 is a liquid xenon TPC that contains 175 kg of 80.6% enriched xenon [8]. It is in the WIPP facility in New Mexico, USA. The key feature of the experiment is that the TPC allows the event topology to be used to very effectively reject multi-site background events (from gamma rays scattering in the detector). Liquid xenon also has effective self-shielding and the combined scintillation and ionization signal offers good energy resolution.

Results from EXO-200 include the first observation of the $2\nu\beta\beta$ decay of $^{136}$Xe [9] and a lower limit on the $0\nu\beta\beta$ half-life of $T_{1/2} > 1.6 \times 10^{25}$ yr [8], very similar to that from KamLAND-Zen.
This comes from a 26.3 kg-yr data set taken between 09/2011 to 04/2012. Background control after single-site event selection was very successful with an expectation of 4.1 ± 0.3 background events in a ±1σ region around $Q_{3\beta}$ and an observation of 1 count therein. Their multi-site and single-site energy spectra from [8] are shown in Fig. 5.

The future plans for the experiment are called nEXO and the goal is a 5 tonne LXe TPC as similar to EXO-200 as possible. The desired site for nEXO is the Cryopit in SNOLAB [10]. A five-year run with nEXO aims to reach neutrino mass sensitivity toward the bottom of the inverted hierarchy band (as in Fig. 2).

3.4. GERDA
The GERDA experiment [11] in Gran Sasso Lab has operated 18 kg of bare Ge diodes in liquid argon. The Ge detectors are from the Heidelberg-Moscow and IGEX experiments. These detectors are isotopically enriched in $^{76}$Ge to 86%. Ge detectors have excellent energy resolution; deployment in liquid argon aims to reduce backgrounds from adjacent detector components. During operation from 11/2011 to 05/2013, two diodes had high leakage current and were shut off; thus, the total mass of enriched detector that was used in the analysis was 14.6 kg.

Pulse-shape analysis was used to reject surface events and also multi-site events from gammas. The data set from a 21.6 kg-yr exposure [12] is shown in Fig. 6. There were 3 counts in the ±2σ window around $Q_{3\beta}$. The expectation for the claimed [7] signal would have been $5.9 ± 1.4$ signal events over $2.0 ± 0.3$ background events in the same window. The GERDA results strongly disfavour this claim. The lower limit on the half-life of $^{76}$Ge is $T_{1/2} > 2.1 \times 10^{25}$ yr at the 90% CL. The GERDA collaboration compares their background levels in a ±2σ window, noting their value of 0.01 counts/mol-yr versus 0.07 for EXO-200 and 0.2 for KamLAND-Zen.

Phase I of GERDA ended in 09/2013 and all detectors have been dismounted. Phase II involves adding 30 enriched BGE detectors (a mass of 20 kg). They aim for further background suppression by a factor of 10. This will be achieved by improved radiopurity in the HV and signal cabling, lower radon emanation, improved PSD with the BGE detectors and instrumenting the liquid argon to function as a scintillation veto.
4. Neutrinoless double beta decay experiments under construction

4.1. CUORE

The CUORE experiment [13] in Gran Sasso Lab is under construction with a test-scale detector CUORE-0 already taking data. CUORE is a cryogenic bolometer detector that will have over 700 kg of TeO\textsubscript{2} crystals containing 206 kg of \textsuperscript{130}Te isotope. The features of this experiment are the large natural abundance of \textsuperscript{130}Te and the exquisite energy resolution of a bolometer. There has been a careful approach to background control in CUORE, as is required for an experiment with high sensitivity.

Detector assembly started in 02/2013 and will finish in 2014. Cryostat commissioning and tests are ongoing and full data taking is expected to begin in 2015. Meanwhile CUORE-0 has been taking data since 03/2013. A single CUORE-like tower of 52 TeO\textsubscript{2} bolometers has been installed in the CUORICINO cryostat. This contains 11 kg of \textsuperscript{130}Te, roughly the same detector mass as in CUORICINO; however the backgrounds in the crystal are expected to be better due to the superior background control efforts used for the CUORE crystals. In particular, the surface alpha backgrounds seen in CUORICINO are expected to be reduced in CUORE, and has been studied with CUORE-0 data.

Fig. 7 from [14] shows the background comparison between CUORE-0 data and CUORICINO. While external gamma backgrounds are expected to be the same (same cryostat), the continuum alpha background in the CUORE crystals is lower due to improved detector surface treatment. The goal for the full CUORE detector, after 5 years of livetime, is an effective Majorana neutrino mass sensitivity at the 47-100 meV level, just touching the top of the inverted mass hierarchy region (shown in Fig. 2).

4.2. MAJORANA

The MAJORANA experiment [15] is aiming for a tonne-scale experiment with enriched Ge detectors. Currently under construction in the Sanford Underground Research Facility in South Dakota, USA is the MAJORANA Demonstrator (MJD). With 30 kg of enriched \textsuperscript{76}Ge detectors (86% enriched) and 10 kg of \textsuperscript{nat}Ge detectors, the goal is to demonstrate backgrounds are low enough to proceed with a tonne-scale experiment. The approach is different from GERDA in that a modular array of Ge detectors in ultra-clean copper cryostats is used rather than immersion of bare Ge crystals in liquid argon.

A notable accomplishment of the MJD effort is electroforming of copper underground in Sanford Lab. Fig. 8 shows a photo from [16] of copper being electroformed on a stainless steel mandrel. MJD aims to be taking data in 2014 and will have a second cryostat operational in
2015. The sensitivity of MJD, for a 30 kg-yr exposure and zero background should be in the 100-200 meV range for $\langle m_{\beta\beta} \rangle$.

Figure 9. NEXT-DEMO prototype TPC track reconstruction [17].

Figure 10. Schematic of a SuperNEMO Demonstrator Module [19].

4.3. NEXT-100
The NEXT collaboration aims to build a 100-150 kg high pressure Xe TPC to search for neutrinoless double beta decay [17]. The plan is to install the detector in the Canfranc underground laboratory in Spain. Enriched xenon gas (90% $^{136}$Xe) will be operated at 10-20 bar. Electroluminescence is used to amplify the signals from electrons that have been drifted in order to achieve very good energy resolution. As a gaseous TPC (albeit at high pressure) track reconstruction is an objective for background reduction; the identification of two electron-like tracks in an event will strongly suppress gamma-ray (and other) backgrounds.

The signals in a NEXT TPC would include prompt scintillation (S1) and the electroluminescence (S2) from ionization (drifted electrons). This approach is similar to that used in the two-phase xenon TPC dark matter experiments. In small-scale prototypes, the energy resolution was measured using a $^{22}$Na source, and then projected to be 0.7% FWHM at $Q_{\beta\beta}$. Track reconstruction has been demonstrated in prototype detectors, illustrating the charge “blob” at the end of an electron track, as shown in Fig. 9.

Currently under construction is a 10 kg (15 bar) version of the detector called NEXT-White (NEW). The pressure vessel for the TPC has been built and the remaining detector HV and light detection (PMTs and SiPMs) components are being designed and built.

4.4. SuperNEMO
The SuperNEMO experiment is based on the successful NEMO-3 experiment [18]. The detector is a tracking calorimeter which has superb background rejection (using event spatial topology). Source foils of double beta decaying isotopes are deployed in a tracking detector with plastic scintillator calorimeter modules as “book ends” to measure the energy of the electron tracks emitted by the source foil. A schematic of a SuperNEMO detector module is in Fig. 10 [19]. A Demonstrator Module for the full SuperNEMO is under construction and will be deployed in the Modane underground lab in France; it is one module of the full 20 that would constitute SuperNEMO. Each of the 20 modules would have roughly 5 kg of $^{82}$Se on the source foil.
The tracker for the Demonstrator Module, being built in the UK, is a 2000-channel Geiger-mode detector. Strict background control is required in its construction and assembly. The energy resolution of the calorimeter readout is expected to be 4% FWHM at $Q_{\beta\beta}$ [19].

![Figure 11. Simulated energy spectrum for SNO+.](image)

![Figure 12. Photo of the SNO+ detector filling with water.](image)

4.5. SNO+

The Sudbury Neutrino Observatory (SNO) concluded operations in 2006 and the detector is being refurbished as the SNO+ experiment [20]. With 780 tonnes of liquid scintillator in the detector, SNO+ aims to deploy 0.3% Te, by weight, in the liquid scintillator to conduct a search for neutrinoless double beta decay; this would be 800 kg of $^{130}$Te isotope. The main feature of SNO+ is the same as that of KamLAND-Zen; a massive quantity of isotope can be deployed in a low background environment. The SNO+ concept with tellurium goes beyond the 0.3% experiment. I note here that this tonne-scale deployment of Te costs of the order of $1M for the double beta isotope material, as no enrichment is required. This is between 20-100 times cheaper than the cost of a tonne-scale isotope deployment in any other experimental approach. The potential thus exists for the SNO+ approach to make a further step in neutrinoless double beta decay sensitivity, to the 10 tonne scale! Recently, the SNO+ collaboration has succeeded to make 3% Te-loaded liquid scintillator with good light yield.

A liquid scintillator has fast timing that enables good position reconstruction (to suppress external gamma backgrounds) as well as enabling strong background rejection using delayed coincidence events in various decay chains. Factors of several thousand rejection are possible (and have been achieved in KamLAND-Zen). With a liquid scintillator detector, energy resolution is not as good as in other detector technologies. It is an important fact that the $2\nu\beta\beta$ rate in $^{130}$Te is one of the slowest of all of the candidate isotopes for a double beta decay experiment; this helps minimize the background from $2\nu\beta\beta$ that tails into the energy region at $Q_{\beta\beta}$. With this fact, plus purification for reducing backgrounds and background rejection techniques, SNO+ has the goal that in the energy region of interest for $0\nu\beta\beta$, corresponding roughly to $[-0.5\sigma, 1.5\sigma]$ around $Q_{\beta\beta}$, the dominant background will be $^8$B solar neutrinos.

SNO+ has studied the purification of tellurium and Te-loaded liquid scintillator, including a thorough study of possible cosmogenic backgrounds. The expected backgrounds and signals in SNO+ are shown in Fig. 11. With 0.3% Te loading, SNO+ sensitivity to $\langle m_{\beta\beta} \rangle$ is expected to reach as low as 50 meV. The successful demonstration of background control at this level would pave the way for a 3% Te SNO+ experiment with $\langle m_{\beta\beta} \rangle$ sensitivity reaching to the bottom of the inverted mass hierarchy allowed region. SNO+ is currently under construction. The detector is being filled with water (see Fig. 12) and the scintillator purification plant is being installed. Data taking with scintillator is expected to begin in 2015.
Acknowledgments
I wish to thank all the representatives of the experiments who provided me with material to present at NuPhys 2013. Citations have been included in this report. In addition, communications and information were received from R. Saakyan, F. Avignone, E. Fiorini, O. Cremonesi, K. Kumar, J. Farine and S. Schönert.

References
[1] Pascoli S updated figure in RPP 2013 “Neutrino Mass, Mixing and Oscillations”, originally in Pascoli S and Petcov S 2008 Phys. Rev. D 77 113003
[2] Simkovic F 2014 J. Phys.: Conf. Series this volume
[3] Robertson R G H 2013 Mod. Phys. Lett. a 28 1350021
[4] Umehara S and Kishimoto T 2013, private communication
[5] Inoue K 2013, private communication
[6] Gando A et al. 2013 Phys. Rev. Lett. 110 062502
[7] Klapdor-Kleingrothaus H V and Krivosheina I V 2006 Mod. Phys. Lett. A 21 1547
[8] Auger M et al. 2012 Phys. Rev. Lett. 109 032505
[9] Ackerman N et al. 2011 Phys. Rev. Lett. 107 212501
[10] Gratta G 2013, private communication
[11] Ackermann K-H et al. 2013 Eur. Phys. J. C 73 2330
[12] Agostini M et al. 2013 Phys. Rev. Lett. 111 122503
[13] Artusa D R et al. 2014 Searching for neutrinoless double-beta decay of $^{130}$Te with CUORE Preprint arXiv:1402.6072
[14] Brofferio C 2013 private communication, subsequently in Aguirre C P et al. 2014 Initial performance of the CUORE-0 experiment Preprint arXiv:1402.0922
[15] Martin R D et al. 2013 Status of the MAJORANA DEMONSTRATOR experiment Preprint arXiv:1311.3310
[16] Elliott S R 2013, private communication
[17] Gómez-Cadenas J J 2013, private communication
[18] Arnold R et al. 2005 Nucl. Instrum. Meth. A 536 79
[19] Waters D 2013, private communication
[20] Chen M C 2008 The SNO+ experiment, proceedings of the 34th International Conference on High Energy Physics (ICHEP 2008) Preprint arXiv:0810.3694