New techniques: EXO and other tracking detectors

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Abstract. Neutrinoless double beta ($\beta\beta0\nu$) decay has become an area of interest of the neutrino physics community. A new generation of $\beta\beta$-experiments is under design or construction to provide clear and unambiguous evidence for double beta decay, should it exist. These experiments aim to optimize the key aspects of $\beta\beta0\nu$-experiments: source strength, detection efficiency, energy resolution, and background. This article will focus on tracking detectors, with emphasis on the EXO experiment.

1. Introduction

Neutrino flavor oscillations and thus non-zero masses of at least two mass eigenstates have been widely accepted throughout our field. The three flavor mixing model is the new paradigm of neutrino physics. It allows an elegant and simple description of all oscillation experiments but LSND. Depending on the outcome of the ongoing MiniBooNE experiment, it may thus require revision. Within the three flavor model two mass differences (Δm_{12}, Δm_{23}), two mixing angles (θ_{12}, θ_{23}), and the mass hierarchy of the first two mass eigenstates ($m_1 < m_2$) suffice to describe the diverse array of oscillation experiments, covering a wide area of techniques, sources, and energies. The third mixing angle (θ_{13}), the absolute values of the neutrino masses (m_1, m_2, m_3), the mass hierarchy ($m_1 < m_2 < m_3$ *normal*, $m_3 < m_1 < m_2$ *inverted*, $m_1 \approx m_2 \approx m_3$ *degenerate*), the CP-phases, and behavior of neutrinos under CPT-conjugation remain undetermined.

This article will focus on two double beta decay modes: the allowed two neutrino double beta decay ($\beta\beta2\nu$), $\mathrm{A(Z,N)} \rightarrow \mathrm{A(Z+2,N-2)} + 2\ \mathrm{e}^- +\ 2\ \overline{\nu}_\mathrm{e}$ (Z: nuclear charge, N: neutron number, A=Z+N), resulting in a continuous sum energy spectrum of the emitted electrons, and the the neutrino less mode ($\beta\beta0\nu$) $\mathrm{A(Z,N)} \rightarrow \mathrm{A(Z+2,N-2)} + 2\ \mathrm{e}^-$, which violates conservation of Lepton number, of B-L conservation and requires neutrinos to be massive Majorana particles. In the latter decay the electron sum energy has a discrete distribution. Assuming that $\beta\beta0\nu$-decay is mediated by the exchange of light neutrinos, its decay rate is given by: $\left(T_{1/2}^{\beta\beta0\nu}\right)^{-1} = G^{\beta\beta0\nu}\ |M^{\beta\beta0\nu}|^2\ \langle m_{\beta\beta}\rangle^2$. Using theoretically calculated phase space, $G^{\beta\beta0\nu}$, nuclear matrix element, $M^{\beta\beta0\nu}$, a measured decay rate (or limit of it) can be translated into an average Majorana neutrino mass, $\langle m_{\beta\beta}\rangle$. While theory claims to have good control over the accuracy of $G^{\beta\beta0\nu}$ the calculation of $M^{\beta\beta0\nu}$ remains a difficult and controversial issue. A dedicated talk covered this topic. It should therefore suffice to say that estimates for the uncertainty of theoretically calculated nuclear matrix elements range from a depressing factor 3 to a more aggressive ±30% in a more recent systematic evaluation [1]. The detection of $\beta\beta0\nu$-decay would prove the Majorana character of neutrinos, independent of any uncertainties of the computed parameters entering above equation. Such demonstration of Lepton number violation would, in itself, be a worthy price.

The effective Majorana neutrino mass, the quantity of interest, is given by:

$$\langle m_{\beta\beta} \rangle = \left| \sum_i \eta_i \, U_{ei}^2 \, m_i \right|, \tag{1}$$

where the sum goes over all active flavors, η_i denotes the complex CP-phases, U_{ei} the elements of the upper row of the mass mixing matrix, and m_i the physical neutrino masses.

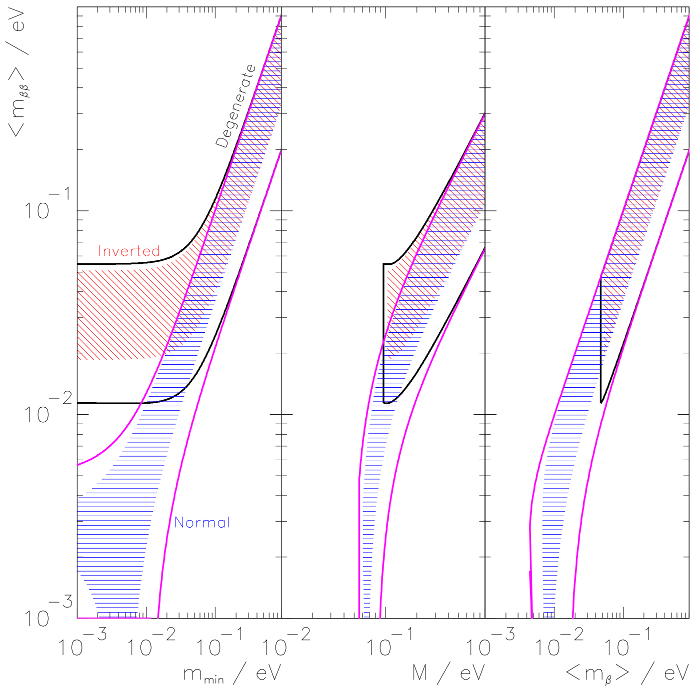

Figure 1. Dependence of $\langle m_{\beta\beta} \rangle$ on the mass of the lightest neutrino m_{min} (left panel). $\langle m_{\beta\beta} \rangle$ as a function of $M = m_1 + m_2 + m_3$ is shown in the middle panel. The right panel depicts $\langle m_{\beta\beta} \rangle$ as a function of $\langle m_\beta \rangle$. In all panels the width of the hatched areas is due to the unknown Majorana phases and thus irreducible. The allowed areas given by the solid lines are obtained by taking into account the errors of the oscillation parameters.

Equation 1 can be used to derive a relation between $\langle m_{\beta\beta} \rangle$ and the minimal neutrino mass, m_{min}, utilizing the known oscillation parameters. This projection is different for the three mass scenarios mentioned before. The global three flavor oscillation analysis of reference [2] has been used as input data for figure 1. It covers the first MINOS data release. The left panel of figure 1 shows the parameter values of $\langle m_{\beta\beta} \rangle$ (as a function of m_{min}), consistent with oscillation data. From figure 1 one can see that a sensitivity of 10 meV is required to conclusively probe the degenerate and inversely hierarchical mass scenarios.

Figure 1 further shows the interplay of $\langle m_{\beta\beta} \rangle$ with two other observable neutrino mass quantities: the total neutrino mass $M = m_1 + m_2 + m_3$, evaluated by observational cosmology (middle panel), and $\langle m_\beta \rangle = [\sum_i |U_{ei}|^2 m_i^2]^{1/2}$ determined in beta-endpoint experiments (right panel). These two panels can be used to directly compare projected sensitivities of these different experimental approaches.

To compensate for the lack of a clear experimental $\beta\beta0\nu$-decay signature and the uncertainty of the nuclear matrix elements it would seem prudent to conduct several experiments world wide, using different decaying nuclides. In case of an observation only redundancy will allow to make an unambiguous case. Truly redundant results will require at least one competitive tracking detector in the suit of world wide experiments.

2. Tracking detectors

A variety of new experiments is being planned to explore the degenerate and inversely hierarchical mass scenarios. These projects will further test the evidence for $\beta\beta0\nu$-decay in ^{76}Ge, brought forward by part of the Heidelberg component of the Heidelberg-Moscow experiment [3]. No project sensitive to the normal hierarchy has been proposed to date.

For $\langle m_{\beta\beta}\rangle$ =10 meV $\beta\beta0\nu$-half lives are of order 10^{28} y for isotopes of practical interest. Large detectors, containing order of tons of the decaying substance, are thus needed to arrive at a detectable decay rate of at least a few per year. Most next generation experiments plan to use large quantities of isotopically enriched source material in order to reduce the target for background radiation while maximizing source strength. Typical decay energies are between 2 and 3 MeV. Natural, anthropogenic, and cosmogenic radioactivity, as well as cosmic radiation contribute to the background. In the presence of a finite energy resolution $\beta\beta2\nu$-decay constitutes a background for the discrete spectrum of the $\beta\beta0\nu$-mode. Its contribution depends in the 5.8^{th} power on the energy resolution. Good energy resolution is of the utmost importance to reduce all continuous backgrounds under the $\beta\beta0\nu$-line and to suppress the otherwise irreducible $\beta\beta2\nu$background. Source strength, detection efficiency, energy resolution, and background are the key parameters of these experiments.

The two main approaches, used in real-time double beta decay experiments, are calorimetric and tracking. In calorimetric experiments the source usually doubles as detection medium, thus optimizing the electron detection efficiency. These experiments rely on their excellent energy resolution. The detectors are typically simple in design, reducing the risk of introducing unwanted radioactivity into the technical components near the active volume. Examples are Ge semiconductor detectors and bolometers. Limited tracking is achieved through detector granularity and time analysis of the collected charge. Separate articles are devoted to this approach.

Tracking detectors offer more active background rejection, however, at the expense of technical complexity making background control harder. This article will focus on three new projects: MOON, Super-NEMO, and EXO.

The somewhat unbalanced lengths of the following sections has something to do with the different state of preparation of the various projects and the fact that the author of this article is a member of the EXO collaboration. No judgment is implied or intended.

2.1. *MOON*

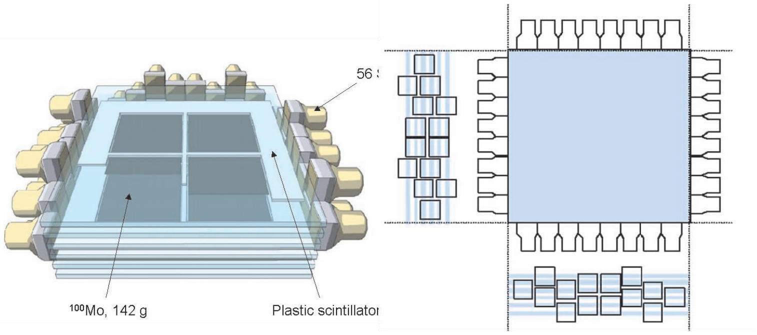

Figure 2. Sketch of a prototype detector module of MOON 1.

The Japanese-US-Czech-Russian MOON collaboration proposes to build a multi layer passive source tracking detector based on plastic scintillator calorimetry [4], an expansion of the 2-layer detector ELEGANT V. The goal is to use of order 1 ton of enriched isotope to achieve a mass sensitivity of 30 meV within 5 ton $\cdot$ y of exposure.

In this design single electron background events can be distinguished from double events. In case of a measurement of double beta decay both the single electron spectra and the angular correlation of the electrons will be recorded. ^{82}Se, ^{100}Mo, and ^{150}Nd sources are being considered. Thin (20 mg/cm^2) double beta unstable sources would be sandwiched between two thin detector planes, used for position and particle identification. Detector options are scintillating fibers or wire chambers. These will be surrounded by thick plastic scintillator acting as calorimeter. The typical size of the plastic scintillator would be 1.3 m × 1.3 m × 0.015 m. 150 of these units would be combined to form a module, containing about 30 kg of double beta unstable isotope. The concept is sketched in figure 2. Light read out would be by photo multiplier. A valid hit would require two planes, adjacent to a source film, and their associated calorimeters to be active. All other planes would be used as anti-coincidence to reduce γ-background. Energy resolution arond 2.9% (in units of σ), at the 3 MeV Q-value of ^{100}Mo, has been achieved with a prototype detector, called MOON 1. Based on tests with various plastic scintillators, the collaboration hopes to achieve a resolution of 2.5% or better, including the contribution due to electron scattering within the source foil. In MOON 1, containing 6 layers of plastic scintillator, background is further suppressed by means of an active outer NaI-shield, followed by passive Cu and Pb radiation shields. Background is assumed to be mainly due to residual ^{214}Bi (a ^{238}U daughter) contained in the source. For a design background of 0.3 /ton y the collaboration estimates a purity requirement of 20 μBq/kg, or 1.6 ppt U assuming chain equilibrium. The MOON collaboration plans to prepare an experiment proposal after the work on MOON 1 has been concluded.

2.2. Super-NEMO

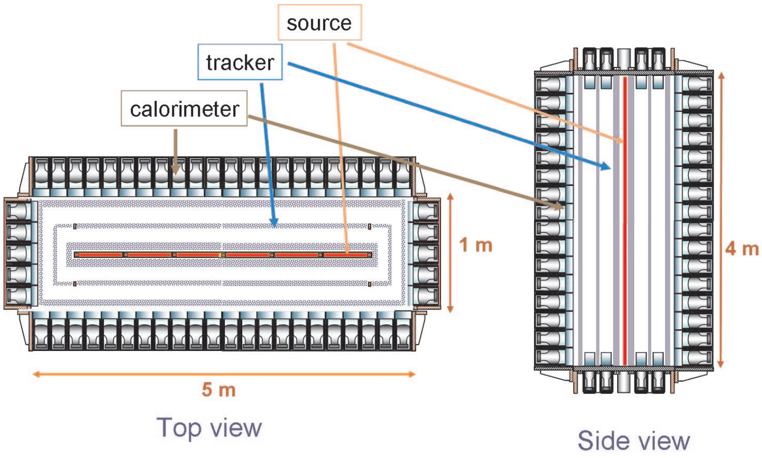

Figure 3. Cross section of a Super-NEMO detector module. The thin source foil is placed into a gas filled multi wire tracking detector. Electron calorimetry is provided by scintillator modules covering the module walls.

A large international collaboration explores an extended and improved version of the successful NEMO 3 experiment [5]. Their goal is to use about 100 kg of enriched isotope(s) in a passive source tracking calorimeter. The use of ^{82}Se and ^{150}Nd is being envisioned, with the goal of achieving a neutrino mass sensitivity of 40 meV. Isotopical enrichment of Se is by ultra centrifugation. The collaboration is exploring the use of a French laser enrichment facility for the production of a large amount of ^{150}Nd. An active R&D program is funded in France, Spain and the UK.

As in the previous project, Super-NEMO would have double electron detection capability. Thin, 5 kg, source foils are to be installed into large modular multi wire gas tracking detectors, its walls covered with scintillator calorimeters for energy measurement. Read out would be via 300 to 1000 PMTs per module. Figure 3 shows a sketch of this concept. A magnetic field will be used for particle identification. A total of 20 modules is envisaged at this time. Passive shielding

would be provided by 2 ktons of water for the 20 modules. The collaboration hopes to achieve an energy resolution of 1.7% (in units of σ) at 3 MeV. Research on different calorimeter technologies is ongoing. Resolution scattering of $\beta\beta 2\nu$-events into the $\beta\beta 0\nu$-analysis interval is an important background. The $\beta\beta 2\nu$-background into the 200 keV $\beta\beta 0\nu$-analysis interval is expected to be about 1 event/year for 100 kg of ^{82}Se. Radiopurity requirements for the source foils are of the order 0.5 to 0.8 ppt for Th and U, respectively. Careful Rn reduction is important, just like in any other double beta experiment. Possible sites for the experiment are: Frejus, Gran Sasso, Canfranc, and Bulby.
The collaboration aims at having a proposal ready by 2008, start of data taking is envisaged for 2010-2011.

2.3. EXO

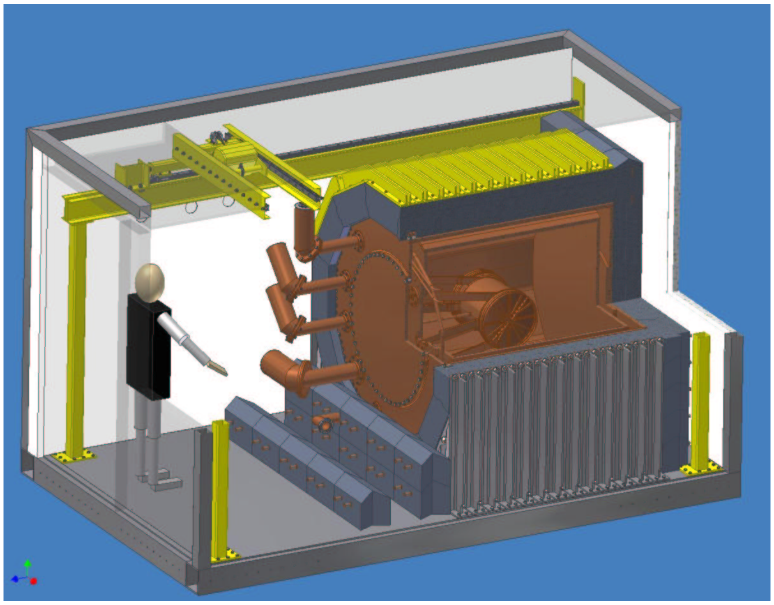

Figure 4. EXO-200 detector and its components. The cylindrical TPC and the 12-sided cryostat are made from high purity Cu. The tightly fitted passive lead shield minimizes γ-ray leakage and trapper internal Radon. A steel support structure is attached to the outside of the lead.

Goal of the US-Canadian-Russian-Swiss EXO collaboration is to use 1 to 10 tons of enriched ^{136}Xe in an active source TPC, equipped with final state Ba-tagging [6]. Liquid and high pressure Xe options are under investigation. Due to lack of space only the liquid option will be discussed here. Based on a recent mass determination [7], ^{136}Xe has a fairly high Q-value of 2457.8 ± 0.4 keV. As a noble gas enrichment can be done economically by ultra centrifugation, requiring no chemical conversion. The enrichment of ton quantities is technically and fiscally feasible. As a gas, Xe can be re-purified during operation of the experiment.
Electrons can be drifted through liquid Xe. Liquid Xe is further a high light yield scintillator (in the UV). It has been shown that liquid Xe detectors, with simultaneous read-out of ionization and scintillation, can achieve an energy resolution of about 1.5% (σ) at $Q_{\beta\beta}$ [8]. When used in a TPC with read out of the scintillation light three dimensional track reconstruction is possible. This allows tagging of γ-ray induced background due to its extended vertex.
Double beta decay of ^{136}Xe results in the formation of a doubly charged ^{136}Ba ion. Owing to their different ionization potentials Ba^{++} is stable in Xe. Ba^{+} single ions can be detected through optical pumping with blue and red lasers. This opens the possibility to capture the Ba ion at the decay vertex, transfer it into an ion trap, and then detect it by laser pumping. Such additional event signature would yield a large suppression of all random backgrounds.
The EXO collaboration estimates that a neutrino mass sensitivity of about 10 meV can be

achieved within 5 years of data taking, when using 10 tons of enriched Xe equipped with final state Ba tagging. The background was assumed to be dominated by $\beta\beta2\nu$-decay. Research toward this goal is two pronged: construction of a high resolution, low background liquid Xe TPC, using 200 kg of enriched ^{136}Xe , and development of the single Ba atom transfer and detection technology. The former aspect of the project is called EXO-200. Its goal is to demonstrate that a large Xe TPC with good energy resolution, high tracking power, and sufficiently low background can be build and stably operated. The development of the Ba tagging explores two options: in situ detection of single Ba ions in gaseous Xe, and retrieval of Ba ions from liquid Xe, followed by detection in an ion trap.

2.3.1. EXO-200 The EXO-200 detector is fully funded and under construction. It is to be installed in the WIPP underground facility near Carlsbad, NM at an overburden of 1600 mw.e.. 200 kg of enriched Xe are at hand. It will be contained in a thin walled cylindrical copper vessel, with a high voltage cathode in the middle. The high purity copper has been custom manufactured and will only be transported in a concrete shielded container to avoid activation by the cosmic radiation. Either side of the TPC will have 114 x- and the same number of y-wires (arranged at 60^0 angle to each other), grouped in three, for charge read-out and position reconstruction. The spatial resolution will be about 1 cm. Scintillation light will be read out by 258 large area avalanche photo diodes on each side. These low-mass devices offer good UV sensitivity, high quantum efficiency, and low background. It is estimated that about 115 kg of Xe will be fully active. The counting chamber will be submerged in HFE-7000, a highly radiopure heat transfer fluid, thermally coupled to the heat exchanges. It further serves as the innermost radiation shield (50 cm thickness). A double walled copper cryostat, containing the HFE-7000, is serviced by 3 refrigerators to have triple redundant cooling. The cryostat vessels have a combined thickness of 5 cm. 25 cm of low activity lead form the outer radiation shield. The setup is depicted in figure 4. Plastic scintillator modules will be installed outside the lead to provide an active muon veto. The experiment is to be housed in modular cleanrooms.

At this time part of the lead, the copper cryostat and the xenon piping have been installed in the cleanrooms at Stanford, CA. The pre-instrumented cleanrooms will later be transferred to WIPP.

All construction materials used in EXO-200 go through a rigorous radioactivity testing process. The required level of radiopurity is determined by means of a Monte Carlo simulation. Testing to the required sensitivity is then performed by means of α-spectroscopy, γ-ray spectroscopy, mass spectroscopy, and neutron activation analysis. Th and U sensitivities as low as 0.3 ppt have been achieved in the course of this work. More than 250 materials measurements have been conducted thus far in preparation for EXO-200. Depending on the material and its location, tracking background suppression factors between 3 and 60 have been determined by Monte Carlo, using a simple track length test. All materials are selected so that their summed background will to not exceed 30 events per year in the $\beta\beta0\nu$-analysis window, and 10 events per day in the $\beta\beta2\nu$-window. It is assumed that all are at their screening limits. This is conservative as not all materials will be at or close to their screening limits.

The current schedule calls for the start of operations underground sometimes in 2007. The EXO collaboration hopes to achieve a neutrino mass sensitivity of about 0.3 eV within 2 years of running EXO-200.

2.3.2. Ba tagging In a liquid Xe detector collision broadening requires removal of the Ba ions from the detector, transfer into an ion trap, followed by laser detection. Each step has to be performed with high efficiency. Extraction of the Ba ion will be done by means of a movable negatively biased probe. For events of sufficient energy the probe will be steered into the vicinity of the reconstructed event vertex, the Ba ion will be attracted to it and then removed together with the probe. The removal of ^{222}Ra ions (chemically similar to Ba) from liquid Xe, by means of a charged probe, has been experimentally demonstrated. The Ra was injected into Xe by means of α recoil and then detected via its subsequent alpha decay.

Ba single ion detection has been achieved using the EXO linear RFQ trap. The trapping potential is arranged such as to allow the Ba ions, after loading, to gradually fall into the potential minimum where the laser detection happens. High loading efficiencies have been reported for such traps. Measurements of the loading efficiency are now being planned with this trap.

Once attached to the probe, Ba forms a strong bond with it and is difficult to release. To achieve release three options are under study: (1) the charged probe is covered with a thin layer of Xe ice (about 100 atomic layers). To release the Ba the Xe ice is thawed at the entrance of the trap. (2) On a field emission tip the Ba attaches to the very sharp tip. For release a very large positive field is created. (3) With a resonance ionization tip (a 200 μm fiber with semitransparent metalization at its end) the Ba ion is first electrically attracted to the metalization, where it is neutralized. A powerful desorption laser pulse evaporates the Ba in the trap. A second pulse (at a different wavelength) resonantly ionizes the Ba while it is still close to the tip. The appropriate lasers needed to test this method are now at hand.

In parallel a grabber transfer system is under construction. This device, equipped with a liquid Xe vessel, a charged probe, and the linear trap will allow to exercise the entire capture, release, detection sequence, verify the concept and allow to measure its efficiency.

The collaboration hopes to be ready to submit a full experiment proposal one to two years after data taking commenced with EXO-200.

3. Conclusion

The next generation of double beta decay experiments will, hopefully, play an important role in the effort to obtain complete understanding of the physics of neutrinos. Neutrino oscillation experiments have defined the task. Their data suggests that Majorana masses down to 10 meV have to be probed in order to fully cover the degenerate and inversely hierarchical mass patterns. Tracking detectors can play an important role in providing redundant and unambiguous evidence for double beta decay, if it indeed exists. Many groups are working hard to make this a reality within the next ~5 years. It is hoped that the funding agencies will be supportive of this effort!

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