Solving the Neutrino Mass Mystery using Double Beta Decay

An examination of the feasibility of xenon purification and
ion capture and release using an electrostatic probe

Verena I. Martinez Outschoorn
Office of Science, SULI Program
Harvard University, Cambridge MA
Stanford Linear Accelerator Center
Menlo Park, California

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Participant:

Signature

Research Advisor:

Signature

Contents

Abstract	3
1 Introduction	4
1.1 Double Beta Decay	5
1.2 Detecting Double Beta Decay in ^{136}Xe	6
2 Xenon Purification	7
2.1 Materials and Methods	7
2.2 Results and Discussion	8
3 Ion capture and release using an electrostatic probe	10
3.1 Materials and Methods	10
3.2 Results and Discussion	12
References	12
Acknowledgments	13

List of Figures

1	Ionization and scintillation diagram	14
2	Sample data from the xenon purity monitor (XPM)	15
3	Electron lifetime for different fields	16
4	Drift velocity of electrons for different fields	17
5	α spectrum of source and grabbed ions	18
6	Control and release data for ion capture and release in xenon gas	19

Abstract

Solving the Neutrino Mass Mystery using Double Beta Decay. An examination of the feasibility of xenon purification and ion capture and release using an electrostatic probe. VERENA I. MARTINEZ OUTSCHOORN (Harvard University, Cambridge MA, 02138) Peter C. Rowson (Stanford Linear Accelerator Center, Menlo Park, California, 94025)

Double beta decay has long been recognized as a useful avenue for the study of electron neutrinos, especially the neutrino mass and its fundamental nature (Majorana or Dirac). Recent neutrino oscillation experiments have provided compelling evidence that the neutrino has mass. The detection of the neutrinoless mode of double beta decay would finally set a lower limit on the mass of the electron neutrino, as well as prove that the neutrino is a Majorana particle (with opposite spin, it is its own anti-particle). The Enriched Xenon Observatory (EXO) project attempts to detect neutrinoless double beta decay using ^{136}Xe that decays by this process to $^{136}\text{Ba}^{++} + e^- + e^-$. Perhaps one of the most significant characteristics of this project is the reduction of the background through the identification of the Barium ions for each individual event using laser fluorescence techniques. This project also proposes to collect scintillation light in addition to the ionization electrons in order to further improve energy resolution. Current work at SLAC includes the development of a purification system for xenon, as well as tests for the capture and release of single ions using an electrostatic probe.

1 Introduction

Double beta decay has long been recognized as a useful avenue for the study of electron neutrinos, especially the neutrino mass and its fundamental nature (Majorana or Dirac). Recent neutrino oscillation experiments have provided compelling evidence that the neutrino has mass. However, rather than providing absolute values for the neutrino mass, these experiments have only measured mass differences between the different neutrino types. The massiveness of the neutrino has opened up the possibility of detecting a neutrinoless mode of double beta decay, with very important consequences. The detection of such a mode would finally set a lower limit on the mass of the electron neutrino, as well as prove that the neutrino is a Majorana particle (with opposite spin, it is its own anti-particle). Moreover, characteristics of this mode such as lepton number violation have repercussions that constitute evidence for physics beyond the Standard Model, and impact cosmology as well.

The Enriched Xenon Observatory (EXO) project attempts to detect neutrinoless double beta decay using ^{136}Xe that decays by this process to $^{136}\text{Ba}^{++} + e^{-} + e^{-}$. Perhaps one of the most significant characteristics of this project is the reduction of the background through the identification of the Barium ions for each individual event using laser florescence techniques. This project also proposes to collect scintillation light in addition to the ionization electrons in order to further improve energy resolution. Current work at SLAC includes the development of a purification system for xenon, as well as tests for the capture and release of single ions using an electrostatic probe.

1.1 Double Beta Decay

Double beta decay occurs for isotopes where the single beta decay process is kinematically forbidden (the single beta decay daughter is more massive than the parent nucleus). In these cases (true for a few dozen isotopes) the simultaneous decay of two neutrons is observable. One such isotope is ^{136}Xe , which undergoes decay to $^{136}\text{Ba}^{++} + e^- + e^- + (2\bar{\nu}_e)$. The general form of such a process is:

$$(A, Z) \longrightarrow (A, Z \pm 2) + 2e^\mp + X \quad (1)$$

In the 2-neutrino double beta decay mode ($2\nu\beta\beta$), X corresponds to $2\bar{\nu}_e$ or $2\nu_e$. This process can occur in the standard model and has been observed for a few different isotopes. Alternative modes include the neutrinoless double beta decay mode in which there is no additional decay product X . This process occurs if the neutrinos are Majorana particles, so the electron neutrinos or antineutrinos generated in this decay are reabsorbed ($(A, Z) \longrightarrow (A, Z \pm 2) + 2e^\mp$), and if the neutrino is massive. The neutrinoless mode of double beta decay is particularly interesting for the determination of neutrino masses of the Majorana type, since for this mode of double beta decay, the decay rate is proportional to the neutrino mass squared,

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} \propto \langle m_\nu \rangle^2 = \left(\sum_i m_i U_{ei}^2\right)^2 \quad (2)$$

where U_{ei} corresponds to the mixing matrices of the mass eigenstates to the electron neutrino and m_i to the eigenvalues of the neutrino mass matrix. Even though neutrinoless double beta decay has never been observed, the detection of such a mode would constrain the Majorana electron neutrino mass. Combined with neutrino oscillation data, which constrains the elements of the mixing matrix U , the absolute neutrino mass can be determined.

In the 2-neutrino case, the spectrum sum energy of the two electrons covers the full range from zero to E_0 , the maximum allowed total kinetic energy, peaking at approximately $\frac{1}{3}E_0$. The method for the detection of the neutrinoless mode relies on the fact that in such a process all the reaction energy is carried by the two electrons, yielding a signal at the highest possible energy (peak at E_0). The detection of such an event is a great challenge because the decay rate is extremely low and all manner of background effects become a serious experimental problem. These characteristics require an experiment with extremely low background noise (arising from natural radioactivity and cosmic radiation) and very good energy resolution in order to separate the neutrinoless mode signal from the tail of the 2-neutrino double beta decay signal.

1.2 Detecting Double Beta Decay in ^{136}Xe

The Enriched Xenon Observatory group (EXO) proposes the calorimetric approach, searching for the double beta decay signal which corresponds to examining the two electron sum energy spectrum. In particular, this experiment will search for a peak at the highest energy value, corresponding to the neutrinoless mode of double beta decay. As mentioned previously, the detection of such a signal requires high energy resolution since neutrinoless events need to be separated from 2-neutrino events, and the peaks may be enlarged depending on the energy resolution of the detector. Xenon, however, presents many advantages as both the active material and the internal medium of the detector. ^{136}Xe may be obtained by isotopic separation, and given its inert properties, it is relatively easy to chemically purify. It constitutes a good ionization detecting medium, and is an efficient scintillator upon being ionized (see. Fig. 1). UV scintillation light is produced by the ionizing radiation in the liquid

as the xenon decays from an excimer state (formed by the binding of a ground state atom with an excited atom). The scintillation light may be collected in addition to the ionization signal in order to further improve energy resolution. Furthermore, EXO proposes the use of laser spectroscopy techniques in order to tag the barium ion resulting from the each double beta decay. The method proposed is based on laser-induced fluorescence of Ba^+ ions. These ions can be recognized using two lasers directed at the ion and tuned to the frequencies 493nm to excite ground-state ions to $6^2\text{P}_{1/2}$ state and 650nm to excite the system again to the $6^2\text{P}_{1/2}$ state from a $5^4\text{D}_{3/2}$ state, and observing the blue 493nm photon emitted from the decay to the ground state. This technique would enable coincident detection of Ba^+ ions on an event by event basis, dramatically reducing backgrounds.

R&D research at SLAC as part of the EXO project include studies of ultra-high purification techniques for xenon and the feasibility of ion capture and release methods using an electrostatic probe.

2 Xenon Purification

2.1 Materials and Methods

The experiment proposed requires very low background, involving an underground location that includes shielding and a detector made with materials with very low radioactivity. The purification of xenon is particularly crucial since it is not only the active material, but also constitutes an internal material of the detector (backgrounds associated with external materials may be shielded more easily). Ultra high purity xenon is required. The ionization electrons produced by the electrons from double beta decay must be drifted over large dis-

tances and must not be captured by electronegative impurities such as O_2 or H_2O , and in addition, radioactive impurities must be removed to reduce background.

Purification is carried out in a high vacuum xenon purification system including a hot zirconium "getter" purifier that removes all non noble gas impurities from the xenon to < 0.1 bbp. Future plans include a system of continuous purification that will allow for more efficient and sustained purification. Purity tests are performed using a xenon purity monitor (XPM) that determines the efficiency of drifts of electrons through a chamber of liquid xenon. Electrons for drift are released at a photocathode illuminated by a UV-laser. An electric field is applied in the XPM filled with liquid xenon, that causes the electrons to drift through the length of the chamber (109 mm), from cathode to anode. A signal corresponding to the charge released is detected at a grid 6mm from the photocathode and this charge is subsequently collected in a grid at the other end of the chamber, at a positive potential. The comparison between the initial signal at the cathode and the final signal at the anode allows for the calculation of the electron drift lifetime.

2.2 Results and Discussion

Measurements are taken for different electric fields, though current tests only go up to fields of the order of 1kV/cm. Fig. 2 is a sample plot corresponding to the measurements taken for anode and cathode voltages, where the rising edge corresponds to the released charge by the photocathode and the falling edge to the collected charge. Fig. 3 shows the calculations for the electron lifetime observed in liquid xenon for the different fields applied (range of applied voltages from $V_+ = 30V$ $V_- = 1V$ to $V_+ = 3000V$ $V_- = 1000V$). For the higher fields, the electron lifetime is about 4 ms. Fig. 4 is a sample plot of the drift velocity for

the different fields. The velocity increases until it reaches a plateau at high field of about $1.6 \text{ mm}/\mu\text{s}$. It is important to note, however, that the XPM currently proposed for the double beta decay experiment will employ a higher field (3-4 kV/cm), and extrapolation from current measurements is problematic due to complex impurity capture cross section behavior. Therefore, although the fits to these plots and subsequent calculations show the collection efficiency of ionization charges for lower fields, the implications of such tests for higher fields has yet to be determined exactly.

In order to interpret these measurements in the context of the EXO experiment design, the scale may be set considering an electron lifetime $\tau = 1 \text{ ms}$. In this case, assuming a maximum drift speed of $v \approx 2 \text{ mm}/\mu\text{s}$, the attenuation length $\lambda = v\tau$ is 2 m. The current design for the experiment includes a detector of dimensions involving 10-20cm drifts for the electrons. Such an experiment would then require an electron lifetime of about $\tau = 5 \text{ ms}$, which corresponds to an attenuation length of $\lambda = 10 \text{ m}$. Assuming that the charge decays exponentially as it travels through the detector and that the charge travels at most 10 cm, then $q(x) = q_0 e^{-\frac{x}{\lambda}} = q_0 e^{-\frac{1}{100}}$, that is, at least 99.0% of the charge is collected. However, a correction factor must be included for the different event positions. Since under these conditions most of the charge is collected, the correction factor is small. Supposing a spatial resolution of $\pm 1 \text{ cm}$, by the exponential decay model, the collected charge ranges from 98.9% to 99.1%, constituting about a 0.2% variation in the calculation of the initial charge. Since the resolution for the experiment may be as good as 1%, electron lifetimes of the order of 5 ms are highly desirable. Other uncertainties, however, must also be taken into account such as the uncertainty in the measurement of electron lifetimes and therefore of attenuation lengths. The data obtained so far including measurements of lifetimes of 4 ms indicate that

sustained electron lifetimes of about 5 ms are possible using current techniques, though more tests are necessary in order to be able to reach such a goal.

3 Ion capture and release using an electrostatic probe

3.1 Materials and Methods

Given the challenges of detecting these rare double beta decay events, EXO has proposed a coincidence method that is based on the detection and energy measurement of both the two electrons and the decay product, a barium ion. This method relies on the identification of barium ions on an event-by-event basis using laser spectroscopy techniques. However, laser detection of Ba ions in the body of liquid xenon presents serious difficulties, so a mechanism of removing single barium ions from the liquid xenon and releasing them in another location for the laser tagging is being developed. According to the present design, an electrostatic probe would extract the barium ion from the location of the double beta decay event and then release it for identification by the laser system. Current tests for the feasibility of ion capture and release by such a method are carried out using a U^{230} source in a custom made test cell which includes a movable electrostatic cryoprobe, silicon detectors and a pair of high voltage electrodes.

The prototype probe and test cell has the ^{230}U source at one electrode. The uranium undergoes two α decays producing ^{226}Th and ^{222}Ra ions that are released into the xenon in the cell. The cryoprobe is cooled by Joule-Thompson cooling with argon gas, creating a layer of solid xenon on the tip of the probe (a 2.4 mm surgical cryoprobe was adapted for this application) and may be moved vertically to three stations and horizontally in the cell.

The silicon detectors are placed in the middle station in the cell and are able to detect the α decays of the captured ions. The decay of these ions produces a particular α decay signature (see Fig. 5), corresponding to the following process:

In the liquid xenon, the probe is initially set to a negative potential and the $^{226}\text{Th}/^{222}\text{Ra}$ emitting source is set to a positive potential. The coated tip attracts the ions and their presence is observed at the detectors by raising the probe, leading to the detection of the α decay sequence. The probe is then raised to the release station where the field is reversed and the solid xenon is sublimated using helium gas (which heats in a Joule-Thompson expansion at these temperatures) for the heating of the probe in order to release the ions. Radium is used because barium and radium are chemically similar, with ionization potentials of 5.2 eV and 5.3 eV respectively. Moreover, a single ion is easily observable since the α decays are detectable using these silicon detectors. Since thorium and radium have the longer lifetimes of the decay sequence (the other half-lives are all $< \text{few milliseconds}$), these are the elements that are captured by the probe. However, the interest of such test lies in the study of radium, and since the lifetime of radium is much shorter than that of thorium (38 seconds compared to 30.5 minutes), the timescales associated with these tests must be short. In the figure below one can see the initial domination of radium decays upto about 100 seconds, and the subsequent domination of the thorium decays. Current tests attempt to determine the presence of these radioactive species (with particular focus on the radium) in order to determine whether the barium ions could be released by such a mechanism or whether the probe design needs to be altered.

3.2 Results and Discussion

Tests were carried out to study the feasibility of capture and release of ions in 200 torr of xenon gas. Fig. 6 shows the α decays detected for 15 seconds after ion capture and the period after release and in a control experiment when there was no release (helium gas was not used to melt the xenon ice on the probe). Five tests were carried out releasing ions and 2 runs without releasing ions. In the initial 15 seconds, the data from the ion release tests and the control test show similar high count rates, indicating that ions are captured by the probe. Moreover, in the figure, the previously calculated double exponential corresponding to the radium and thorium decays of the source was included. The double exponential curve does fit reasonably with the data corresponding to the control data. After the release period, the ion release data is well below the control data, indicating that release does take place by this method. This data indicates that ion capture and release is possible in xenon gas.

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Figure 1: Ionization and scintillation in the double beta decay of ^{136}Xe .

Figure 2: Sample data from the xenon purity monitor (XPM).

Figure 3: Electron lifetime for different fields, calculated from XPM data. Red line corresponds to one millisecond lifetime.

Figure 4: Drift velocity of electrons for different fields, calculated from XPM data.

Figure 5: **Top** U^{230} source α spectrum in vacuum. **Bottom** α spectrum of ions grabbed using the electrostatic probe in atmospheric xenon.

Figure 6: Control and release data for ion capture and release in xenon gas