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EXO: A NEXT GENERATION DOUBLE BETA DECAY EXPERIMENT

C. HALL*

Stanford Linear Accelerator Center,
2575 Sand Hill Road,
Menlo Park, CA 94025, USA
E-mail: chall@slac.stanford.edu

The Enriched Xenon Observatory (EXO) is an experiment designed to search for the neutrinoless double beta decay $^{136}\mathrm{Xe}\rightarrow{}^{136}\mathrm{Ba}^{++}e^{-}e^{-}$. To dramatically reduce radioactive backgrounds, the EXO collaboration proposes to tag the final state barium ion event-by-event through its unique atomic spectroscopy. We describe here the current status of the EXO R&D effort.

1. The EXO proposal

The recent discovery of neutrino mass in atmospheric, solar, and reactor neutrinos has led to renewed interest in the physics potential of neutrinoless double beta decay. $0\nu\beta\beta$ is the most promising process to distinguish between Majorana and Dirac neutrinos, and may also provide valuable information on the overall scale of the neutrino mass spectrum. The EXO (Enriched Xenon Observatory) collaboration has proposed to search for the $0\nu\beta\beta$ decay $^{136}\mathrm{Xe}\rightarrow{}^{136}\mathrm{Ba}^{++}e^{-}e^{-}$ [1].

Xenon has several properties which make it an attractive candidate for a $0\nu\beta\beta$ experiment. It is a good ionization and scintillation medium, so it can serve as its own calorimeter for the final state electrons. As a noble gas it can be highly purified of radioactive contaminants, and may be repurified *in situ* if necessary. Xenon has no long lived radioactive isotopes, and as a gas at room temperature its isotopic enrichment is relatively easy through ultra-centrifugation.

Most importantly, the final state nuclear species of xenon double beta decay is barium, and single barium ions are routinely observed using mod-

*for the EXO collaboration, http://hep16.stanford.edu/exo/

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ern atomic spectroscopic techniques. This raises the possibility of tagging the barium ion on an event-by-event basis, eliminating all radioactive backgrounds and leaving only the $2\nu\beta\beta$ and $0\nu\beta\beta$ decays [a]. These two processes can then be separated by their energy distributions.

We are considering both a high pressure gaseous xenon TPC and a cryogenic liquid xenon detector. While both options have strengths and weaknesses, this article will focus on our liquid xenon work, which is at a more advanced stage.

The EXO roadmap is as follows. We are currently performing R&D work to demonstrate the feasibility of the barium tag technique. In parallel we are developing a 200 kg prototype which will not have the barium tag feature. The goals of the prototype are to measure the half life of the $2\nu\beta\beta$ process in ^{136}Xe, to understand the radioactive backgrounds, and to set a limit on the $0\nu\beta\beta$ half life which is competitive with other current experiments. The prototype would be followed by a one ton experiment with barium tagging, to be operated for five years, and expanding to a ten ton experiment operated for ten years.

2. Barium spectroscopy results

The Ba^+ ion has three energy levels which define its spectroscopy[b]. The $^2S_{1/2}$ ground state and $^2P_{1/2}$ excited state are separated by a 493 nm (blue) transition. Once in the excited state, there is a 30% probability to decay to the metastable (47 second lifetime) $^4D_{3/2}$ state by a 650 nm transition (red), and a 70% probability to return to the ground state. If both transitions are saturated by lasers at the appropriate frequencies, then the ion will rapidly cycle between all three states and scatter the laser light into 4π at a rate of $\sim 10^7$ photons per second. This is enough light to "see" a single ion with the naked eye.

Several techniques can distinguish laser scattering due to the barium ion from ambient backgrounds. For example, one can scan the frequency of the blue laser across the expected transition frequency and observe the resonance. This is shown in Figure 1, where the signal from a single barium ion observed in the EXO spectroscopy lab is plotted. This data was taken with the ion held in an RF quadrupole trap in vacuum. As explained in

[a] The barium tag was suggested by M.K. Moe [2], and in a different format by M. Miyajima, S. Sasaki, and H. Tawara [3].

[b] the Ba^{++} ion created by the $0\nu\beta\beta$ decay is expected to collect one (but not two) electrons from the liquid xenon, leaving it in the charge +1 state.

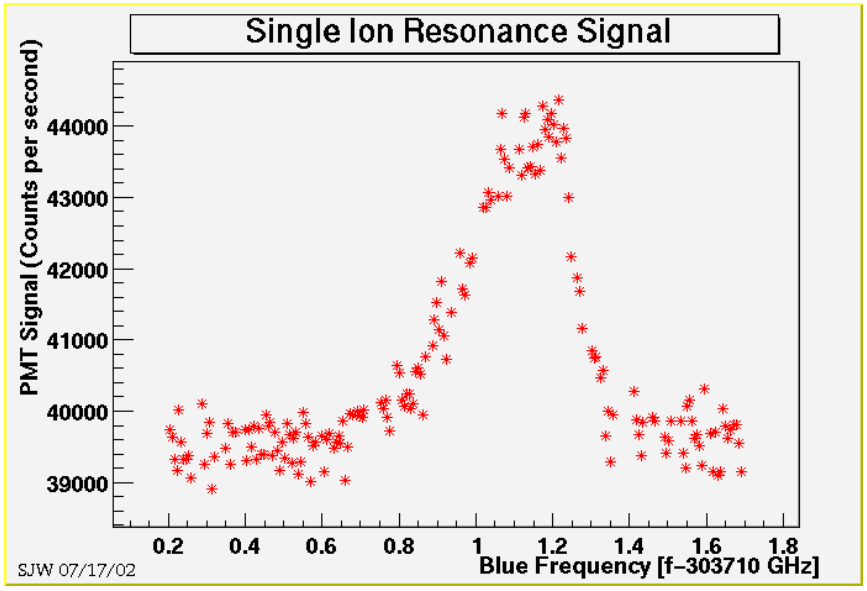

Figure 1. PMT count rate as a function of the frequency of the blue laser. The resonance is due to the light scattered by a single barium ion. Note the suppressed zero on the y-axis.

Section 3, we expect that the EXO spectroscopy will be done in a xenon buffer gas, perhaps up to a pressure of several atmospheres. In the near future we intend to check that the spectroscopy is possible under these conditions. However, similar work in argon and helium buffer gases was successful, so we do not anticipate any fundamental problems [4].

3. Ion grabbing experiments

In the case of a liquid xenon EXO, it will be difficult, if not impossible, to do the barium spectroscopy at the event location. This is because the liquid will scatter the laser light, causing large backgrounds, and because the energy levels of the barium ion change significantly in a liquid xenon bath. Therefore we are developing a system to transfer the barium ion from the liquid to a trap above the surface where it can be identified in a xenon buffer gas. Our basic model for this system is an electrostatic probe which can be inserted into the liquid to the event location and "grab" the barium ion with an applied voltage. The probe would then be removed to the trap

location, and the ion released.

To test the ion grabbing concept we have built a prototype electrostatic probe. To simplify the experiment we use ^{226}Th and ^{222}Ra ions to simulate the barium ions, since these isotopes can be easily identified by their alpha decays, and because they have similar chemistry to barium. To get the radium and thorium into the liquid xenon we use a ^{230}U source, which is deposited on a foil immersed in the liquid xenon. When the uranium alpha decays, the recoil of the decay can kick the produced thorium ion off the foil and into the liquid xenon. The thorium then alpha decays to radium.

The first version of the electrostatic probe is simply a tungsten rod with a spherical tip, about one millimeter in diameter. To grab the ions, the probe is placed in the liquid xenon near the ion source and a voltage is applied. To detect the ions the probe is retracted to an upper station above the liquid surface where an alpha counter is located. We find that when the voltage of the probe is set to collect positive ions, the alpha counter subsequently observes the radium and thorium daughter alphas. If no voltage is applied, or if the wrong sign voltage is applied, no alphas are observed. This demonstrates that ion grabbing in liquid xenon is possible.

Releasing the ions from the probe is more difficult that collecting them. We are currently pursuing a cold-probe technique, where the ion would be embedded in a layer of xenon ice on the probe. To release the ion the ice would be allowed to melt. We expect to have initial results from this technique very soon.

4. Liquid xenon energy resolution results

Barium tagging would eliminate all radioactive backgrounds except for the $2\nu\beta\beta$ decay of xenon. Like the $0\nu\beta\beta$ decay, the final state nucleus of the $2\nu\beta\beta$ decay is barium, so theses two processes can only be distinguished by their energy spectra. Therefore EXO requires the best energy resolution possible in liquid xenon.

To study the energy resolution of liquid xenon we have built a small gridded ionization chamber with a ^{207}Bi source. This isotope produces gammas at 570 keV and 1064 keV, as well as associated escape electrons and xrays. The ionization produced when the gammas and electrons interact in the liquid xenon is collected on an anode and amplified with a charge amp. In addition, a photomultiplier tube observes the 175 nm scintillation light produced by the interaction in the liquid xenon.

We find that the energy resolution of the ionization signal is $\sigma(E)/E =$

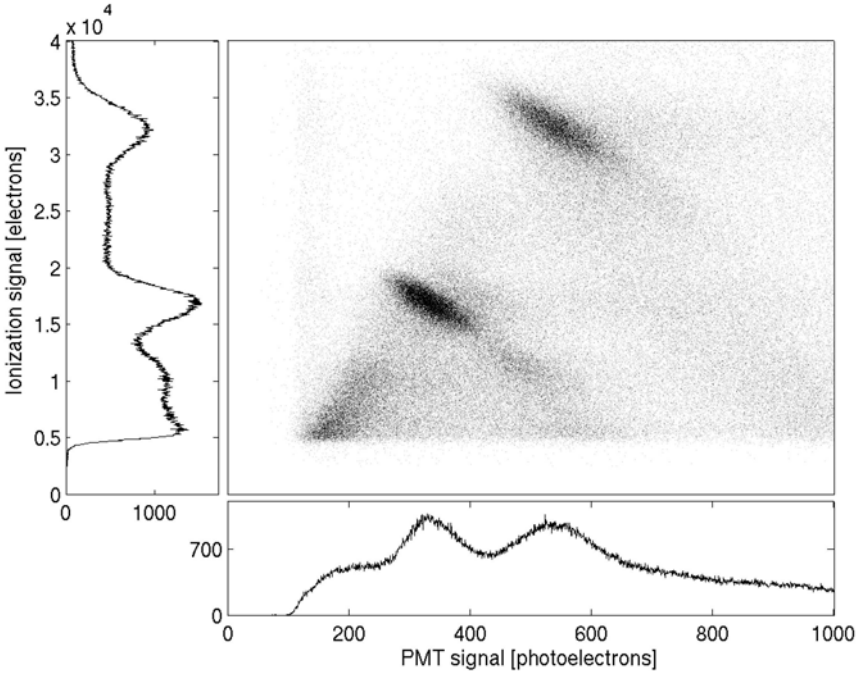

Figure 2. Scatterplot of the ionization and scintillation signals of a ^{207}Bi source in the liquid xenon gridded ionization chamber at a field of 4 kV/cm. The two islands correspond to the 570 keV and 1064 keV gammas and their satellite internal conversion peaks. The rotation of the islands demonstrates that the energy resolution can be improved by using a linear combination of the ionization and scintillation signals. The one-dimensional projections are shown on each axis.

3.7% for the 570 keV gamma at a field of 4 kV/cm, in agreement with the results of other authors[5c]. The energy resolution of the scintillation signal observed with the PMT is much worse. However, we also find that the PMT signal is anti-correlated with the ionization signal on an event-by-event basis, as shown in Figure 2. This means that the scintillation signal can be used to make a correction to the ionization signal and improve upon the previous state-of-the-art energy resolution in liquid xenon. At 4 kV/cm we are able to achieve an energy resolution of $\sigma(E)/E = 3.0\%$ at 570 keV after making the scintillation correction[6].

[c]These resolutions are after a small correction to remove electronic noise.

5. Plans for a 200 kg prototype

We are proceeding with plans to build a 200 kg liquid xenon EXO prototype. The prototype will be located underground at the DoE Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico. The 200 kg of xenon, enriched to 80% in ^{136}Xe by ultra-centrifugation in Russia, has already been obtained. The prototype will not have barium tagging, but will measure the $2\nu\beta\beta$ half-life of ^{136}Xe, as well as study the other radioactive backgrounds. We also intend to set a limit on the half-life of the $0\nu\beta\beta$ decay which is competitive with the most sensitive double beta decay experiments.

6. Sensitivity

We have calculated the expected sensitivity of EXO to neutrinoless double beta decay under the assumption that barium tagging has eliminated all radioactive backgrounds. For a one ton detector, enriched to 80% in ^{136}Xe, with an efficiency of 70%, five years of live-time, and an energy resolution of $\sigma(E)/E = 2.8\%$ at 2.5 MeV, we anticipate a half-life sensitivity of 8.3×10^{26} years, which corresponds to a neutrino mass sensitivity between 51 meV and 140 meV (depending on the nuclear matrix element calculation). A ten ton detector, operated for ten years, with an improved energy resolution of $\sigma(E)/E = 2.0\%$ at 2.5 MeV, could push the half-life sensitivity up to 1.3×10^{28} years (neutrino mass between 13 and 37 meV).

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