Dissertation

Barium Tagging in Solid Xenon for the nEXO Neutrinoless Double Beta Decay Experiment

Submitted by

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Abstract

abztrakt

Acknowledgements

Bill, Chris for all the help in the lab and building things, Shon and Brian for creating the system and training me (Shon) and for the preliminary results, Adam, Cesar, Kendy.

If you want the Leif thing, uncomment it in csuthesis.cls. It says something like ”this dissertation is typeset in ... designed by Leif Anderson.

Jamie and LEW, and other fam.

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CHAPTER 1

Introduction

Neutrinos have provided illumination as well as great challenge to physics since their discovery. They first entered our consciousness through W. Pauli, who proposed in 1930 the existence of a neutral, unobserved particle to explain the apparent violation of energy conservation in beta decay. He admitted that neutrinos (then deemed "neutrons" – what we now know as neutrons had not been discovered yet either) should be difficult to observe experimentally, but also that it seemed unlikely that they would never have been noticed before [ref: Pauli letter, or a following paper?]. As it turns out, they are much more difficult to observe than he predicted; there is no way *to* notice them without extreme experimental techniques.

A theory formulated in 1933 by E. Fermi for beta decay, including the neutrino, would be the beginnings of weak theory, and the development of the very successful Standard Model of particle physics. But neutrinos continued to challenge theory with the discovery of non-zero neutrino mass, and they remain at the forefront of our exploration of the universe.

The possibility that neutrinos are Majorana particles makes the search for neutrinoless double beta decay very important for the further development of particle theory. Majorana formulation can describe the origin of neutrino mass, and possibly explain why the mass is very small via the Seesaw Mechanism [ref]. Observation of neutrinoless double beta decay would simultaneously demonstrate that neutrinos are Majorana particles, as well as give a measurement of the absolute mass itself [ref? this is said later too].

To motivate barium tagging, this chapter outlines the current theory for neutrinos, and then describes the neutrinoless double beta decay experiments EXO-200 and nEXO.

1.1. Neutrinos

Neutrinos are chargeless leptons which only interact via the weak force (and gravity). There are three known "flavors" of neutrinos, each corresponding to one of the three known leptons: ν_e, ν_μ, and ν_τ. These are the eigenstates in the basis of the weak force, so they are the states in which a neutrino will interact via the weak force.

History: Neutrinos were first proposed while studying beta decay. If the emitted electron and daughter nucleus in beta decay were the only products, the electron's energy should be essentially the same for every observed beta decay for a given isotope, since there is a certain energy difference between the initial and final states of the nucleus, and since the final kinetic energy of the nucleus is negligible due to its mass. But instead of a sharp peak at this Q-value, a very broad electron energy spectrum is observed, all beneath and decreasing toward the Q-value.

In 1930, Wolfgang Pauli proposed that this variable "loss" in energy could be due to an additional particle being emitted along with the electron, but which is not observed.

[Fermi, massless]

[observation, and discovery of nu mu]

1.1.1. Neutrino Oscillation and Mass.

Neutrinos exhibit mixing between their energy eigenstates and their weak force eigenstates, and these are not the same basis. **not really:** This means that a flavor eigenstate is not a stationary state [the fact is that quark mixing happens, and one theory was that neutrinos would do something similar, and then oscillation is discovered...etc.]— a neutrino which begins as a pure flavor state (as all neutrinos will, coming out of a quantum process involving one of the three leptons) will oscillate into the other two flavors as it evolves in time, i.e. the probability of measuring it to be one of the other two flavors is no longer zero.

History: The first indications of neutrino oscillation came around 1970 with the Ray Davis Experiment [ref.], which measured the flux (at Earth) of solar electron neutrinos. The flux measured was quite a bit lower than predicted by solar models, and this became known as the Solar Neutrino Problem. The discovery of neutrino oscillation in the late 1990s [ref.] solved this problem, as only a fraction of the sun's neutrinos, produced as pure electron neutrinos, would interact as such.

The very small mass of a neutrino, specifically relative to its momentum, lets one write its Hamiltonian in terms of mass squared differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$, where $i,j = 1,2,3$, referring to what we then call mass states. The mass basis is really the energy basis with the small mass approximation, along with dropping some constant terms in the Hamiltonian (which do not affect time evolution). Writing the time evolution in terms of mass squared differences means that neutrino oscillation experiments can produce measurements of these differences. In fact, the discovery of neutrino oscillation was the first (and only, so far) demonstration that neutrinos have a non-zero mass. Without neutrino mass (particularly without differences between the masses of the mass states), neutrinos would not oscillate.

Neutrino oscillation experiments also provide measurements on the amount of mixing between the flavor basis and the mass basis. We define the mixing between them by a rotation in terms of three mixing angles, θ_{12}, θ_{23}, and θ_{13}. Transformation between the flavor and mass bases is done with the following unitary matrix, called the Pontecorvo–Maki-Nakagawa-Sakata (PMNS) matrix:

$$
U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}
$$

(1)

$$
= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}
$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. δ is a phase factor related to lepton CP violation, and α_i are Majorana phases.

Studying oscillations of neutrinos from different kinds of sources, with different energies and path lengths, can isolate sensitivities to the different parameters (not really sure if this is the right thing to say). For example, the study of solar neutrinos (neutrinos emanating from nuclear fusion reactions in the core of the sun) provides sensitivity to θ_{12} and Δm^2_{12} (*right? θ_{12} may not be specifically solar...*). Beamline neutrino detectors can be designed for maximum sensitivity to parameters. The parameters so far measured are as follows in Table 1.1:

Table 1.1. up to date values with references, and denote "solar", "atmos.", etc.

Parameter	Measurement
Δm^2_{12}	
$\|\Delta m^2_{31}\|$	
$\sin^2\theta_{12}$	
$\sin^2\theta_{23}$	
$\sin^2\theta_{13}$	

Note that only the absolute value of Δm^2_{31} is known. As a consequence, there are two possibilities for the hierarchy of the three neutrino masses. These are called the Normal and Inverted Hierarchies, as shown in Fig. 1.1.

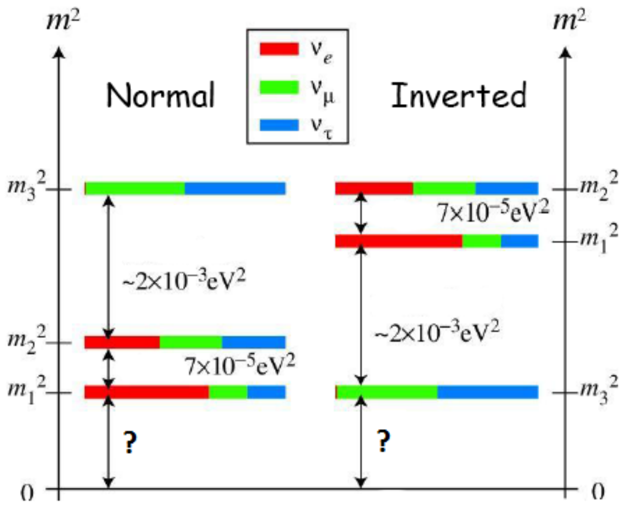

FIGURE 1.1. The two possible hierarchies of neutrino masses. The colors depict the mixing between the mass and flavor bases. **[ref]**

The correct mass hierarchy remains unknown, but next-generation neutrino experiments, possibly including nEXO, will be able to discern this.

Neutrino oscillation demonstrates that neutrinos have non-zero mass, and though oscillation experiments can measure the mass squared differences, we still do not have a measurement of the absolute masses of the three neutrinos. *History:* mention Pauli's first statement of limit near electron mass? Then maybe say the 0 assumption, which I think came from Fermi's beta decay theory, but if you mention that above, just refer to it here.

The current upper limits on the mass come from...(KATRIN($\rightarrow \nu_e$)?$Cosmology(\rightarrow sum)$?

Neutrinoless double beta decay experiments like EXO-200 can put upper limits on specifically the Majorana neutrino mass (i.e., upper limits on the neutrino mass if neutrinos are indeed Majorana particles). As discussed in the next chapter, [EXO-200 and KamLAND (sp?) ZEN (sp?) together provide the strongest Majorana neutrino mass upper limit of [] (IS THAT TRUE?)].

Neutrino oscillation and non-zero neutrino mass are physics beyond the Standard Model (SM) of particle physics, and though much has been discovered through oscillation experiments, there is much yet to learn about neutrinos. Since they are chargeless, they may be Majorana particles, and their small mass could be explained by the See-saw Mechanism [ref]. Majorana particles are their own anti-particle, and this, along with the discovery that neutrinos have mass, allows for a unique test of the Majorana (vs. Dirac) nature of neutrinos: neutrinoless double beta decay.

1.1.2. Neutrinoless Double Beta Decay. Double beta decay is the simultaneous emission of two electrons from a nucleus. Two-neutrino double beta decay, shown in Fig. 1.1.2(left), is allowed by the Standard Model and has been observed in several isotopes which are listed in Table (table). Similar to beta decay, a neutrino accompanies each electron in this decay, broadening the spectrum of the summed electron energy. This is a second-order process, making it a rare decay, and requiring low backgrounds to measure.

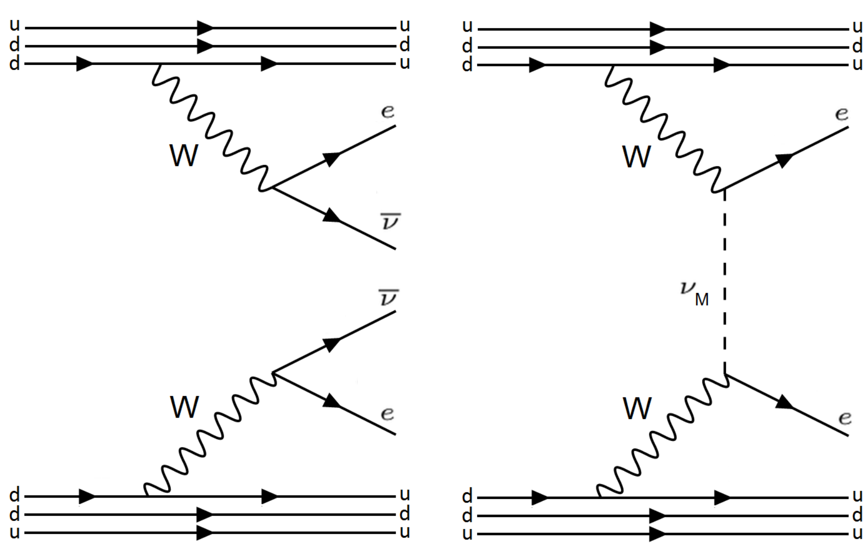

Figure 1.2. Two-neutrino (left) and Neutrinoless (right) double beta decay.

Neutrinoless double beta decay, shown in Fig. 1.1.2(right), is a postulated mode of double beta decay. In this case, the neutrino is exchanged as a virtual particle (which would require that it is a Majorana particle), and there are no neutrinos in the final products. If discovered, not only would neutrinos be determined Majorana particles, but their absolute mass could also be measured in the form of an effective electron neutrino mass, since the rate of neutrinoless double beta decay will depend on the absolute neutrino mass as shown in Eqn. 2:

$$T^{0\nu}_{1/2} = (G^{0\nu}(Q,Z)|M^{0\nu}|^2 \langle m_\nu \rangle^2)^{-1} \tag{2}$$

where $T^{0\nu}_{1/2}$ is the $0\nu\beta\beta$ half-life, $G^{0\nu}$ is a known phase space factor, and $M^{0\nu}$ is a model-dependent nuclear matrix element. The effective electron neutrino mass $\langle m_\nu \rangle$ is the expectation value of the mass for a pure electron neutrino:

$$\langle m_\nu \rangle = \sum_i U^2_{ei} m_i. \tag{3}$$

The sum of the energies of the emitted electrons in double beta decay will serve as the distinction between the two-neutrino and zero-neutrino modes, shown in Fig. 1.3. In the two-neutrino mode, the total decay energy is shared probabilistically between the electrons and the neutrinos (the nucleus recoil energy is negligible), resulting in a broad distribution in the summed electron energy. (Recall the similarly broad electron energy in single beta decay, which ultimately led to discovery of the neutrino involved.) But in the zero-neutrino mode, all of the decay energy is carried away by the two electrons, resulting in only a single allowed value for the summed electron energy – a peak in the summed electron energy spectrum at the Q-value.

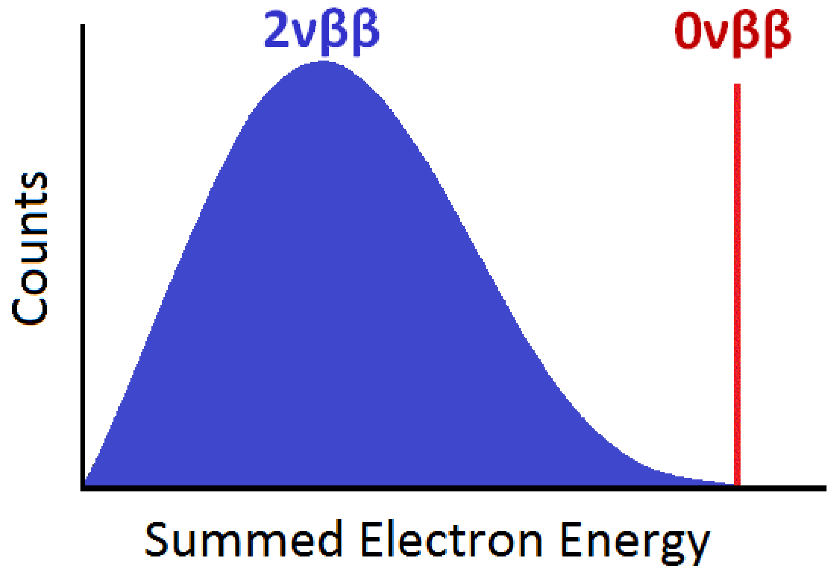

Figure 1.3. Conceptual two-neutrino (blue) and zero-neutrino (red) double beta decay spectra.

The rarity of double beta decay (see the very long half lives in Table (table)) requires very low backgrounds, especially around the Q-value for the $0\nu\beta\beta$ search. The next sections describe EXO-200 and it's next-generation successor, nEXO.

1.2. Enriched Xenon Observatory

The Enriched Xenon Observatory (EXO) is a set of two experiments, each a LXe time projection chamber (TPC) designed to study the double beta decay of the isotope ^{136}Xe, and ultimately to search for the zero-neutrino mode. There are several advantages to a LXe detector. Xe is extremely transparent, and scintillates at [around?] [xxx] nm, which is [efficiently collected by [type that the APDs are]] [reference]; so the Xe acts as a detection medium in addition to being the source of the double beta decay [reference? I didn't make up that kind of sentence]. Xe can be continuously purified to maintain large electron lifetimes in the LXe. Also, the ratio between observed scintillation light and remaining ionized electrons (drifted from the decay site by the TPC's electric field) exhibits a well-known microscopic anti-correlation [ref.], the understanding of which improves the energy resolution of the detector. Finally, a LXe TPC approach offers the opportunity, [fairly] unique in double beta decay, to reach in and identify, or "tag", the daughter Ba^{++} at the site of the double beta decay event, which would provide a background-free identification of neutrinoless double beta decay. Barium tagging is the focus of our group at CSU and is the subject of this thesis.

EXO-200 is the first of the two experiments, and has been operational since April of 20[xx](?). It is a liquid xenon TPC designed to probe Majorana neutrino masses down to around 100 meV. [EXO instrum. paper part I] The following sections decribe the EXO-200 experiment, as well as nEXO, the next-generation tonne-scale liquid xenon TPC which is now in the design stages. EXO-200 does not have barium tagging implemented, but it is hoped that nEXO will.

1.2.1. EXO-200.

1.2.2. nEXO. **old stupid intro:**

The study of the neutrino has required extremes in experimental technique from the beginning. Neutrinos were described by W. Pauli, who first proposed their existence to remedy an apparent violation of energy conservation in beta decay, as being [impossible to detect] [ref.]. Rather, it requires a great deal of sensitiviy, ingenuity, and hardship (just "ingenuity and hardship"? sensitivity may be redundant) to observe them, and it was [] years before they were first observed by [Reines and Cowan] in [], by [] [ref.]. (is "rather, ..." too demoting-sounding? it is absolutely not meant to be, of course)

Neutrino experiments of greater discovery power have been developed around the world, and command large collaborations of scientists. ummmmmmmm this is supposed to kind of allude to barium tagging as an extreme technique

Neutrinoless Double Beta Decay experiments like EXO are a different kind of neutrino experiment, not detecting neutrinos directly, but searching for an effect (neutrinoless double beta decay itself) which would demonstrate the Majorana nature of neutrinos. A liquid xenon experiment like EXO provides a the challenging opportuniy for another extreme experimental technique, barium tagging, where a single barium ion would be observed at a specific double beta decay site in the volume. This thesis is part of an exploration of one promising barium tagging technique. (these things may be saved for the EXO chapter... idk).

From the first formulation of beta decay theory by E. Fermi [ref.], neutrinos have provided an avenue into a world of new physics, and they continue to be such an avenue. Questions which may be answered by this up and coming generation of neutrino experiments are expected to help explain how the universe came to be this way.

[lead into barium tagging discussion]

1.3. something like "Can We Do This?", but probably not that at all.

A liquid xenon double beta decay detector allows unique access to the daughters of decays in the liquid volume. The feasibility of grabbing and detecting a single ion from the volume is what must be determined next.

CHAPTER 2

Theory

Theory relevant to the spectroscopy of Ba in SXe is discussed.

2.1. Barium Spectroscopy

Do we want this here? It flows more to have this theory after the proposition of the tagging technique, but maybe that's more appropriate for a talk.

2.2. Matrix Isolation Spectroscopy

(same thing)

CHAPTER 3

Apparatus

Should data results of diagnostic stuff, like Ba^+ velocity (from pulses), be in this chapter?

This chapter describes the apparatus at Colorado State University, which we have used for all described studies of Ba fluorescence in SXe after deposition in vacuum. Our main Ba source, the Ba^+ ion source/beam, is first described, as well as the measurements (using Faraday cups) used for determining the number of ions we deposit. A purely Ba neutral source is described. The co-deposit of Ba/Ba^+ with Xe gas onto a cold sapphire window, subsequent laser excitation, and finally the collection optics for the fluorescence, are described.

3.1. Ion Beam

3.1.1. Barium Ion Source/Acceleration. Barium ions are produced in a Colutron [type?] ion gun system [reference], as depicted in Fig. x. A solid barium charge is placed into the hollowed end of a stainless steel rod, which is then inserted into the discharge chamber, near the hot filament. The heated barium vaproizes, allowed to escape the hollowed rod around a loosely threaded set screw at the end of the rod. The discharge chamber then fills with barium vapor. A voltage is appled to the anode plate, which then creates a discharge, through the barium vapor, between the anode and the filament. The resulting plasma, containing barium ions, then escapes through the small hole in the anode plate, where it enters the acceleration potential.

The acceleration potential is 2 kV, between the ion source anode and an aperture, which constitutes the first element of the "acceleration lens" (Fig. 3.1). The acceleration lens is an

Einzel lens, the voltagesfor which are chosen to approximately collimate the ion beam for passage through the ExB velocity filter.

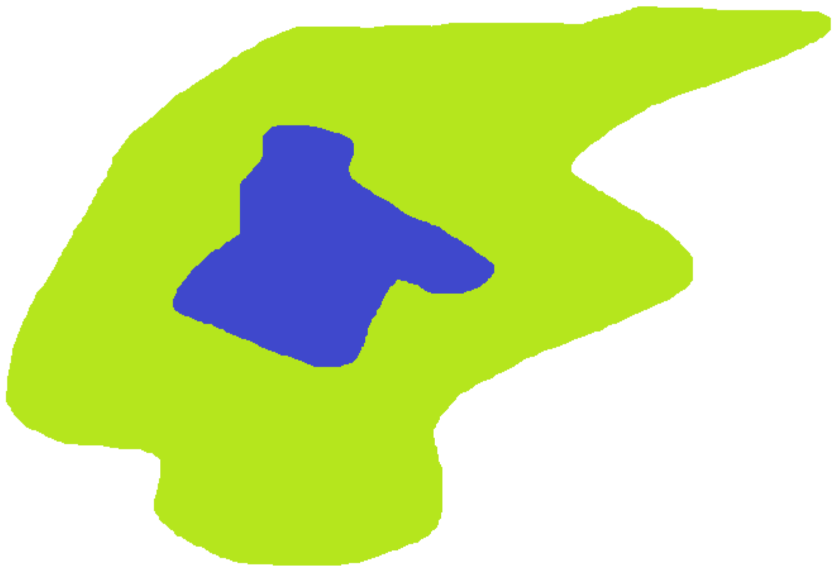

FIGURE 3.1. figyer

3.1.2. VELOCITY FILTER, LENSING. The $E \times B$ velocity filter selects Ba^+ by providing perpendicular electric and magnetic fields, which produce opposing forces on charged particles moving straight through the filter. Those fields are chosen such that those forces are equal for Ba^+, according to Eqn. 4:

$$\sigma = 1. \tag{4}$$

Other ions will be deflected, while Ba^+ will continue along the beam path.

The full ion beam is shown in Fig. xxx. The Decelerator lens can be used to reduce the beam energy, but is not needed for 2 keV beams, which are used in this work. Einzel Lens 3 focuses the beam onto the main Faraday cup, which is used during experiments to meaure ion current. The final set of deflection plates, H2 and V2, are also used during experiments to steer the beam for deposits.

3.1.3. Ion Beam Pulsing. To deposit small numbers of ions in a controlled manner, a set of pulsing plates can be used (Fig. xxxx). When running in this mode, the pulsing plates are first placed at 200 V and -200 V to deflect the beam, and are pulsed to 0 V for 1 μs for each pulse.

The pulses can be detected by the Induction Plates. Since they use induction, they can be used to observe the pulses during an ion deposition (unlike using the Faraday cup to measure ion current during a DC deposit). An example of an oscilloscope readout of the pulsing plate signa,l and subsequent induction plate signal, is shown in Fig. 5x.

3.2. Ba Getter Source

Ba "getters" are typically used in vacuum systems to improve vacuum by emitting Ba atoms, which grab gas molecules and hold them to the chamber walls. We employ getters as a neutral Ba source in our system.

...

It is very helpful to have a completely different type of Ba source, to rule out any source-related quirks, e.g. source-produced impurities.

3.3. Solid Xenon Matrix Deposition

The final destination of the barium ions is in the solid xenon matrix, which is deposited onto a cold sapphire window. Sapphire has good thermal conductivity, good optical transparency in the visible, and does not fluorescese in the wavelength region where barium fluoresces.

Xenon freezes around 73 K (?) at our pressures (0.5 - 1×10^{-7} Torr), so the window is cooled to temperatures below that. The window is held to a cold finger (Fig. 6x, picture of), cooled by a -brand- cryostat.

3.3.1. Deposition Procedure.

Before barium ions are let through, xenon gas is allowed to flow, controlled by a leak valve, onto the cold sapphire window, where it freezes and begins growing the solid matrix. The Faraday cup is then retracted, to clear the path for barium ions. The cup serves as a shutter for DC deposition, or if pulsing is being used, they are performed at this time. Barium ions land in the solid xenon as the matrix continues to grow. The cup is then replaced, and the xenon leak stopped.

CHAPTER 4

Results

CHAPTER 5

Conclusions

Ba^+

APPENDIX A

Supplementary Material

make these also into separate files plz

A.1. Some Sample Material

Did the name for the written material come before the name of the organ? Here [**?**] is a citation in an appendix.

APPENDIX B

Another Supplement