Imaging individual Ba atoms in solid xenon for barium tagging in nEXO

Bill Fairbank
Chris Chambers, David Fairbank, James Todd, Danielle Harris, Adam Craycraft, Alec Iverson
nEXO Collaboration
Extending the Sensitivity of Neutrinoless Double Beta Decay in the nEXO Detector

\[ ^{136}Xe \rightarrow ^{136}Ba^{++} + 2e^- \]

• **Ba Tagging:** also detect the daughter \(^{136}\text{Ba}\) ion or atom located at the decay position.
• **Potential to eliminate all but 2\(\nu\beta\beta\) backgrounds

Current experiments detect the emitted electrons
nEXO sensitivity vs. background

Barium Tagging in Solid Xenon

- Locate the decay position with the TPC
- Insert a cryogenic probe and trap the Ba daughter in solid Xe
- Extract the probe and cool
- Tag the Ba daughter in the solid Xe via laser induced fluorescence

1 Ba $\rightarrow$ $\beta \beta$ decay
0 Ba $\rightarrow$ Not $\beta \beta$ decay

Requires counting of **single** Ba in solid Xe

Probe in observation region - Use single Ba imaging technique we present in this work.
1. Cool sapphire window to 50K
2. Begin Xe gas flow for ~ 6 s
3. Pulse Ba\textsuperscript{+} beam onto window
4. Stop Xe gas flow after ~ 6s
5. Cool window to 10K

Deposition

- Mass selection: just Ba\textsuperscript{+}
- Pulses of few Ba\textsuperscript{+}
- Measure # Ba\textsuperscript{+}
- Clean Ba\textsuperscript{+} source
Observation of Ba in Solid Xe

Sample CCD Image

DBD18 Workshop October 21, 2018 Hawaii
Imaging and Background Reduction

Observed from above, there are two sources of background: surface, bulk

Cold Surface \quad \text{Cr}^{3+} \text{from the sapphire bulk}

Raster 532 nm laser across window overnight at 100K
30x background reduction in 90\mu m \times 90\mu m area

\text{Ba} \quad \text{Xe}

\text{Sapphire Window} \quad 10K

\text{Cr}^{3+} \text{reduced with high purity windows}

Image of background:
In vacuum, when the electron decays to the metastable D state, it is no longer excited by the laser.

Forbidden in vacuum but probably not in SXe
Since we excite single atoms up to $10^7$ times.
Spectra of Ba in Solid Xe

Ba Fluorescence Spectra

Three emission lines have more bleaching.

Ba atoms with 619 nm emission have little bleaching.

Ba Excitation Spectra

Two Ba sites have characteristic 3-peak excitation spectrum.

We have identified 4 distinct emission peaks, corresponding to 4 different matrix sites.

Identification of matrix sites of Ba in solid Xe for two peaks

New: identification of 3\textsuperscript{rd} matrix site of Ba in solid Xe: 619 nm peak

Single Vacancy (SV) site simulation shape qualitatively agrees with experiment. Cramped configuration is more sensitive to uncertainty in repulsive potential model.
Fluorescence signal is linear with # of ions deposited: not $\text{Ba}_n$ molecule!
Imaging single Ba atoms with laser scans

Each camera exposure is for a position in a grid:
Scanning for Single Ba Atoms: raw CCD images

Scan Parameters

- 12 x 12 grid
- x step: 4.0 μm
- y step: 5.6 μm
- Exposure: 3s/spot
Composite images of individual Ba atoms in solid Xe: counting Ba atoms

Making a Composite Image

Each frame is a CCD image of the laser at a grid spot
Between frames, the laser is moved to the next spot
Each frame is integrated around the laser region
Normalize by the laser exposure in mW*s
Signals plotted according to grid spot

Comment: count 2 detected Ba atoms in the scan area

48_{-10}^{+5} \text{ Ba}^+ \text{ ions deposited in the scan area.}

C. Chambers et al., arXiv 1806.10694, submitted to Nature
Composite images of individual Ba atoms in solid Xe: counting Ba atoms

First Scan: 2 Ba atoms

Repeat Scan: 2 Ba atoms still there
Then laser moved to near the left peak. 3s images are taken for 150 s. Atoms emit for ~25s more, then turn off: (>300 s for other atoms) Lots of photons emitted by one Ba atom! (700,000 - >10^7)
Repeat scan after sitting on one Ba atom

First Scan: 2 Ba

Repeat Scan: 2 Ba

Repeat Scan: after sitting near peak: one Ba is gone
Comparing scans of deposits with and without Ba pulses

Evaporate at 100K

Xe-only deposit Before

First Scan

Xe-only deposit After

No Ba left behind after evaporation!

C. Chambers et al., arXiv 1806.10694, submitted to Nature
Erasing a large Ba deposit

Even after a large deposit (7000 ions) all detectable Ba atoms are removed. Thus no “history effect” interfering with subsequent deposits.
Limit of <0.16% Ba signal after evaporation
Thus no “history effect” interfering with subsequent deposits

C. Chambers et al., arXiv 1806.10694, submitted to Nature
Comment on formation of matrix sites of Ba in Solid Xe

Ba atoms are too large to fit in a single vacancy (SV) site, preferring the 4- and 5-vacancy sites.

Ba implanted as an ion has a much tighter bond to Xe, thus preferring the SV site.

This has already been demonstrated experimentally for Na⁺ ions in SAr:
D. C. Silverman and M. E. Fajardo,
Comment on formation of matrix sites of Ba in Solid Xe

Ba atoms are too large to fit in a single vacancy (SV) site, preferring the 4- and 5-vacancy sites.

Ba implanted as an ion has a much tighter bond to Xe, thus preferring the SV site.

Ba\(^+\) then neutralizes later to Ba, but is trapped in the cramped SV site by the Xe matrix.
Apparatus to capture Ba in SXe on a cryoprobe

- Capture Ba in SXe at >161K.
- Raise probe to observation region.
- After close gate valve, reduce probe T and reduce Xe gas pressure, following gas-solid vapor pressure curve -> 10K.

Successful freezing from LXe and extraction to observation volume
Working on implantation of Ba\(^+\) ions into SXe on cryoprobe

- Ba\(^+\) ions created by laser ablation in Xe gas
- E-field to drift ions into LXe and to cryoprobe.
- Then spectroscopy of Ba in SXe in observation chamber
A better cryoprobe for single Ba imaging

Mount sapphire window on end of cryoprobe

We are working to adapt Peter Fierlinger’s helium cooled probe that included capacitive measurement of SXe thickness.

*P. Fierlinger et al., Rev. Sci. Instrum. 79, 045101 (2008).*

- Probe will dip into LXe and extract barium in SXe to upper observation cube
- *Similar optics of ion beam setup*
Summary
First imaging of single atoms in solid rare gas, a major step for Ba tagging in nEXO

Key features:
• Single Ba atoms can be counted with $S/\sigma \approx 70$.
• Ba deposit is “erased” by evaporating and re-freezing a new solid Xe coating.
• No sensitivity to any stray Ba atoms on window surface.
• $Ba^+$ ions preferentially go into single vacancy sites – if they neutralize after they form in SV site, they will be in the site for which we have demonstrated single Ba imaging. (This might occur for capture from LXe!)