Single Barium Atom Detection in Solid Xenon for the nEXO Experiment

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Neutrinos

- Fundamental particles
- Neutral
- Weakly Interacting
- Small Mass (< 1 eV)
- Common

Open Questions:
- Are neutrinos their own anti-particle?
- What are the neutrino masses?
- Can neutrinos violate lepton # conservation?
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Postulated nuclear decay process

$$^{A}_{Z}X \rightarrow ^{A}_{Z-2}Y + 2e^-$$

Normally $2\bar{\nu}_e$ are also emitted

The discovery of neutrinoless double beta decay will answer:

**Open Questions:**

- Are neutrinos their own anti-particle? → Yes
- What are the neutrino masses? → $\langle m_{\beta\beta} \rangle \sim 10 - 100$ meV
- Can neutrinos violate lepton # conservation? → Yes

Lepton # conservation violation is an important requirement for many theories that seek to explain the matter-antimatter asymmetry of the universe.
The nEXO Experiment:
Next-generation Liquid Xenon (LXe) Time Projection Chamber (TPC)

\[
\begin{align*}
\text{136} & \text{Xe} \rightarrow \text{136} \text{Ba}^{++} + 2e^- \\
\end{align*}
\]

**Barium Tagging**: identify barium daughter at 0νββ decay site for **complete** background elimination

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**100% Ba Tagging Efficiency**

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**nEXO Collaboration**

Barium Tagging R&D Program for nEXO

• Extraction to Gas Phase with Ion Trapping
  • McGill and Carleton Universities and TRIUMF

• Electrically Biased probe with Resonance Ionization Spectroscopy
  • Stanford University

• Electrically Biased probe with Thermal Desorption
  • University of Illinois Urbana-Champaign @ ANL

• Electrically Biased probe with Electron Microscopy
  • Brookhaven National Lab

• Cryogenic probe with Fluorescence Spectroscopy in Solid Xenon
  • Colorado State University
Barium Tagging in Solid Xenon

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

\[ ^{0}\text{Ba} \rightarrow \text{Not } \beta\beta \text{ decay} \]
\[ ^{1}\text{Ba} \rightarrow \beta\beta \text{ decay} \]

Requires counting of \textit{single} Ba in solid Xe

Remove probe to observation region – Use single Ba imaging technique we have developed
Deposition of Ba in Solid Xe

1. Cool sapphire window to 50K
2. Begin Xe gas flow
3. Pulse Ba$^+$ beam onto window
4. Stop Xe gas flow
5. Cool window to 10K

Some neutralization of Ba$^+$ to Ba
Observation of Ba in Solid Xe
Spectra of Ba in Solid Xe

Ba Fluorescence Spectra

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

Excited in the green-yellow range, 542 - 590 nm.

Bleaching:
Loss of fluorescence with laser exposure.
Limits the number of photons that can be collected.
Challenge for single-atom imaging.

Ba atoms with 619 nm emission show little bleaching.

Three emission lines exhibit bleaching.

Identification of Matrix Sites of Ba in Solid Xe

Identification of Matrix Sites of Ba in Solid Xe

Incident Ba Atom
\[ r_{\text{eff}} = 5.5 \text{ Å} \]

Incident Ba\(^+\) Ion
\[ r_{\text{eff}} = 3.6 \text{ Å} \]

Ba fluorescence at 619 nm is assigned to Ba atoms in **single vacancy (SV)** matrix sites.

Ba atoms are too large to fit in an 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.

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Ba\(^+\) then neutralizes to Ba, but is trapped in the cramped SV site by the Xe matrix.

Preliminary Simulation

Simulation by B. Gervais

Simulated emission spectrum has unresolved 3-fold splitting.

3-Gaussian fit width agrees reasonably with experiment.

Peak location is significantly different from experiment.

Sensitive to close-range potential which is more uncertain.

Refinement of potential underway.
Fixed Laser Images of Ba in Solid Xe

Number of ions deposited
\[ \varepsilon_N \]
Number of ions that neutralize
\[ \varepsilon_{SV} \]
Number of atoms in SV site

\[ \leq 54 \text{ atoms} \]
\[ \leq 14 \text{ atoms} \]
\[ \leq 5 \text{ atoms} \]

Fluorescence signal is linear with # of ions deposited: not \( \text{Ba}_n \) molecule
Scanning Laser Technique

Each camera exposure is for a position in a grid:

See peaks as laser moves near individual atoms
Scanning Laser Technique

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

Scan Parameters

\textbf{x step:} 4.0 \(\mu\)m \hspace{1cm} 12 \times 12\ grid
\textbf{y step:} 5.7 \(\mu\)m \hspace{1cm} 3s per spot
Composite Images of Ba Atom in Solid Xe

Making a Composite Image

- Each frame is a CCD image of the laser at a grid location.
- Between frames, the laser is moved to the next location.
- Each frame is then integrated around the laser region.
- Each integral is scaled by the laser exposure in mW*s.
- The integrals are then plotted according to laser position.

Composite Images of Ba Atom in Solid Xe

Remember:
Each pixel is the signal from one laser position

Looking at one Ba Atom

Move the laser to this atom

Looking at one Ba Atom

Sudden turn-off is a key feature

- Ensembles decay **smoothly**
- Single emitters are **on/off**

High Signal Definition

- Average signal is $11\sigma$ above background
- Summed signal is $70\sigma$ above background

Comparing Backgrounds

Xe-only Before

First Scan

Xe-only After

Evaporated at 100K

Evaporated at 100K

No Ba left behind after evaporation!

Erasing the Ba Deposit

Even after a large deposit (7000 ions) we remove detectable Ba atoms to a limit of \(< 0.16\%\). Thus no “history effect” interfering with subsequent deposits.
Imaging Single Ba Atoms with 577 nm

- Use 300 nW instead of 30 µW
- 25s or 17s frames instead of 7s frames
- Borrowed an EMCCD camera
- Often the Ba peak was already gone in a repeat scan

We can image single Ba atoms with faster bleaching
Extracting Ba from Liquid Xe

Observe Ba fluorescence in upper chamber

Isolation valves allow for pressure control around sample

Ablate Ba+ and draw to cryoprobe

Extract SXe sample via bellows

Probe
Window
Electrode
Barium
Copper
Holder
Conclusions

• Single atoms imaged in solid noble element for the first time
• Scanning technique allows for counting of individual atoms
• Can image single Ba in two matrix sites – 619 nm and 577 nm
• The fundamental scientific breakthrough for Ba tagging in nEXO
• Cryoprobe apparatus being developed for extraction of Ba from LXe
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• Chris Chambers (now at McGill)
• Adam Craycraft
• James Todd
• David Fairbank
• Alec Iverson
Backup
Energy Levels of Ba in Vacuum

Fluorescence Transition
6s² ¹S₀ ↔ 6s6p ¹P₁
@ 553.5 nm

If the electron decays to metastable state it is no longer excited by the laser
It “Turns off”
Energy Levels of Ba in Solid Xe

If the electron decays to metastable state it is no longer excited by the laser. It “Turns off”.

In the solid Xe matrix, the modified potential may allow transitions forbidden in vacuum.

 Fluorescence Transition 
6s^2 \( ^1S_0 \) \leftrightarrow 6s6p \( ^1P_1 \) 
@ 545 – 585 nm

Broadened in both excitation and emission.
Composite images of Ba$^+$ deposits taken over several days show repeatability of single Ba imaging

Additional Ba Scanning Experiments with 619nm
Achieving a high Ba tagging efficiency: can we image single Ba\(^+\) ions in solid xenon?

\[
\begin{align*}
6p^2P^\circ_{3/2} & \\
6p^2P^\circ_{1/2} & \\
\text{455.4 nm} & \\
649.7 \text{ nm} & \\
\text{614.2 nm} & \\
\text{585.4 nm} & \\
\text{493.4 nm} & \\
5d^2D_{5/2} & \\
5d^2D_{3/2} & \\
\text{matrix?} & \\
6s^2S_{1/2} & \\
\end{align*}
\]

\(\frac{1}{4}\) probability of decay to 5d state
Achieving a high Ba tagging efficiency: can we image single Ba\(^+\) ions in solid xenon?

- 6 emission peaks
- 2-3 excitation peaks
- maybe mainly SV site?