Single Barium Atom Detection in Solid Xenon for the nEXO Experiment

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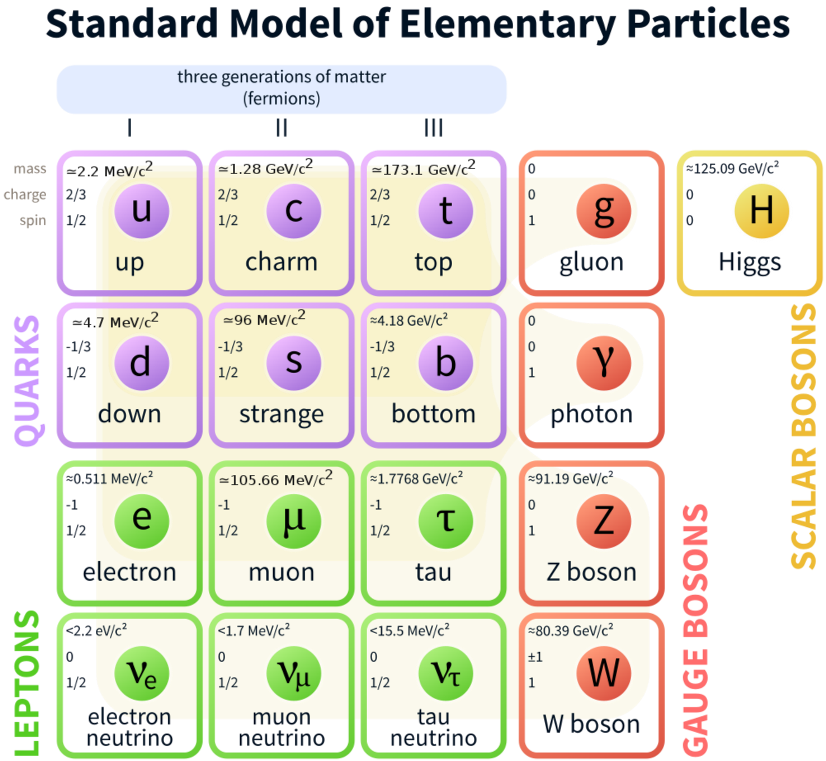
SMI July 2019 McGill University

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 (0νββ)

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

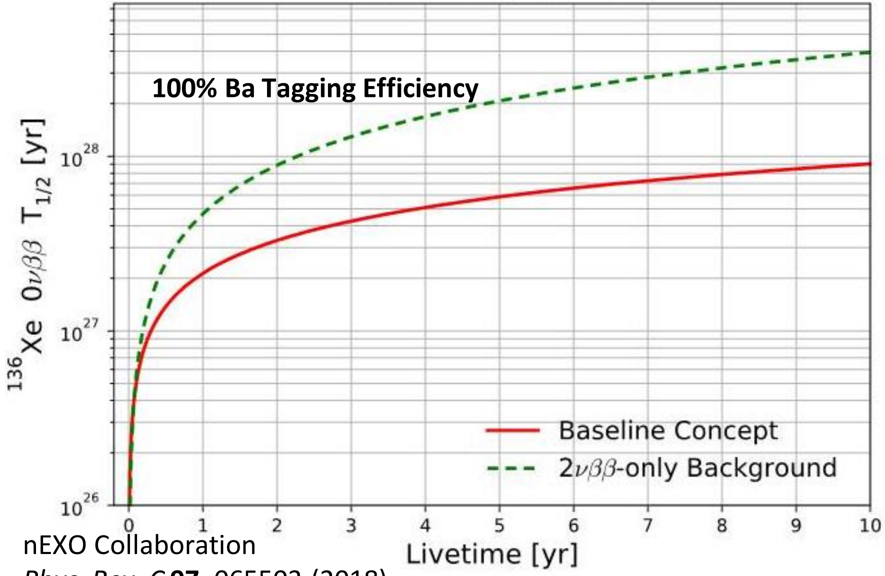
Lepton # conservation violation is an important requirement for many theories that seek to explain the matter-antimatter asymmetry of the universe

The nEXO Experiment:

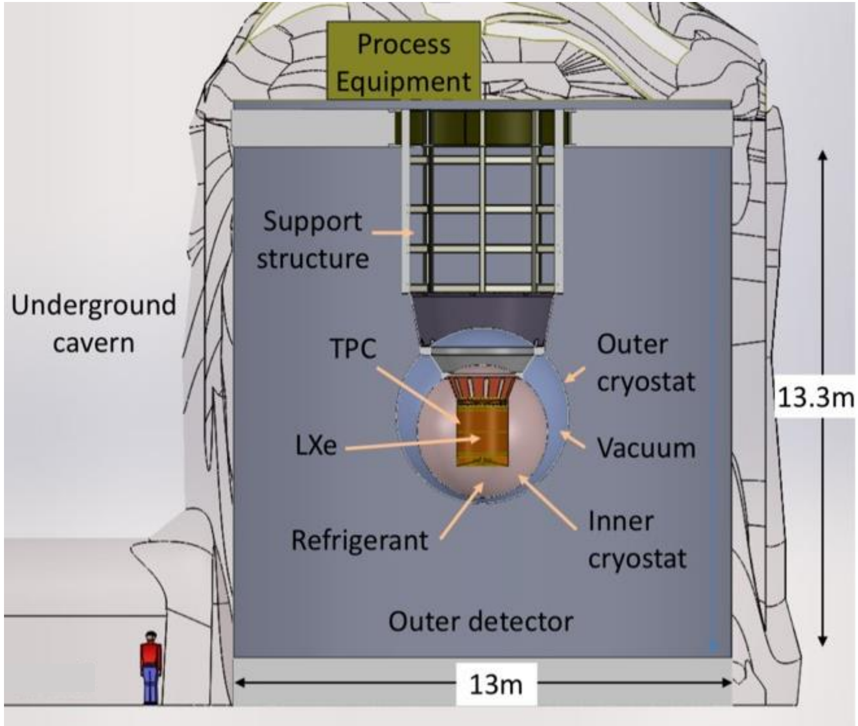
Next-generation Liquid Xenon (LXe) Time Projection Chamber (TPC)

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

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



nEXO Collaboration
Phys. Rev. C **97**, 065503 (2018)



nEXO pCDR, arXiv:1805.11142

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

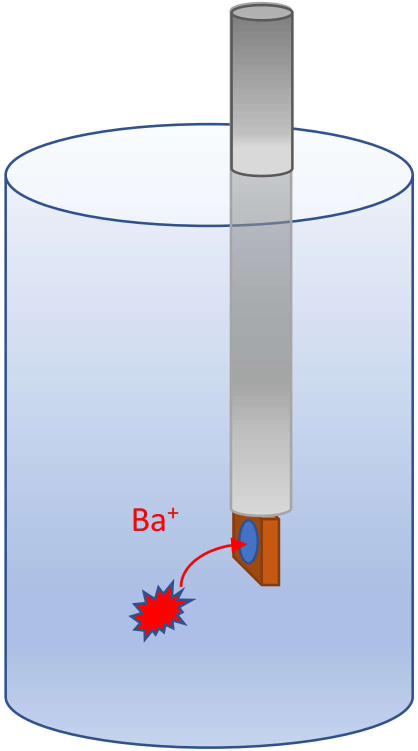
Barium Tagging in Solid Xenon

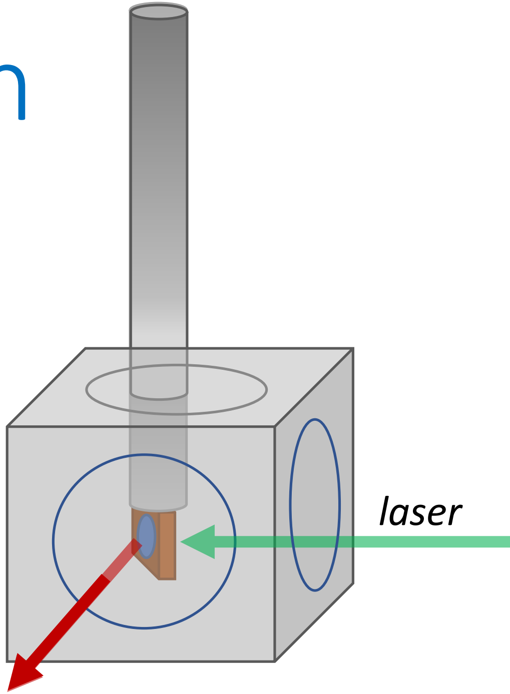
- Locate the decay position with the TPC
- Insert a cryogenic probe and trap the Ba decay daughter in solid Xe
- Extract the probe and cool further
- Tag the Ba daughter in the solid Xe via laser induced fluorescence

0 Ba ⟶ Not ββ decay

1 Ba ⟶ ββ decay

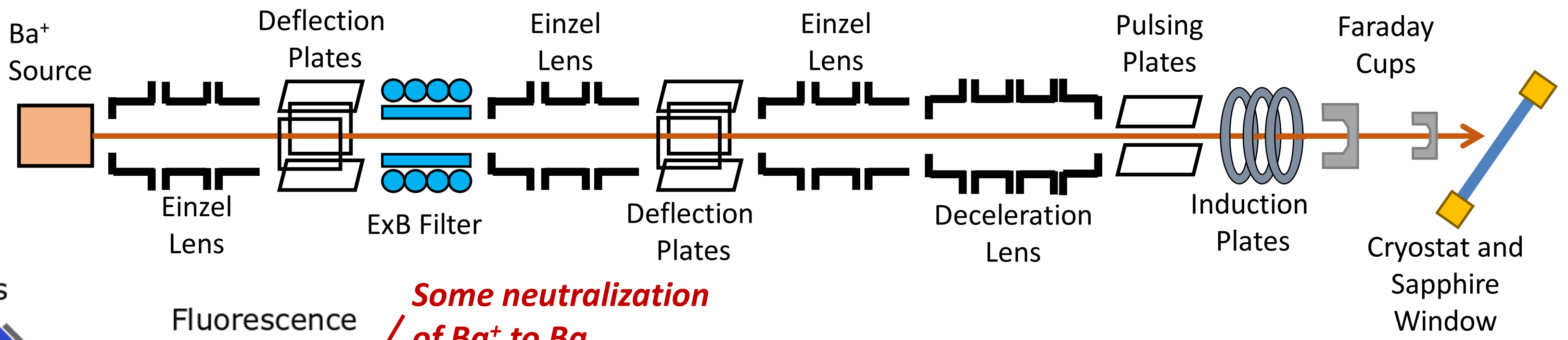
Requires counting of ***single*** Ba in solid Xe

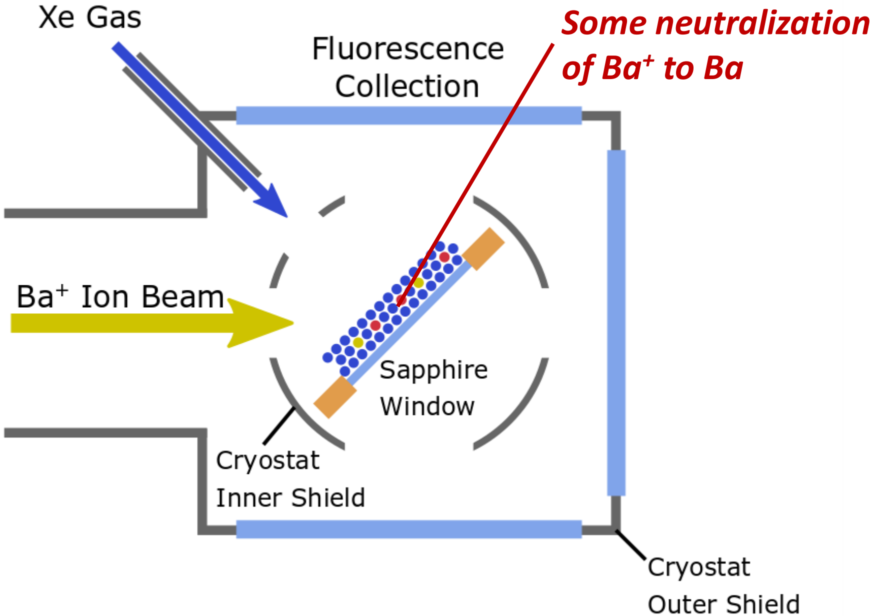




Remove probe to observation region –
Use single Ba imaging technique we have developed

Deposition of Ba in Solid Xe

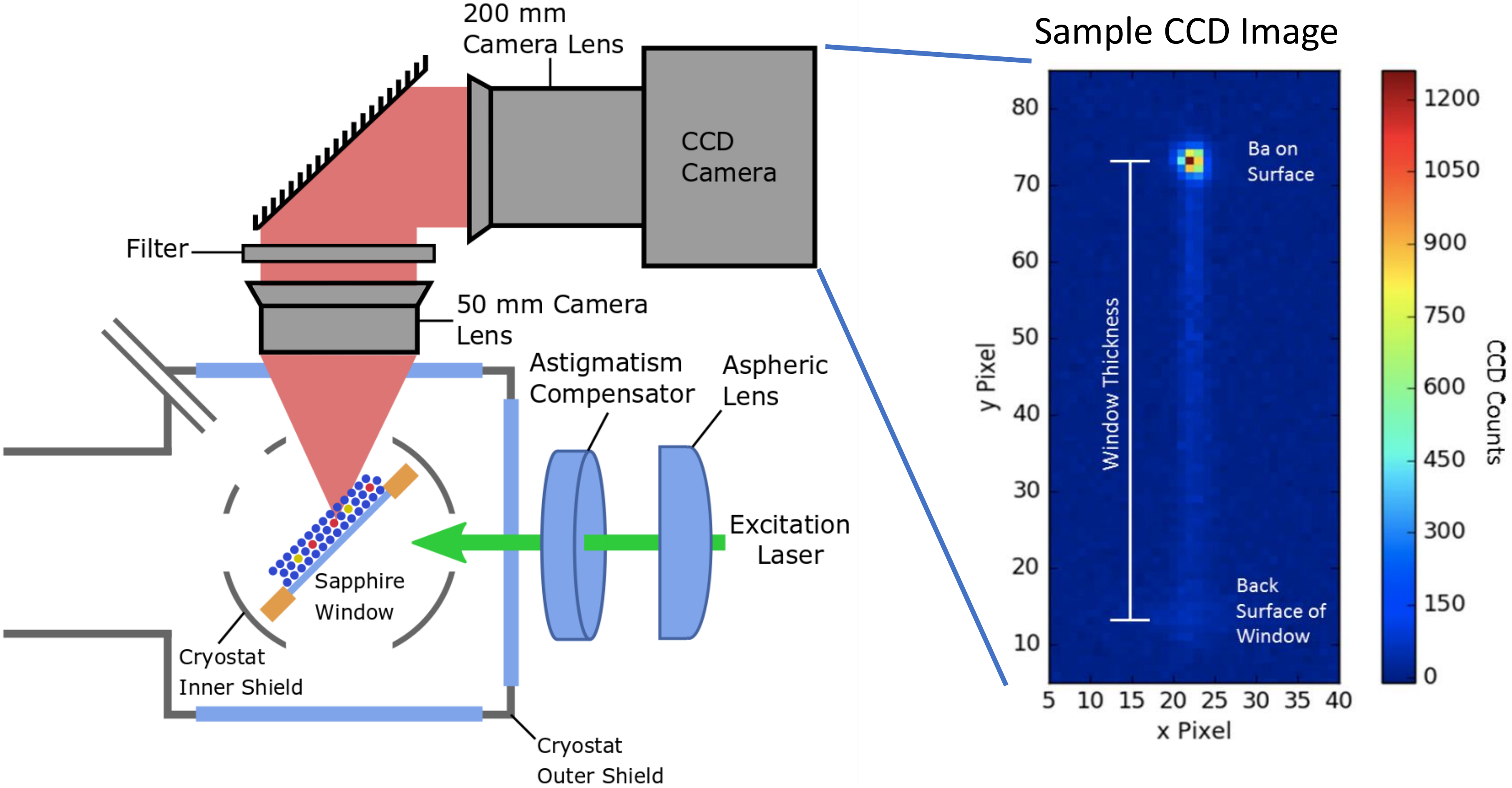




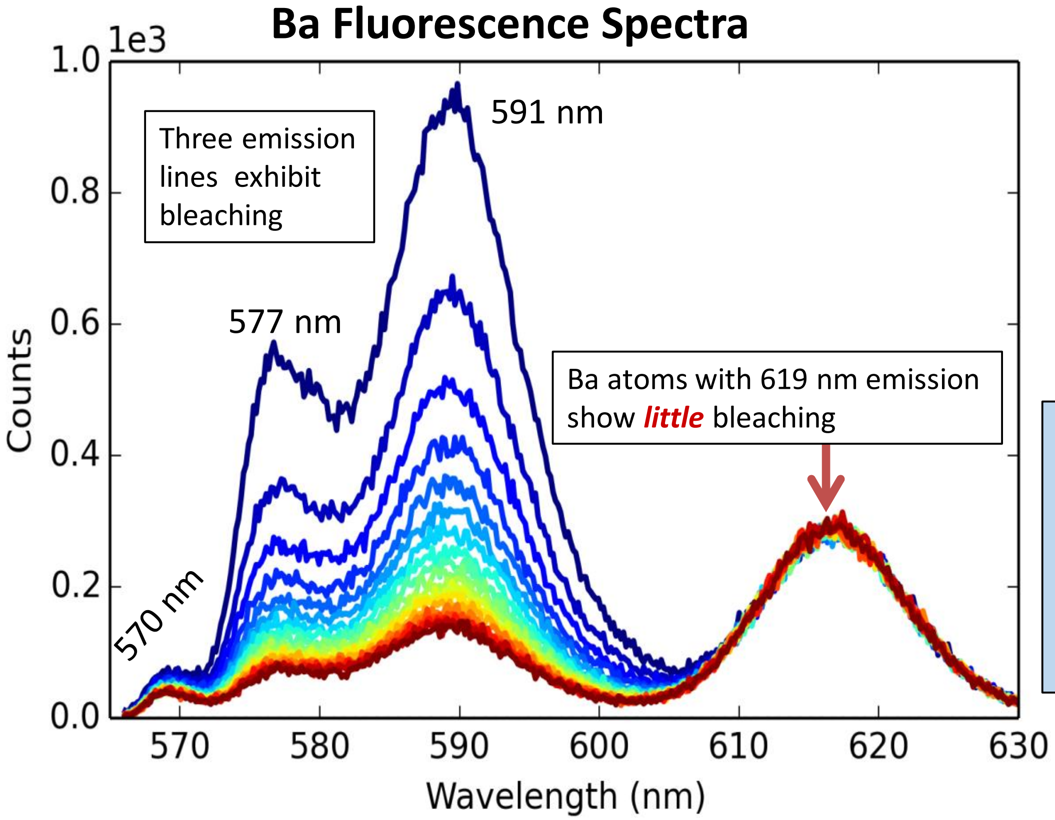
Deposition

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

Observation of Ba in Solid Xe



Spectra of Ba in Solid Xe



B. Mong et. al, *Phys. Rev. A* **91**, 022505 (2015)

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

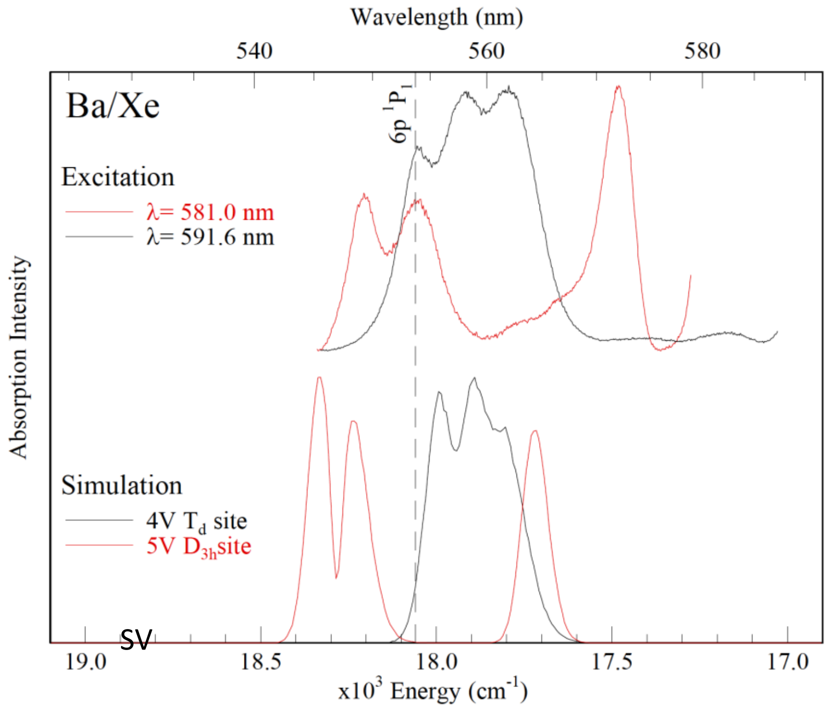
Excited in the green-yellow range
542 - 590 nm

Bleaching :
Loss of fluorescence with laser exposure

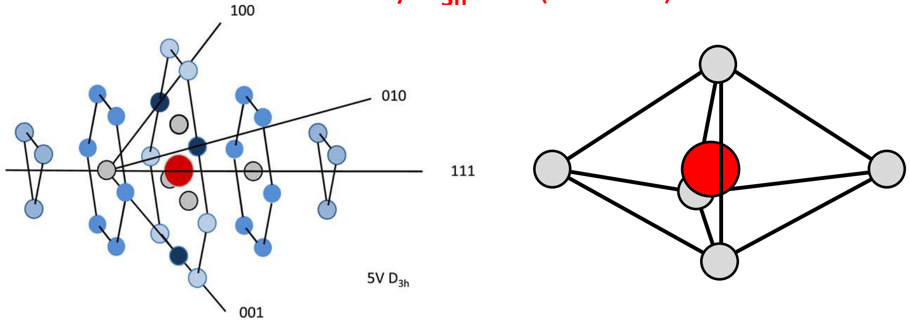
Limits the number of photons that can be collected

Challenge for single-atom imaging

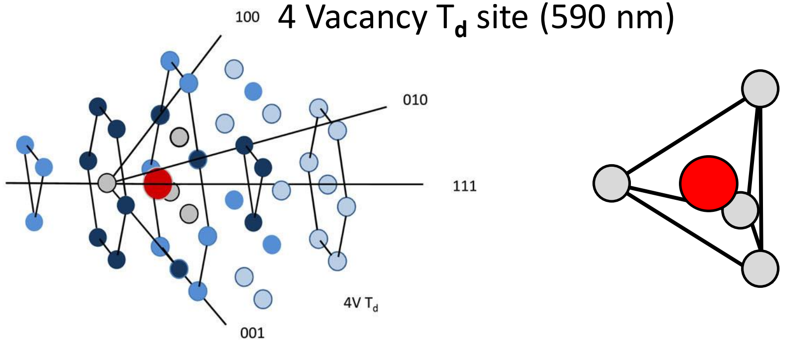
Identification of Matrix Sites of Ba in Solid Xe



5 Vacancy D_{3h} site (577 nm)



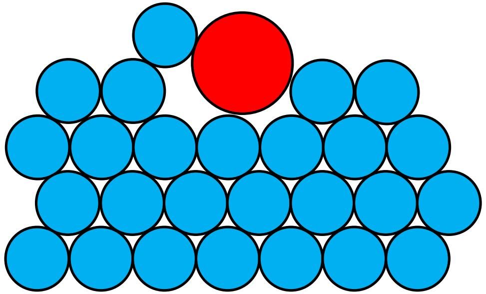
4 Vacancy T_d site (590 nm)



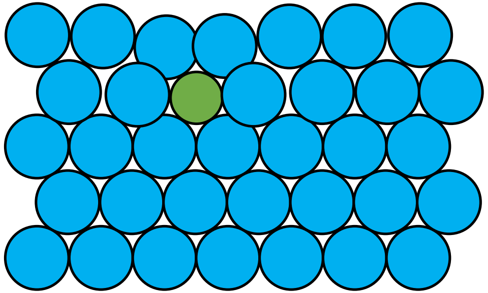
Davis, Gervais, and McCaffrey, *J. Chem. Phys.* **148**, 124308 (2018)

Identification of Matrix Sites of Ba in Solid Xe

Incident Ba Atom
$r_{eff} = 5.5$ Å



Incident Ba^+ Ion
$r_{eff} = 3.6$ Å



Xe $r_{eff} = 4.4$ 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

Mechanism from: D.C. Silverman and M.E. Fajardo *J. Chem. Phys.* **106**, 22 (1997)

Identification of Matrix Sites of Ba in Solid Xe

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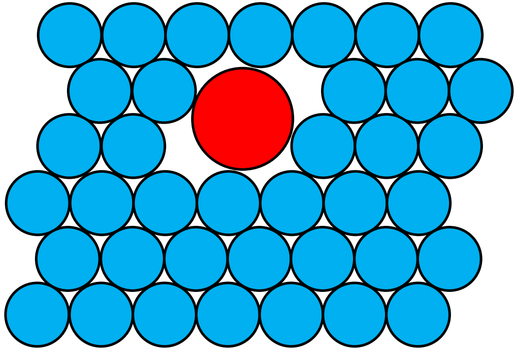

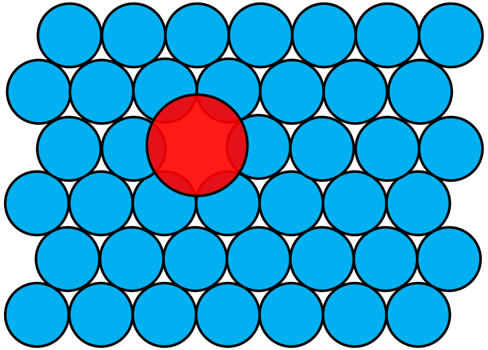

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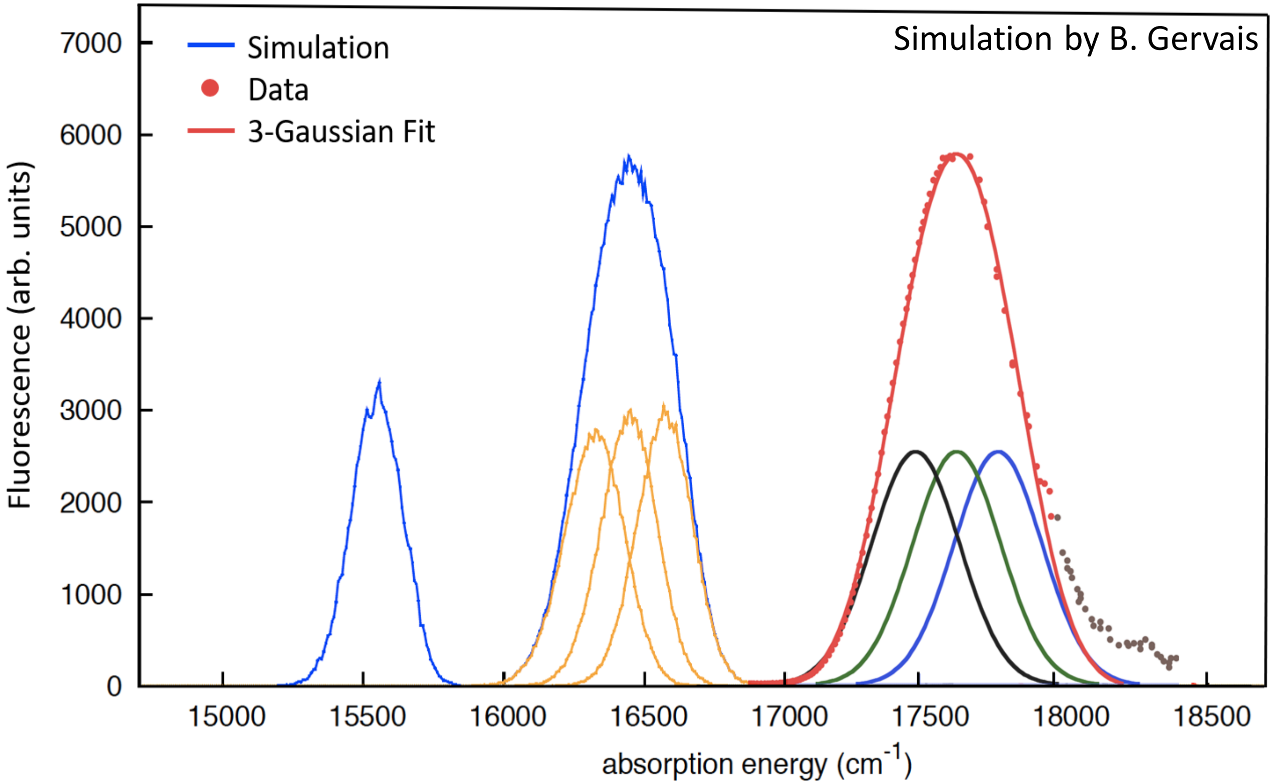
Ba^{+} then neutralizes to Ba, but is trapped in the cramped SV site by the Xe matrix

Mechanism from: D.C. Silverman and M.E. Fajardo *J. Chem. Phys.* **106**, 22 (1997)

Preliminary Simulation



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

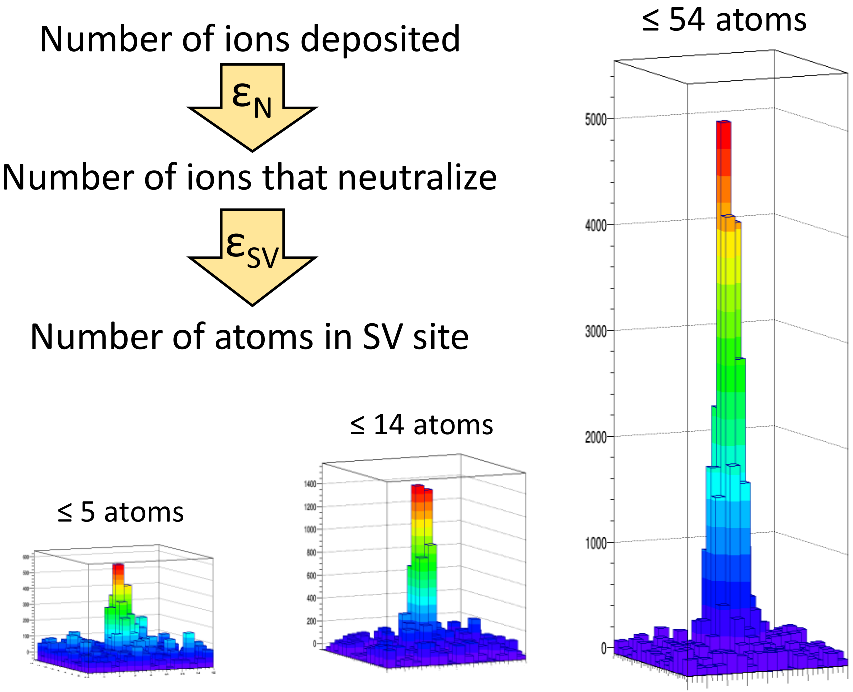
Number of ions deposited

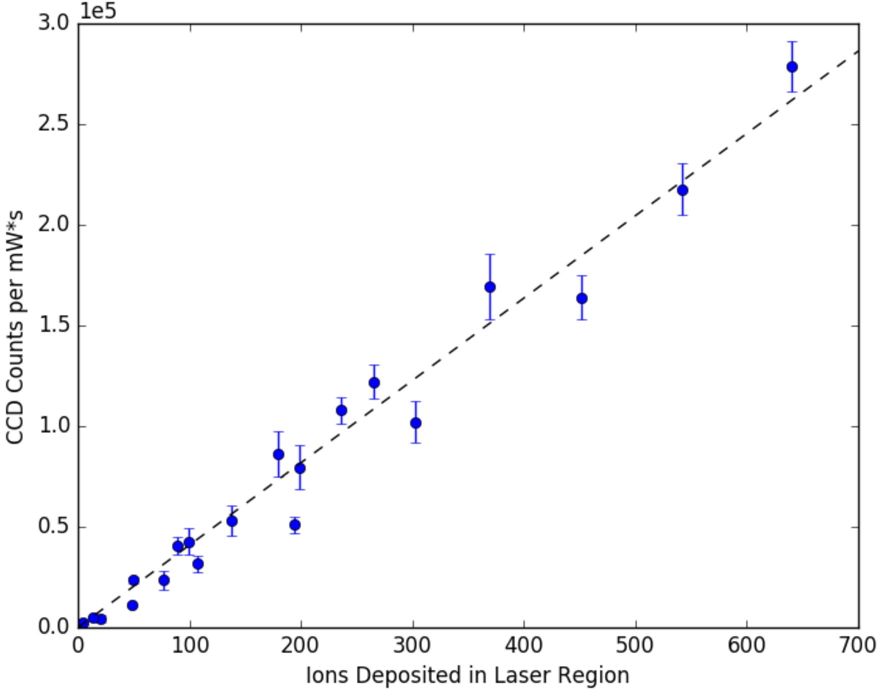
↓ ε_N

Number of ions that neutralize

↓ ε_{SV}

Number of atoms in SV site

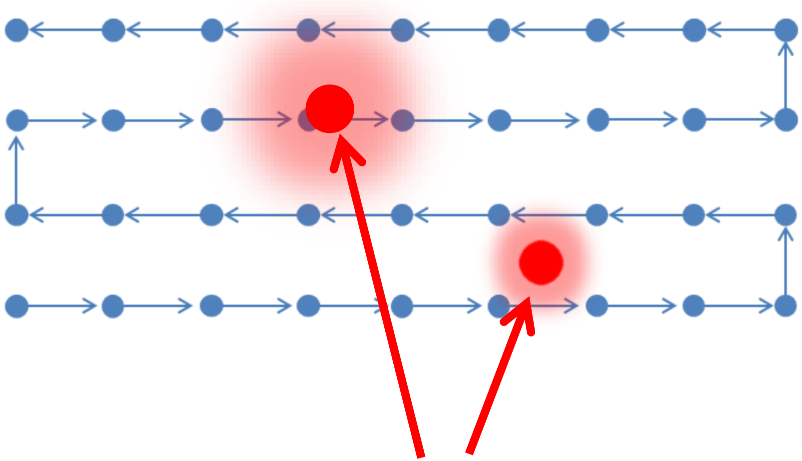




Fluorescence signal is linear with # of ions deposited: not Ba_n molecule

Scanning Laser Technique

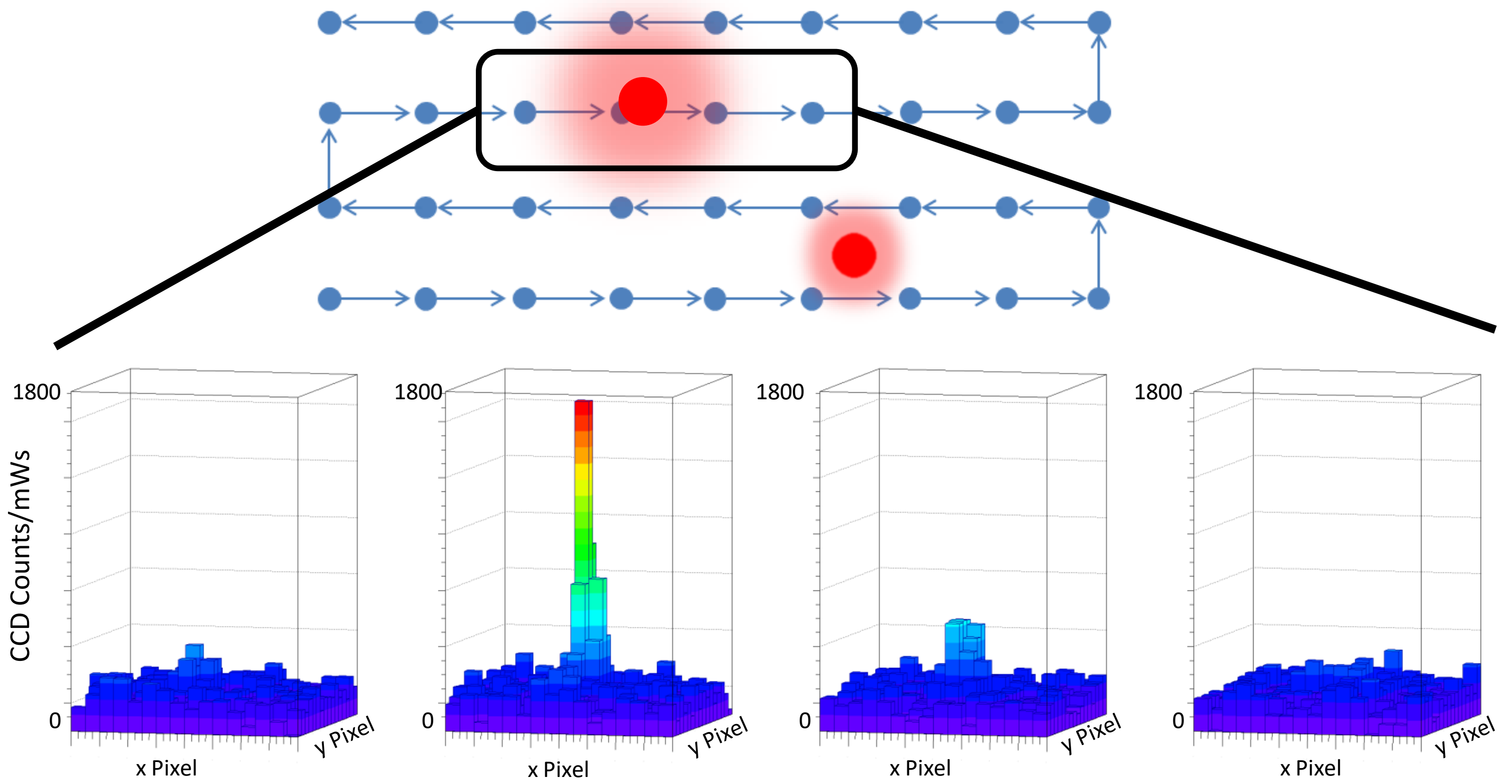
Each camera exposure is for a position in a grid:



See peaks as laser moves near individual atoms

Scanning Laser Technique

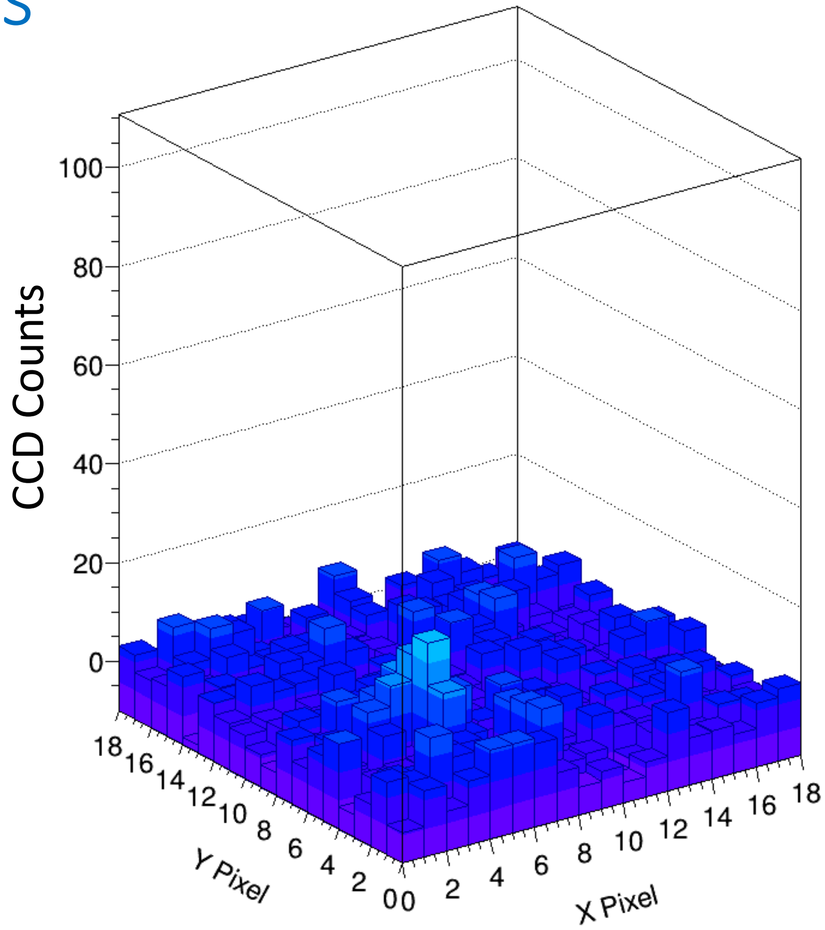
Each camera exposure is for a position in a grid:



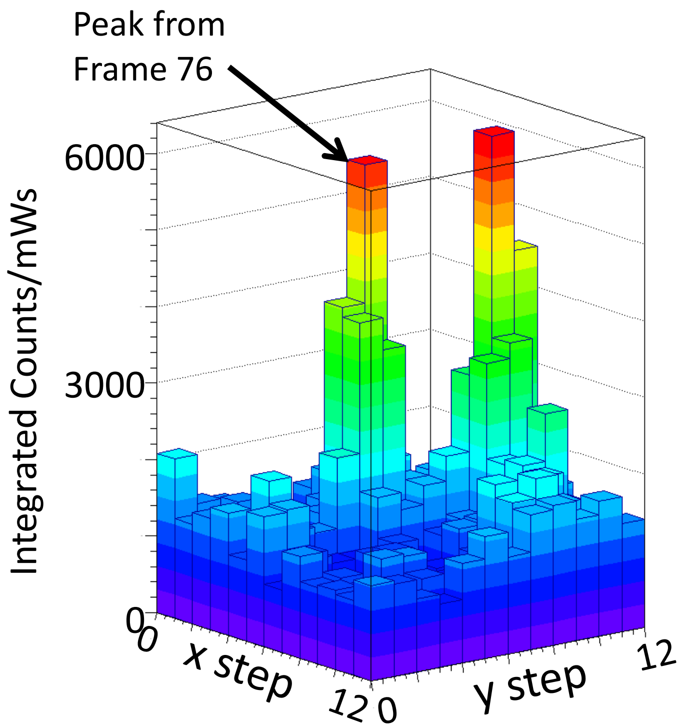
Scanning for Single Ba Atoms

Scan Parameters

x step: 4.0 µm	12 x 12 grid
y step: 5.7 µm	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

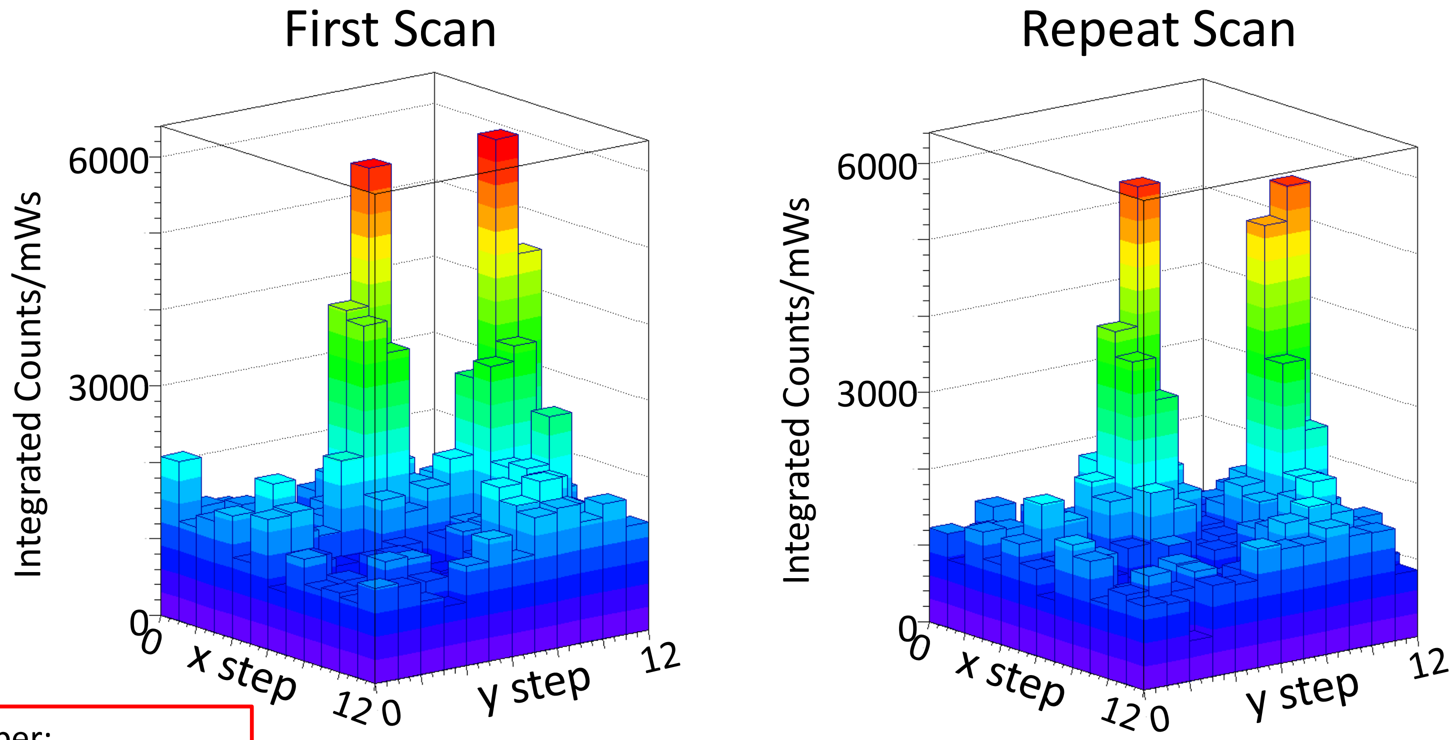
Each frame is then integrated around the laser region

Each integral is scaled by the laser exposure in mW*s

The integrals are then plotted according to laser position

C. Chambers et al. *Nature* **569**, 203–207 (2019)

Composite Images of Ba Atom in Solid Xe

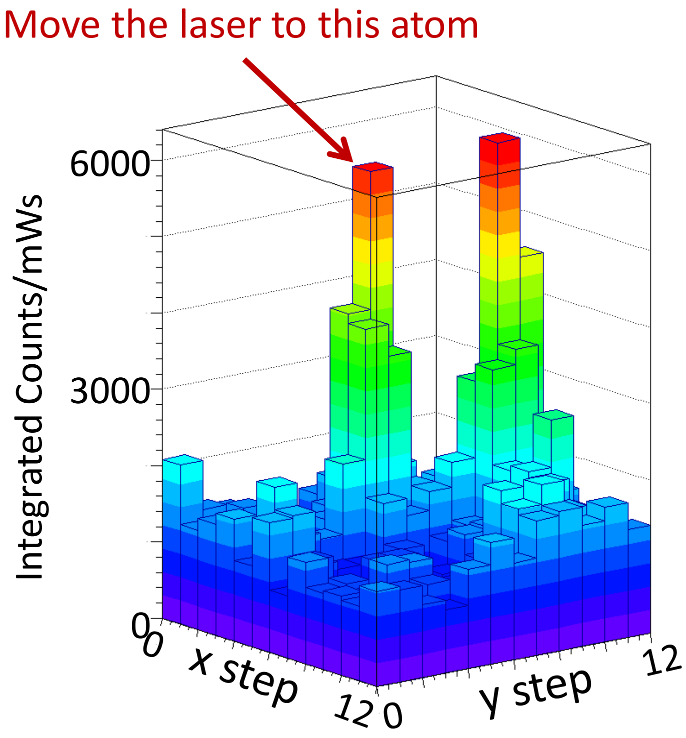


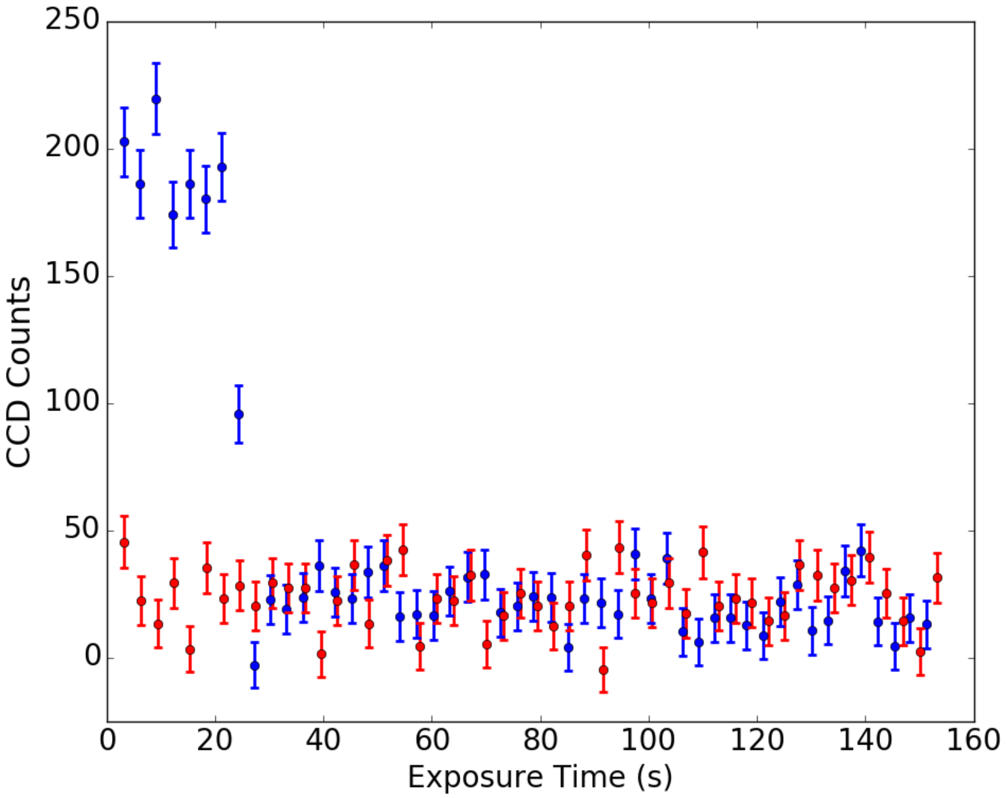
Still there!

Remember:
Each pixel is the signal
from one laser position

C. Chambers et al. *Nature* **569**, 203–207 (2019)

Looking at one Ba Atom





C. Chambers et al. *Nature* **569**, 203–207 (2019)

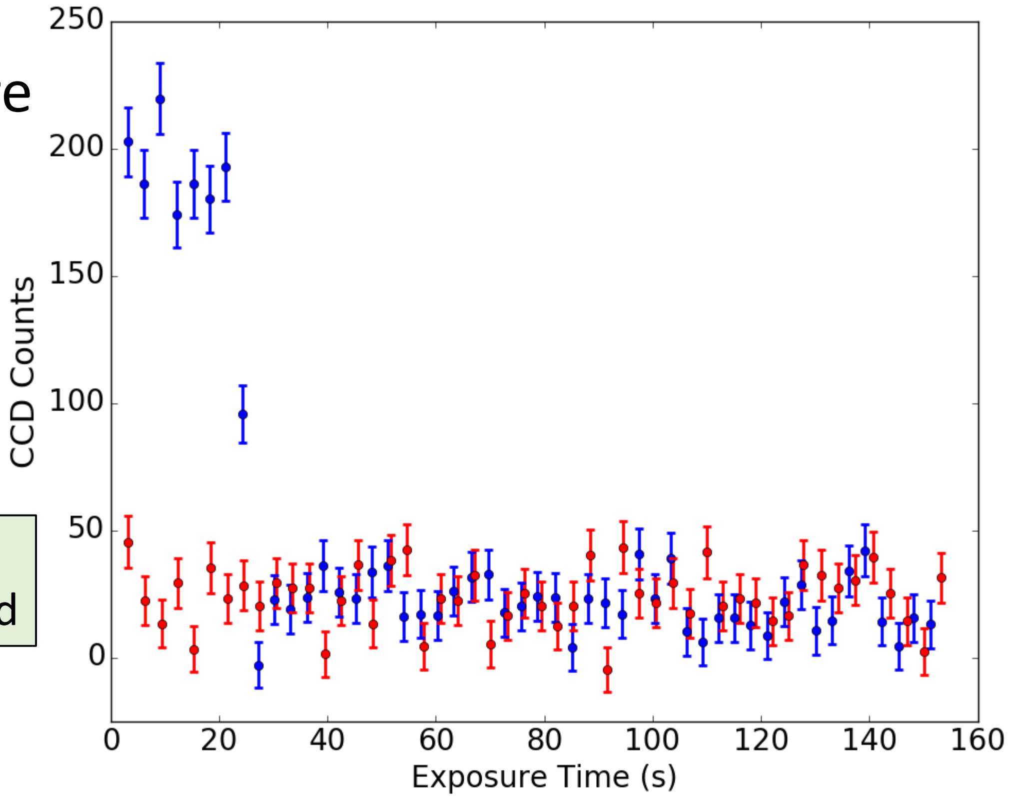
Looking at one Ba Atom

Sudden turn-off is a key feature

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

High Signal Definition

Average signal is **11σ** above background
Summed signal is **70σ** above background



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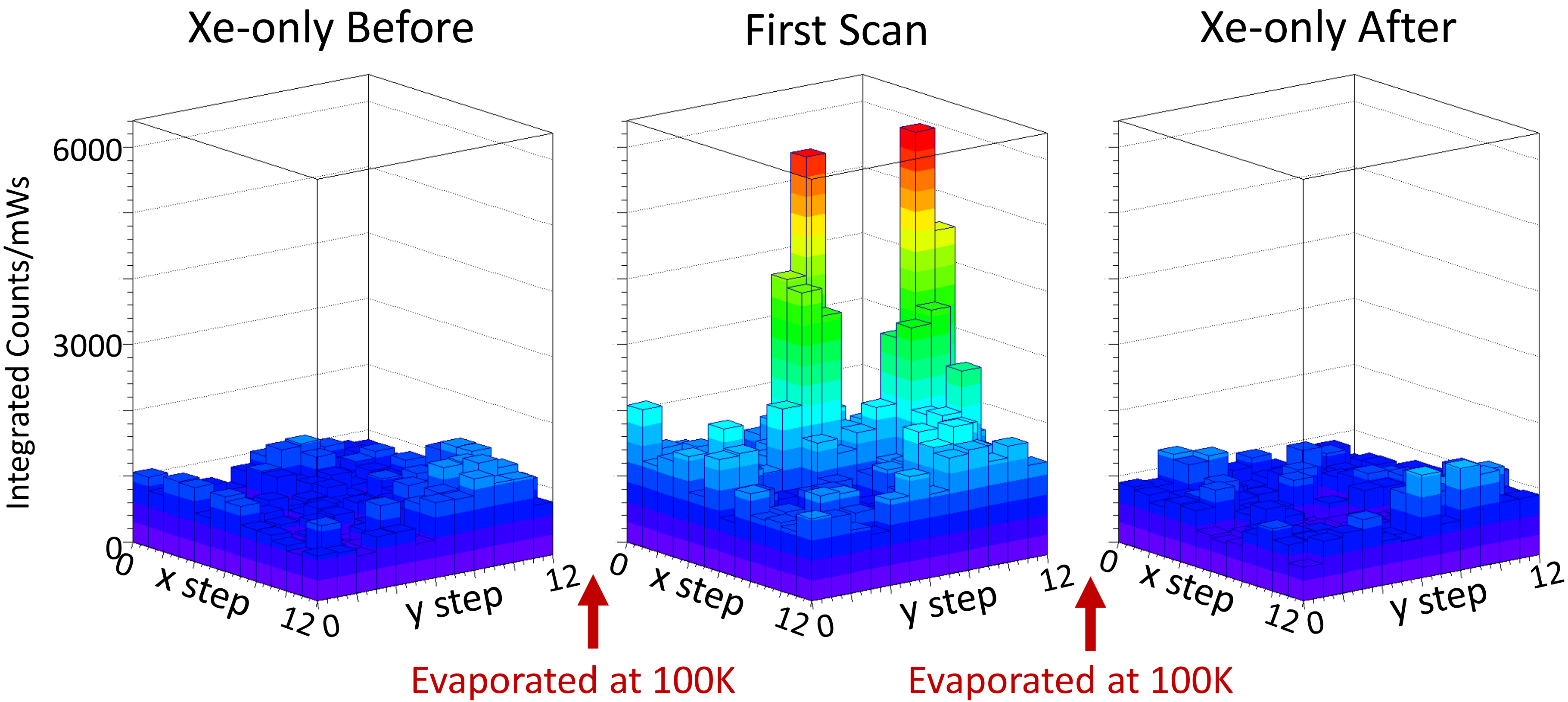
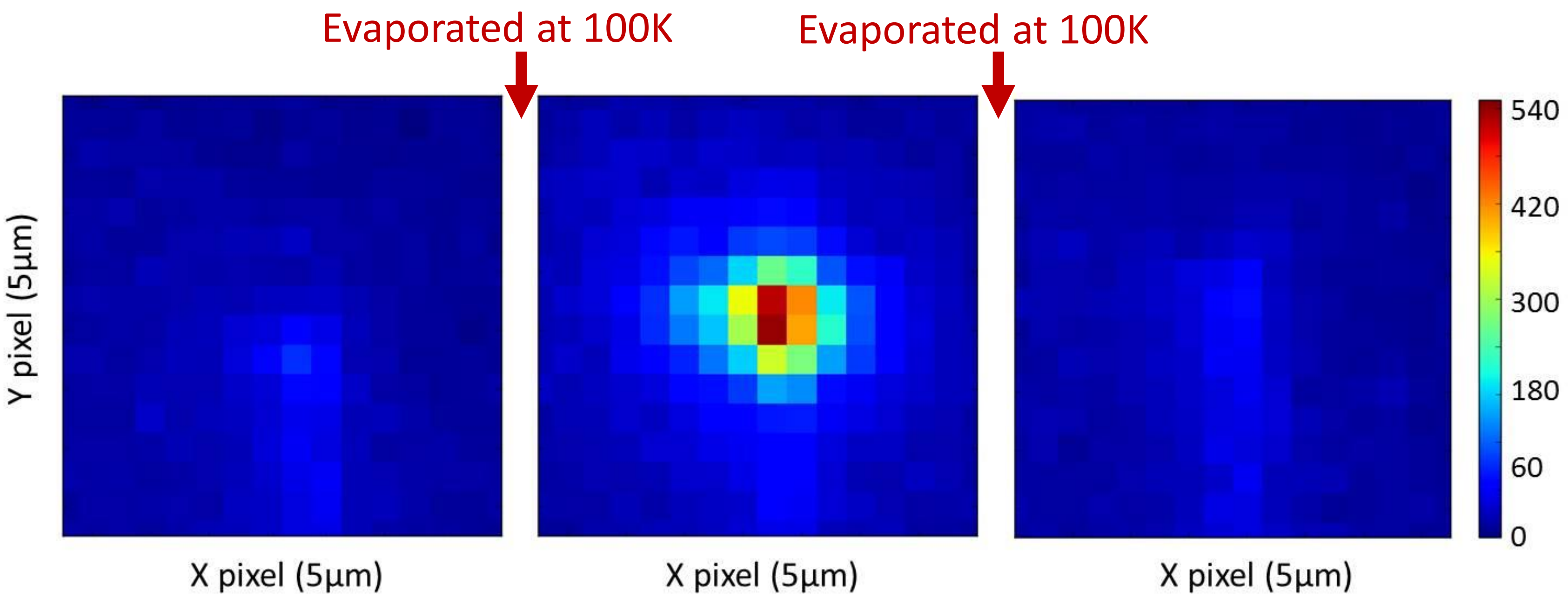
Comparing Backgrounds



No Ba left behind after evaporation!

C. Chambers et al. *Nature* **569,** 203–207 (2019)

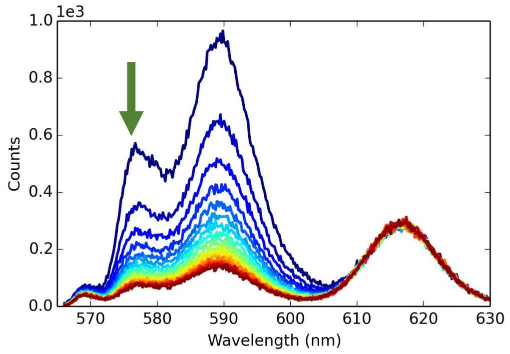
Erasing the Ba Deposit



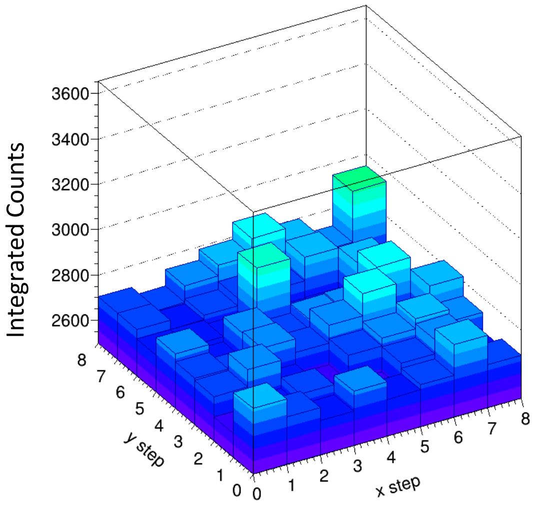
Even after a large deposit (7000 ions) we remove detectable Ba atoms to a limit of **< 0.16%**
Thus no "history effect" interfering with subsequent deposits

Imaging Single Ba Atoms with 577 nm

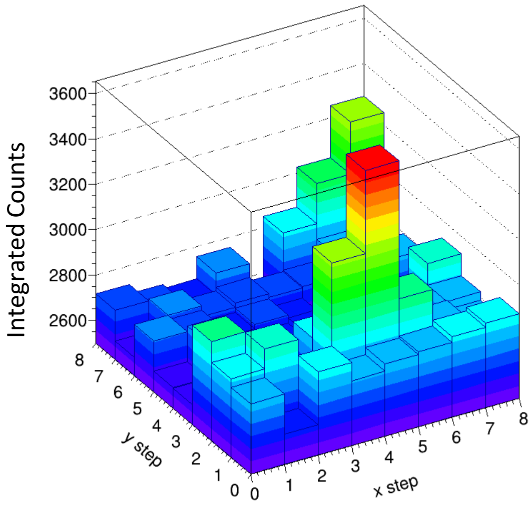
- Use 300 nW instead of 30 μW
- 25s or 17s frames instead of 7s frames
- Borrowed an EMCCD camera
- Often the Ba peak was already gone in a repeat scan



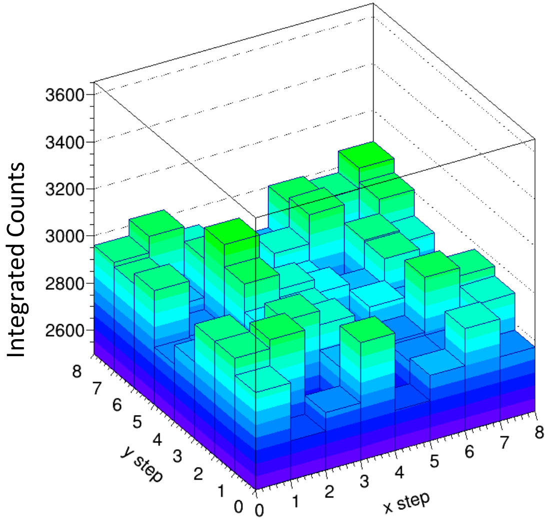
Xenon Only



Barium

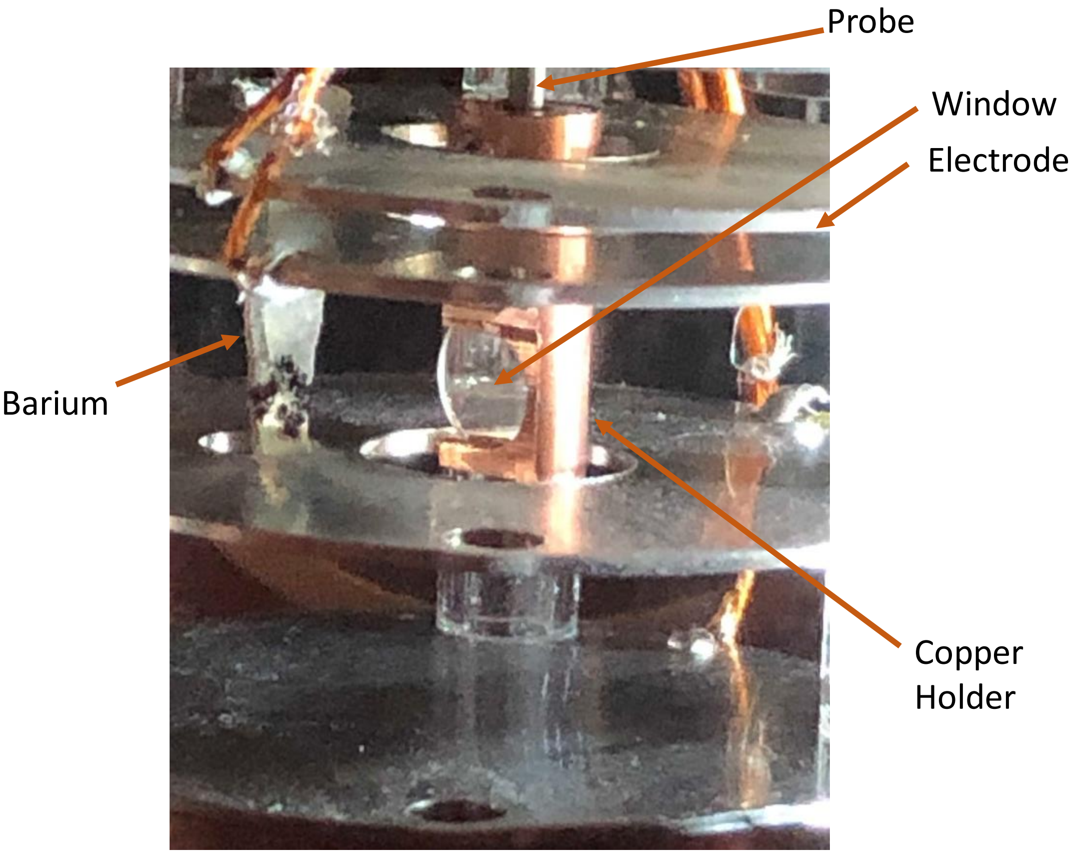


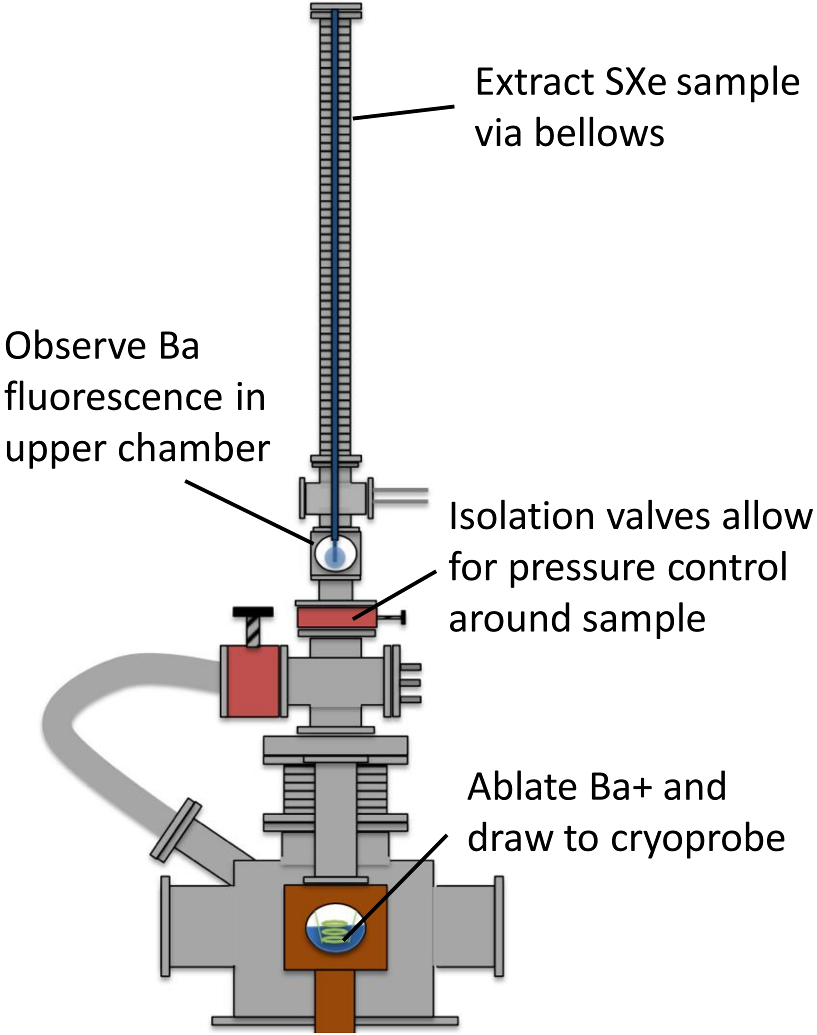
Barium Rescan



We ***can*** image single Ba atoms with faster bleaching

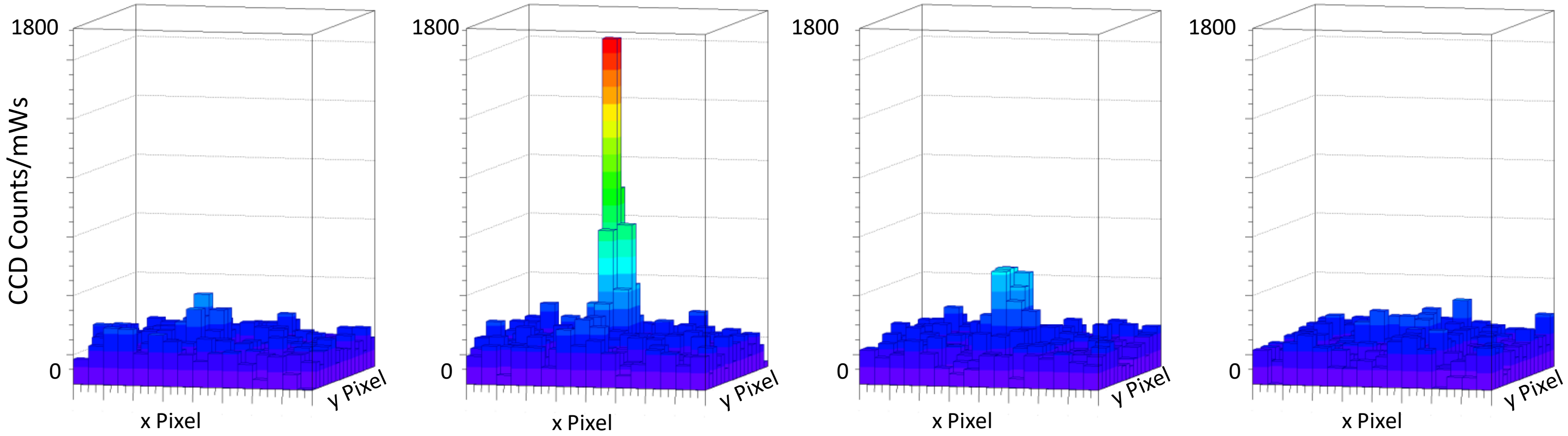
Extracting Ba from Liquid Xe





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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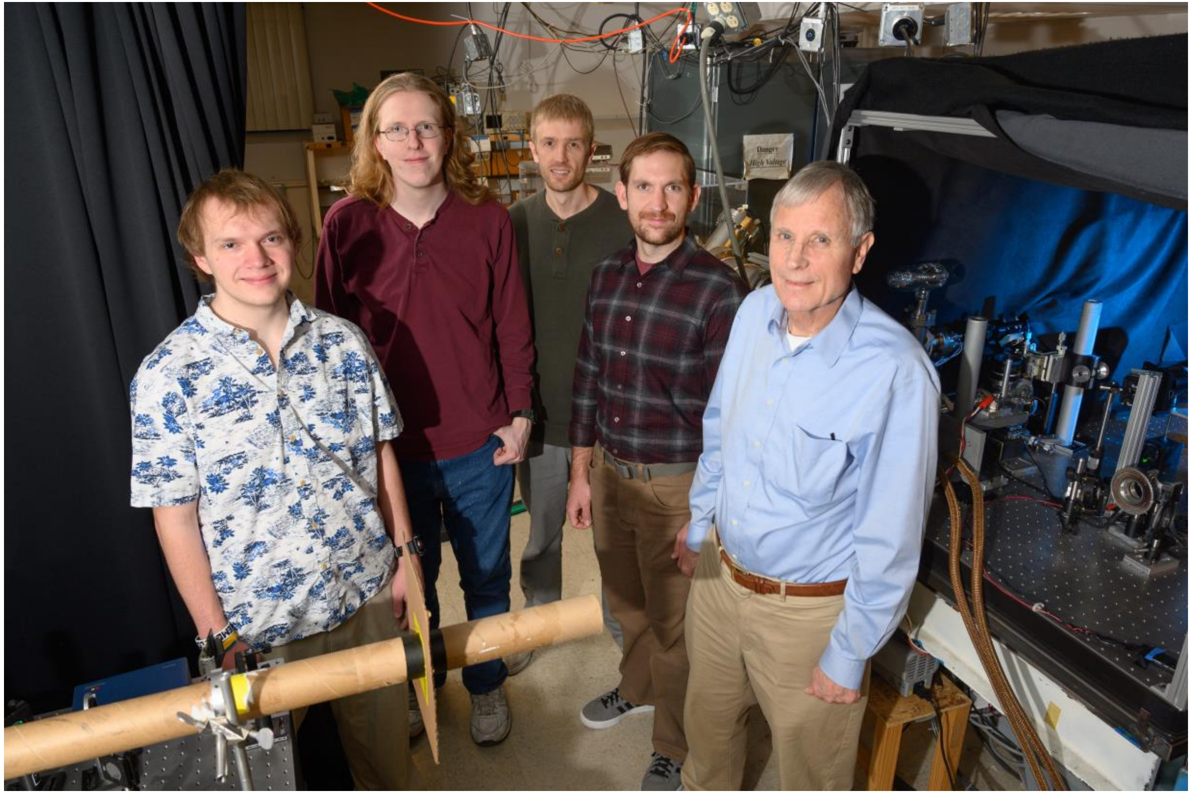


Fairbank Group Members:

- Chris Chambers (now at McGill)
- Adam Craycraft
- James Todd
- David Fairbank
- Alec Iverson

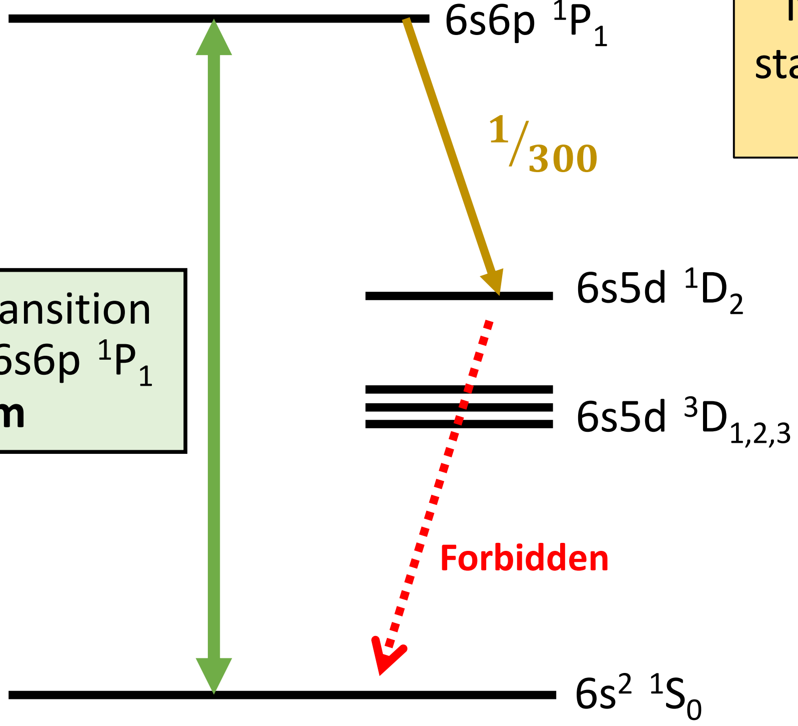
Colorado State University

Backup

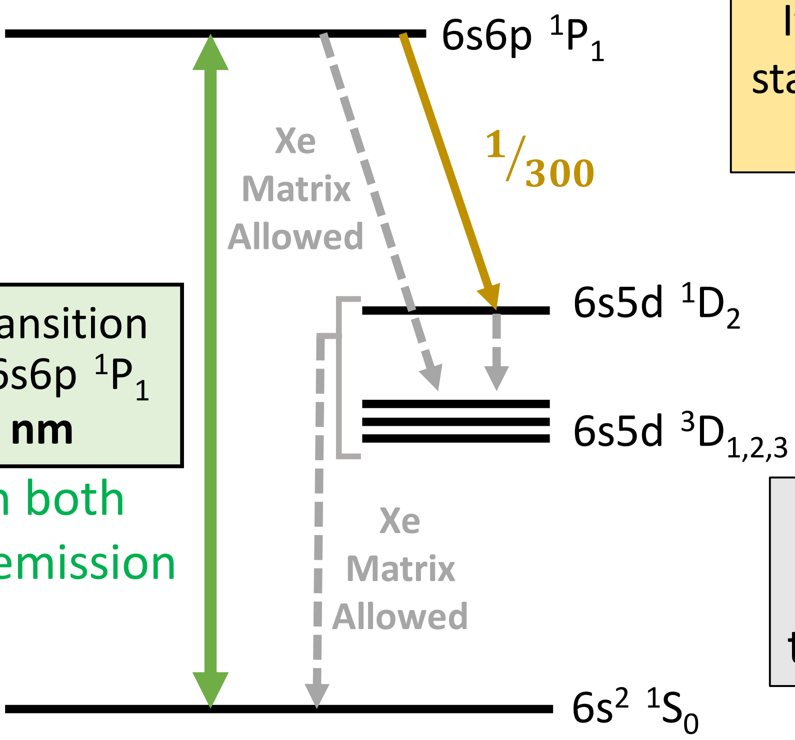
Energy Levels of Ba in Vacuum

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

Fluorescence Transition
$6s^2\ ^1S_0 \longleftrightarrow 6s6p\ ^1P_1$
@ **553.5 nm**



Energy Levels of Ba in Solid Xe



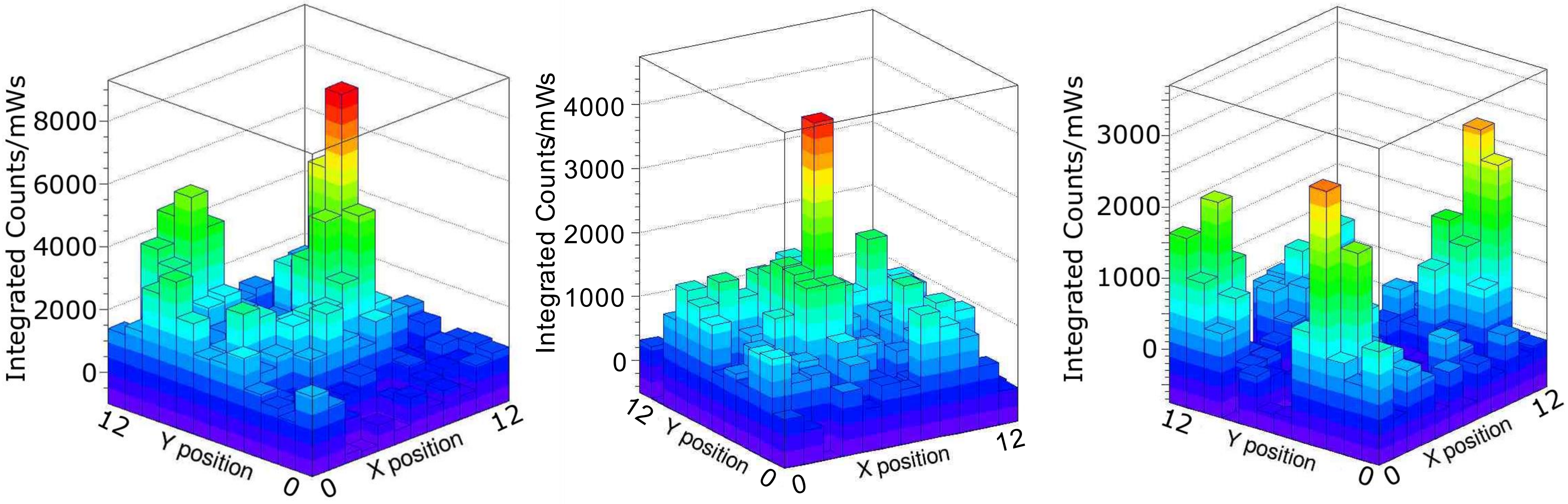
Fluorescence Transition
$6s^2\ ^1S_0 \longleftrightarrow 6s6p\ ^1P_1$
@ 545 – 585 nm

Broadened in both excitation and emission

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

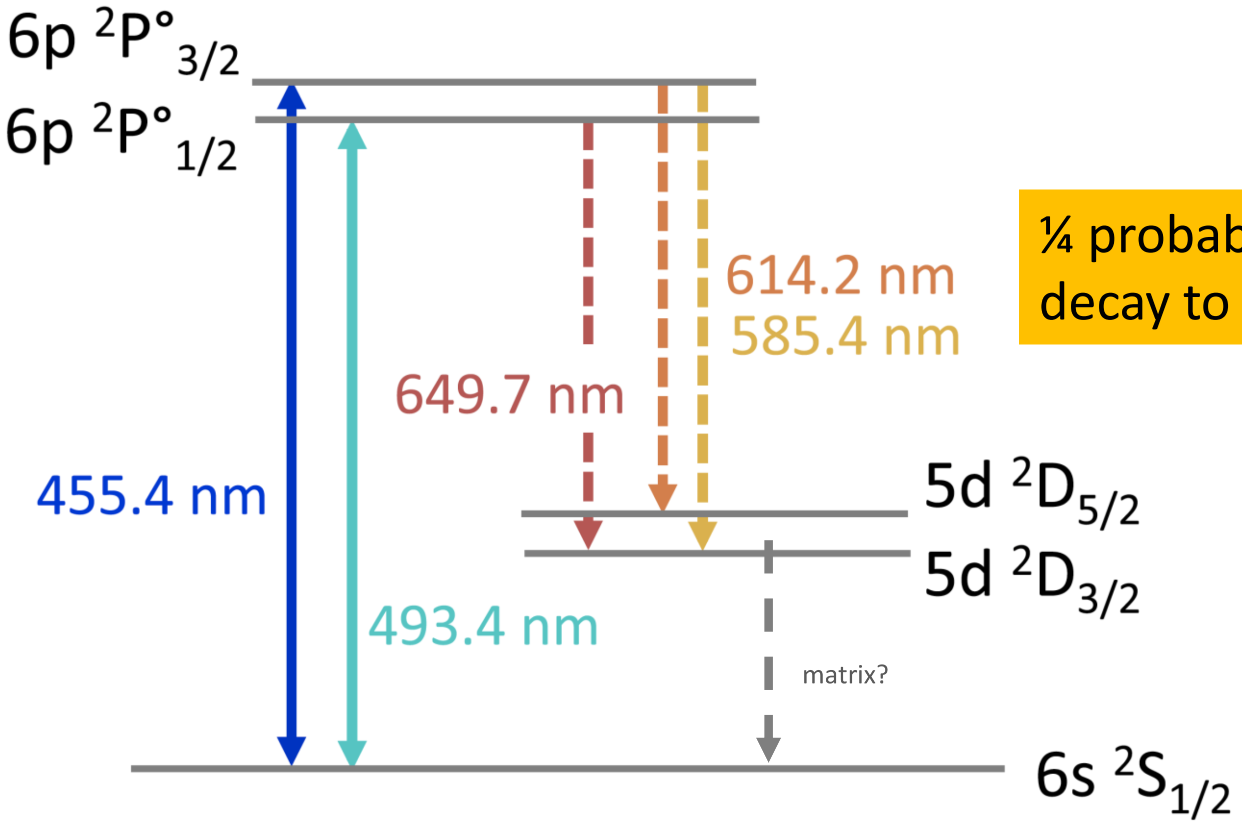
In the solid Xe matrix, the modified potential **may allow** transitions forbidden in vacuum

Additional Ba Scanning Experiments with 619nm



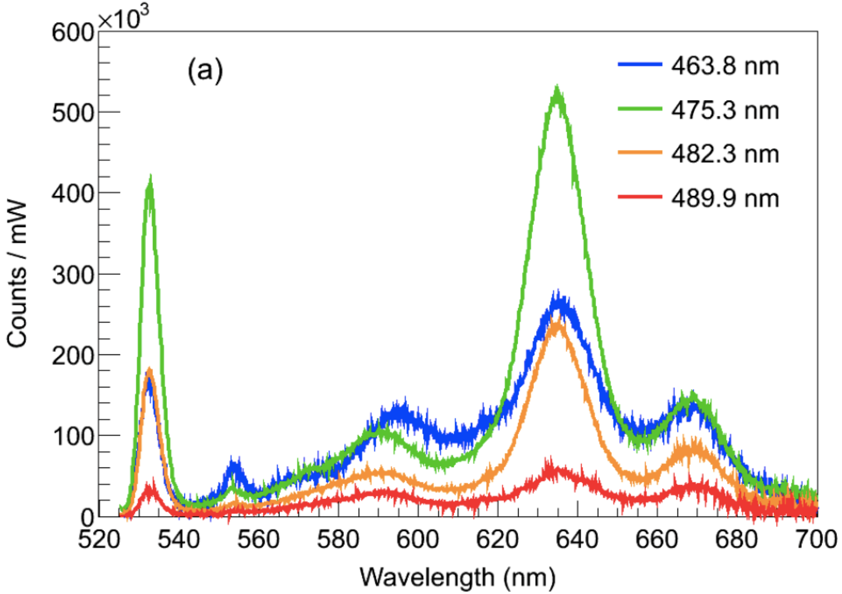
Composite images of Ba^{+} deposits taken over several days show repeatability of single Ba imaging

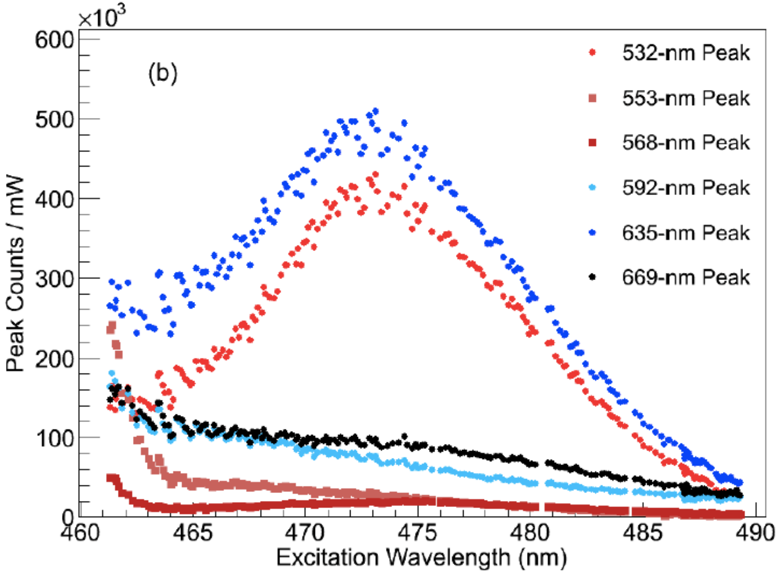
Achieving a high Ba tagging efficiency:
can we image single Ba^+ ions in solid xenon?



¼ 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?