Progress in Barium Tagging for nEXO

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For the nEXO and EXO-200 Collaborations

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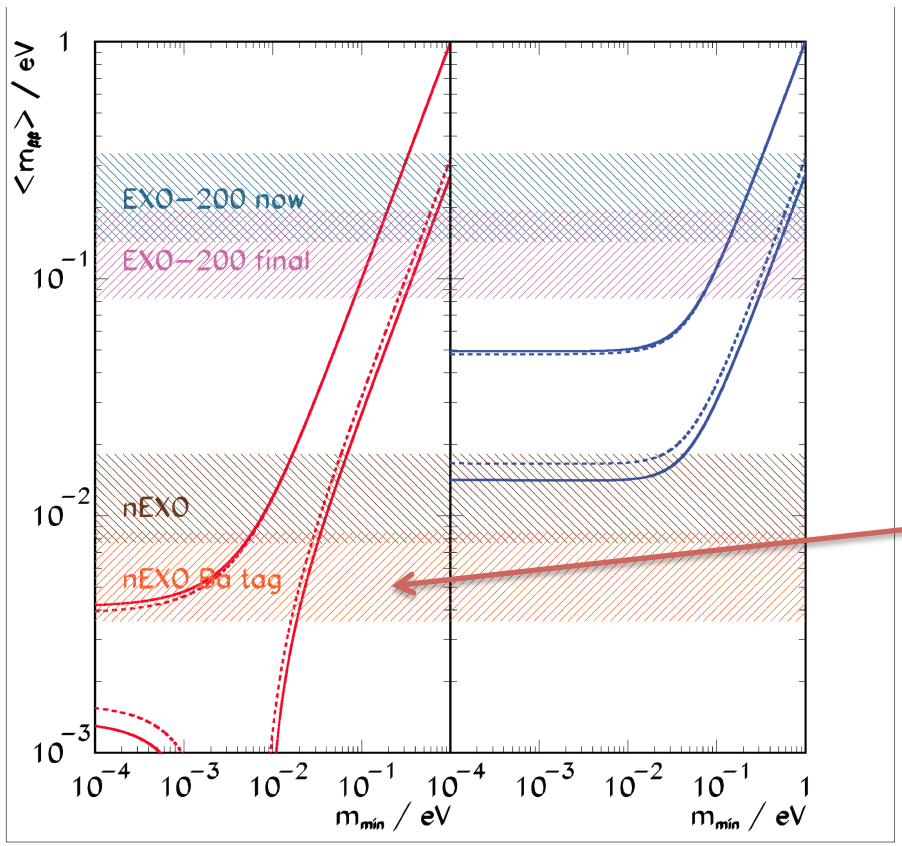
NSERC in Canada and SNF in Switzerland

Barium Tagging

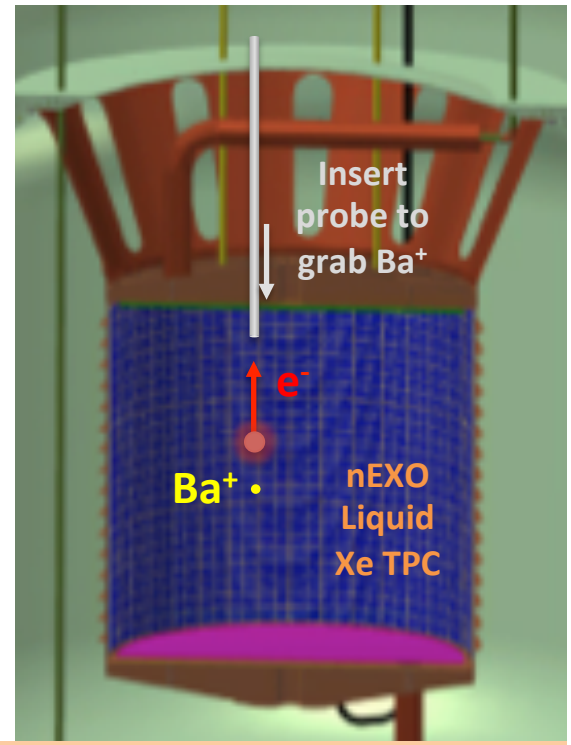
Neutrinoless Double Beta Decay (0νββ) of Xe^{136}:

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

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



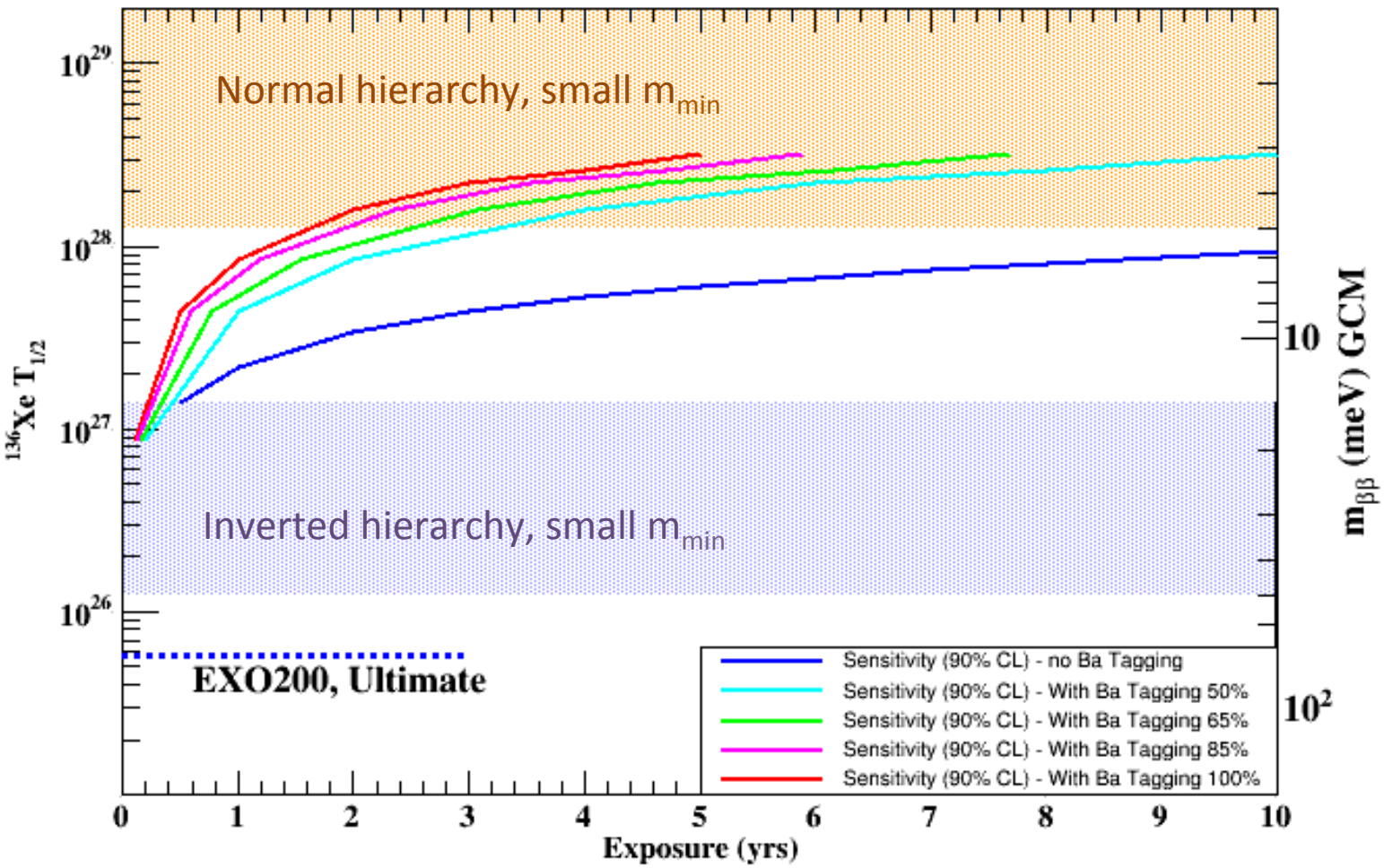
nEXO



- ***Barium tagging allows for a probe further into the normal hierarchy region***
- ***requires grabbing and detecting a single Ba^+ daughter ion out of a large volume of LXe!***

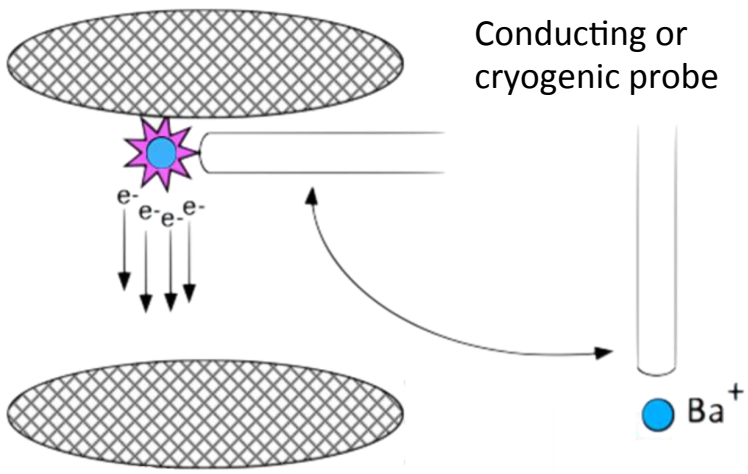
Ba tagging gives up to 5x improvement in nEXO 0νββ lifetime sensitivity with same isotopic mass

- Incremental enriched ^{136}Xe cost from 5 ton to 25 ton is ~$200M
- Substantial cost of a larger detector …



Concept of Ba tagging in liquid Xe for nEXO

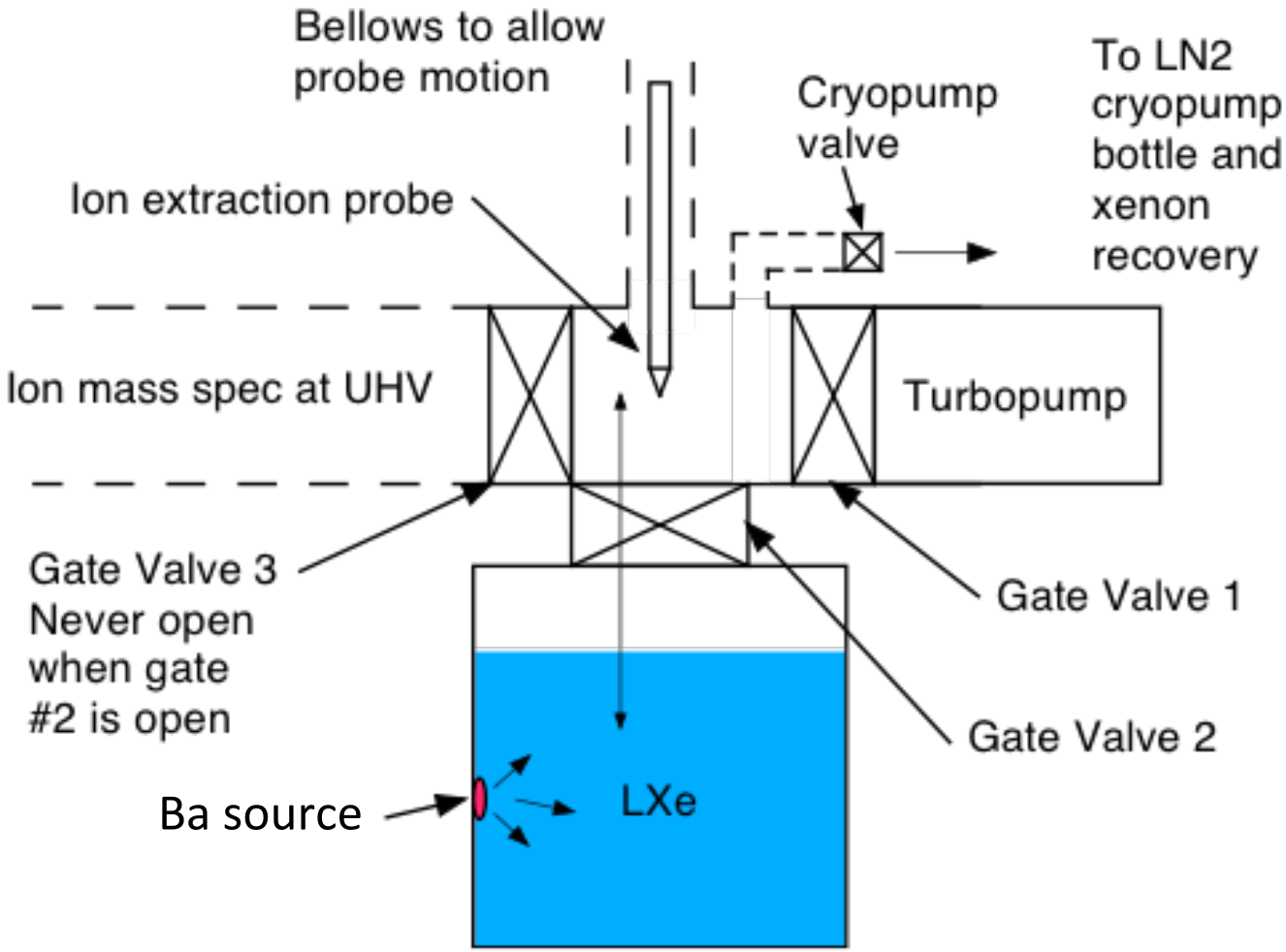
- Candidate event observed:
  - Send probe into TPC near reconstructed position, deposit Ba^+ onto probe
  - Remove probe to identification chamber
- Ba^+ moves slowly in LXe
- Background Ba^+ from 2-neutrino double beta decay negligible



➔ **2νββ half-life first measured by EXO-200 is the longest known at $2.165 \pm 0.016 \pm 0.059 \times 10^{21}$ yr**

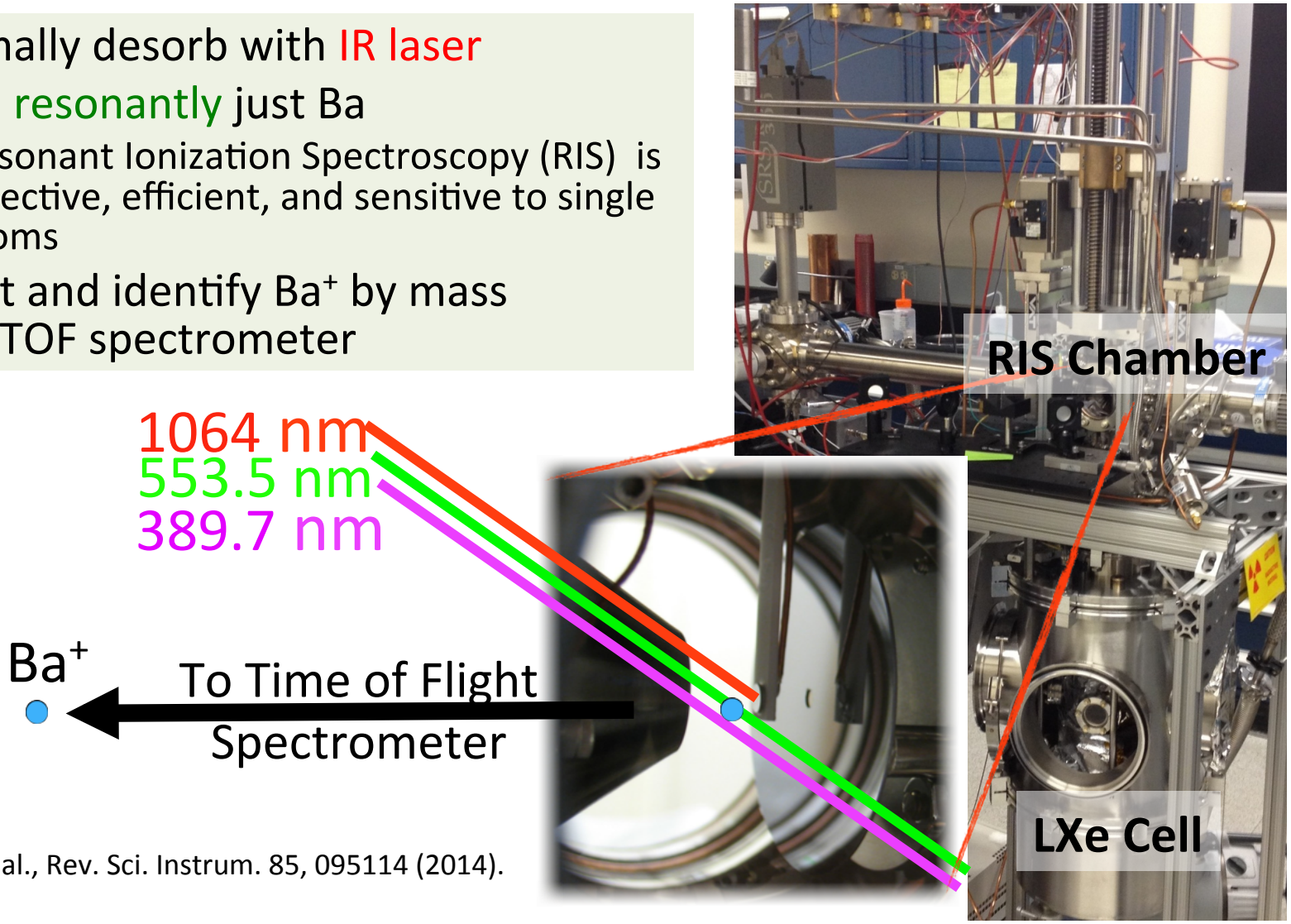
Ba tagging on a conducting probe

Challenge: Recover and identify single Ba, ignoring everything else



Desorption, Ionization and Detection

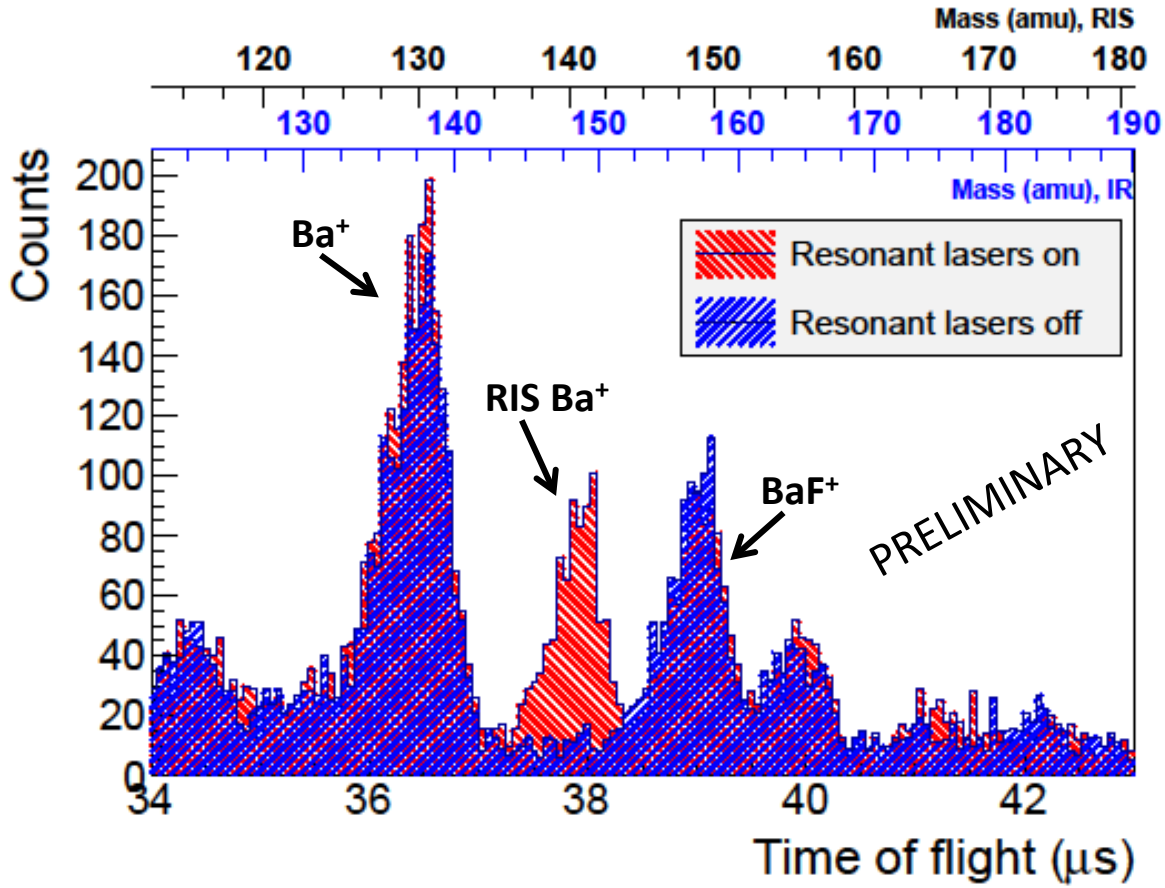
- Thermally desorb with IR laser
- Ionize resonantly just Ba
  - Resonant Ionization Spectroscopy (RIS) is selective, efficient, and sensitive to single atoms
- Detect and identify Ba^+ by mass using TOF spectrometer



K. Twelker et al., Rev. Sci. Instrum. 85, 095114 (2014).

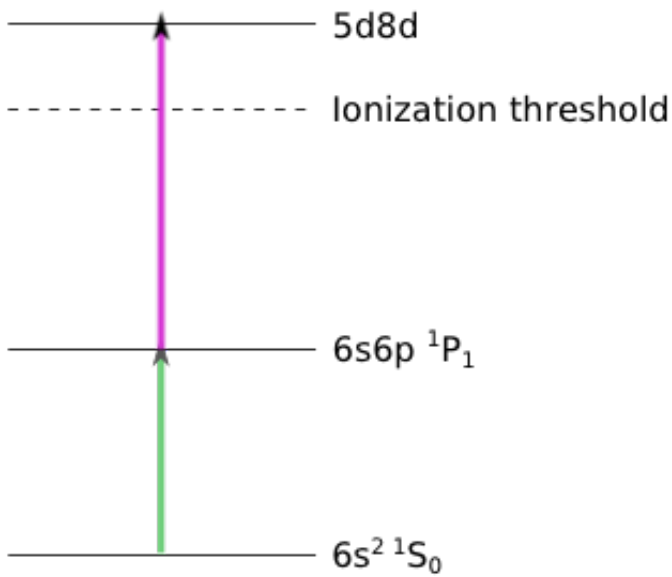
Ba in the TOF

- Can resolve Ba^+ from RIS, Ba^+ from ablation, and BaF^+ from ablation

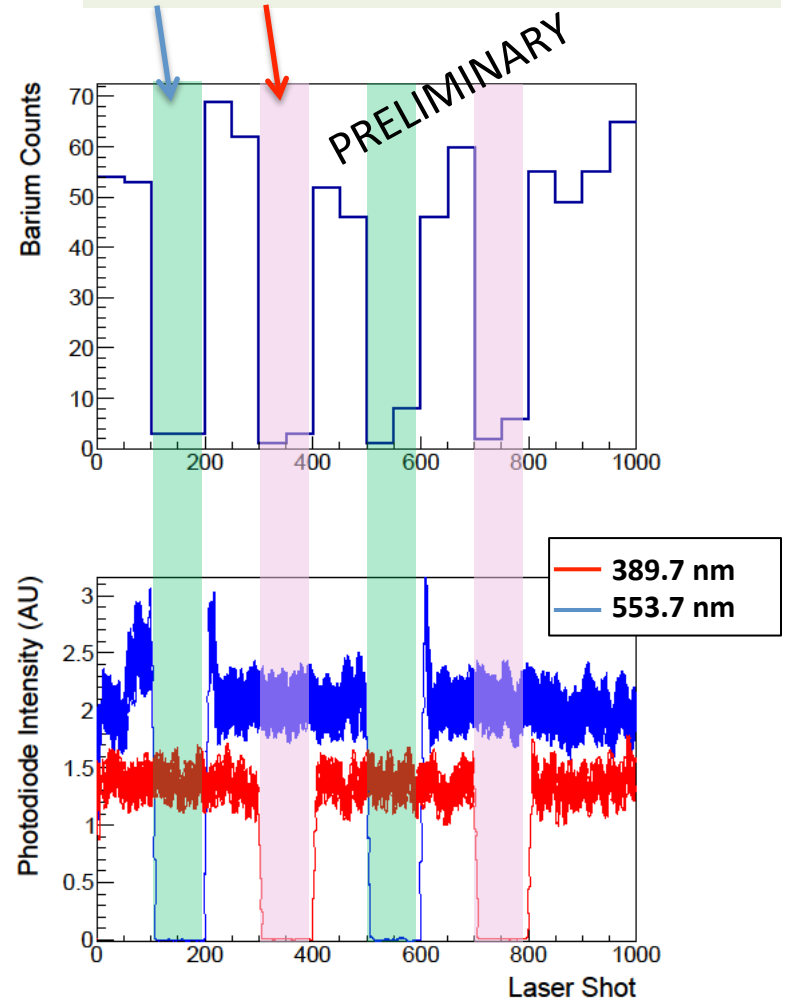


RIS Results

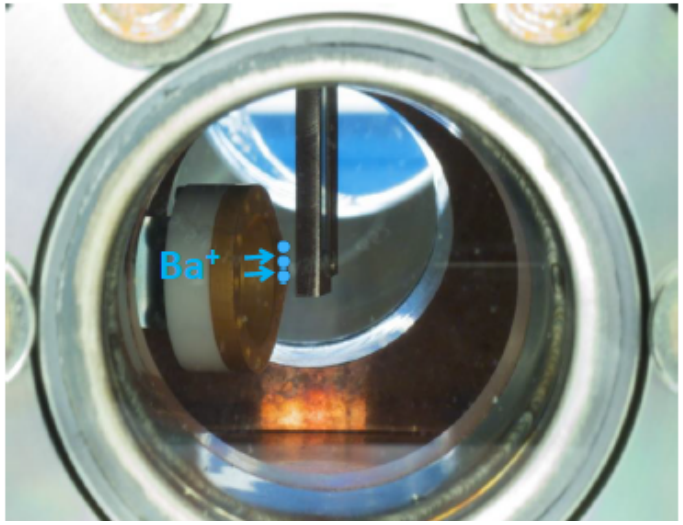
- Repeatably and verifiably do RIS of Ba
- Signal depends on both RIS lasers
- Signal goes away when lasers are detuned



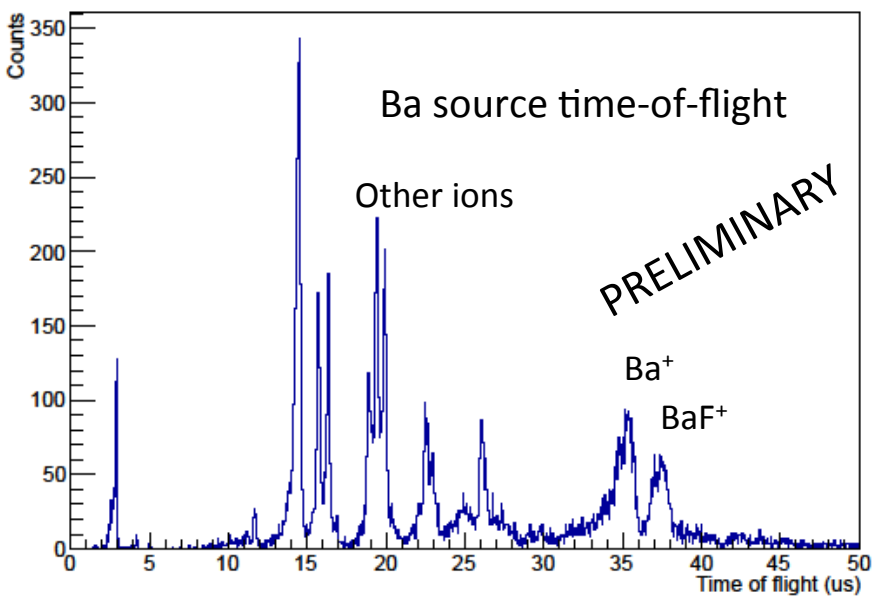
Ba signal goes away when either laser blocked or detuned.

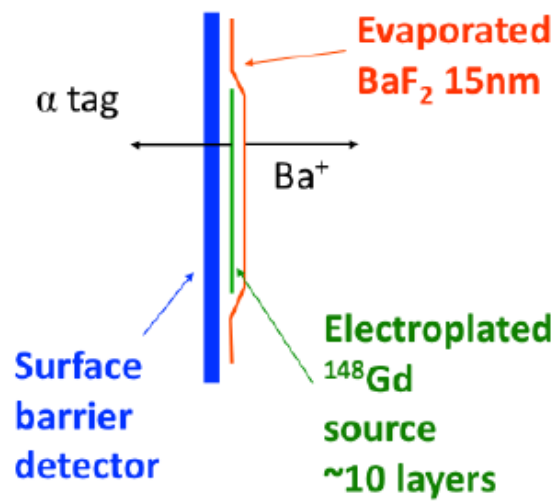


Barium Loading in Vacuum



- Before liquid, test in vacuum
- ^{148}Gd-driven Ba ion source developed for testing
- Deposit ~10-100k Ba^+ initially
- ~10k Ba/hr

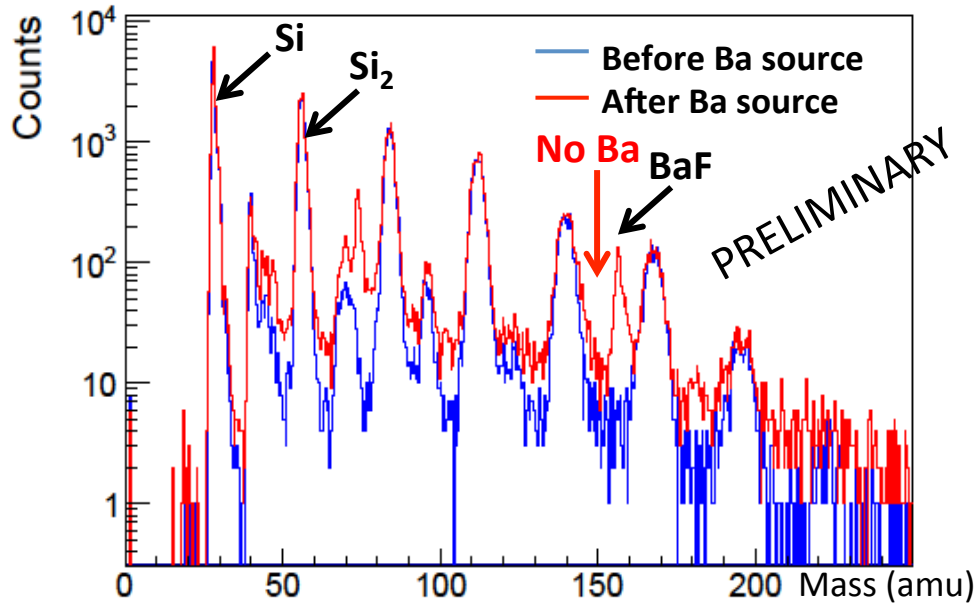




Rev. Sci. Inst. 81, 113301 (2010) 27

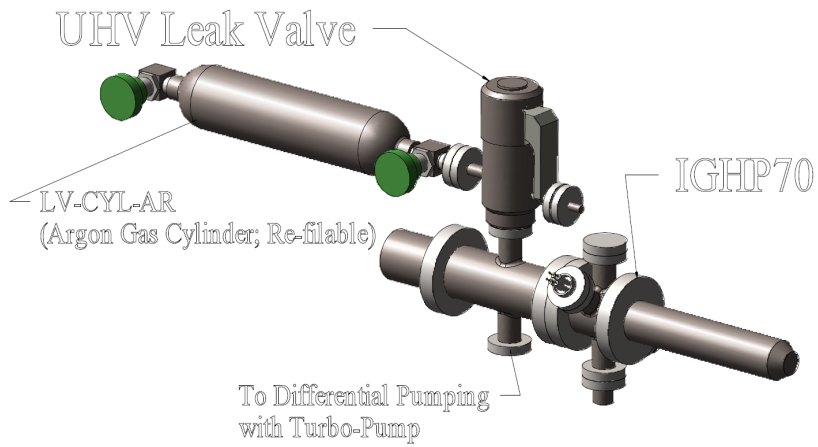
Ba Loading results to date

- *RIS Ba not seen as a result of loading from Ba source – due to Ba molecule formation?*
- Ba loaded from source forms molecules:
  see BaF (source byproduct)
  but not atomic Ba from source
- Can reduce Ba molecule formation with better vacuum, CVD graphene surface



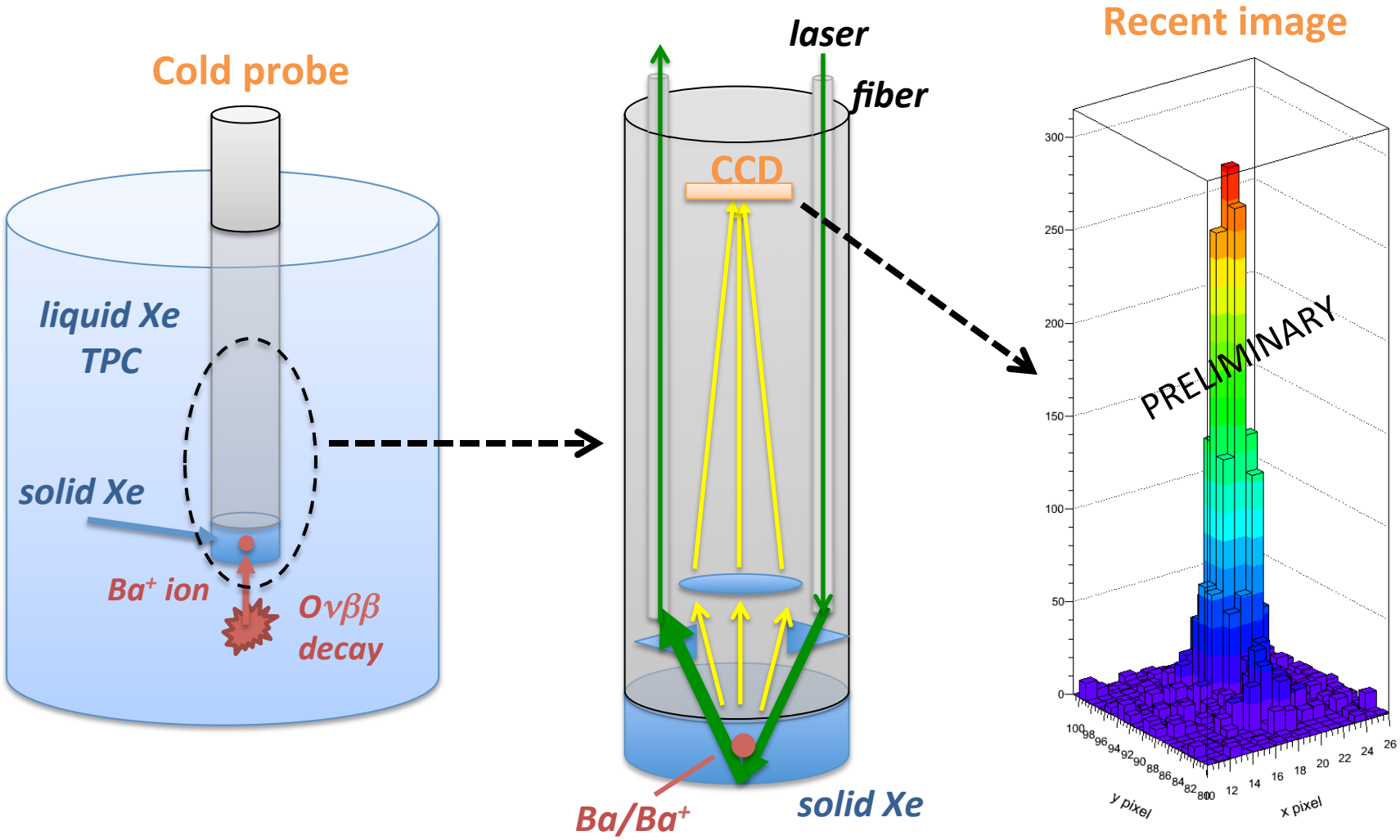
Results with different substrates

- Small numbers of Ba atoms have been found on surfaces of all ultrapure substrates tested to date (Si, SiC, metals).
- Cleaning *in situ* is probably only way to get Ba-free surface – cleaning by rastered laser ablation not yet completely successful.
- Heating surfaces removes oxygen from Si, but led to more background Ba.
- Ar ion gun should remove surface Ba and oxides.
- New Ar gun chamber also is load lock to reduce air exposure when replacing substrates.
- Better vacuum should help reduce Ba molecule formation



Argon ion gun

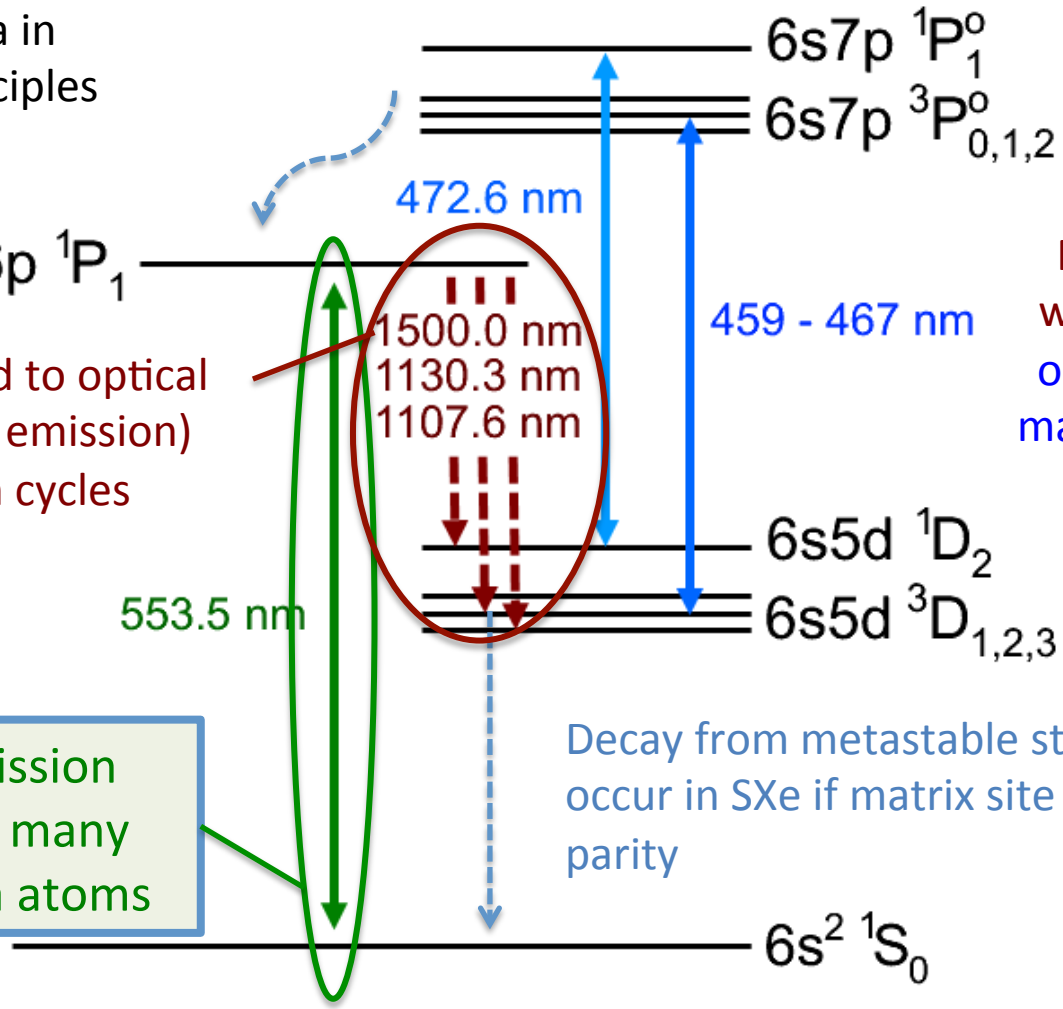
Ba tagging in solid xenon on a cryogenic probe



<3 Ba atoms

Obtaining many photons from single Ba atoms:

Wavelengths are for Ba in vacuum but same principles apply for Ba in SXe



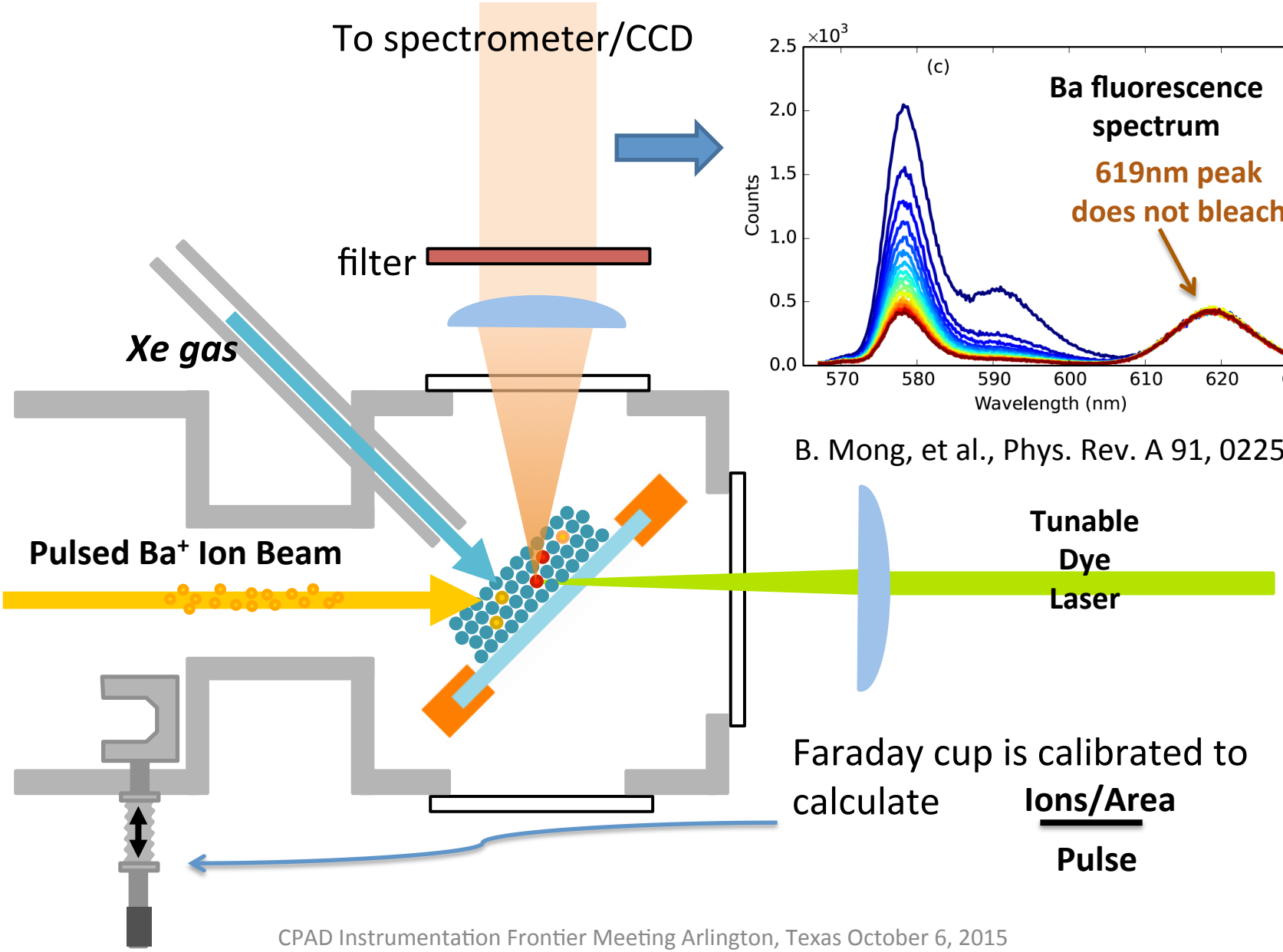
Repumping with IR lasers or blue lasers may be needed

Weak IR transitions lead to optical pumping (bleaching of emission) after ~300 emission cycles

Strong Excitation/Emission Transition: can detect many photons from single Ba atoms

Decay from metastable states could occur in SXe if matrix site has odd parity

Single barium imaging apparatus



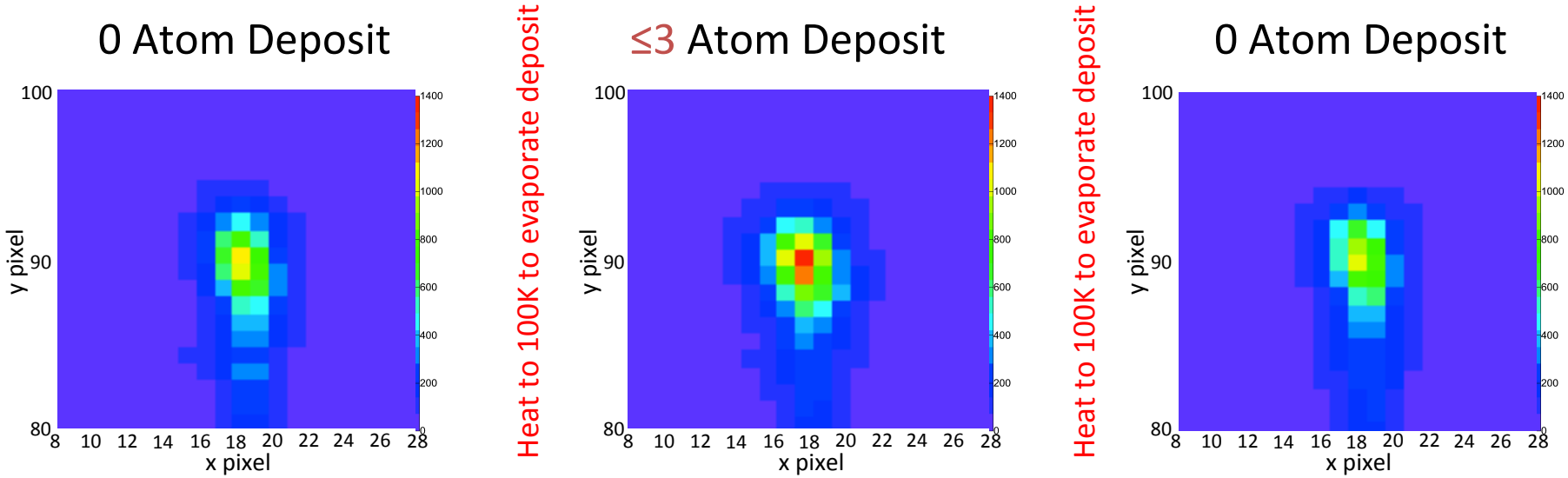
B. Mong, et al., Phys. Rev. A 91, 022505 (2015).

Faraday cup is calibrated to calculate $\frac{\textbf{Ions/Area}}{\textbf{Pulse}}$

Procedure for making images of Ba atoms

Procedure for each deposit:

- SXe deposited on window at 50K for ~6 seconds
- N pulses of Ba^+ ions incident half way through SXe deposit
  - (typically ~20 pulses-> 1 Ba^+ in laser beam)
- Cool to 10K for imaging with better fluorescence
- Evaporate each deposit after imaging by heating to 100K

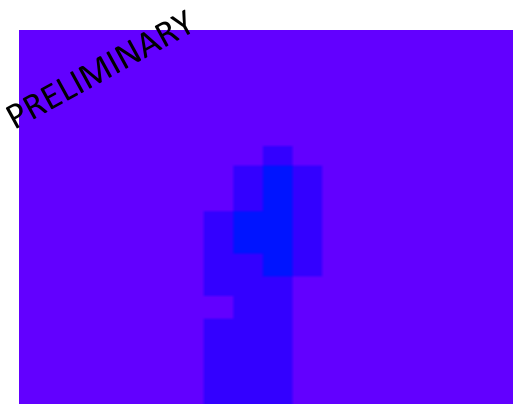


Signal higher for Ba deposit (center) than Xe-only deposit (left and right)

Key result:

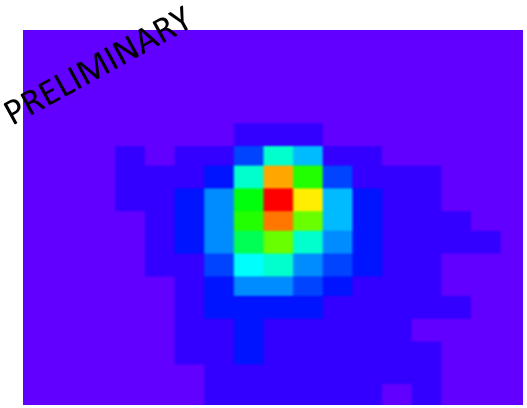
No residual Ba signal even after a large deposit

0 Atom Deposit



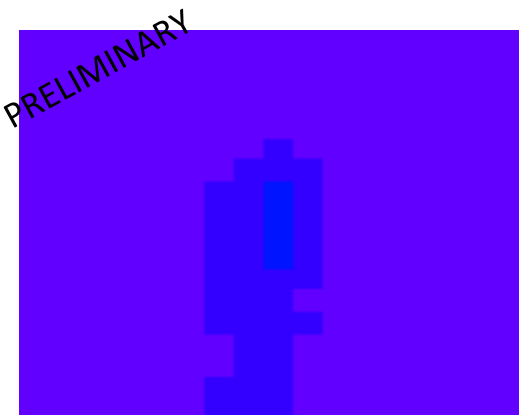
Heat to 100K to evaporate deposit

≤ 1000 Atom Deposit



Heat to 100K to evaporate deposit

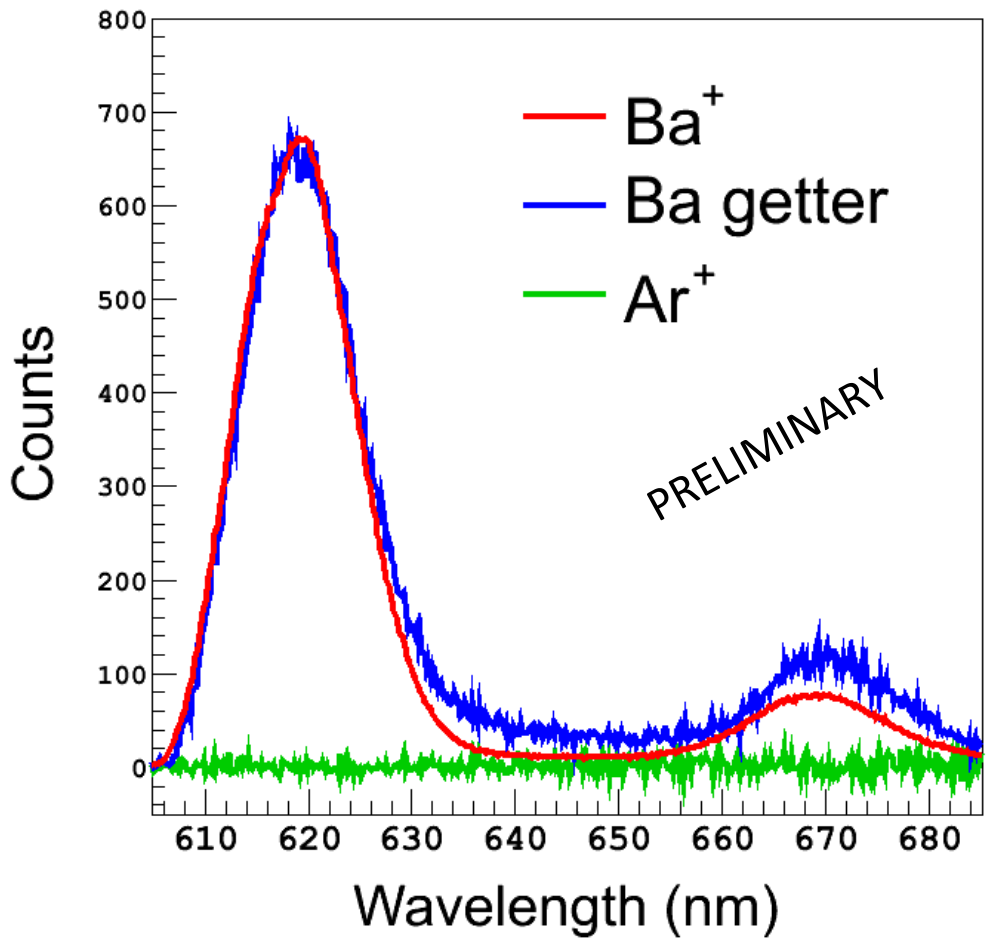
0 Atom Deposit



No "history" effect

Check

Fluorescence of deposits from three different sources:



Important Observations

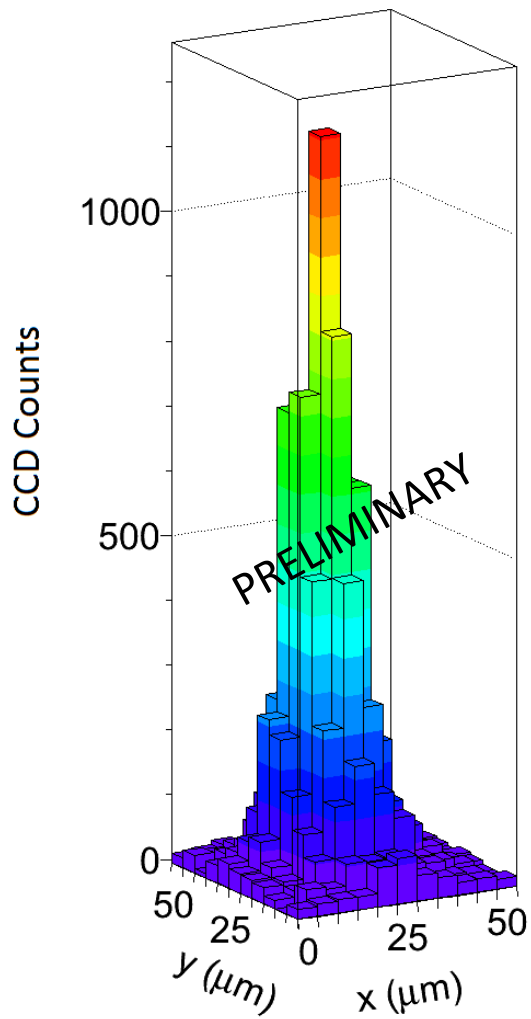
(a) 619 and 670 nm peaks SIMILAR with neutral Ba getter deposits as with Ba^+ beam

(b) NO emission with Ar^+ beam: NOT color centers from ion damage of lattice

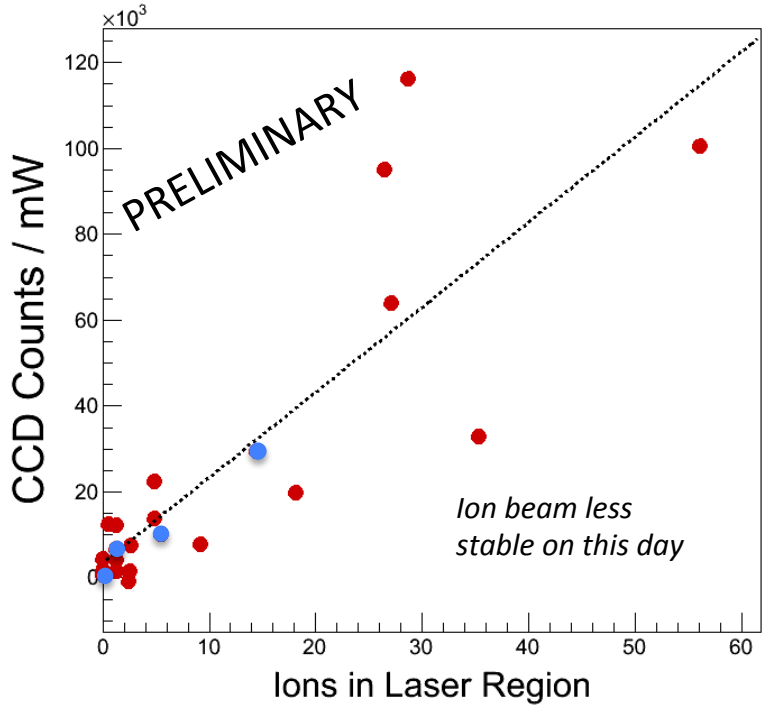
Signal is from Barium atoms!

Images of few Ba atoms in the laser beam

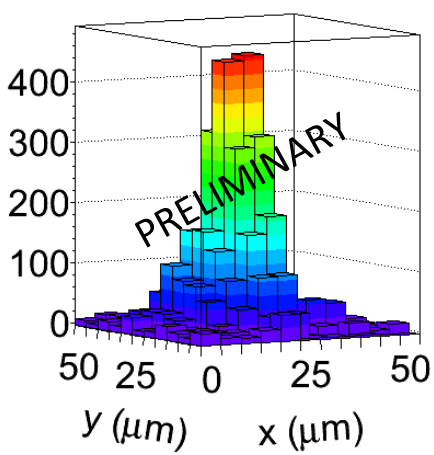
≤ 27 atoms



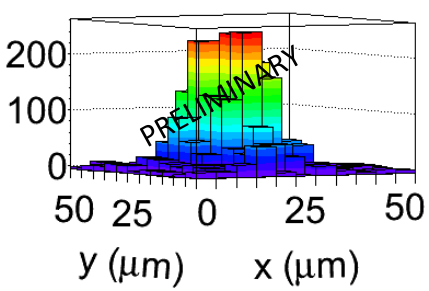
Images of the blue points are shown..



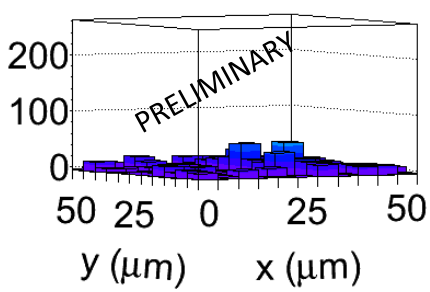
≤ 9 atoms



≤ 3 atoms



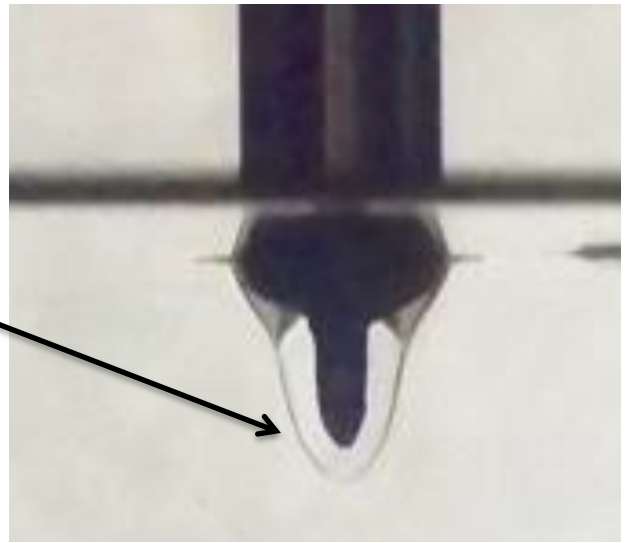
0 atoms

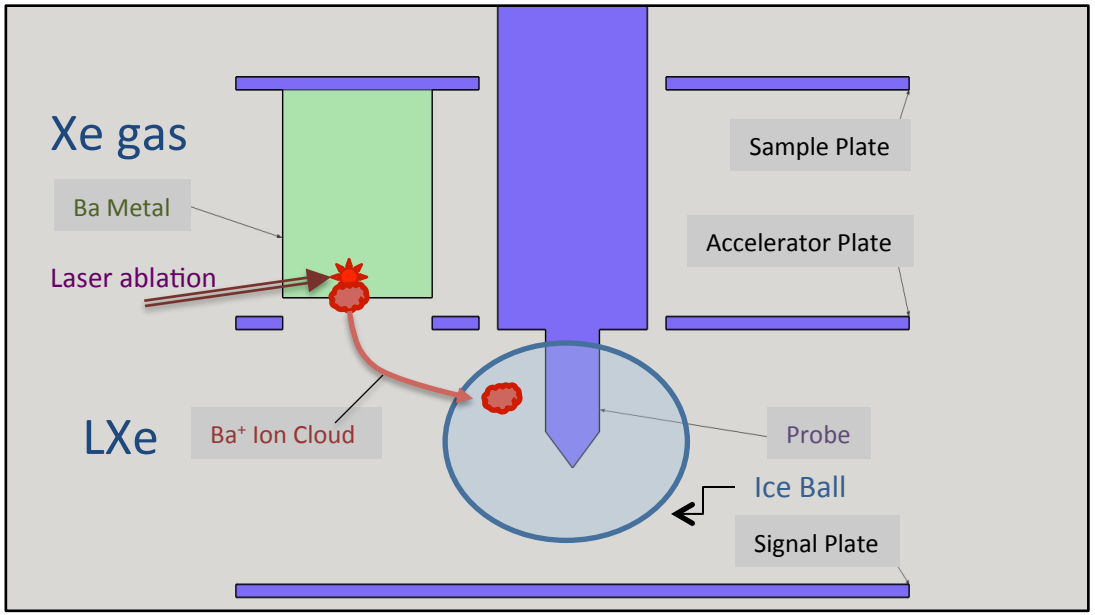


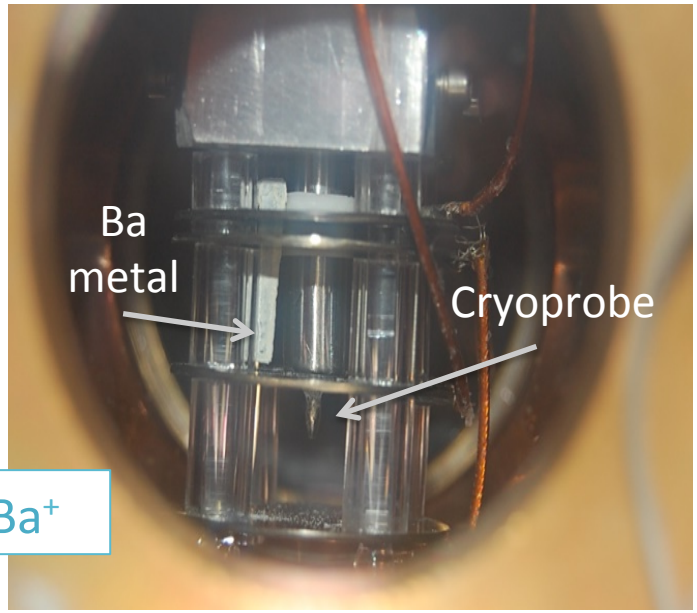
Apparatus for capture of Ba^+ on a cryogenic probe

Use Joule-Thompson cooled probe to freeze xenon on tip in LXe cell

SXe ice ball formed is clear

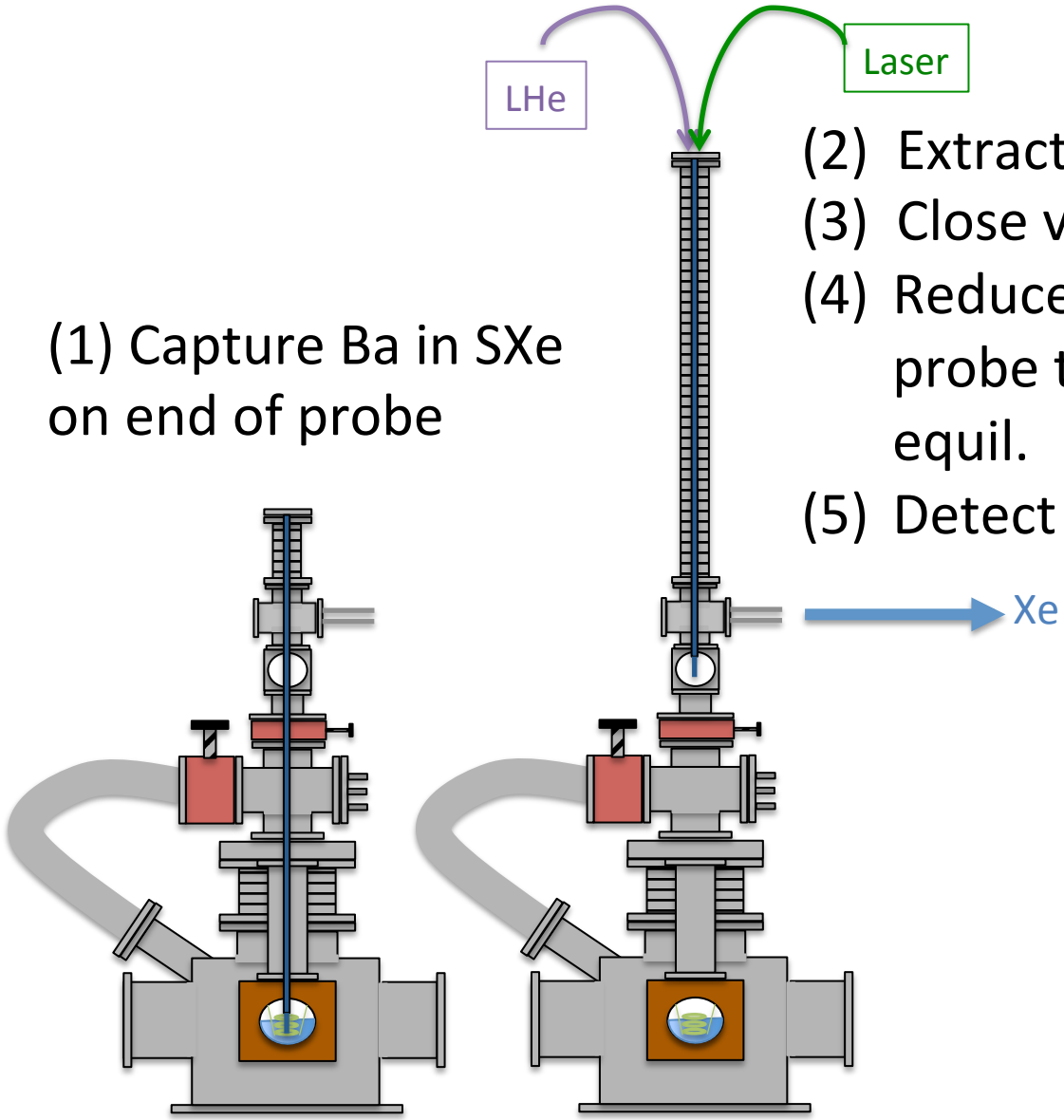






First tests underway with laser ablation source of Ba^+

Probe extraction apparatus in construction

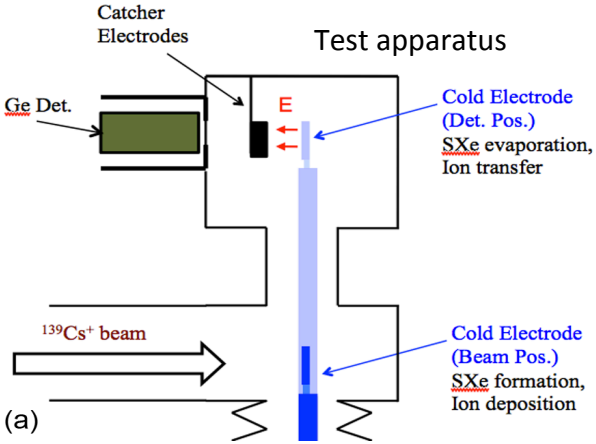


(1) Capture Ba in SXe on end of probe

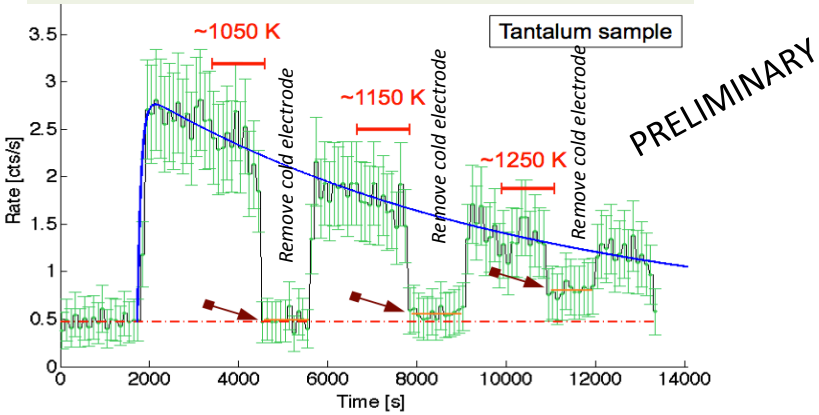
(2) Extract probe
(3) Close valve
(4) Reduce Xe pressure while cooling probe tip to 10K in vapor pressure equil.
(5) Detect Ba in SXe by laser imaging

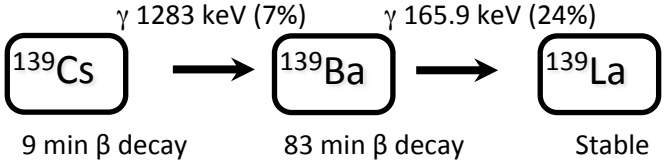
On-line experiments in Ba tagging: clean Ba source may be crucial to success

CARIBU beam at Argonne National Lab provides radioactive beams of Cs-139 or Ba-139

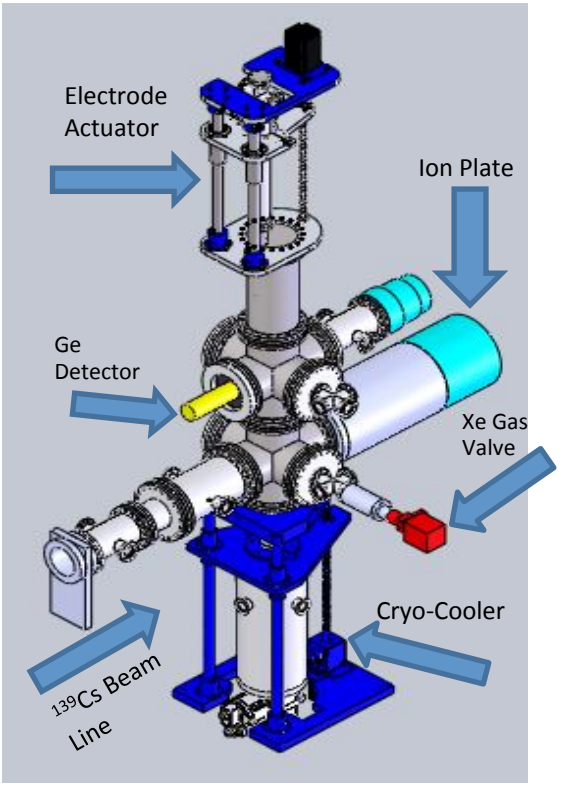


30% transport of Ba ion from Ta surface at 1250 K:





- Study neutralization of Ba in Xenon Ice.
- Study of desorption of Ba from surfaces.



Tests of probe insertion and daughter ion extraction in a LXe TPC

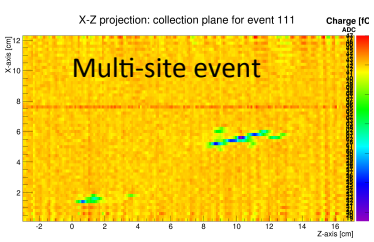
Approach

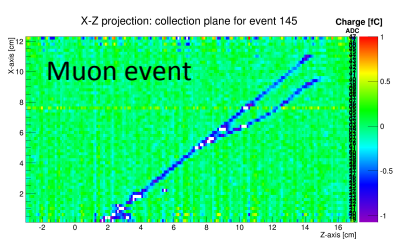
- Detect decay of ^{222}Rn within the TPC volume
- Extract ^{218}Po daughter to the gas phase with probe
- Monitor ^{218}Po decay with alpha detector

$$\tau_{1/2}: \quad \sim 3.8 \text{ day} \qquad\qquad \sim 3.1 \text{ min.}$$

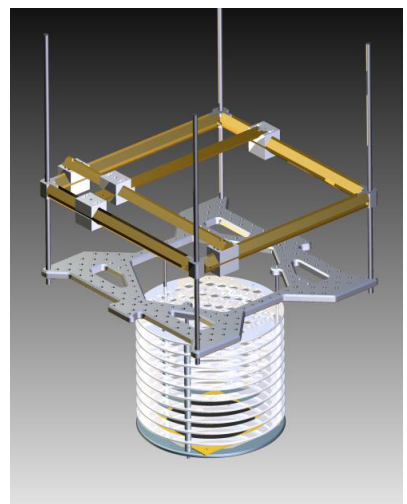
$$^{222}\mathrm{Rn} \xrightarrow{100.\%} \underset{(5.5\ \mathrm{MeV})}{\alpha_1} + {}^{218}\mathrm{Po} \xrightarrow{99.98\%} \underset{(6.0\ \mathrm{MeV})}{\alpha_2} + {}^{214}\mathrm{Pb}$$

TPC events recorded

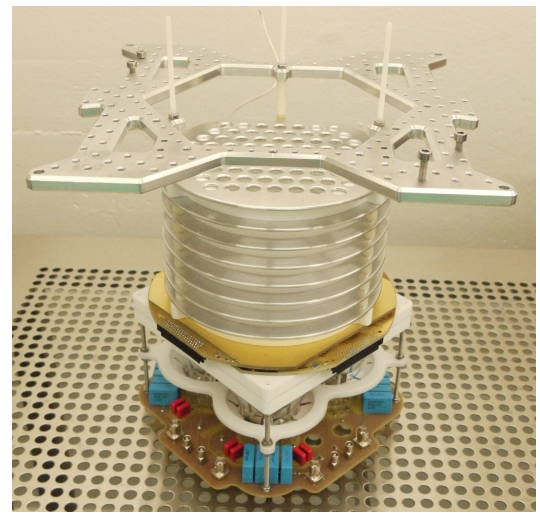




Probe manipulator above TPC



TPC photo: cathode has 10 mm dia. holes for Ba tagging probe

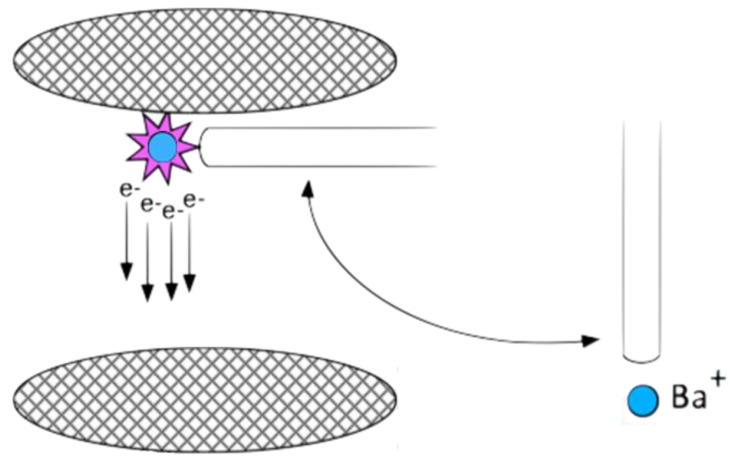


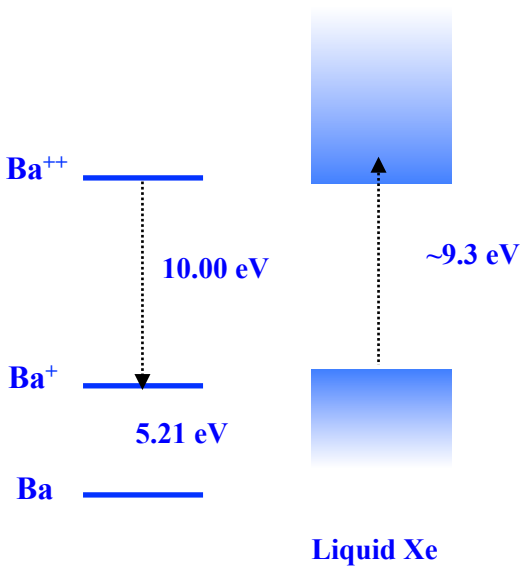
Ba tagging in LXe: What is the Ba charge?

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

$$Then\ \ Ba^{++} + Xe \ \rightarrow Ba^{+} + Xe^{+}\ \ in\ \ LXe$$

Charge exchange should occur to Ba^+ in LXe because IP($Ba^{+)}$ > bandgap (LXe).





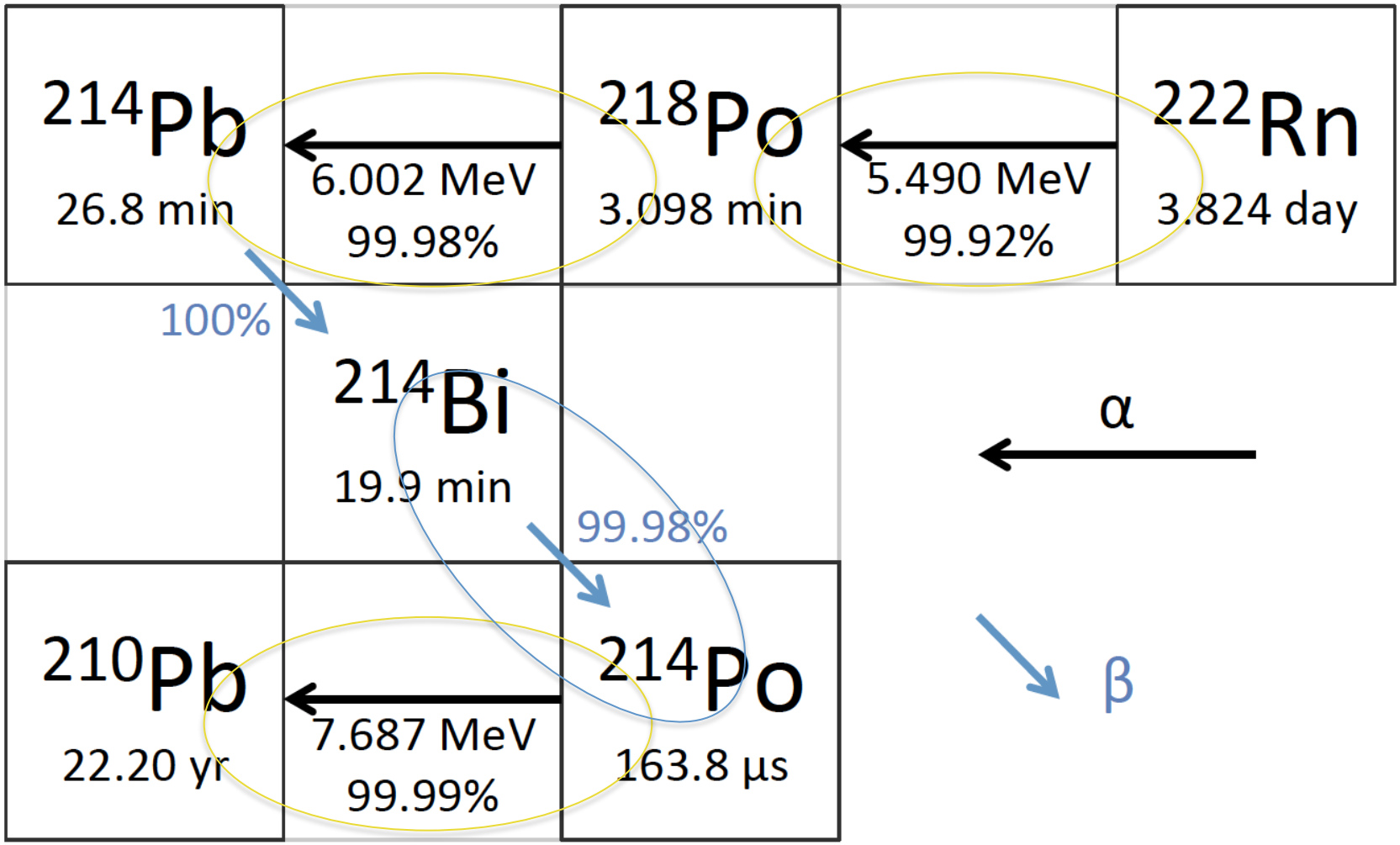
But could further neutralization of Ba+ occur due to electron cloud at decay site?

$$Ba^{+} + e^{-} \rightarrow Ba?$$

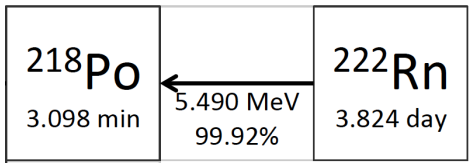
TEST: measure daughter ion fractions in alpha and beta decay in EXO-200.

^{222}Rn chain alpha and beta decays

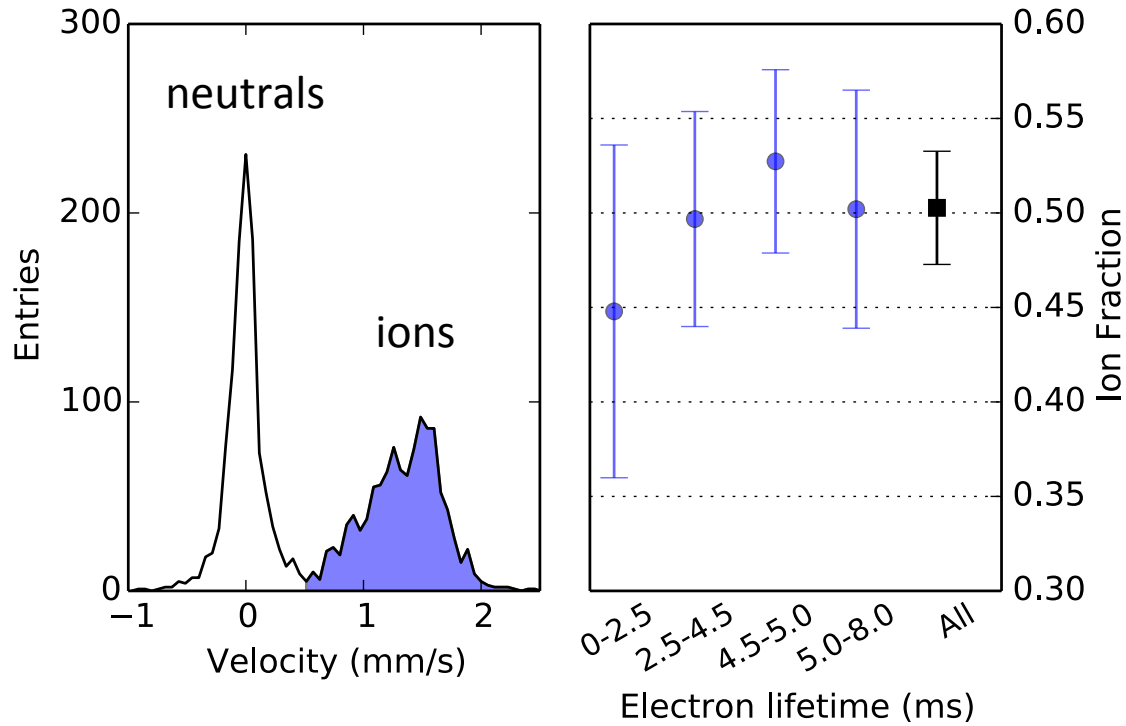
In EXO-200 we detect three alpha decays and one beta decay



^{218}Po ion fraction (α decay)



Measure positions of ^{222}Rn and ^{218}Po alpha decays – determine v
(Apply cut to remove bias due to ions moving out of volume)

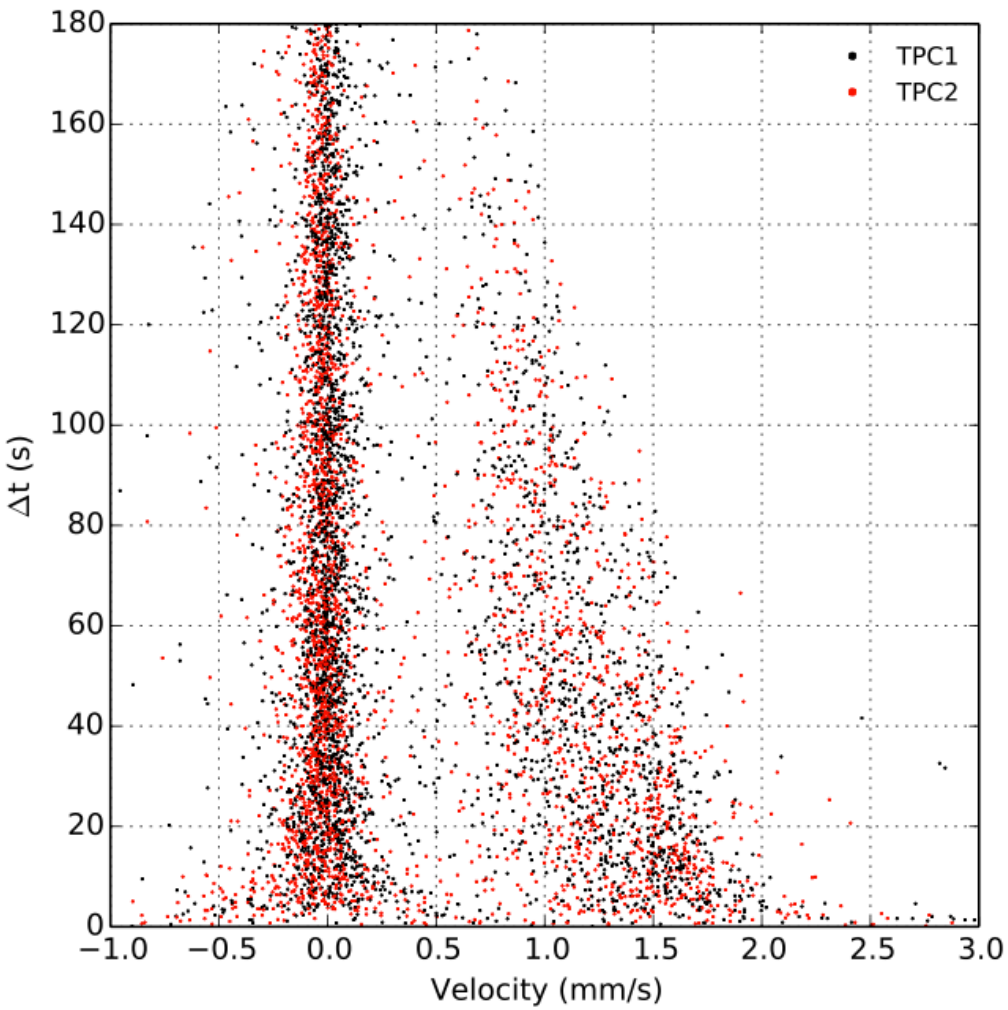


RESULT: Ion fraction of ^{218}Po daughter from α-decay is 50.3±3.0%.
Ion fraction does not depend on purity.

J. B. Albert et al., accepted for publication in Physical Review C (2015) [arXiv:1506.00317]

^{222}Rn and ^{218}Po coincidences: velocity

Average ^{218}Po ion drift speed appears to change with drift time!



Interpretation

^{218}Po ion undergoes reaction along its path:

$$^{218}Po^{+} + X \Rightarrow ^{218}PoX^{+}$$

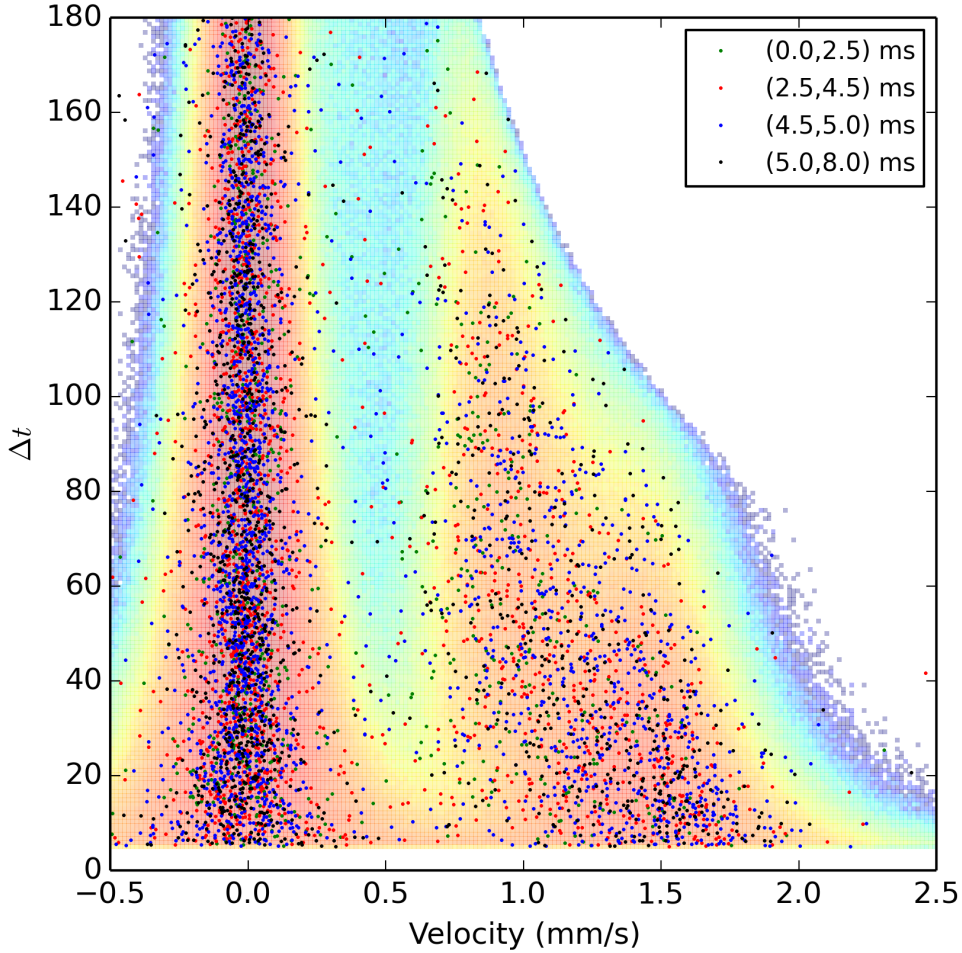
$$^{218}Po^{++} + X \Rightarrow ^{218}Po^{+} + X^{+}$$

1st species has some velocity v_1, second species has velocity v_2

v_1~1.5 mm/s

v_2~0.8 mm/s

MC fit model and results: v vs. Δt



MC Model Parameters:

$v_1 = 1.48 \pm 0.01$ mm/s

$v_2 = 0.83 \pm 0.01$ mm/s

$C = 12600 \pm 660$

$N = 6^{+4.9}_{-1.7} * 10^5$

$D = 0.61 \pm 0.04$ mm^2/s

Mobility of ^{218}Po

$\mu_1 = 0.390 \pm 0.006$ cm^2/(keV•s)

$\mu_2 = 0.219 \pm 0.004$ cm^2/(keV•s)

other ions are 0.13-0.28 cm^2/(keV•s)

C is ratio of reaction lifetime to electron lifetime:

(t_e ~3 ms, $t_{reaction}$ ~ 40s)

*D is ratio or neutralization time to electron lifetime (D=50 * C):*

An important result for Ba tagging: (t_e ~3 ms, t_{neut}>1000s)

^{214}Bi ion fraction (β decay)

Measure ratio of alpha events in LXe $\frac{A^{214}_{\mathrm{Po}}}{A^{222}_{\mathrm{Rn}}}$

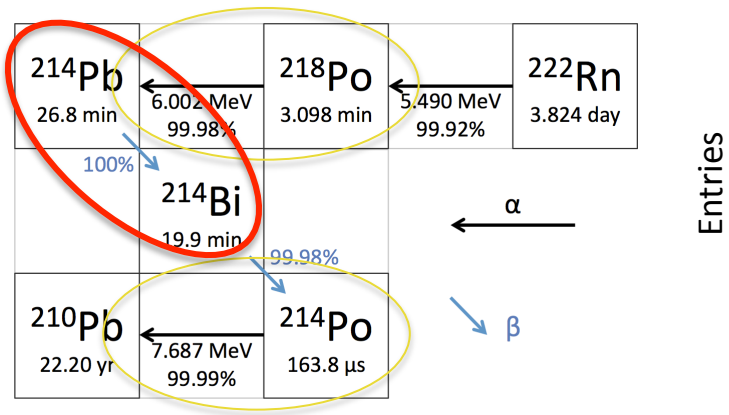
(Assume 50.3(3.0)% of ^{214}Pb are ions)

Neutrals Decay in flight

$$\frac{A^{214}_{\mathrm{Po}}}{A^{218}_{\mathrm{Po}}} = (1 - f'_\alpha + f'_\alpha \epsilon_{\mathrm{Pb}})(1 - f_\beta + f_\beta \epsilon_{\mathrm{Bi}})$$

f_β is daughter ion fraction of β decay

Measure 2 alpha decays in LXe fid. vol.
Deduce beta decay ion fraction



f_β: 76.4 ± 5.7 %

Good news for barium tagging!

J. B. Albert et al., accepted for publication in Physical Review C (2015) [arXiv:1506.00317]

Summary

- Progress on Ba tagging in a number of nEXO groups
- Progress on Ba tagging for nEXO
  - RIS probe work sensitive to small #s of Ba atoms; working on Ba-free surfaces, need cleaner Ba source
  - Single-atom sensitivity level has been reached in imaging Ba atoms in solid xenon; *no history effect*
  - Setup for dipping and moving a probe in a LXe TPC
  - Preliminary work with radioactive beams

- EXO-200 results indicate a high fraction of Ba daughters should be charged in LXe – favorable for grabbing and tagging

Rough plan for Ba tagging implementation in nEXO

- *R&D next 3 years 2016-2019 is critical*
  - *demonstrate Ba tagging concept in lab*
  - *need some R&D on probe dipping in TPC*
- Ba tagging system test with clean Ba source 2018-2021
  - online at ANL or TRIUMF? $2\nu\beta\beta$? In a TPC?
  - *need some R&D to be prepared*
- Ba tagging system engineering 2021-2023
- TPC with Ba tagging construction 2023-2026
- Install in nEXO detector after 5 years of nEXO operation 2027