Progress in Barium Tagging for nEXO

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For the nEXO Collaboration

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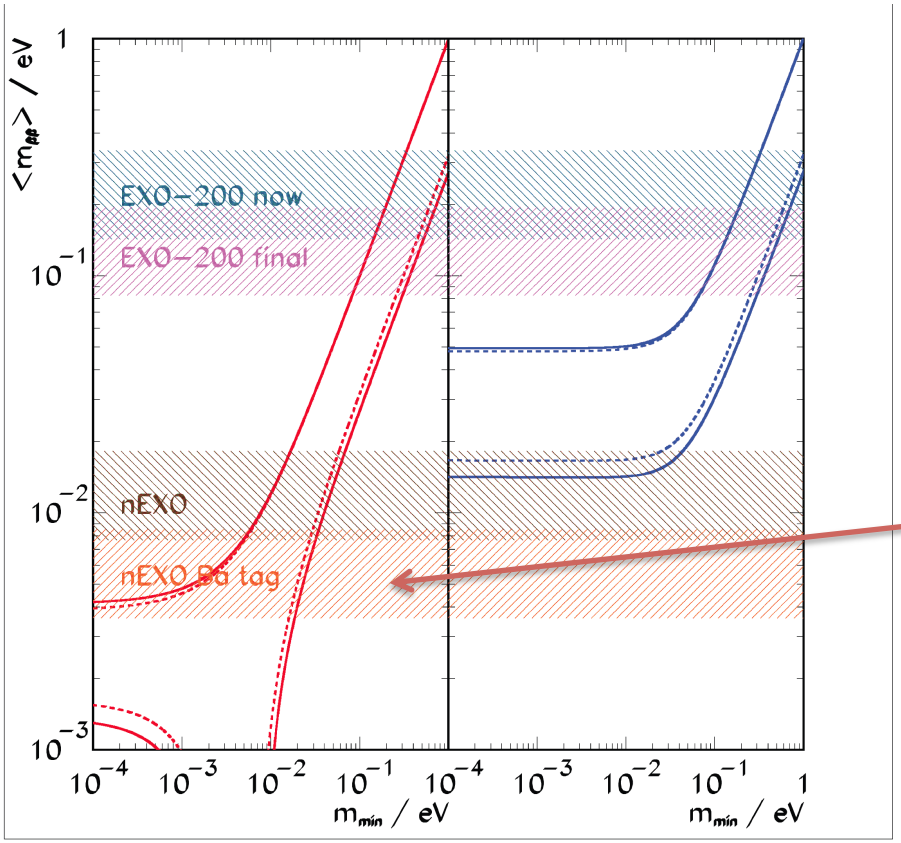
Barium Tagging

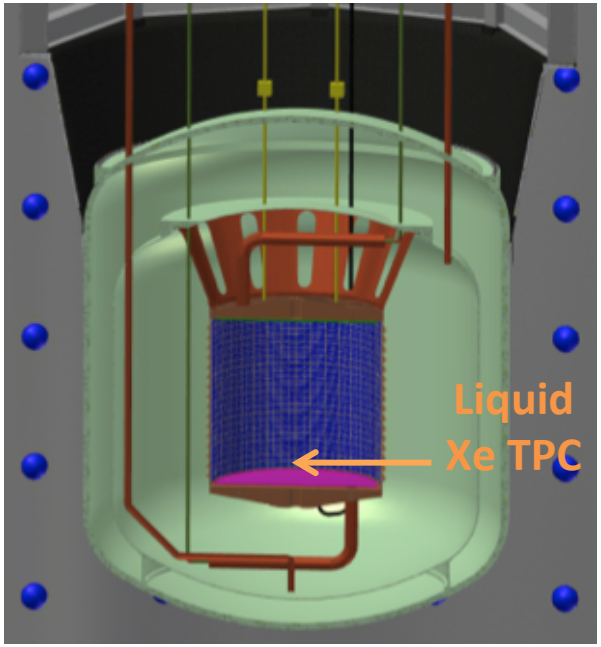
Neutrinoless Double Beta Decay (0νββ) of Xe^{136}:

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

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

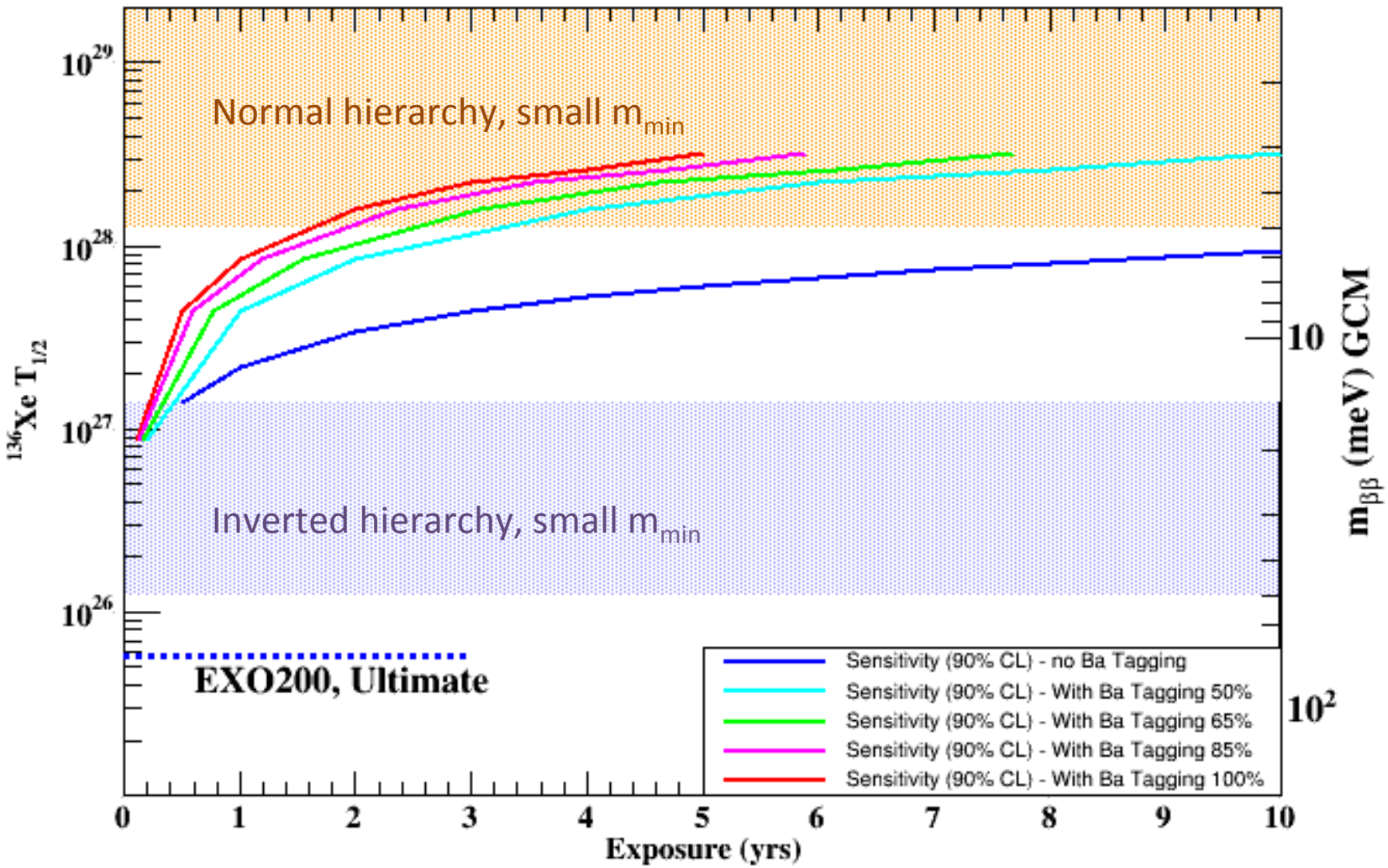


nEXO



- ***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!***

Even a 50% Ba tagging efficiency allows for a substantial improvement in nEXO sensitivity

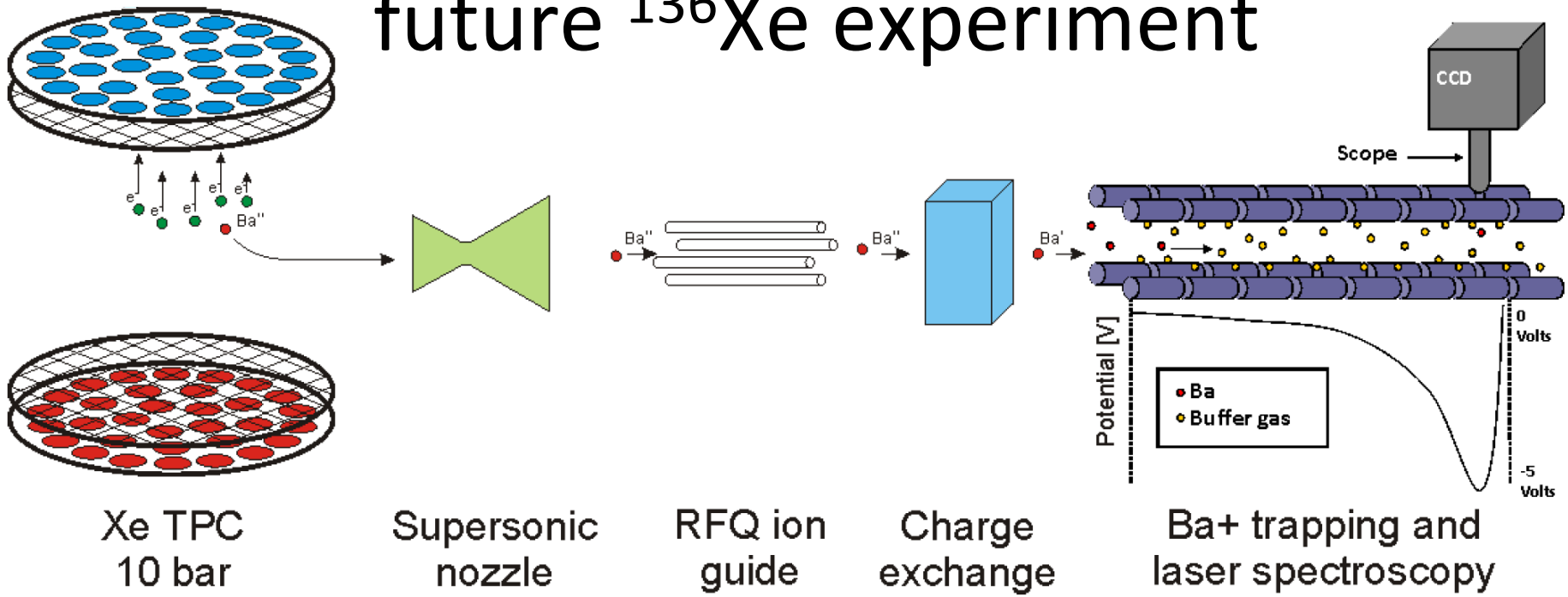


Outline

- Progress on Barium tagging research in for a future gas Xe detector
- ***Progress in barium tagging research for the nEXO liquid xenon detector***
- Interesting new EXO-200 results on daughter ion fraction from beta decay that may be relevant to barium tagging

Most results shown here are preliminary

Concept of Ba tagging in gas TPC for future ^{136}Xe experiment



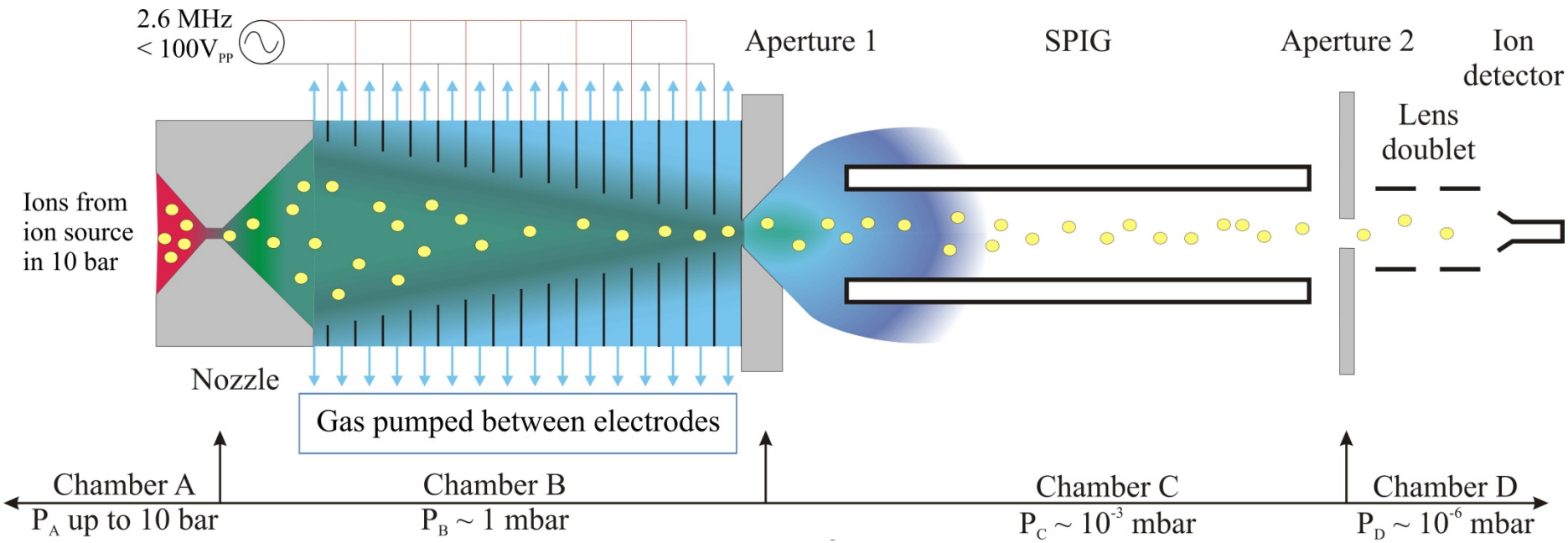
- ✧ Ba^{++} produced in Xe gas
- ✧ Drift Ba^{++} with controlled electric field to exit orifice

- ★ Extract and separate from gas
- ★ Use quadrupole to separate 1 Ba^{++} from 10^5 Xe^+

- ❖ Convert Ba^{++} to Ba^+

- ✸ Trap single Ba^+ ion and identify with laser fluorescence

RF funnel concept (Stanford, moved to McGill)



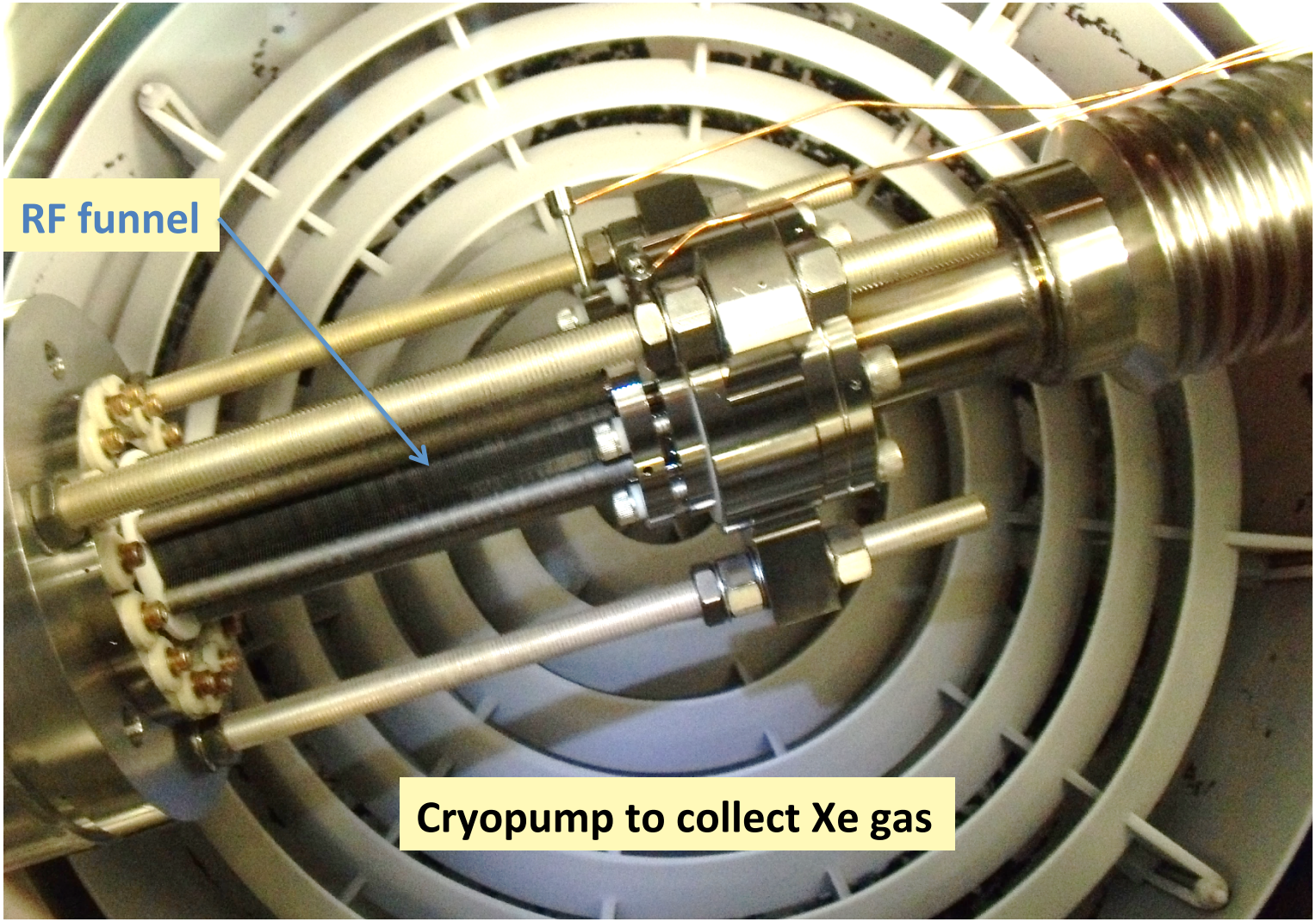
RF-funnel concept:

- Converging-diverging nozzle
- 2 Stacks total 301 electrodes
- RF-field applied to electrodes
- P_A = 10 bar, P_B = 1 mbar

V_{RF} = 120 V, f = 10 MHz

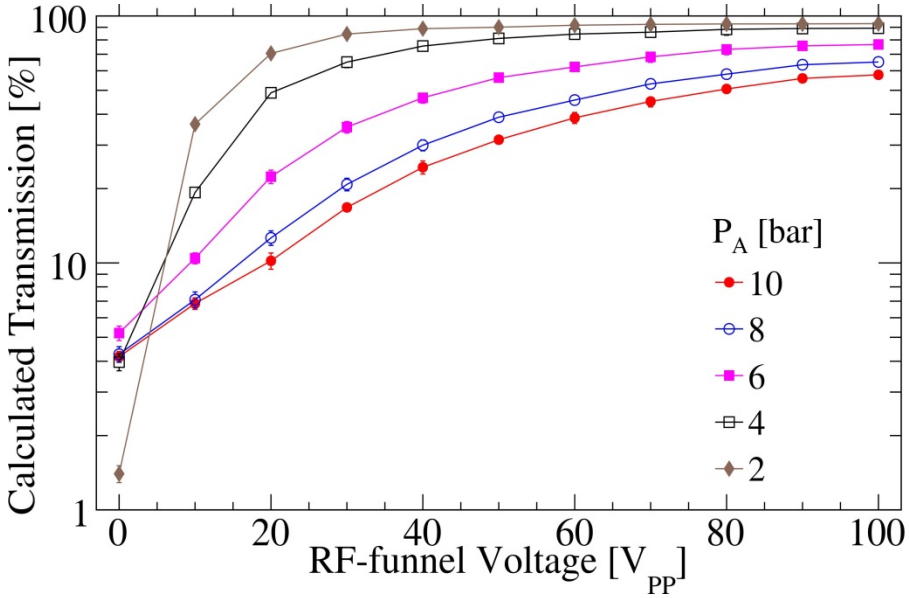
Simulated Ba^+ transmission ~95%

Funnel during xenon operation

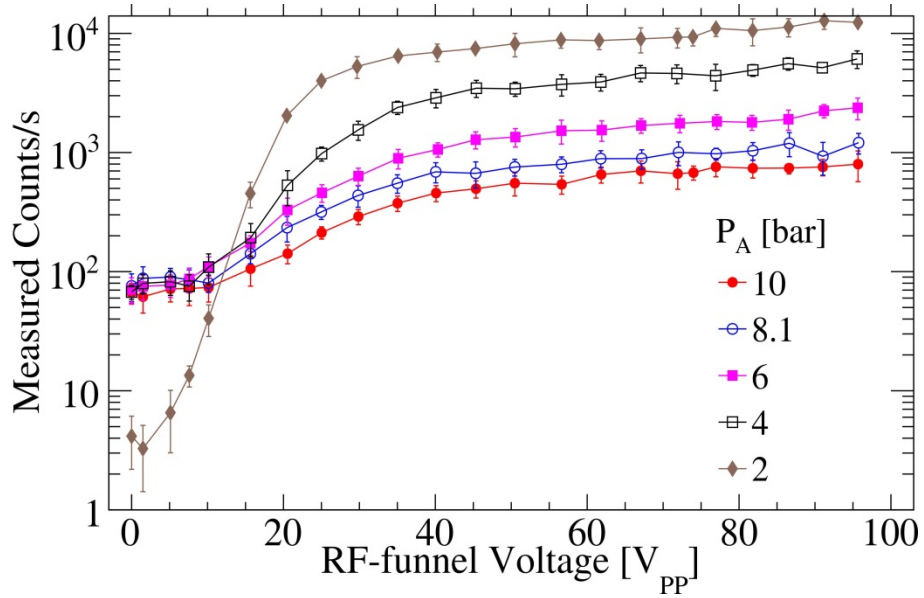


Ion extraction in xenon gas: alpha recoil source in gas Xe

Calculation



Measurement

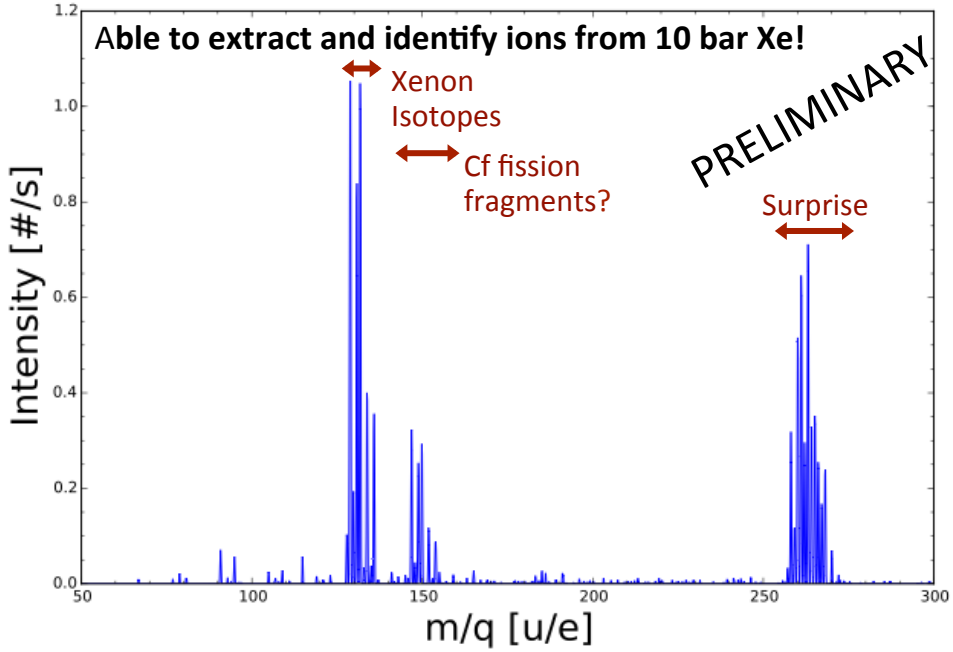


- *General shape well reproduced by simulations*
- *Ion extraction up to 10 bar*

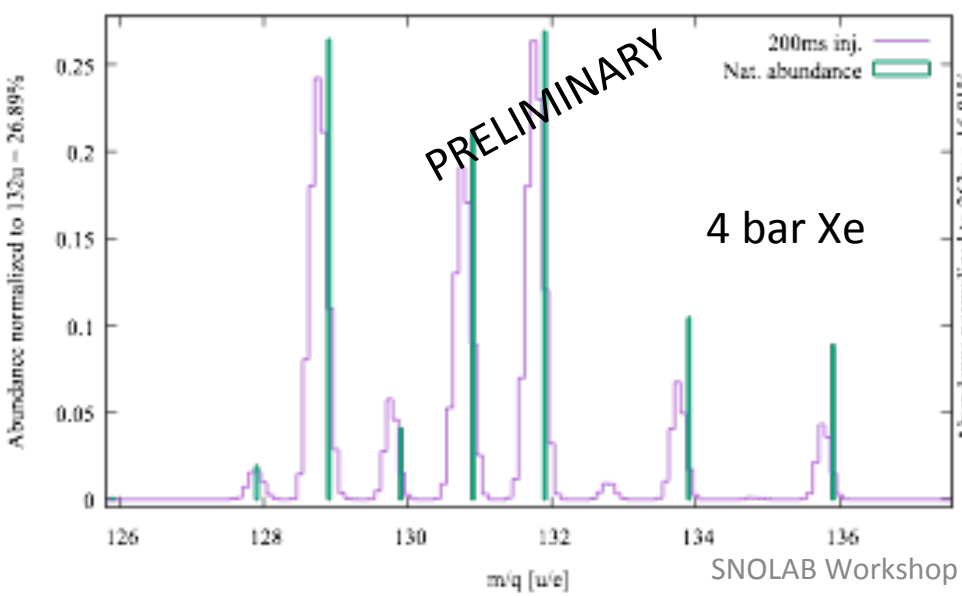
- Ions not identified
- Ion extraction efficiency unknown

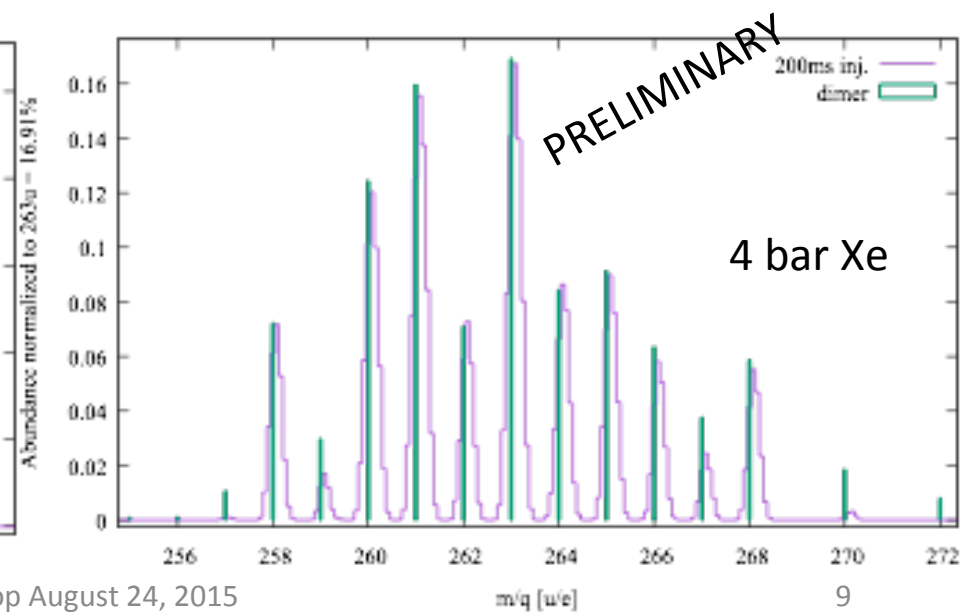
Int. J. Mass. Spectrom. (2015) doi:10.1016/j.ijms.2015.01.003

Mass identification - preliminary



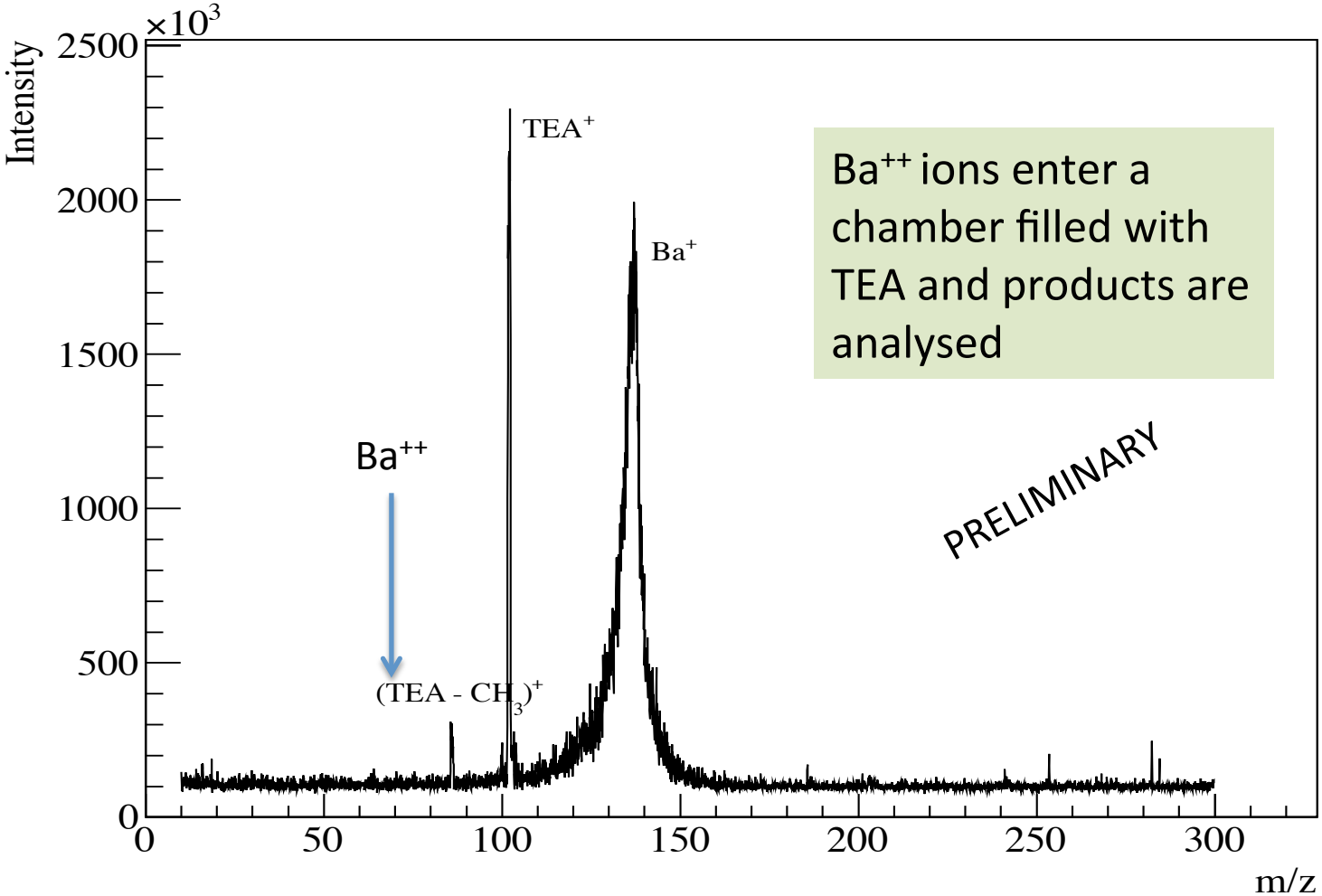
- Ion extraction possible at 10 bar with ^{252}Cf fission source
- Quadrupole mass spectrometer to identify ions extracted
- Ion distribution agrees with natural xenon
- Potential observation of xenon dimers





Charge exchange test (Carleton):

Conversion of Ba^{++} to Ba^{+} is very efficient in TEA gas

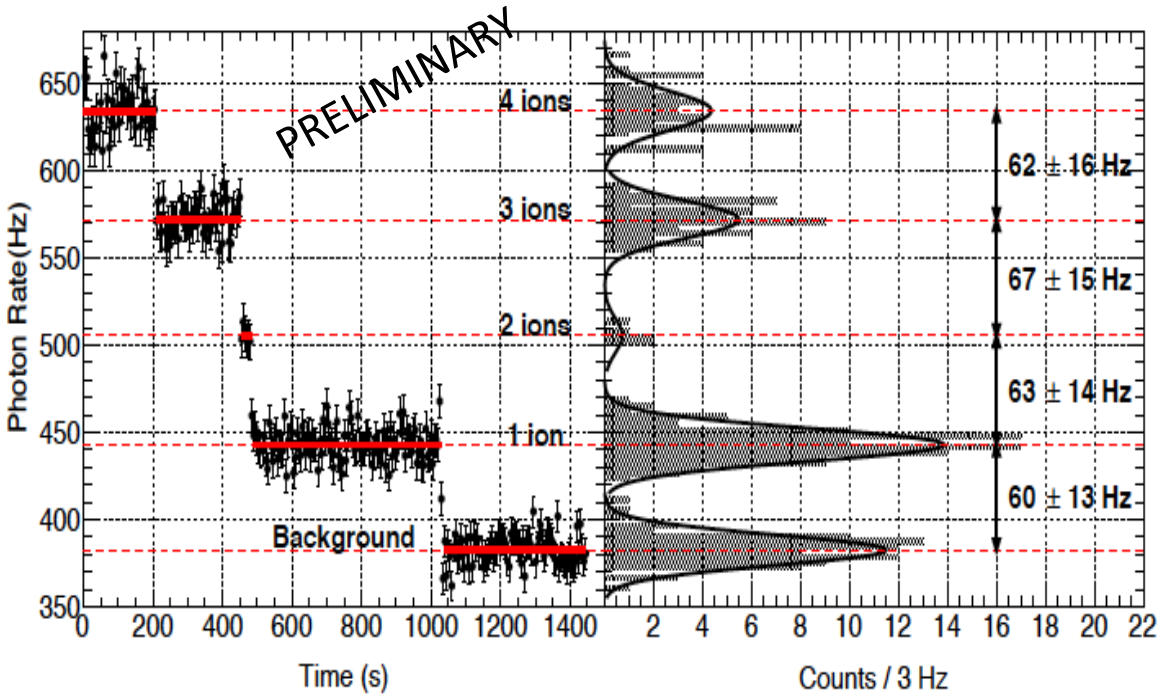


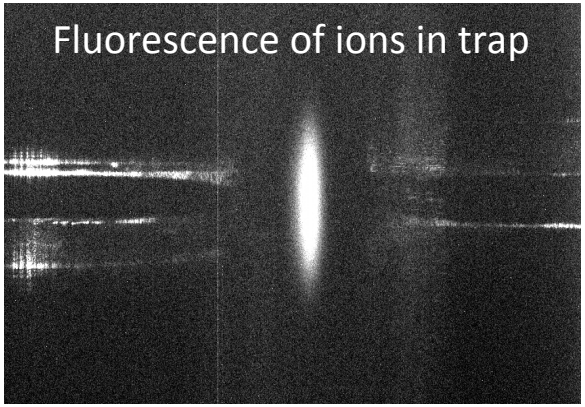
Ba^{++} ions enter a chamber filled with TEA and products are analysed

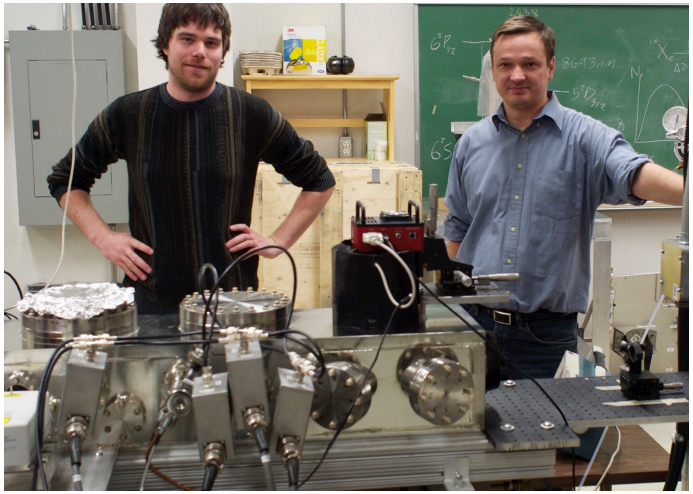
PRELIMINARY

Linear trap with pulsed lasers gives clean identification of Ba^+

Quantized detection of single Ba^+ ions in linear trap

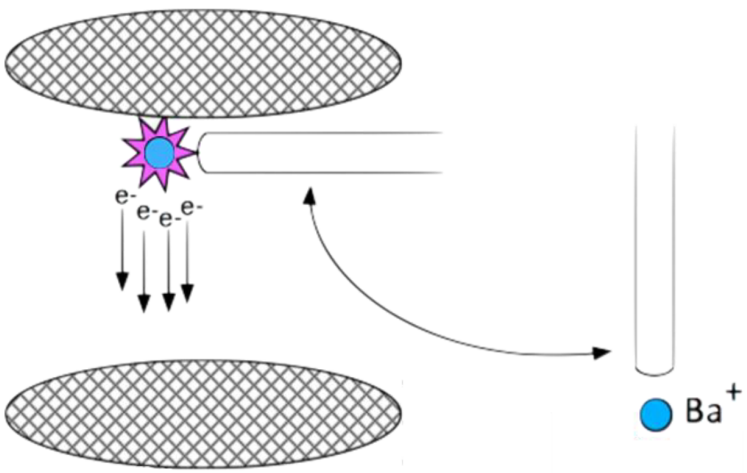






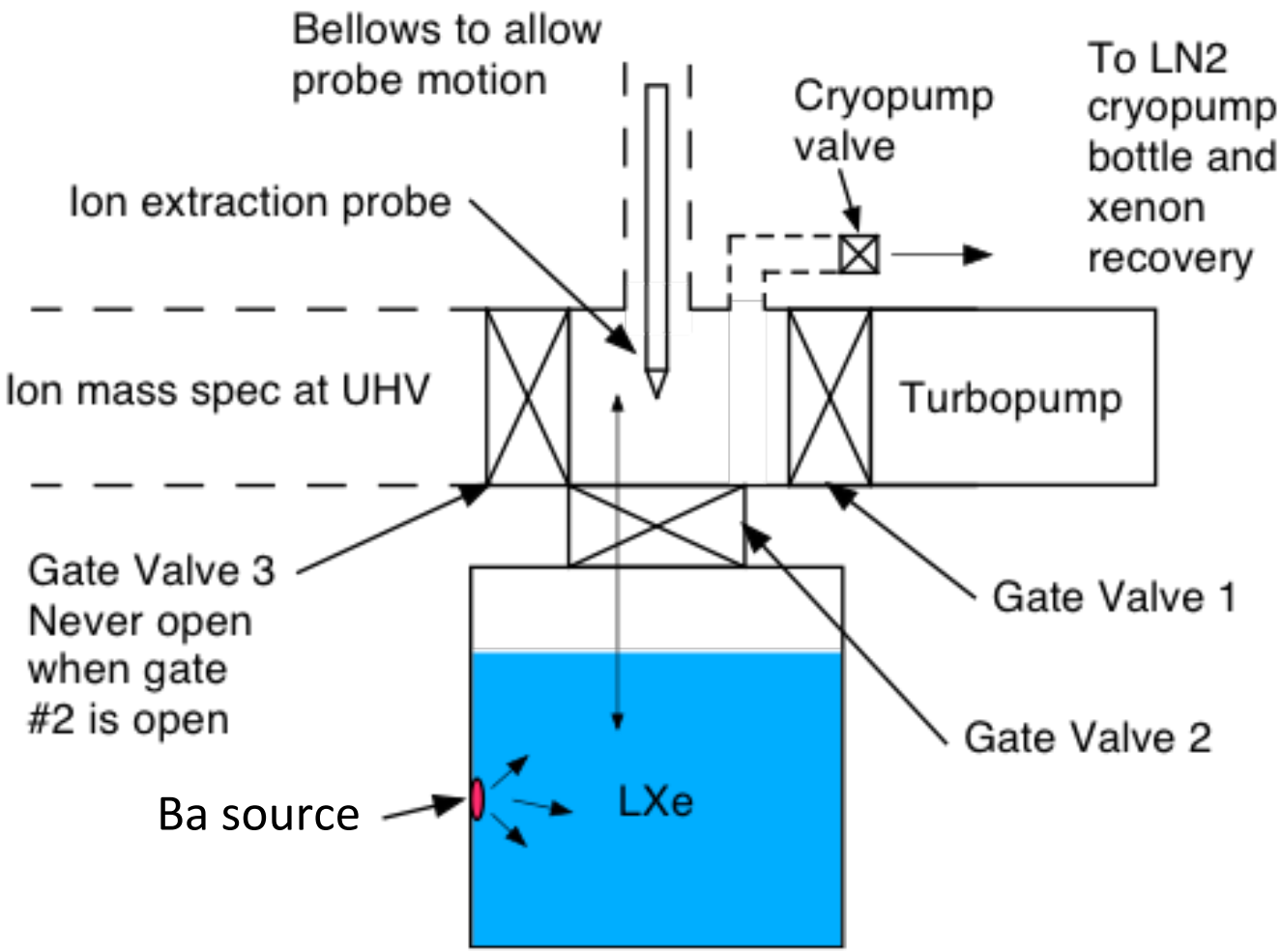
Concept of Ba tagging in liquid Xe for nEXO

- 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



Ba in LXe Tagging Apparatus (Stanford)

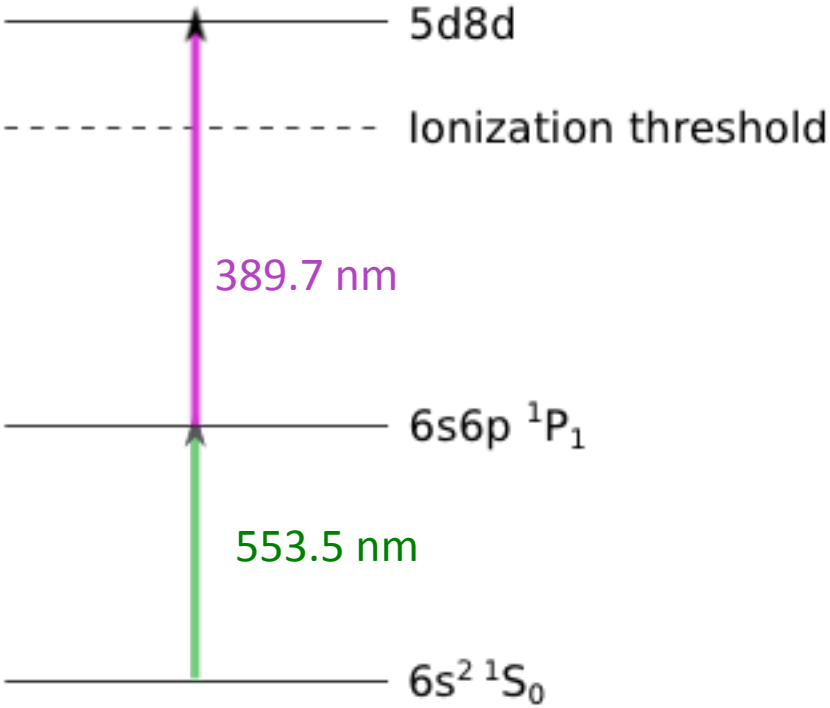
Challenge: Recover and identify single Ba, ignoring everything else



Resonance Ionization Spectroscopy

Identification:
Efficiently and *selectively*
ionize barium
using its atomic spectroscopy

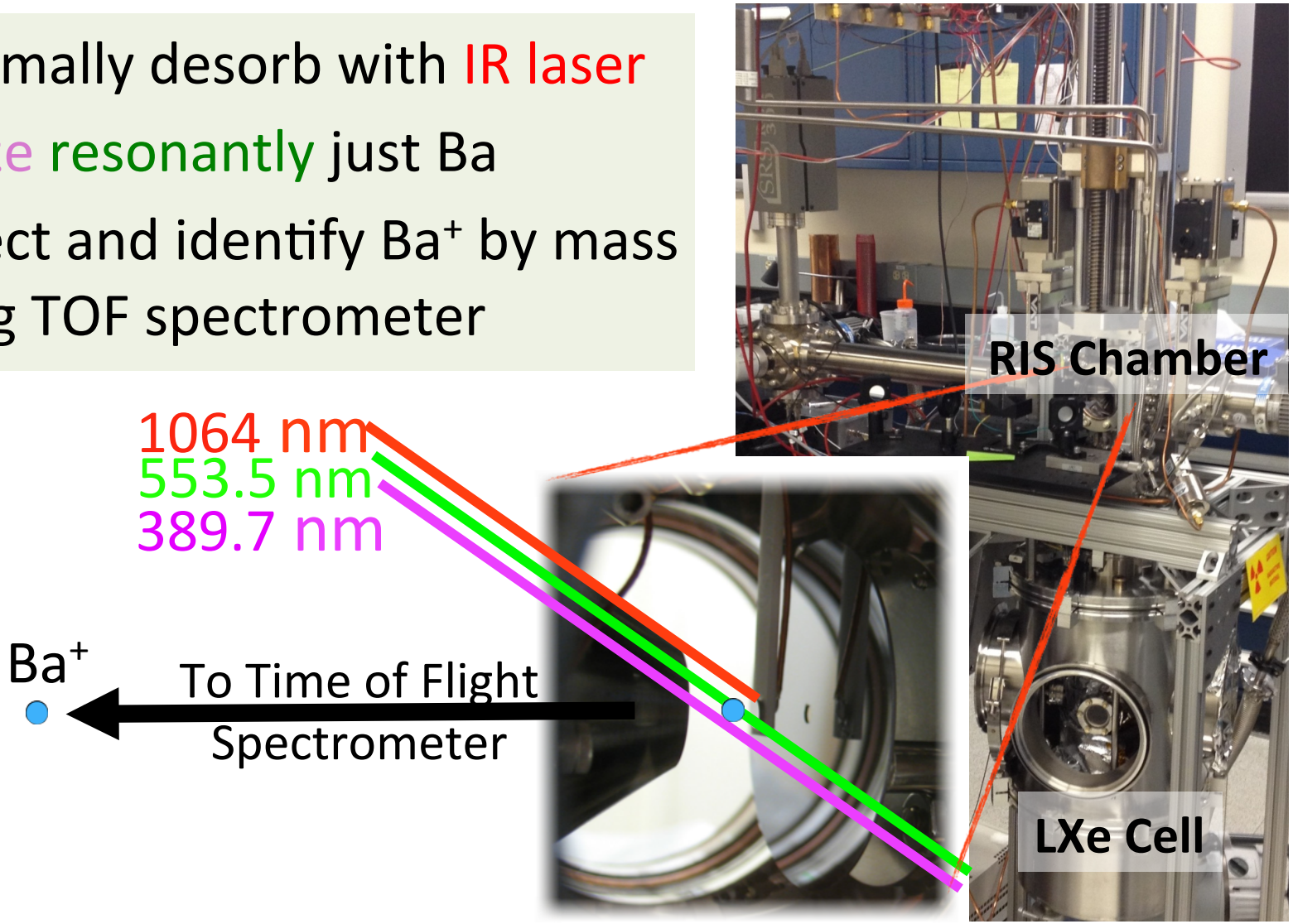
RIS is sensitive to single atoms



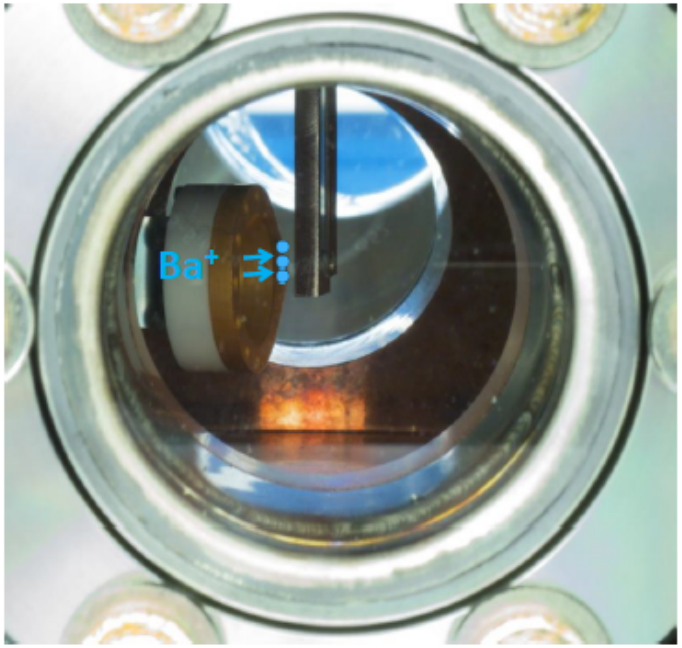
Neutral barium spectroscopy

Desorption, Ionization and Detection

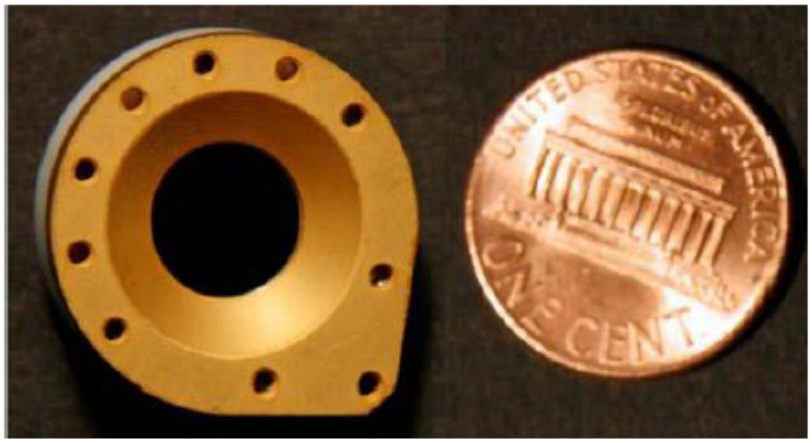
- Thermally desorb with IR laser
- Ionize resonantly just Ba
- Detect and identify Ba^+ by mass using TOF spectrometer

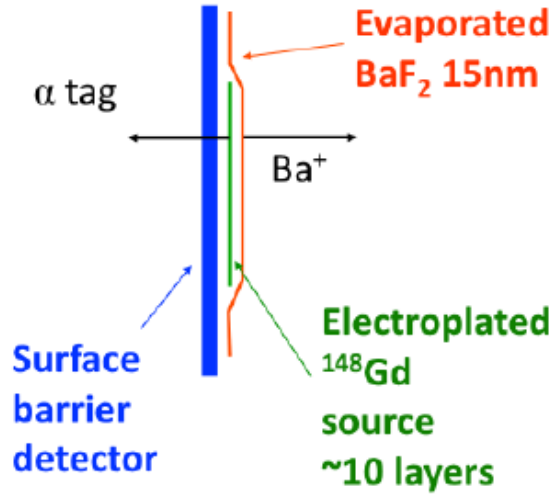


Barium Loading in Vacuum



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





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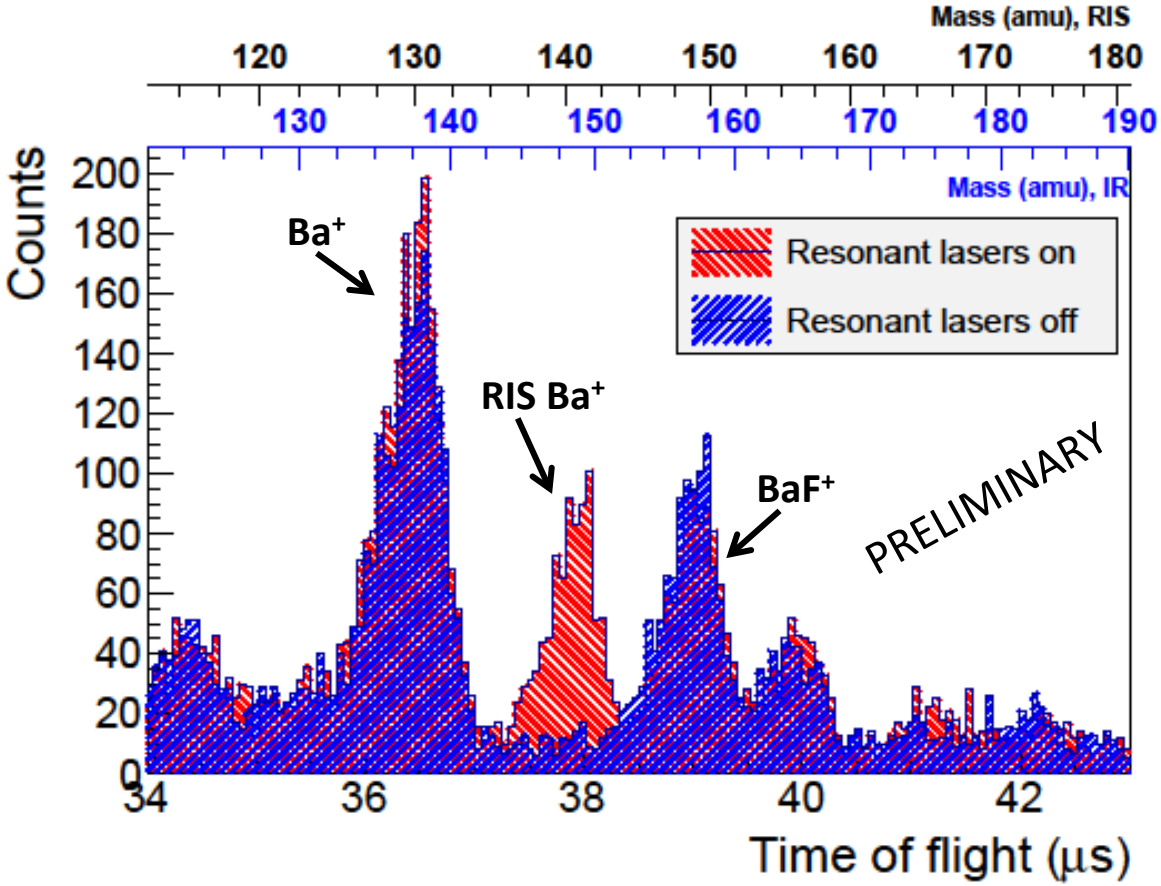
Ba in the TOF

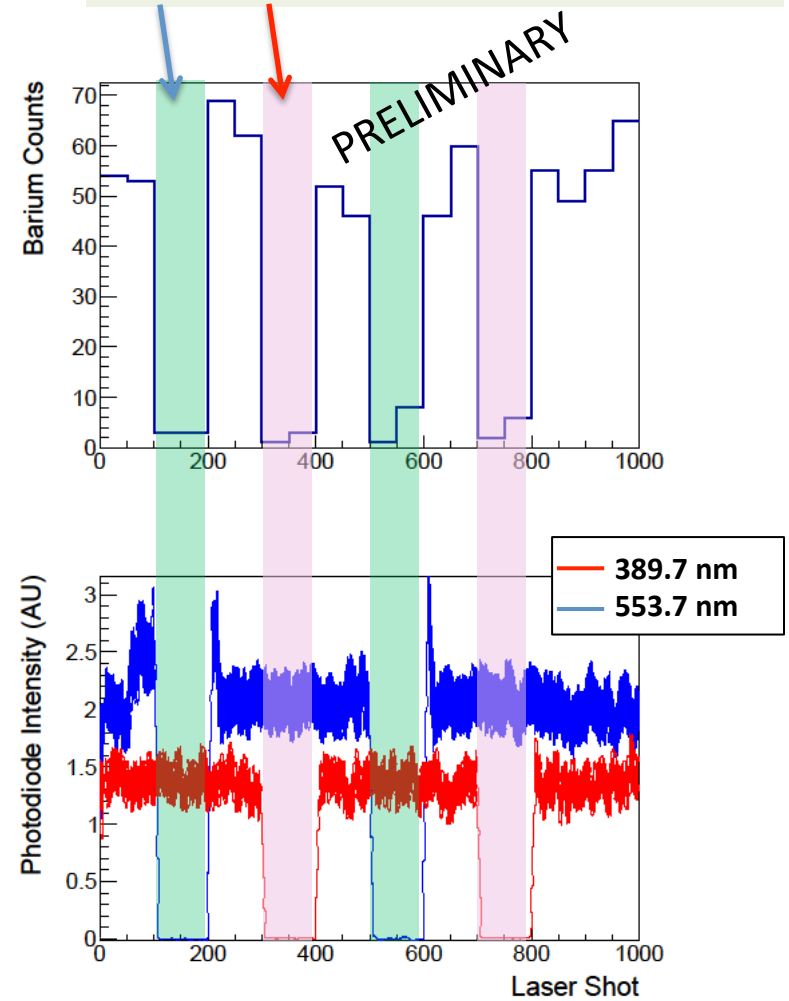
- Can resolve Ba^+ from RIS, Ba^+ from ablation, and BaF^+ from ablation



RIS Results

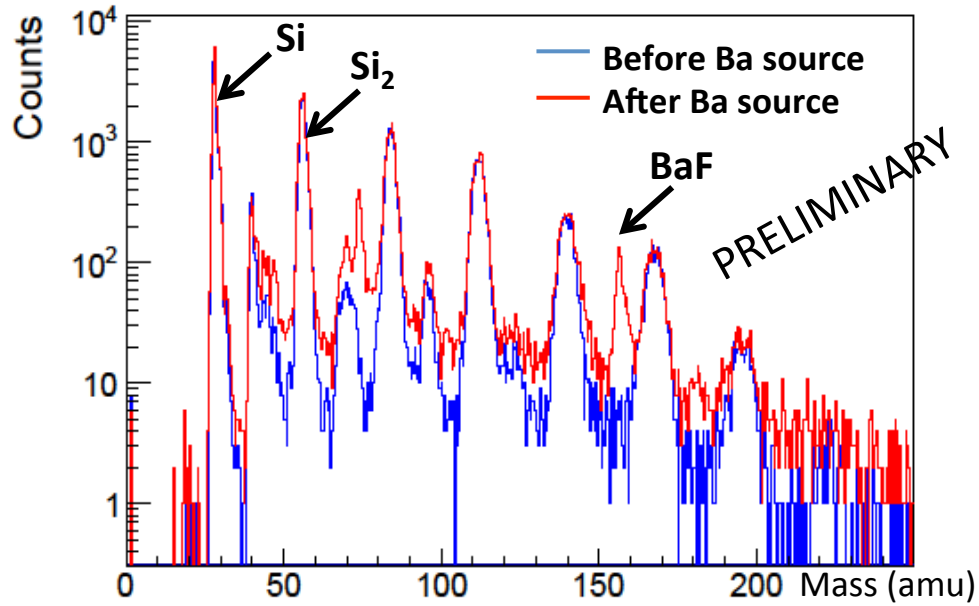
- Repeatably and verifiably do RIS of Ba
- Signal depends on both RIS lasers
- Signal goes away when lasers are detuned

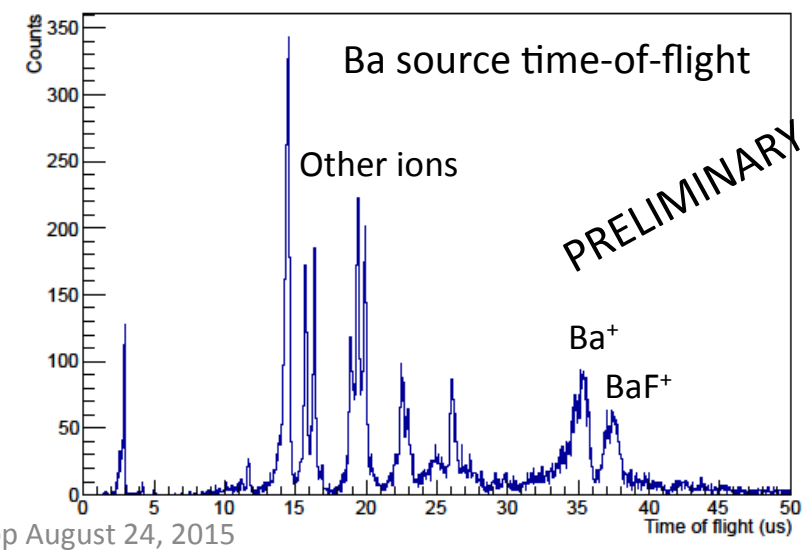
Ba signal goes away when either laser blocked or detuned.



Ba Loading

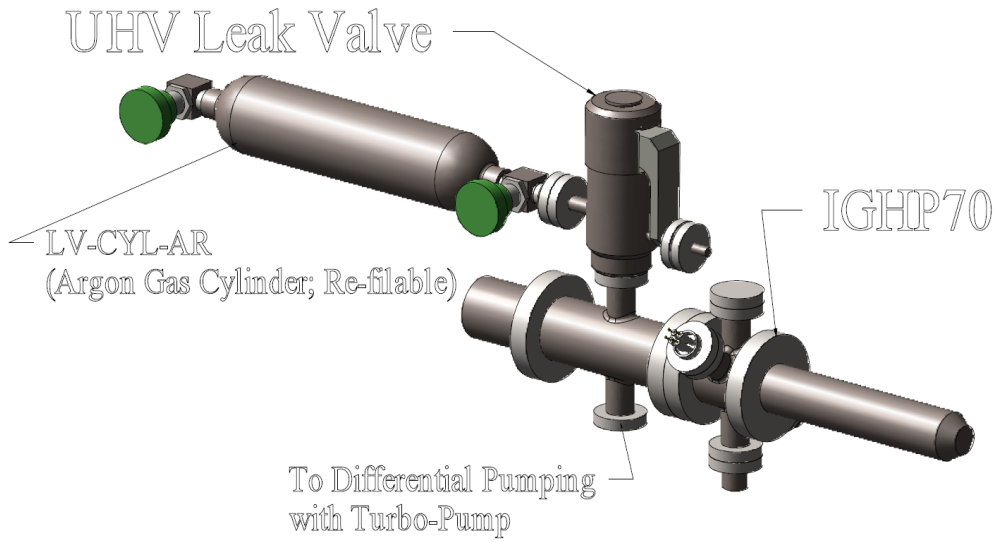
- RIS Ba not seen as a result of loading from Ba source
- Ba loaded from source forms molecules: see BaF (source byproduct) but not atomic Ba from source
- Can reduce Ba molecule formation with better vacuum, CVD graphene surface





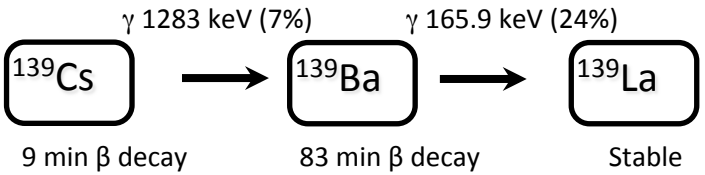
Argon Ion Gun

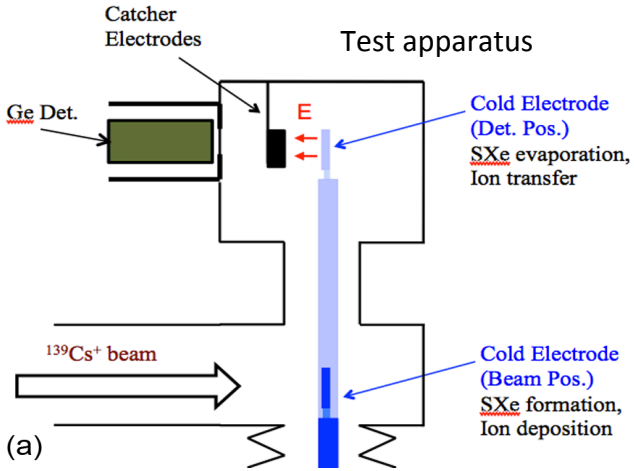
- Cleaning *in situ* is probably only way to get Ba-free surface
- Attempts to clean by heating surfaces led to more background Ba
- Ar ion gun should remove surface Ba, remove oxides, and homogenize surface
- Designing new chamber to reduce air exposure when replacing substrates and allow for targeted Ar sputtering on demand
- Better vacuum could reduce Ba molecule formation



Barium tagging by Thermal Ionization (Illinois, TU Munich)

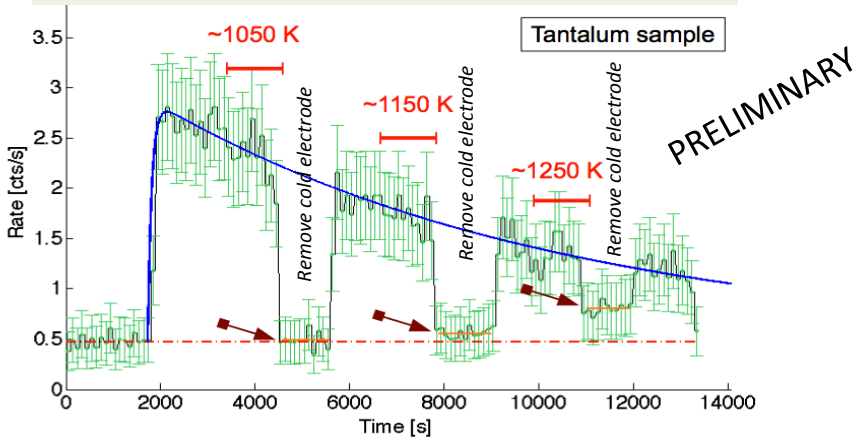
CARIBU beam at Argonne National Lab provides radioactive beams of Cs-139 or Ba-139

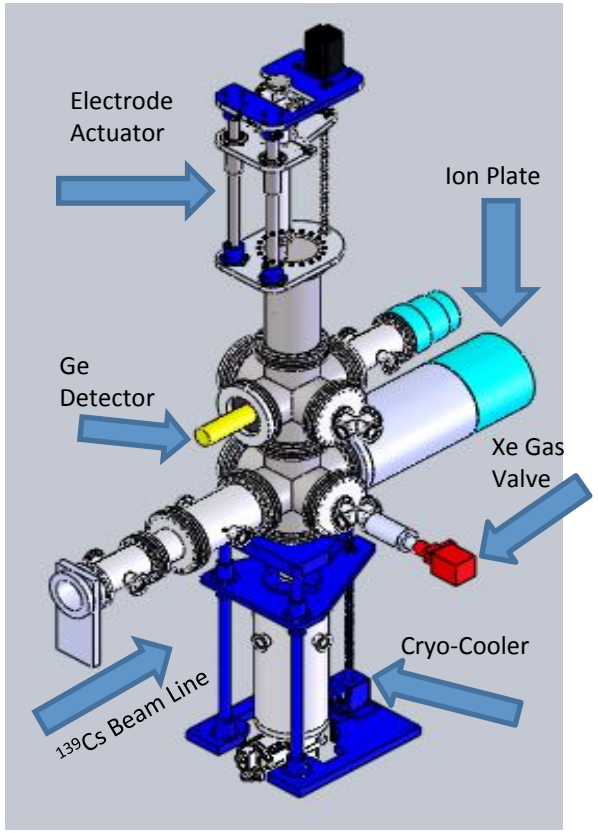




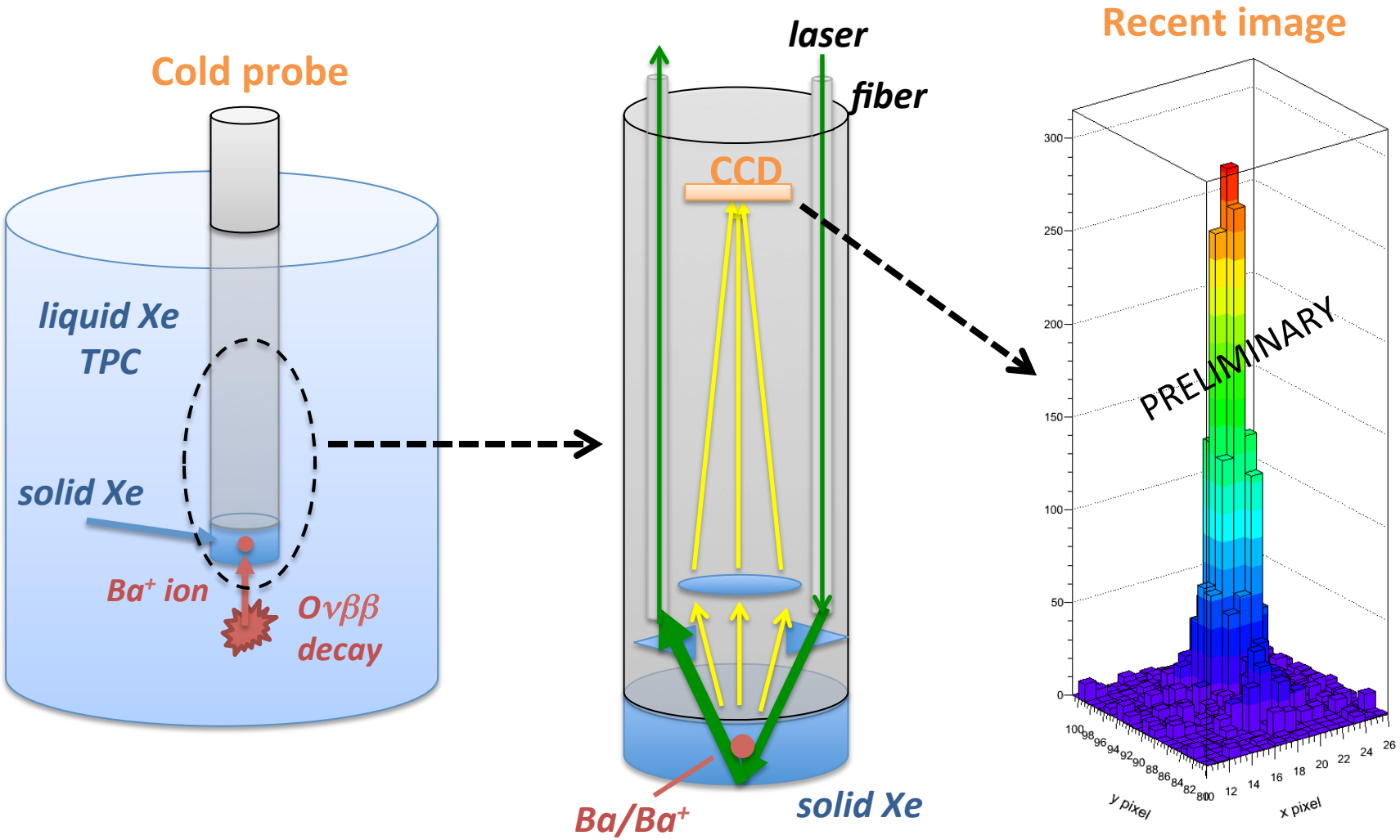
- Study neutralization of Ba in Xenon Ice.
- Study of desorption of Ba from surfaces.

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





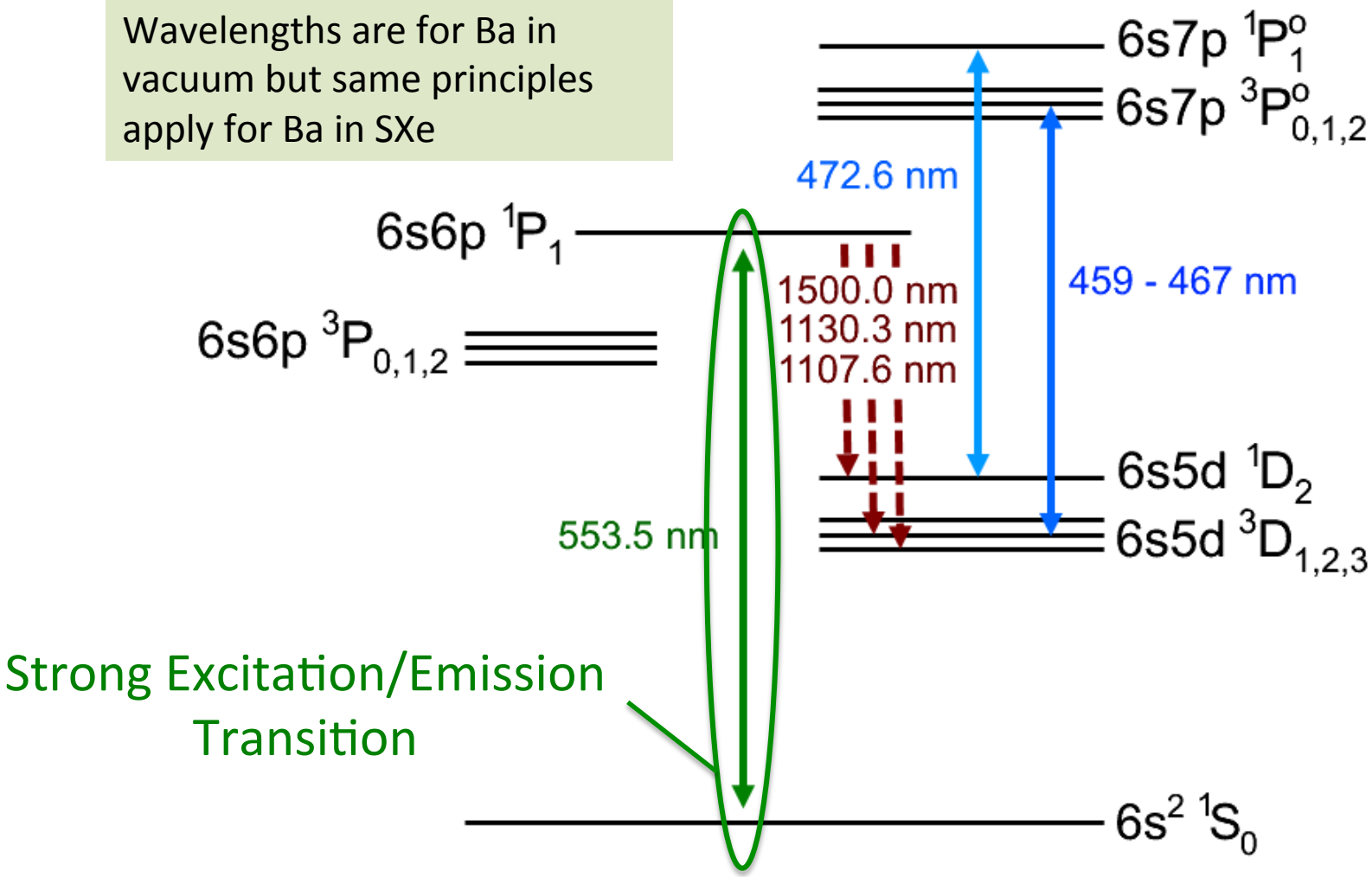
Ba Tagging in Solid Xenon (Colorado State)



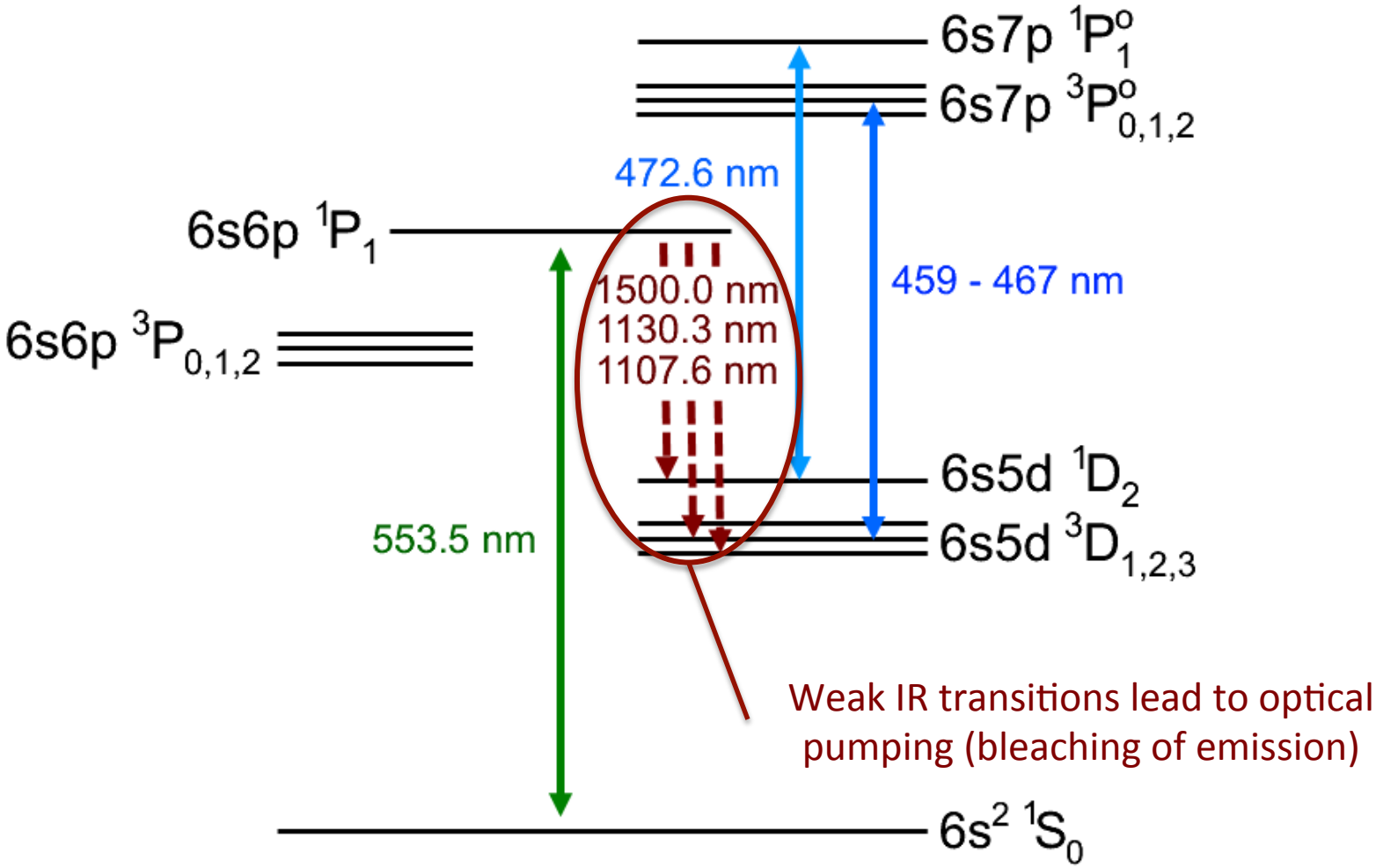
~1 Ba atom

Obtaining many photons from single Ba atoms:

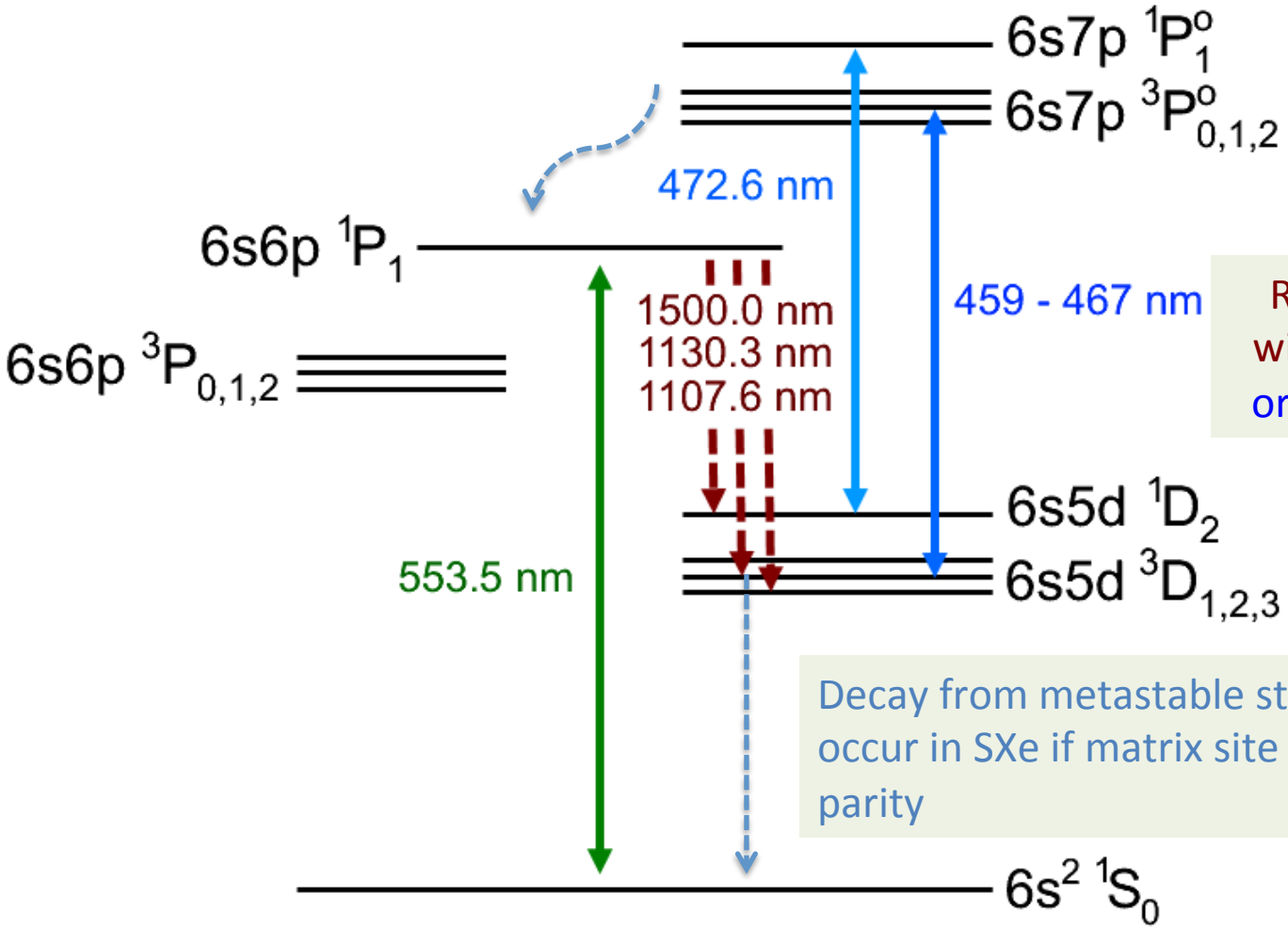
Wavelengths are for Ba in vacuum but same principles apply for Ba in SXe



Obtaining many photons from single Ba atoms: limit due to optical pumping



Overcoming optical pumping to 6s5d states

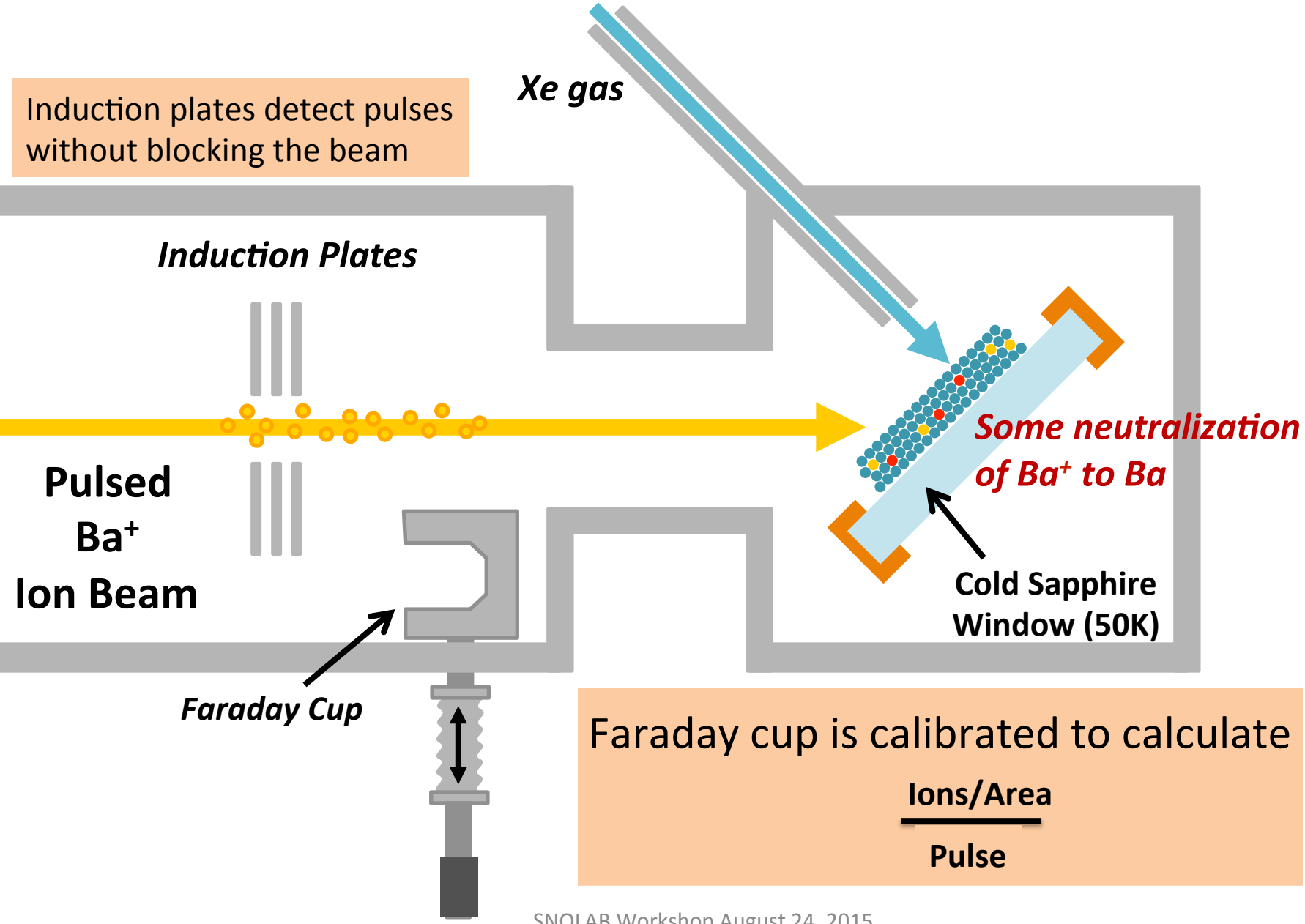


Repumping with IR lasers or blue lasers

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

Ba^+ Ion Deposition in SXe

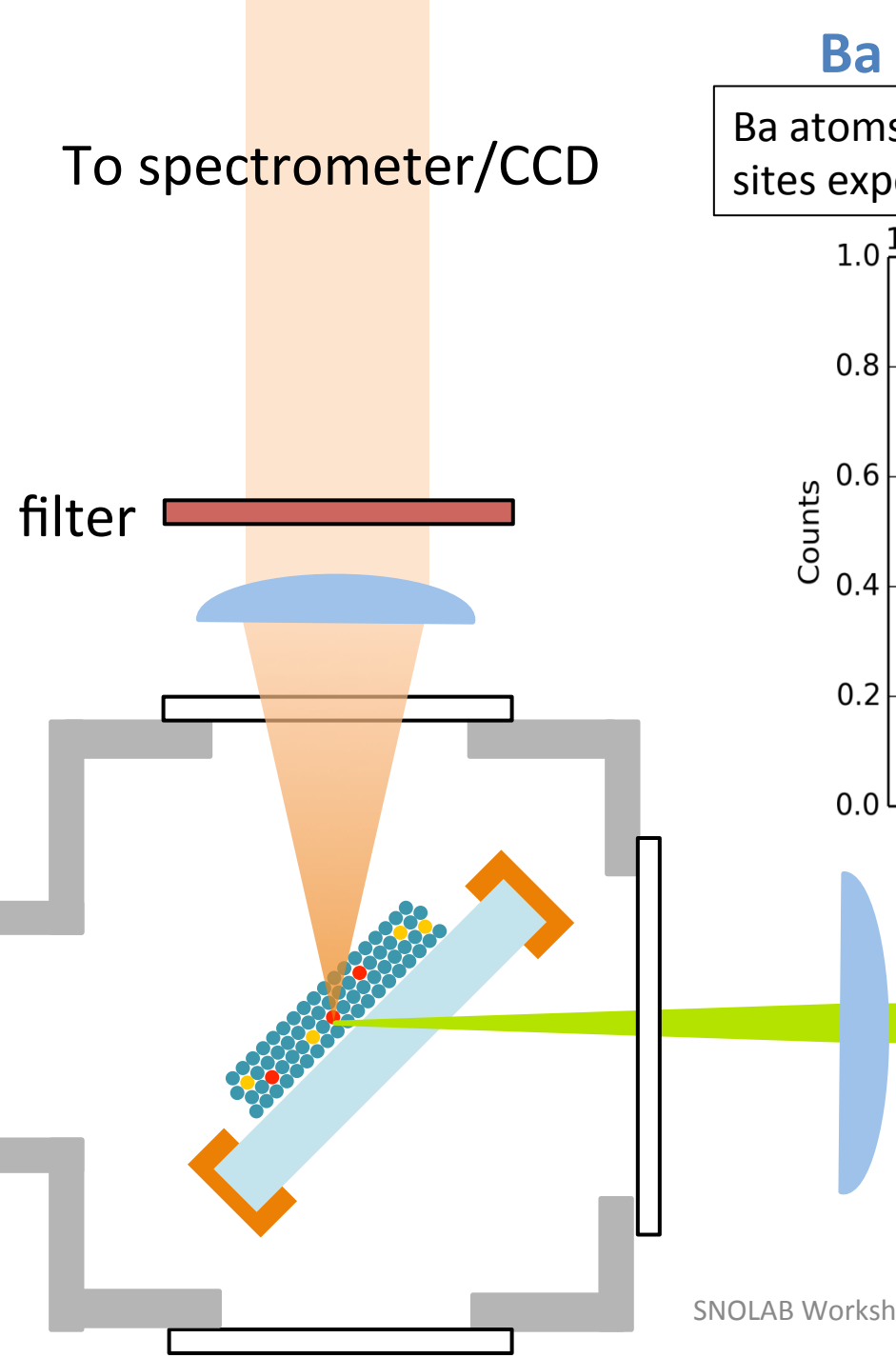
Induction plates detect pulses without blocking the beam



Faraday cup is calibrated to calculate

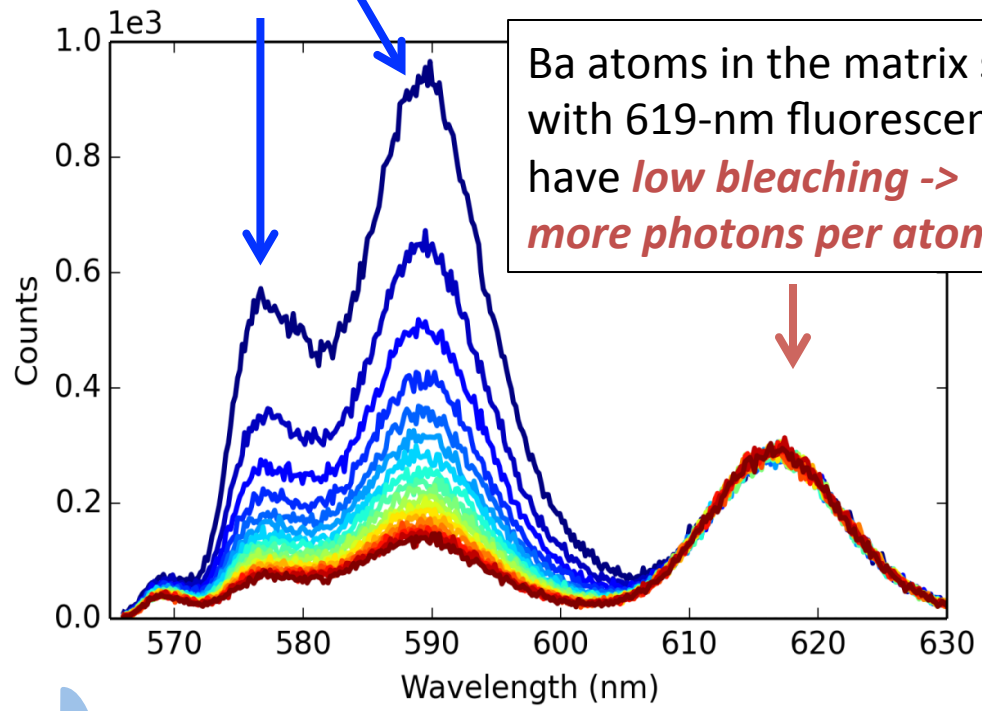
$$\frac{\text{Ions/Area}}{\text{Pulse}}$$

Ba fluorescence spectra, 1-s intervals



Ba atoms in these matrix sites experience bleaching

Ba atoms in the matrix site with 619-nm fluorescence have ***low bleaching -> more photons per atom***



B. Mong *et al.*, Physical Review A **91**, 022505 (2015)

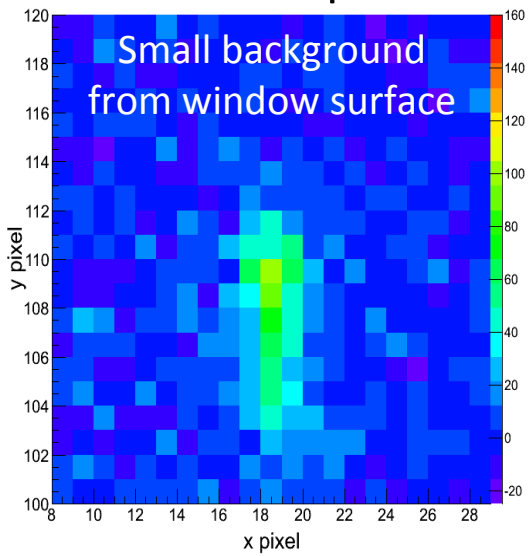
Tunable Dye Laser at 570 nm

Procedure for making images of Ba atoms

Procedure for each deposit:

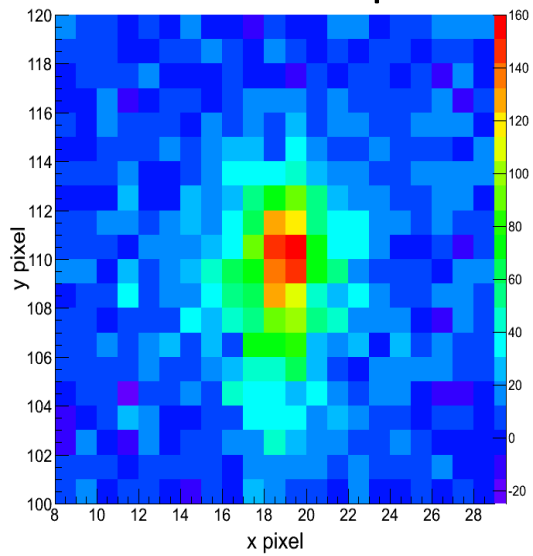
- SXe deposited on window at 50K for ~6 seconds
- N pulses of Ba^+ ions incident half way through SXe deposit
  - (typically ~20 pulses-> 1 Ba^+ in laser beam)
- Cool to 10K for imaging with better fluorescence
- Evaporate each deposit after imaging by heating to 100K

0 Atom Deposit



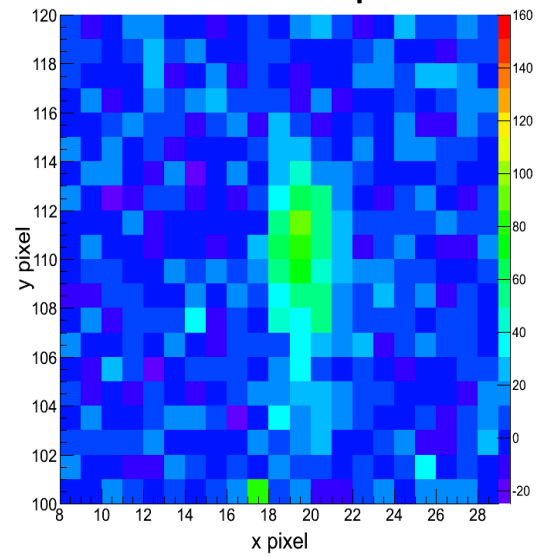
Heat to 100K to evaporate deposit

≤12 Atom Deposit



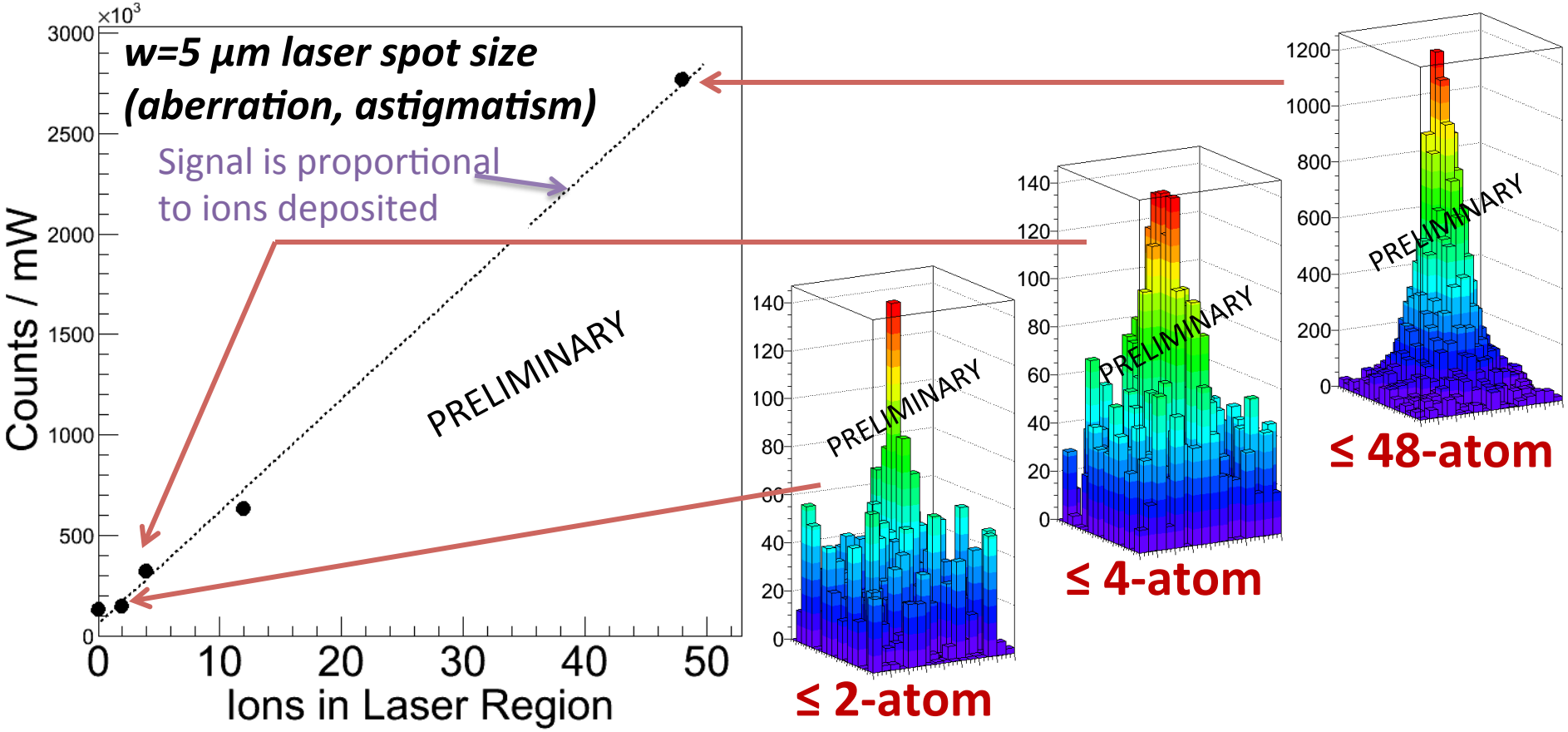
Heat to 100K to evaporate deposit

0 Atom Deposit



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

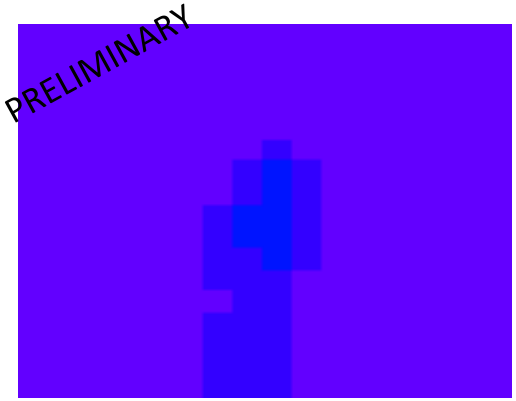
Images of small numbers of Ba atoms in focused laser



Number of <u>atoms</u> in the image is based on the number of <u>ions</u> deposited. The neutralization fraction is unknown, so the number of <u>atoms</u> is less than or equal to the measured number of <u>ions</u>.

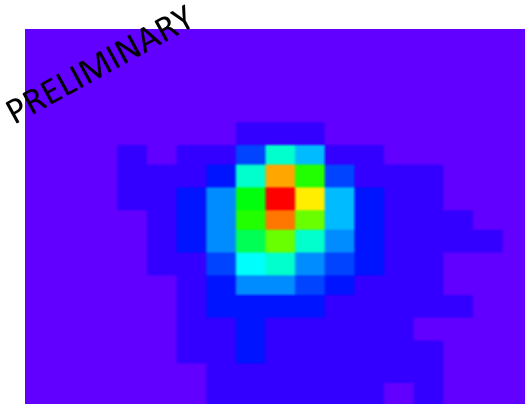
No residual Ba signal even after a large deposit

0 Atom Deposit



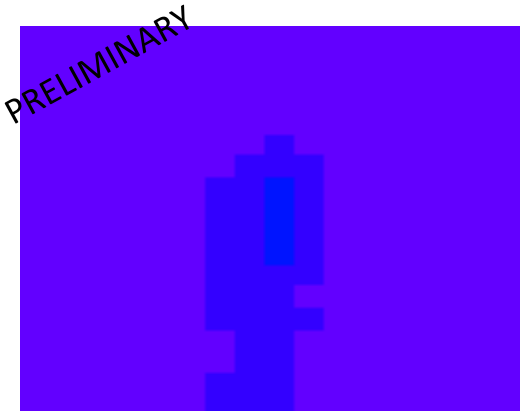
Heat to 100K to evaporate deposit

≤ 500 Atom Deposit



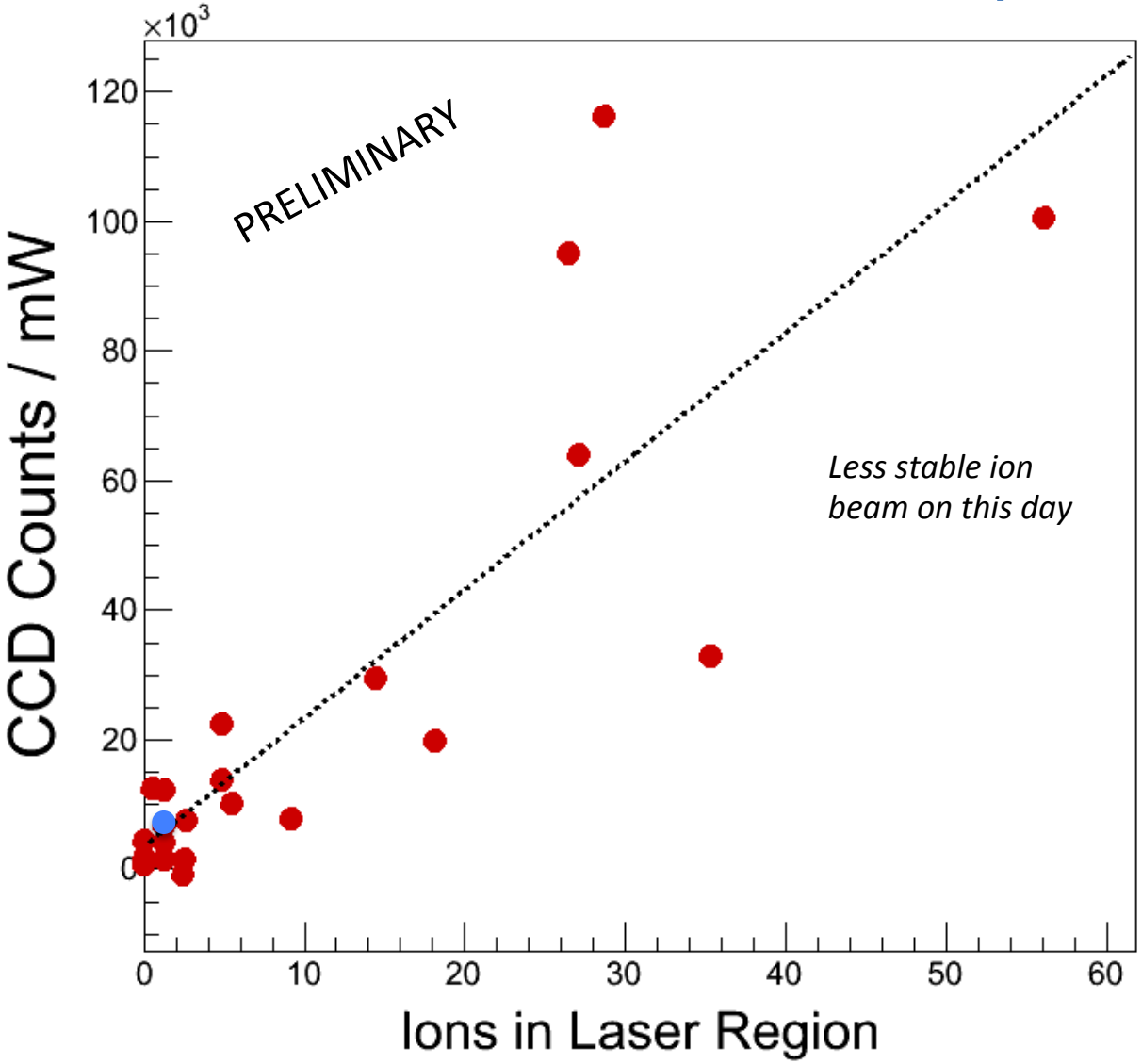
Heat to 100K to evaporate deposit

0 Atom Deposit

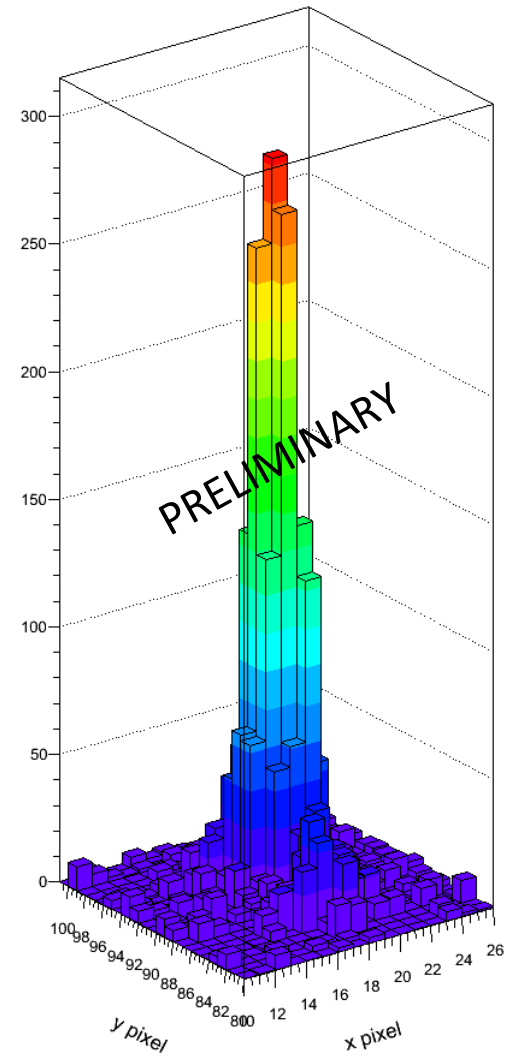


No "history" effect

Toward scanned images: recent results with better focus w=2.5 µm

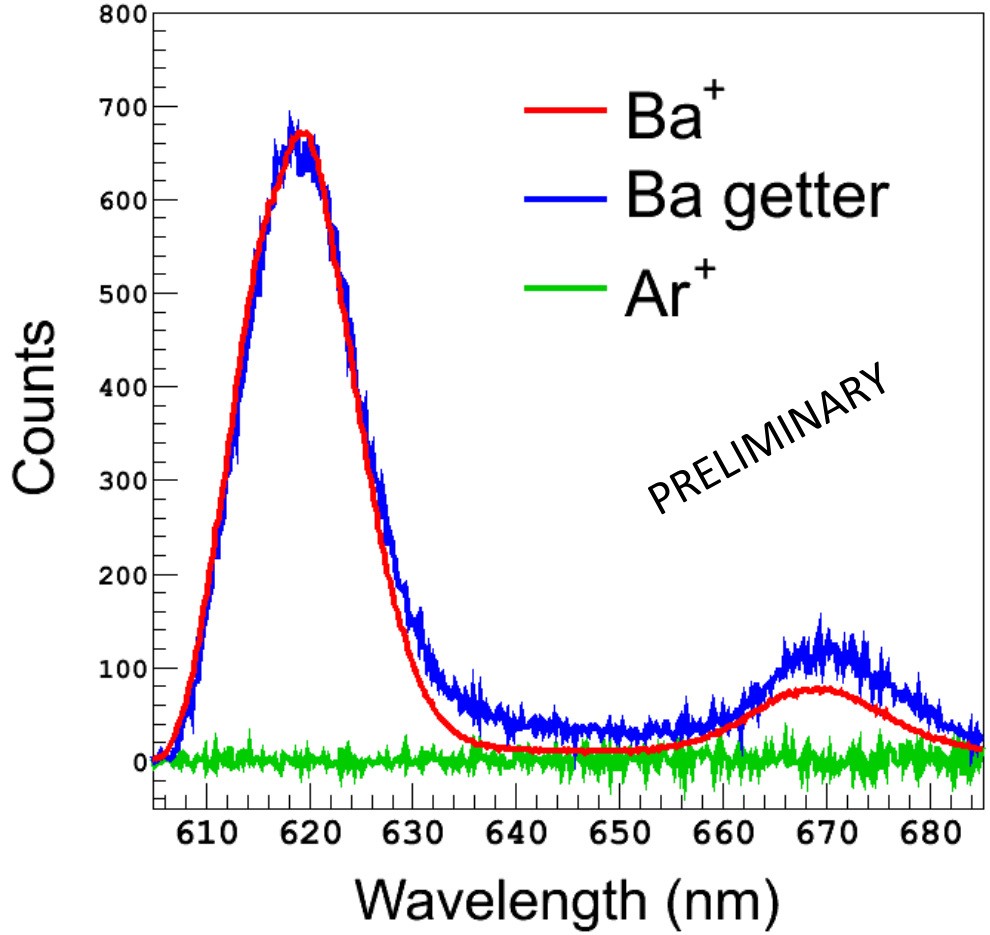


≤1-atom … large signal



Check

Fluorescence of deposits from three different sources:



Important Observations

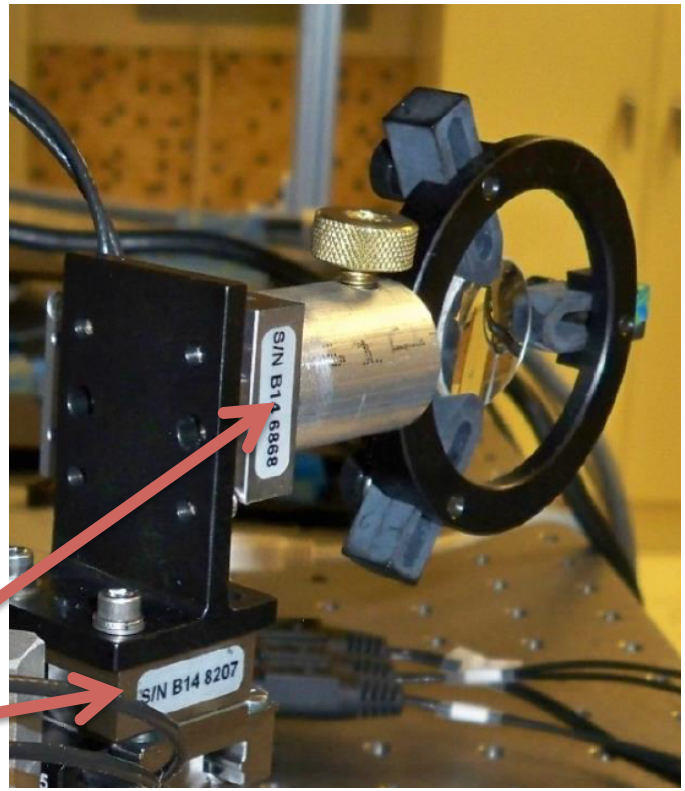
(a) 619 and 670 nm peaks SIMILAR with neutral Ba getter deposits as with Ba^+ beam

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

Signal is from Barium!

Next step

- *Next step: scanned images of single atoms – count Ba!*

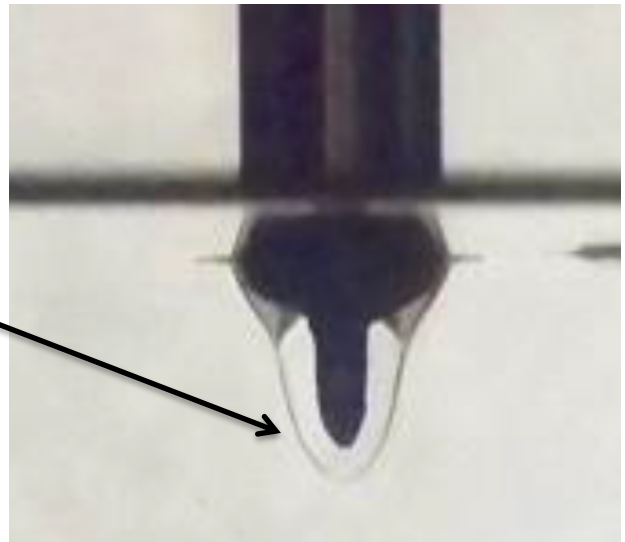


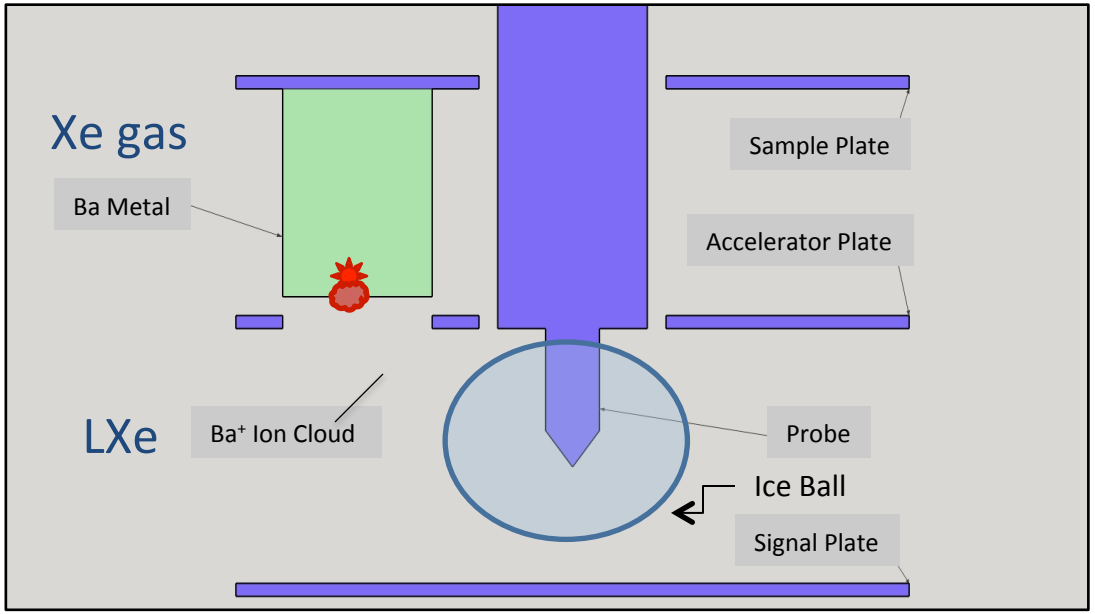
Motorized translation stages for sub-micron scanning steps

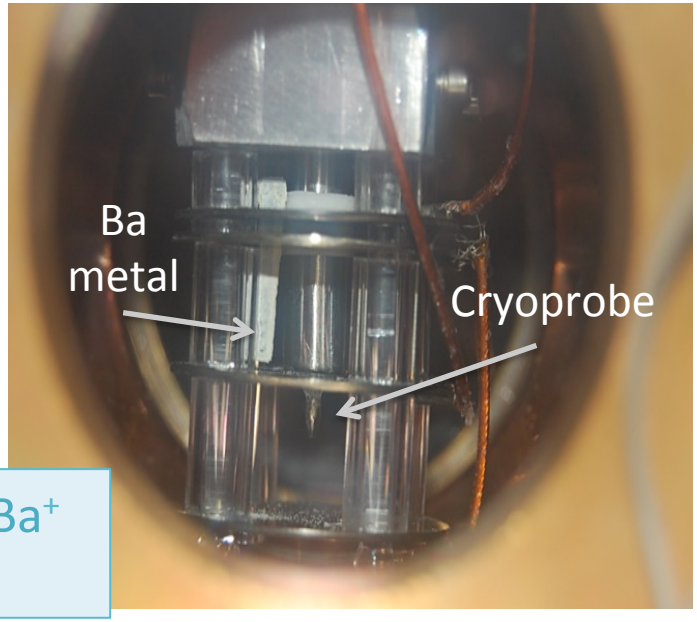
Apparatus for capture of Ba^+ on a cryogenic probe

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

SXe ice ball formed is clear



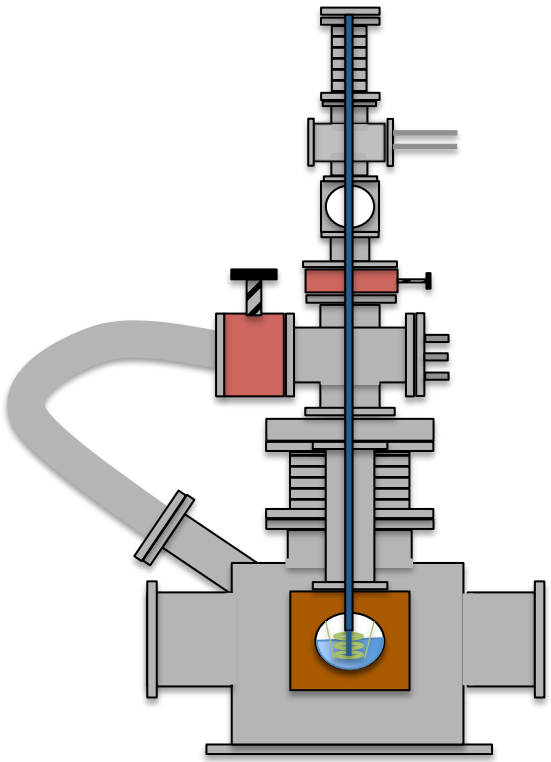




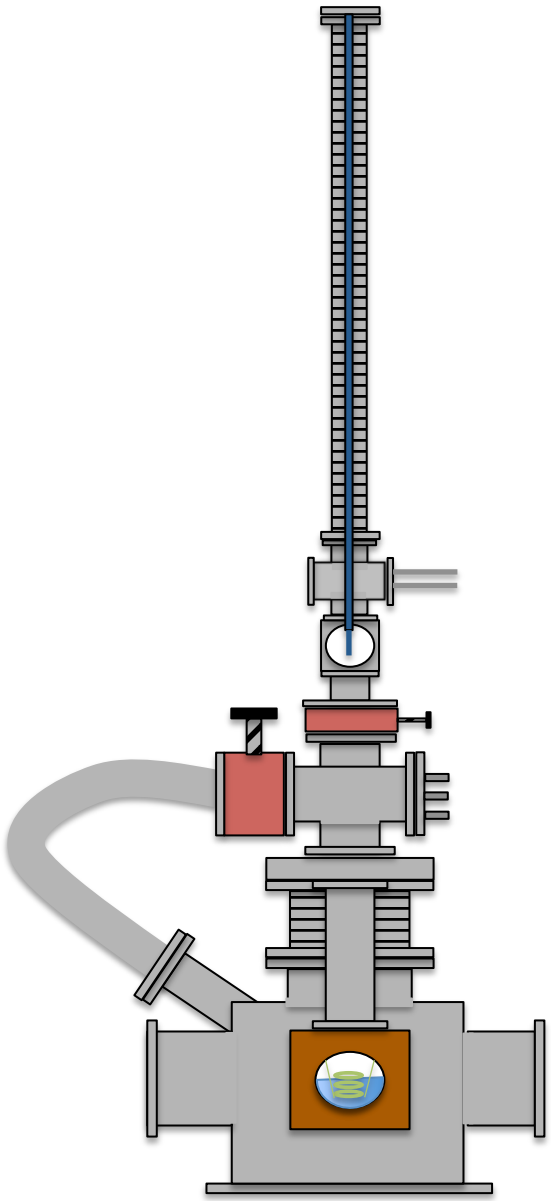
First tests underway with laser ablation source of Ba^+
Then Cf fission source

Probe extraction apparatus

(1) Capture Ba in SXe on end of probe

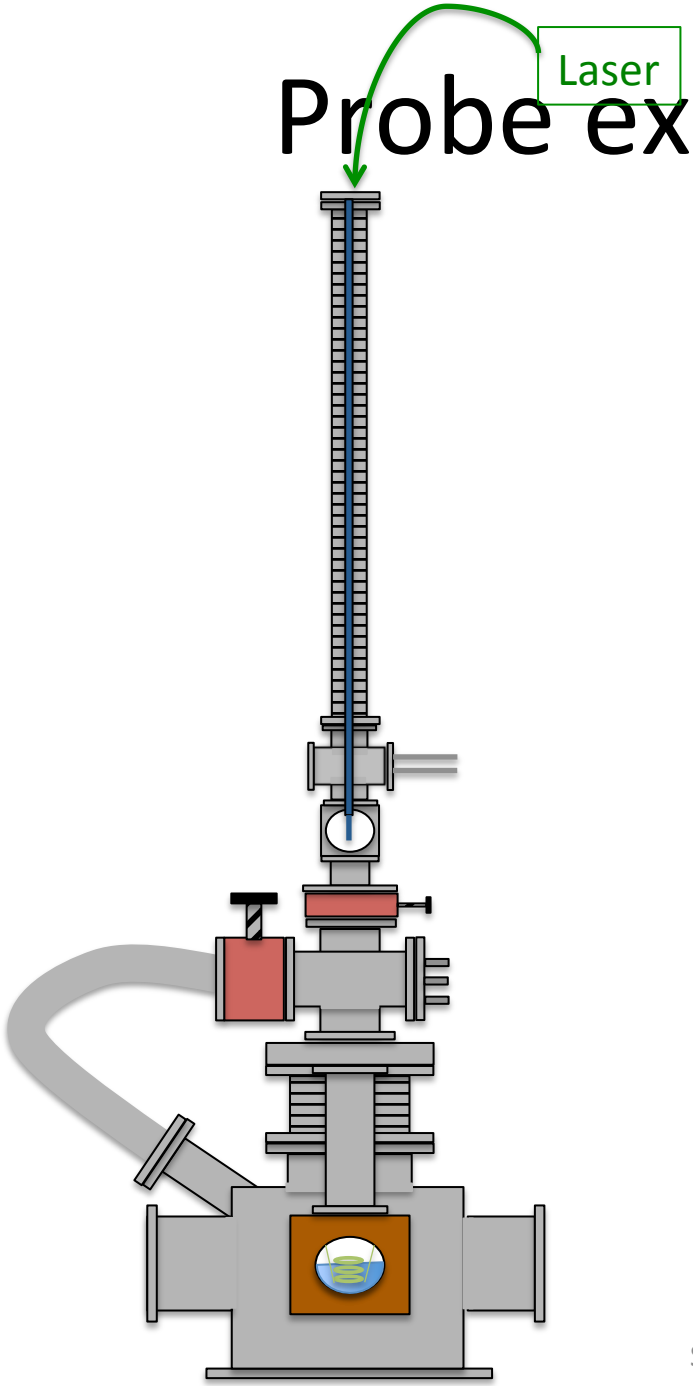


Probe extraction apparatus



(1) Capture Ba in SXe on end of probe
(2) Extract probe

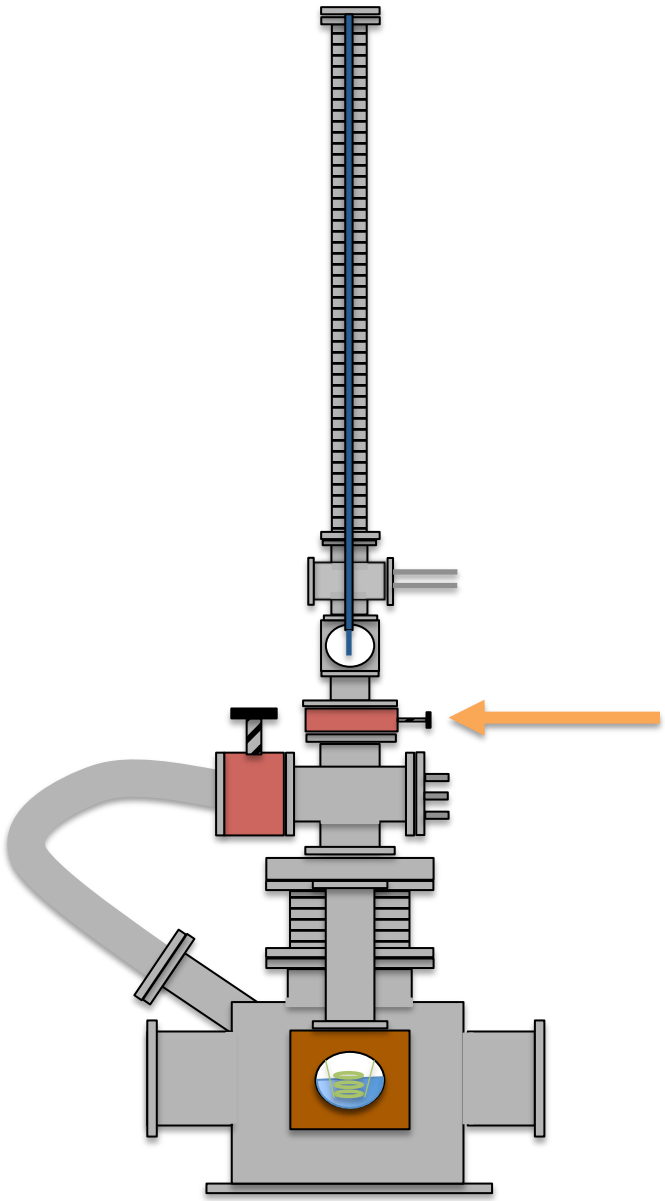
Probe extraction apparatus



(1) Capture Ba in SXe on end of probe
(2) Extract probe
(3) Detect Ba in SXe by laser imaging

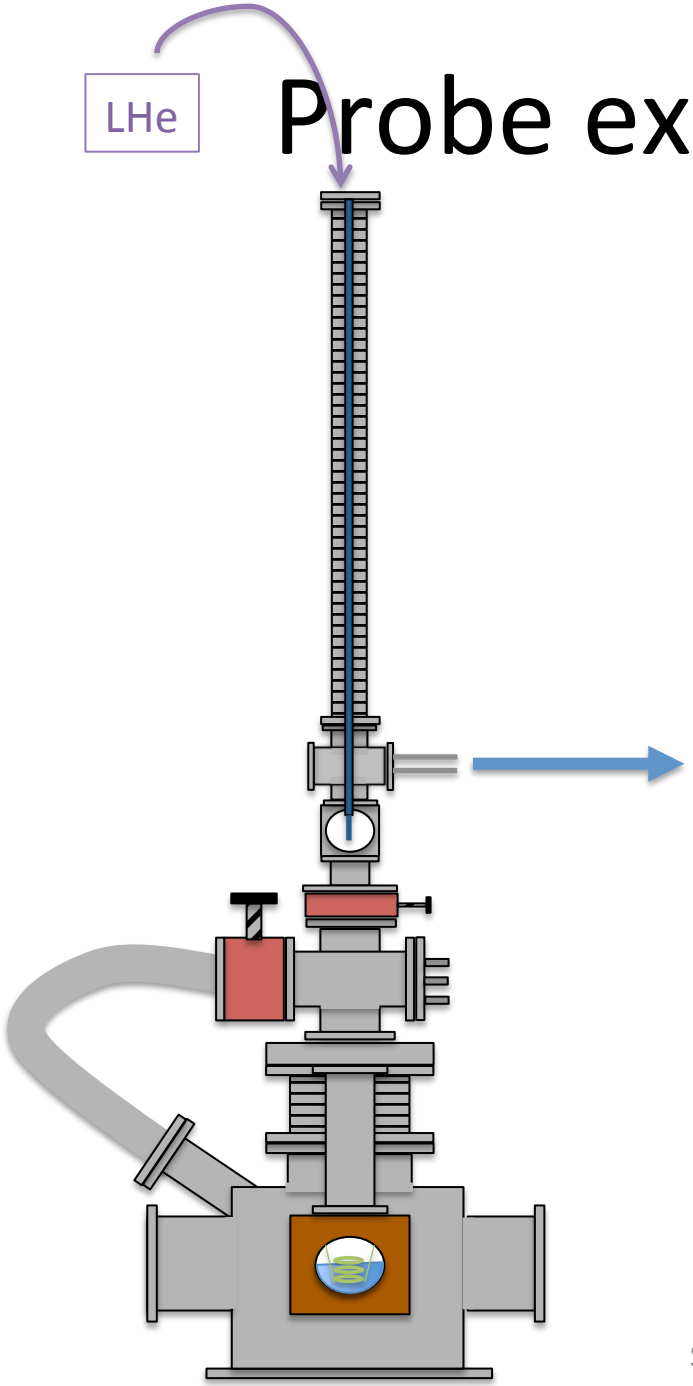
Two concerns:
(1) What if Ba doesn't fluoresce well in SXe at ~160K?
(We know that 619nm emission is weaker at 50 K than 10 K.)

Probe extraction apparatus



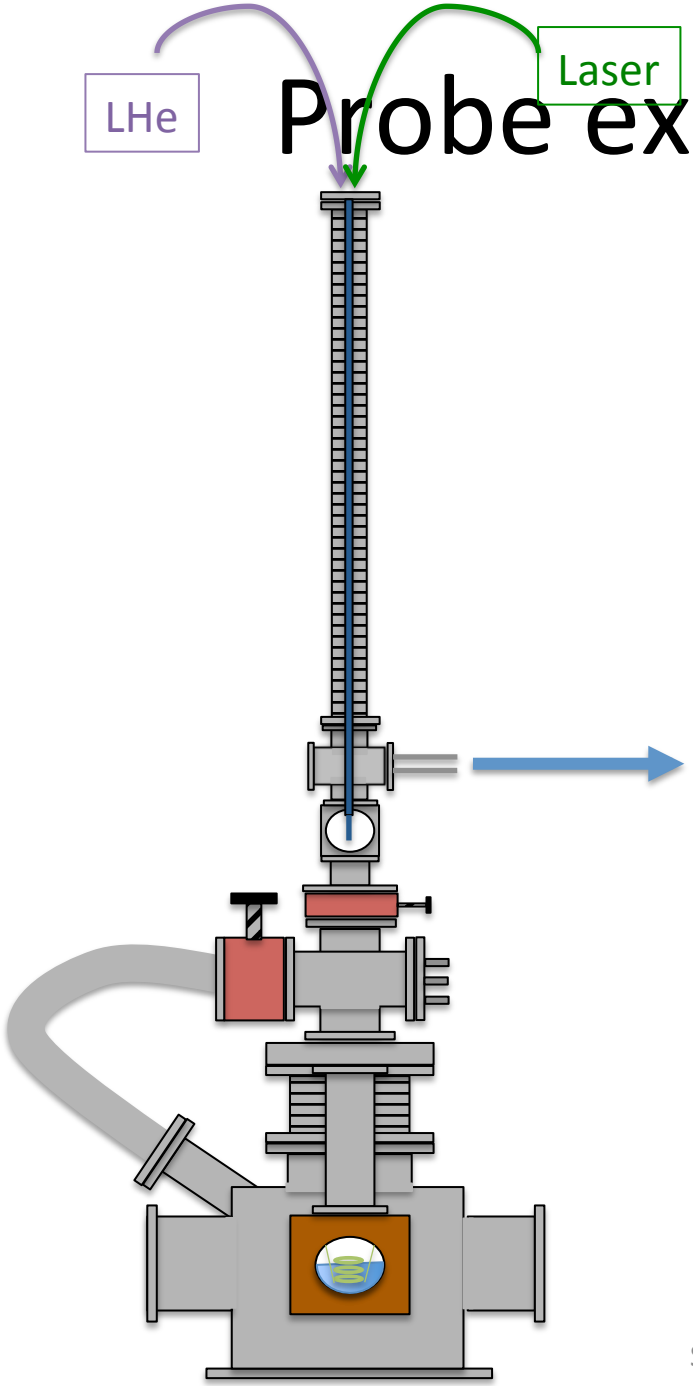
(1) Capture Ba in SXe on end of probe
(2) Extract probe
(3) Close valve

Probe extraction apparatus



(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 equilibrium so SXe layer constant)

Probe extraction apparatus



(1) Capture Ba in SXe on end of probe
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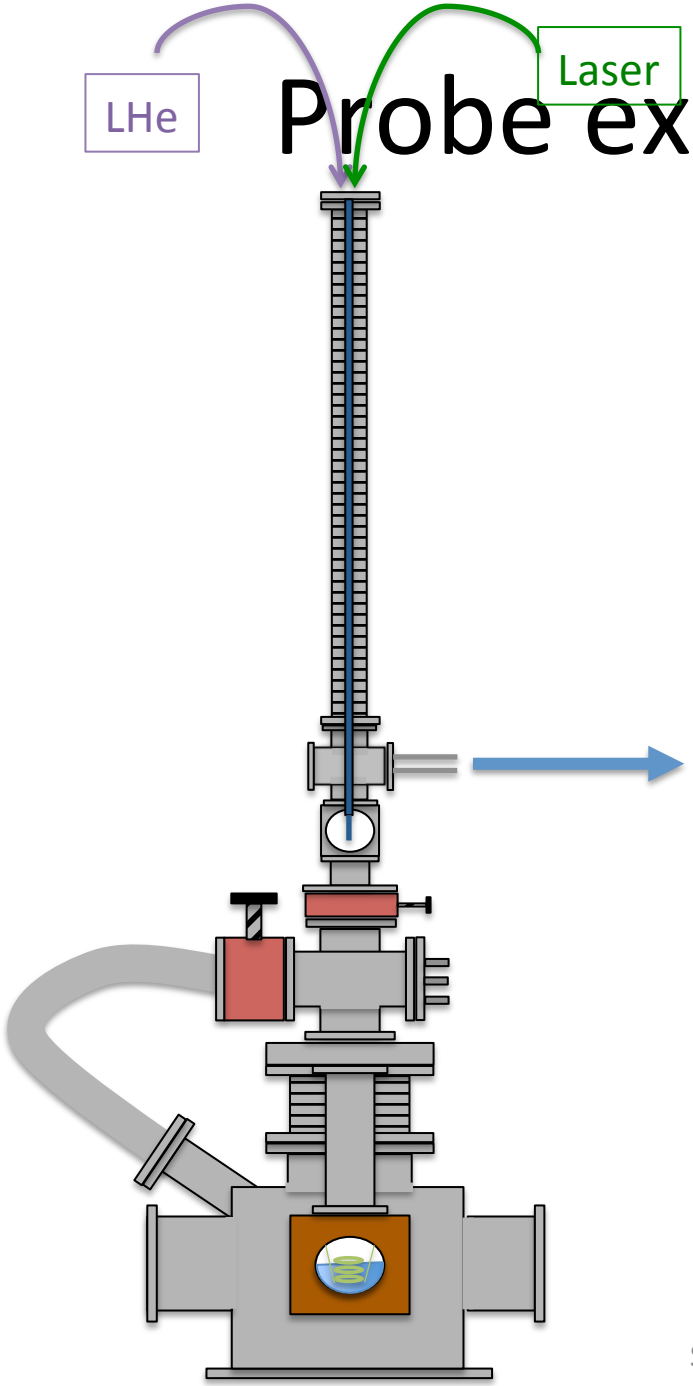
(5) Detect Ba in SXe by laser imaging

Probe extraction apparatus

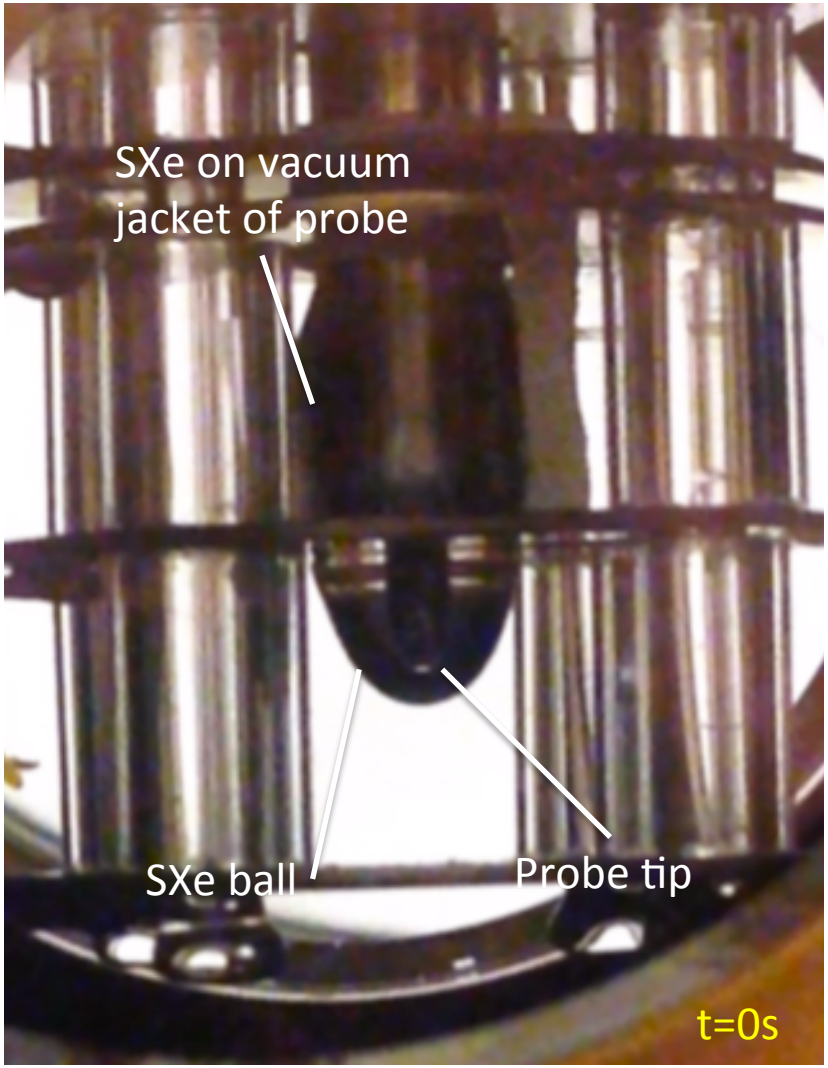


(1) Capture Ba in SXe on end of probe
(2) Extract probe
(3) Close valve
(4) Reduce Xe pressure while cooling probe tip to 10K (in vapor pressure equilibrium so SXe layer constant)
(5) Detect Ba in SXe by laser imaging

Concern (2): when extract the probe from LXe, the SXe layer on probe is not in vapor pressure equilibrium with the gas.

What happens???

Non-equilibrium test

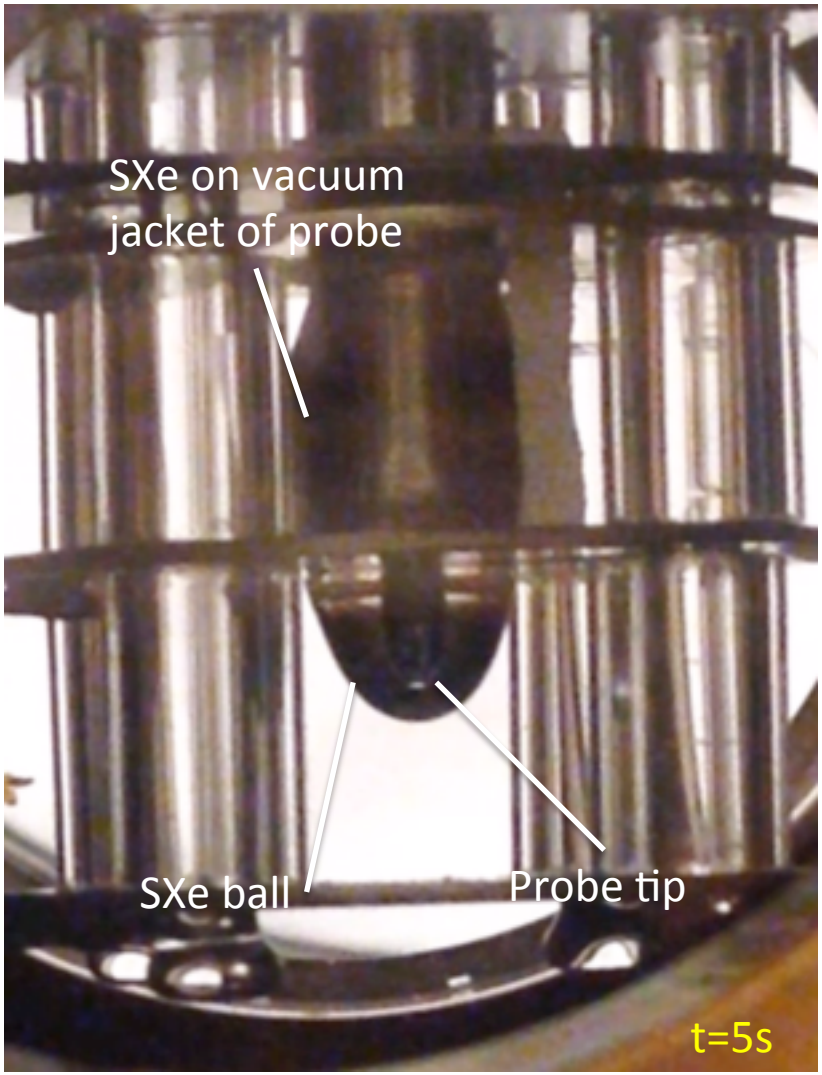


To test non-equilibrium conditions, we make a SXe ball at 163K, 480 Torr (< p_{TP}) Then quickly raise pressure to 760 Torr (> p_{TP})

Observations:

- Start with a SXe ball made at 480 Torr

Non-equilibrium test



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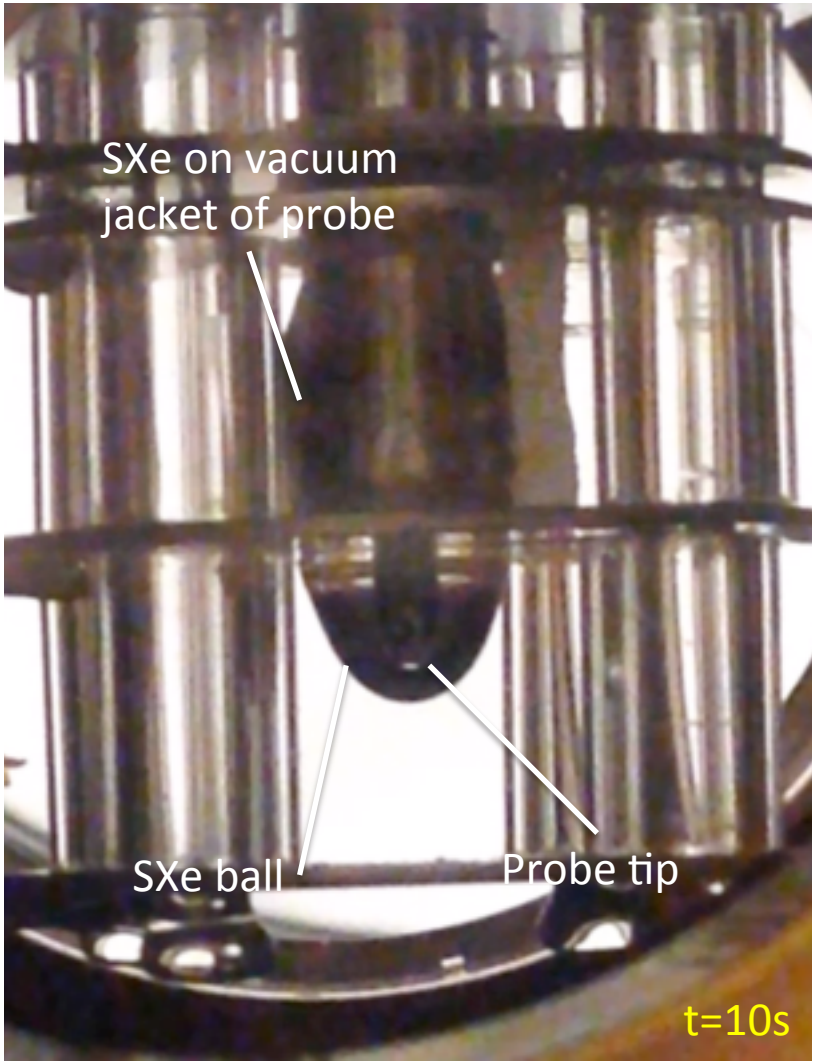
Observations:

- Start with a SXe ball made at 480 Torr
- Not much happens for ~20 s

Non-equilibrium test



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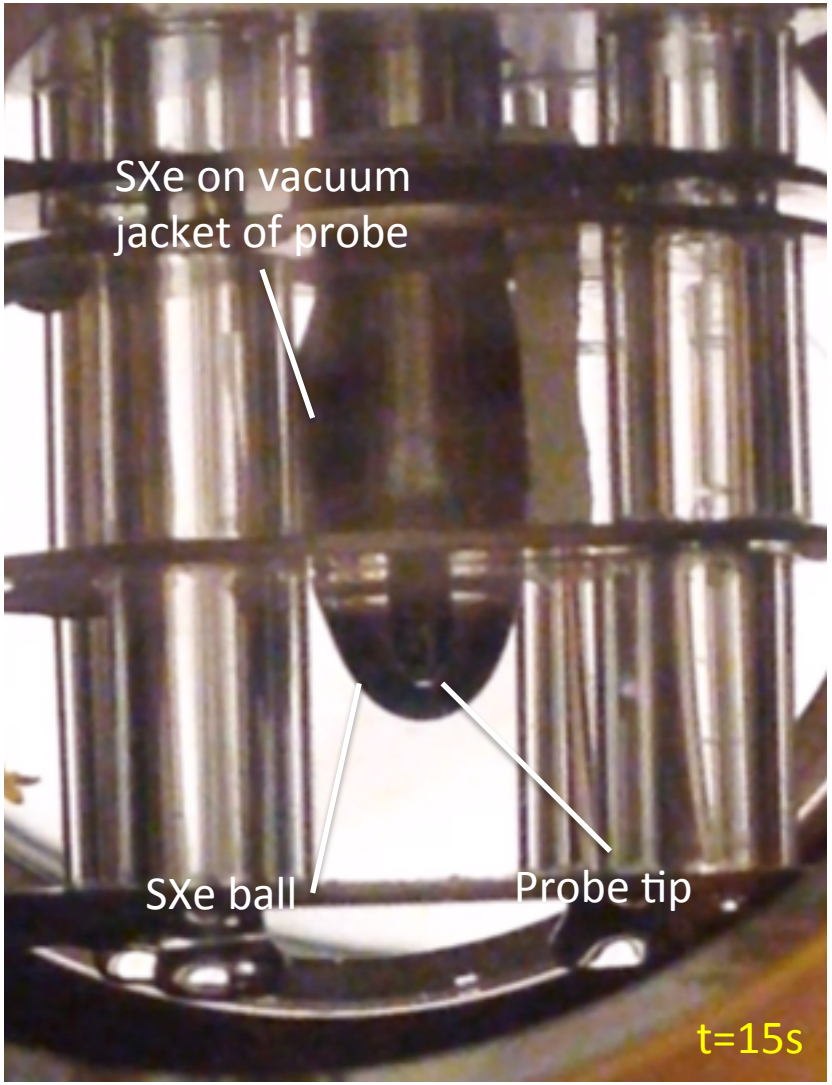

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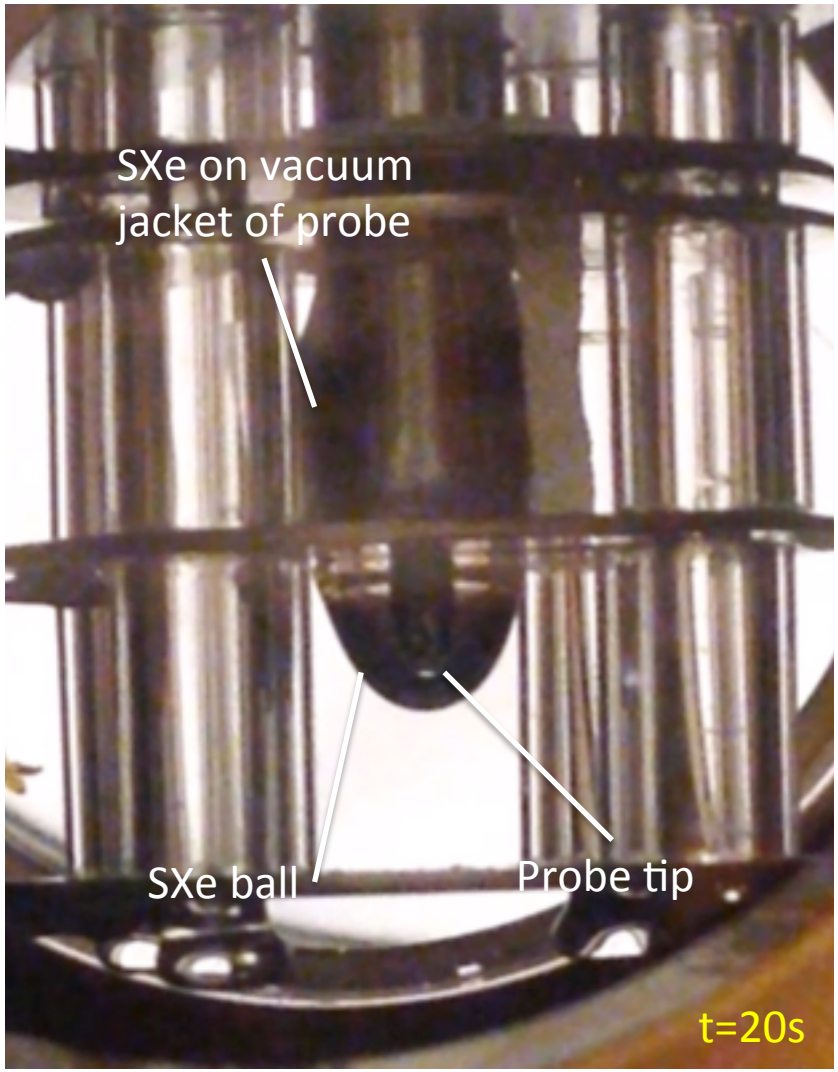

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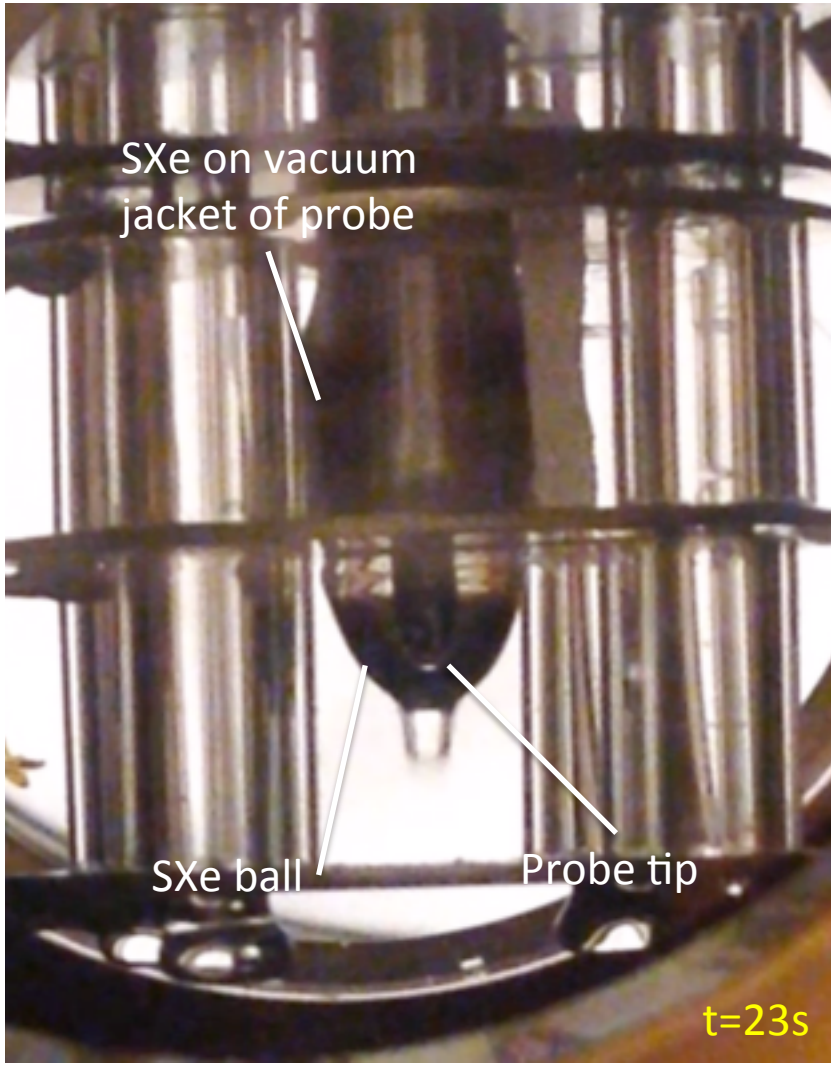
Non-equilibrium test



To simulate non-equilibrium conditions, we make a SXe ball at 163K, 480 Torr (< p_{TP})
Then quickly raise pressure to 760 Torr (> p_{TP})

Observations:

- Start with a SXe ball made at 480 Torr
- Not much happens for ~20 s
- Then SXe on vacuum jacket starts melting and liquid Xe starts dripping from SXe ball

CONCLUSION: plenty of time to close valve and lower pressure after extraction of probe from LXe

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

(Bern – recently moved to Carleton)

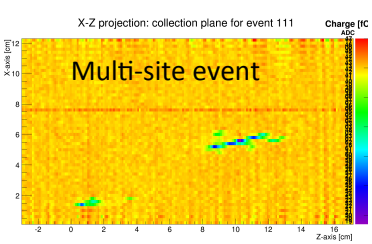
Approach

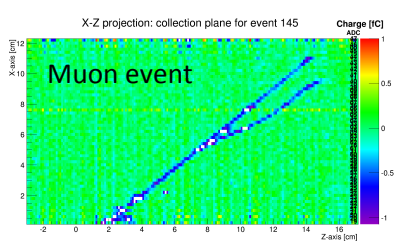
- Detect decay of ^{222}Rn within the TPC volume
- Extract ^{218}Po daughter to the gas phase with probe
- Monitor ^{218}Po decay with alpha detector

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

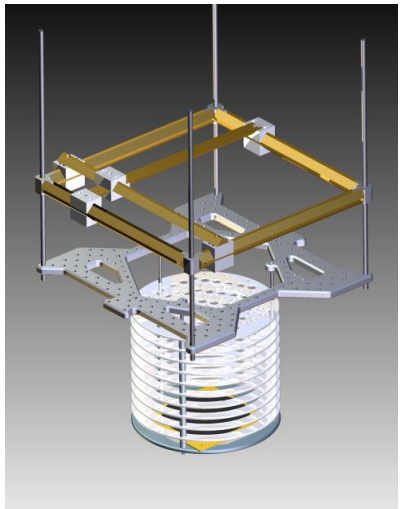
$$^{222}\text{Rn} \xrightarrow[]{100.\%} \underset{(5.5\ \text{MeV})}{\alpha_1} + {}^{218}\text{Po} \xrightarrow[]{99.98\%} \underset{(6.0\ \text{MeV})}{\alpha_2} + {}^{214}\text{Pb}$$

TPC events recorded

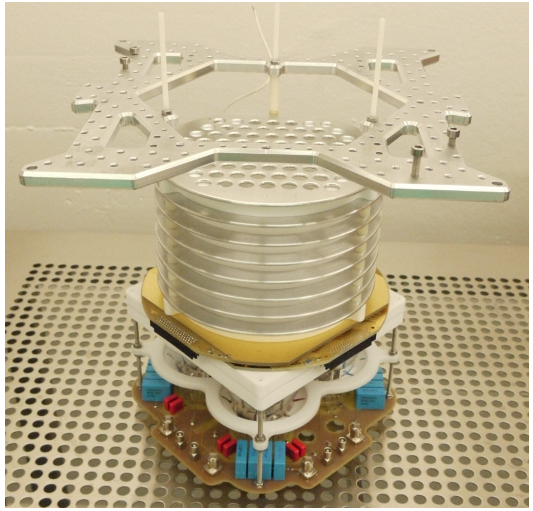




Probe manipulator above TPC



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



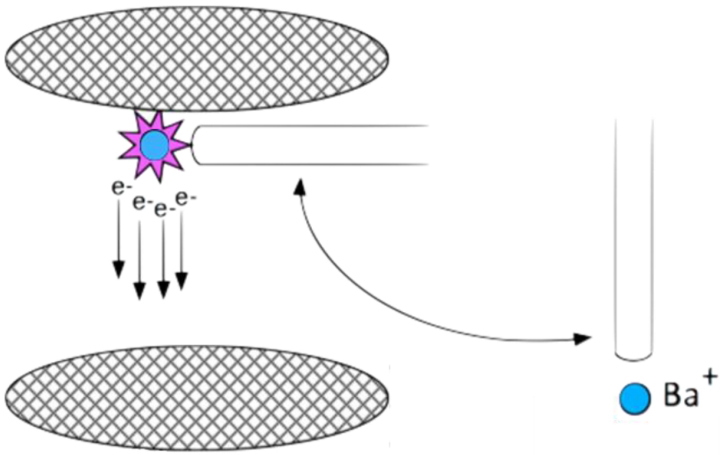
This work is currently on hold as this TPC is being used for HV tests.

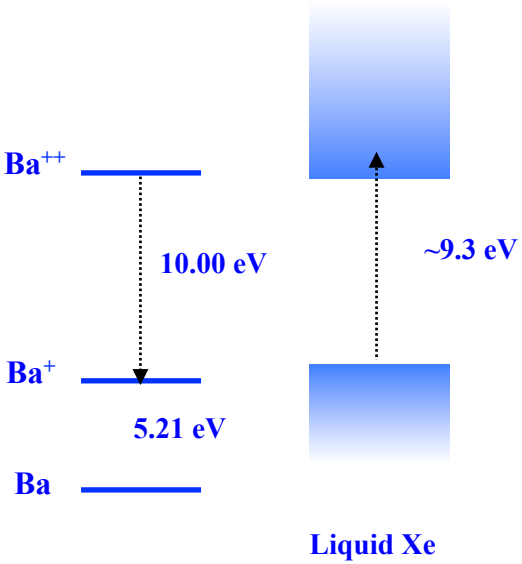
Ba tagging in LXe: What is the Ba charge?

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

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

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





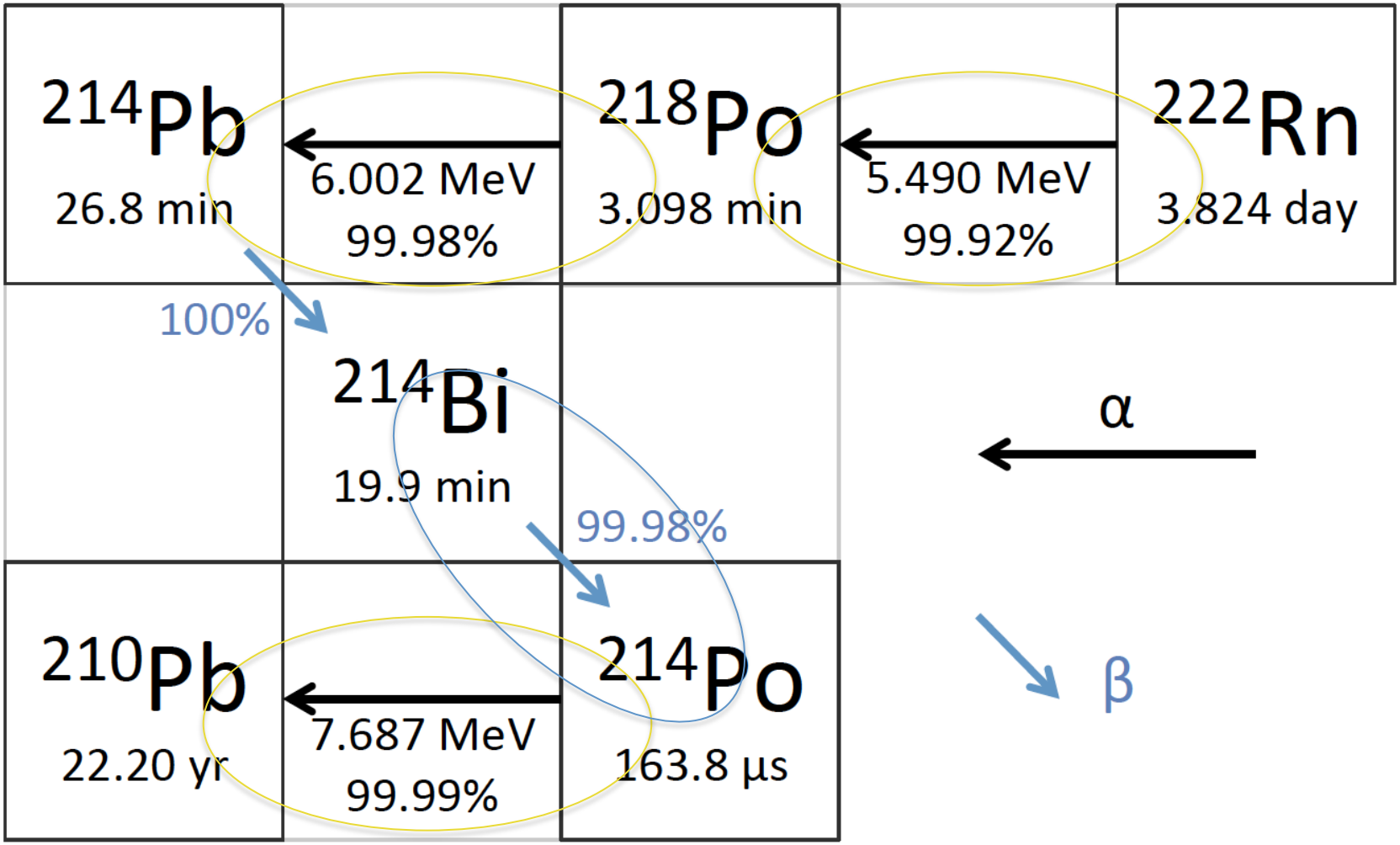
But could further neutralization of Ba+ occur due to electron cloud at decay site?

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

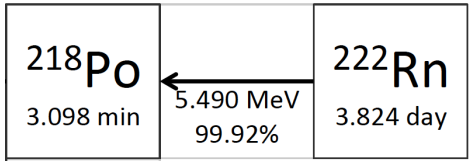
TEST: measure daughter ion fractions in alpha and beta decay in EXO-200.

^{222}Rn chain alpha and beta decays

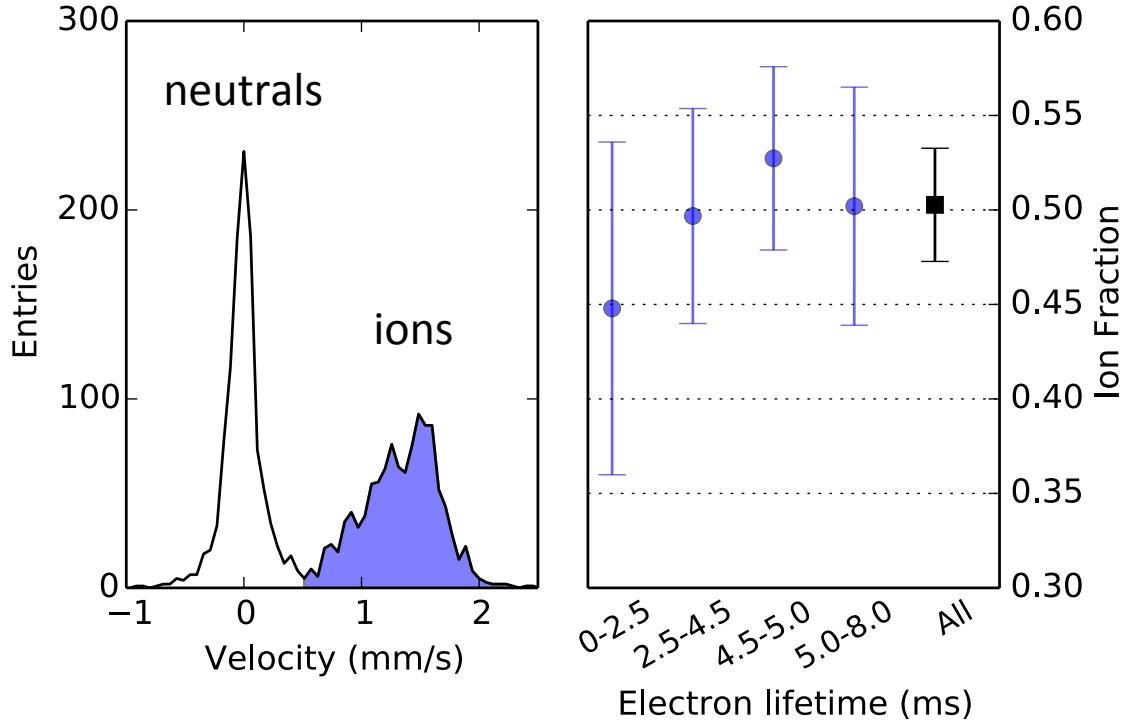
In EXO-200 we detect three alpha decays and one beta decay



^{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)

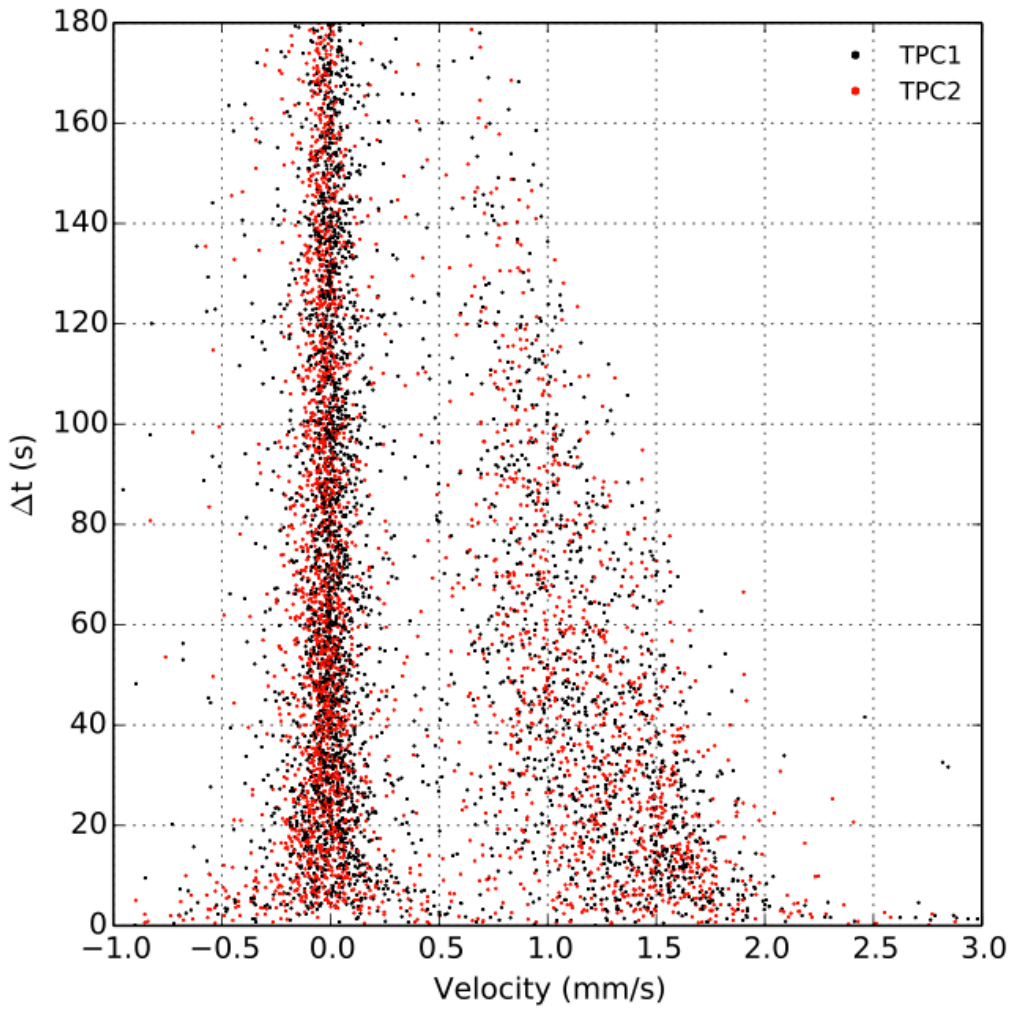


RESULT: Ion fraction of ^{218}Po daughter from α-decay is 50.3±3.0%.
Ion fraction does not depend on purity.

J. B. Albert et al., submitted to 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:

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

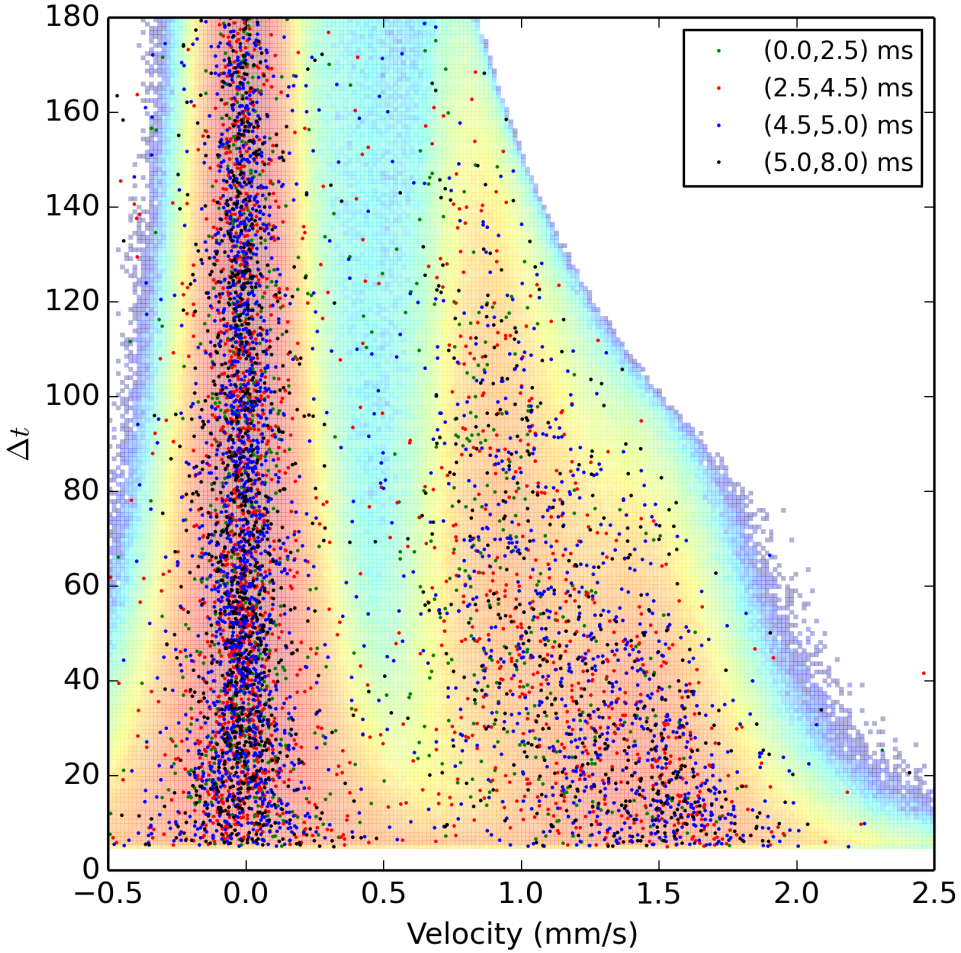
$$^{218}Po^{++} + X \Rightarrow ^{218}Po^{+} + X^{+}$$

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:

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 $\frac{A^{214}_{\mathrm{Po}}}{A^{222}_{\mathrm{Rn}}}$

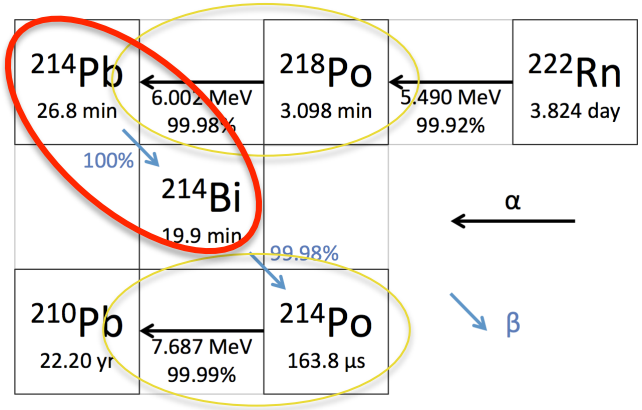
(Assume 50.3(3.0)% of ^{214}Pb are ions)

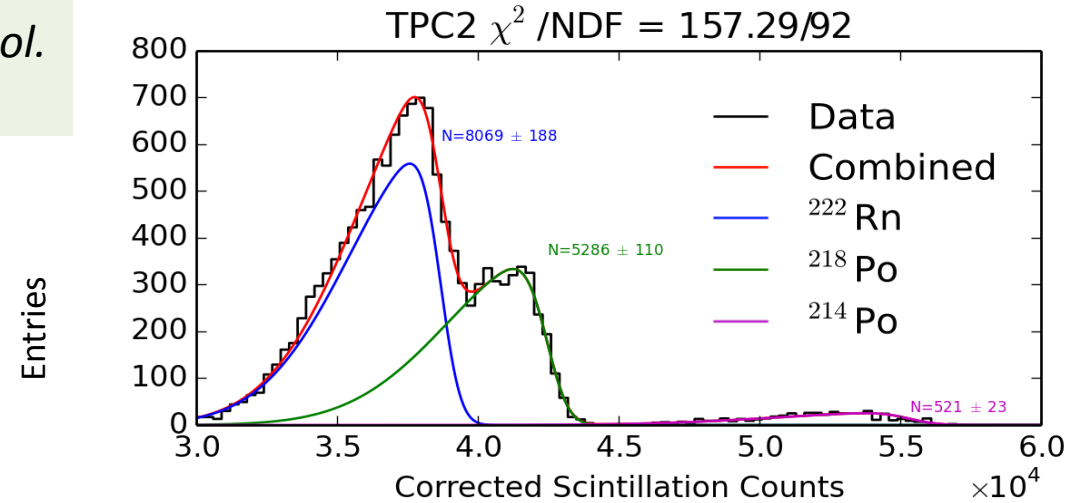
Neutrals Decay in flight

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

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., submitted to Physical Review C (2015) [arXiv:1506.00317]

Summary

- Progress on Ba tagging in a number of nEXO groups, especially in US and Canada
- Demonstration of some key concepts for future gas TPC
- Progress on Ba tagging for nEXO
  - RIS probe work sensitive to small #s of Ba atoms
  - Single-atom sensitivity 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 done

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