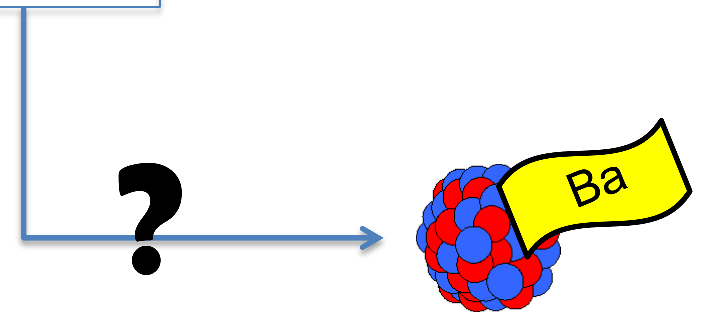
Barium-ion tagging for ^{136}Xe double-beta decay studies with EXO

$$^{136}\mathrm{Xe} \rightarrow \boxed{^{136}\mathrm{Ba}^{++}} + 2e^{-} + 0\nu$$



Thomas Brunner for the EXO collaboration

TIPP2014 – June 5, 2014

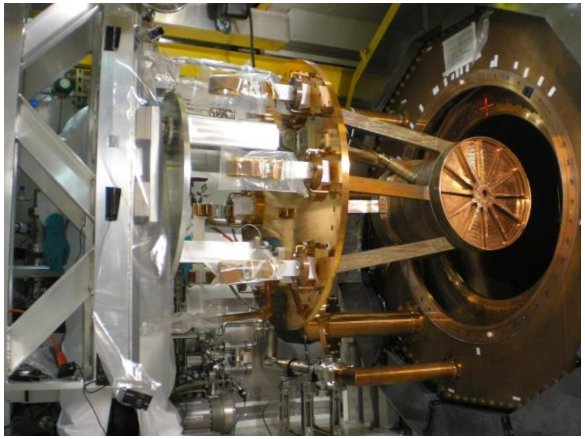
EXO– Enriched Xenon Observatory

The virtues of ^{136}Xe in a large TPC

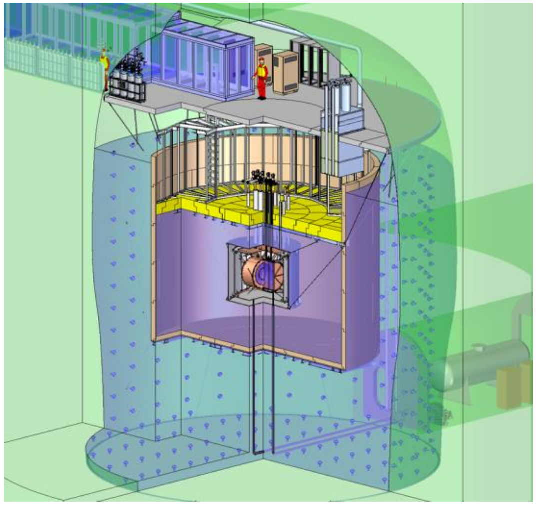
- Easy to enrich: 8.9% natural abundance but can be enriched relatively easily (better than growing crystals)
- Can be purified continuously, and reused
- High $Q_{\beta\beta}$ (2458 keV): higher than most naturally occurring backgrounds
- Minimal cosmogenic activation: no long-life radioactive isotopes
- Energy resolution: improves using scintillation and charge anti-correlation
- LXe self shielding
- Background can be potentially reduced by Ba^{++} tagging

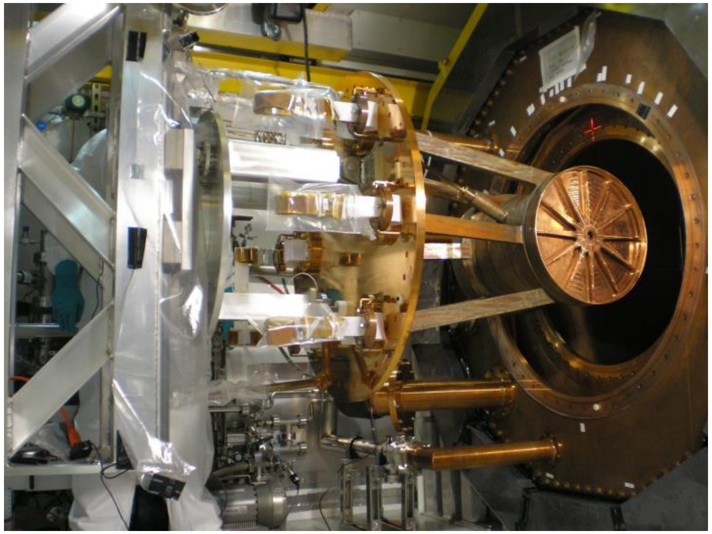
Phased approach:

1. EXO-200: 200kg liquid-Xe TPC

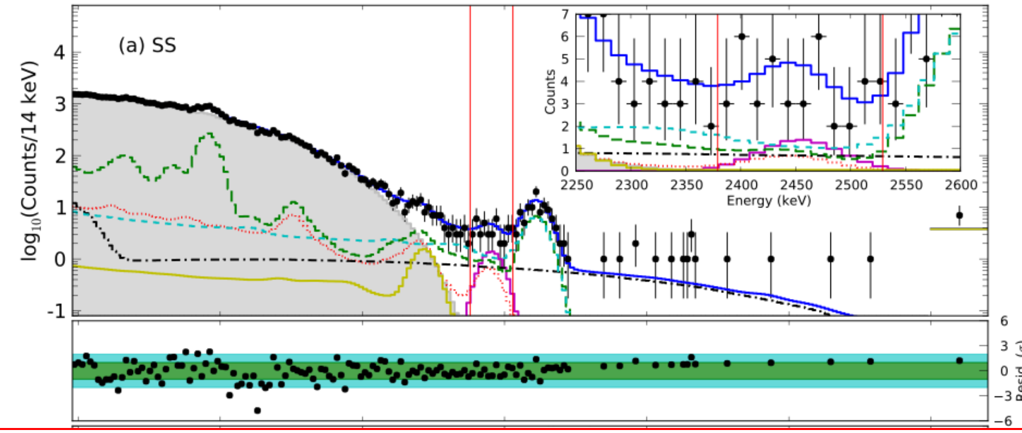


2. nEXO: 5-ton liquid Xe TPC with Ba tagging option (SNO lab cryopit)

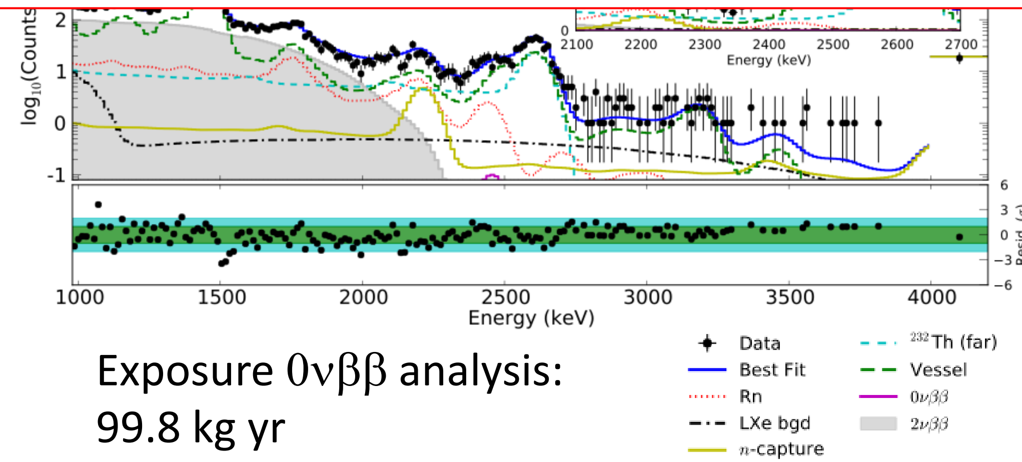




EXO-200



See poster by Lisa Kaufmann



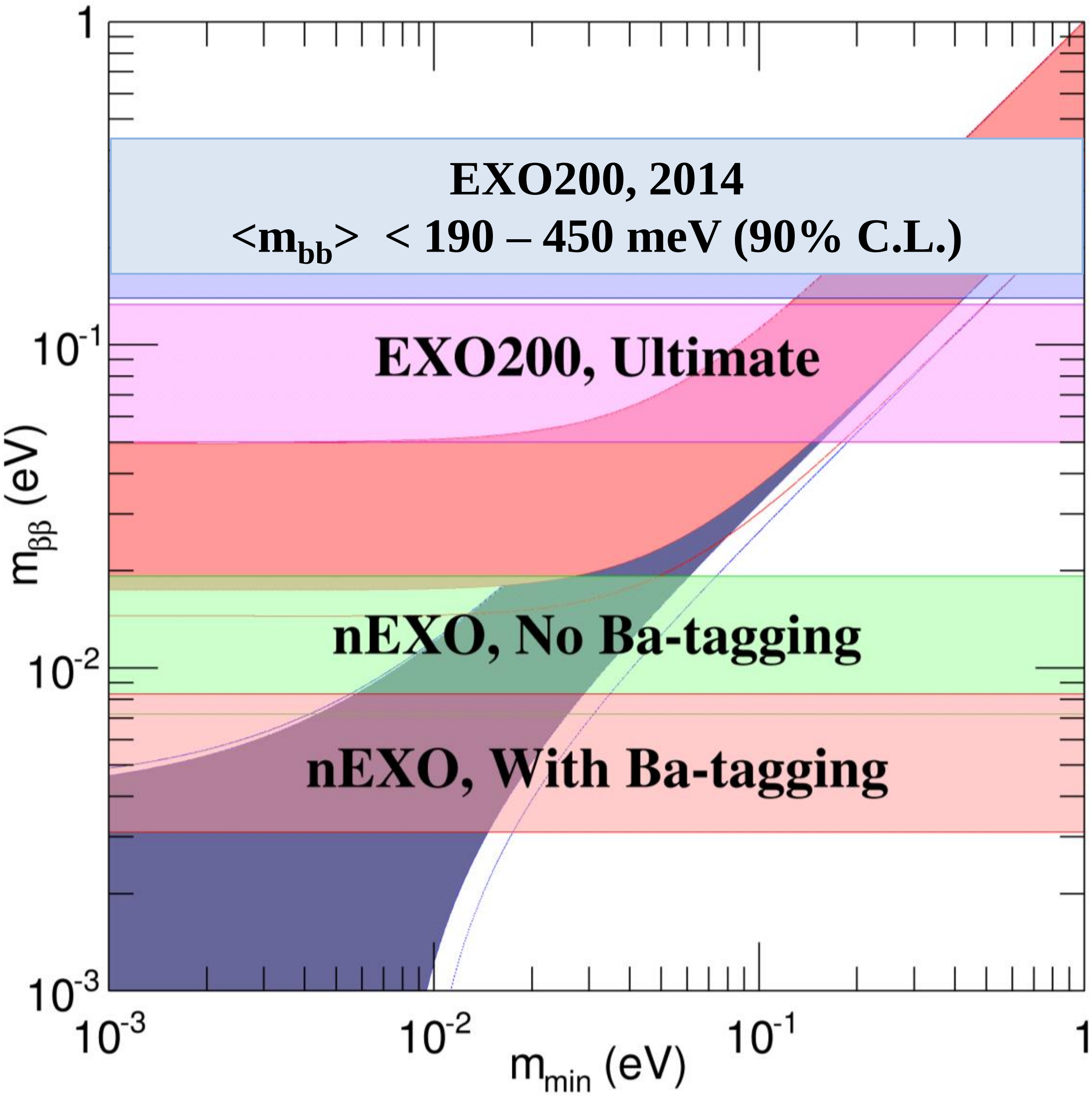
- 2150 feet depth (1585 mwe)
- Low radioactivity levels:
  - U, Th <100ppb
  - Radon background < 10 Bq/m^3
- Liquid Xe TPC (200 kg, 80.6% enriched ^{136}Xe)
- Charge and scintillation light readout → event position

Exposure $0\nu\beta\beta$ analysis: 99.8 kg yr

$T_{1/2}(0\nu) > 1.1 \times 10^{25}$ yr (90%CL) **10.1038/nature13432**
$T_{1/2}(2\nu) = 2.165 \pm 0.016$ (stat) ± 0.059(sys) $\times 10^{21}$ yr
PRC 89(2014)015502

Enriched Xenon Observatory

- Multi-phase program
- EXO-200, in operation:
  - 200 kg LXe
  - Sensitivity: 100-200 meV
- Multi-ton EXO,
  R&D underway:
  - 5 ton liquid Xe
  - Sensitivity: 5-30 meV
  - Improved techniques for background suppression and possibly Ba tagging



→ Development of nEXO, a multi-ton scale detector, is well advanced

Barium tagging in EXO

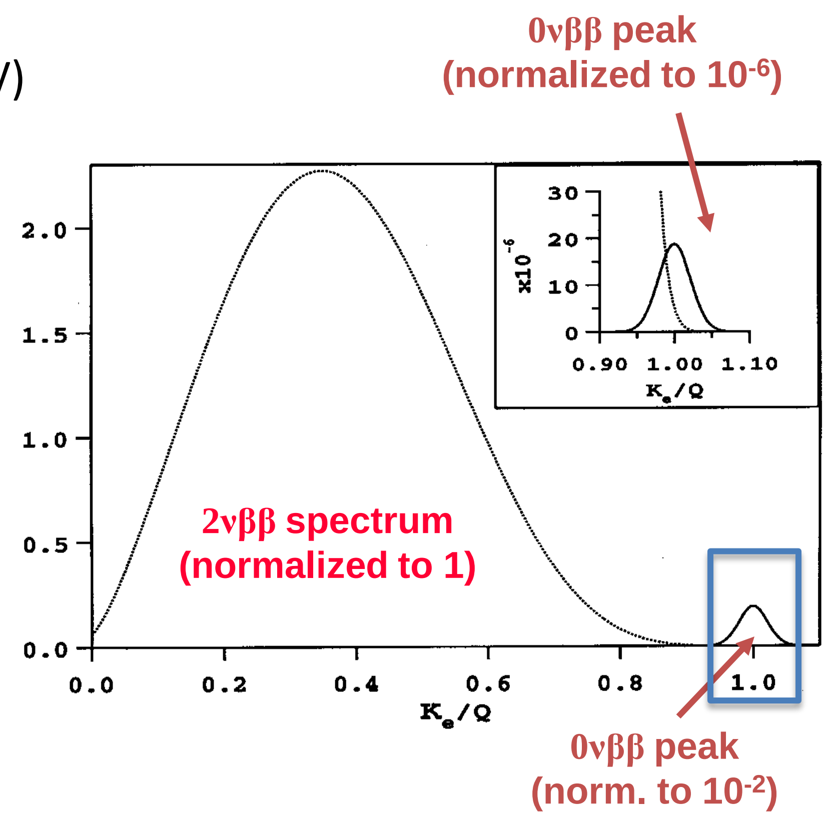
Idea: Perform a background-free measurement by identifying the decay product – Ba-ion tagging

Ba-tagging concept

1. Determine event energy is close to $Q_{\beta\beta}$ (2458keV)
2. Determine position of event
3. Extract decay volume and probe for Barium

$$^{136}\text{Xe} \rightarrow \boxed{^{136}\text{Ba}} + 2e^- + 0\nu$$

Detecting daughter ^{136}Ba provides a "tag" that can discriminate against all background except $2\nu\beta\beta$ decay.



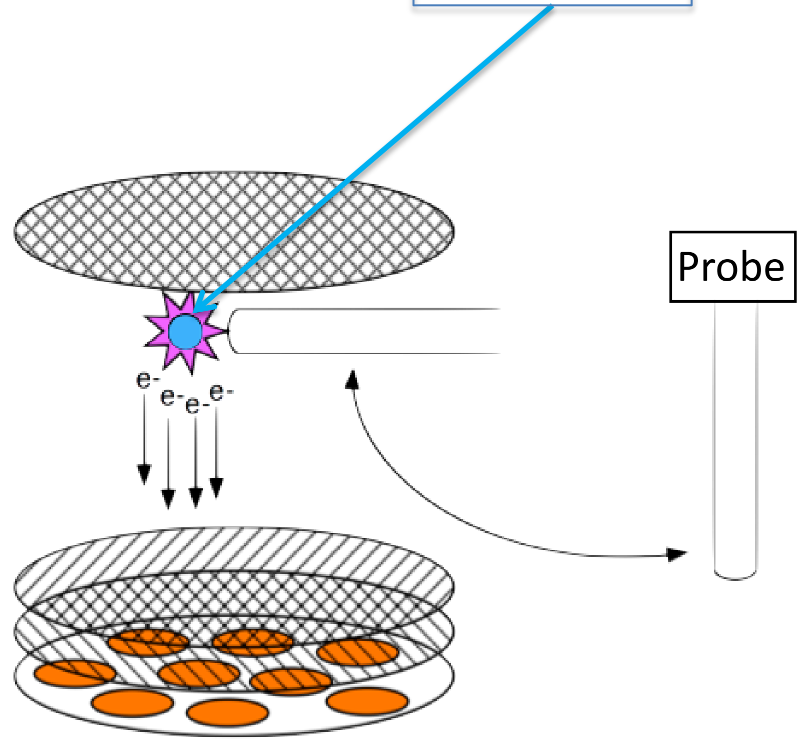
Sensitivity with background $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$$

Sensitivity without background $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/2}$$

Tagging from Liquid

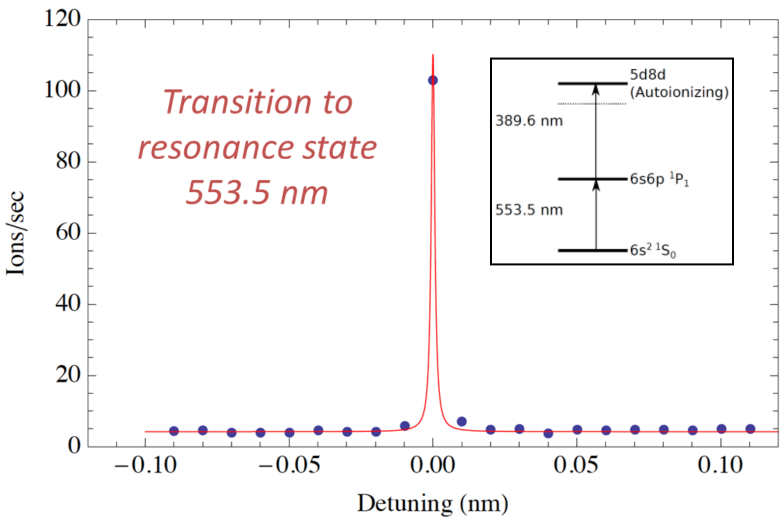
$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$

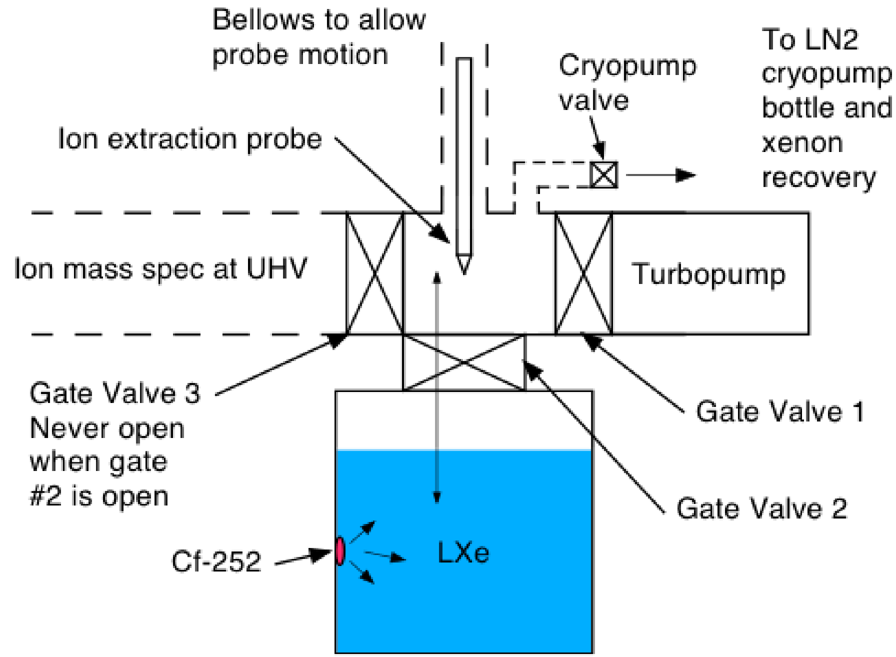
1. Detect and localize decay (like in EXO-200)
2. Send probe in to region of decay
3. Confine the Ba^{++} on probe
4. Remove the probe
5. Identify the barium

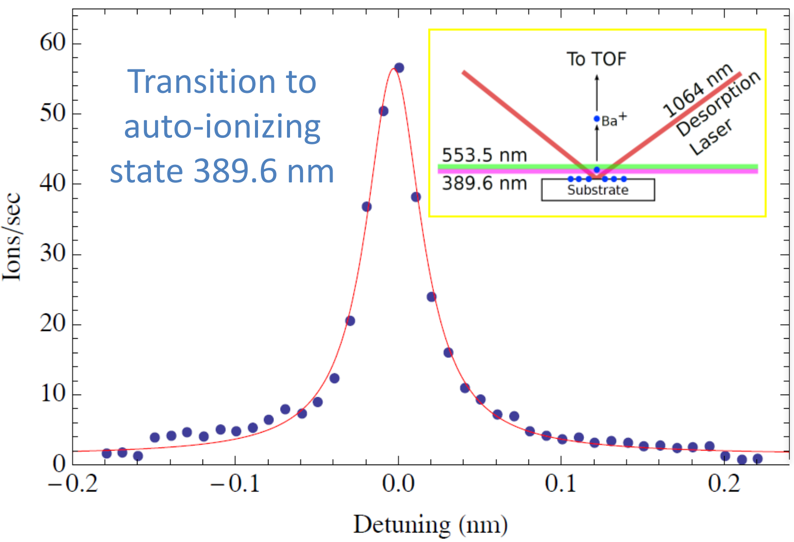


Investigated at Stanford, Colorado State U., U. of Illinois, Technical University Munich, U. Bern

Ba$^+$ tagging by Resonance Ionization







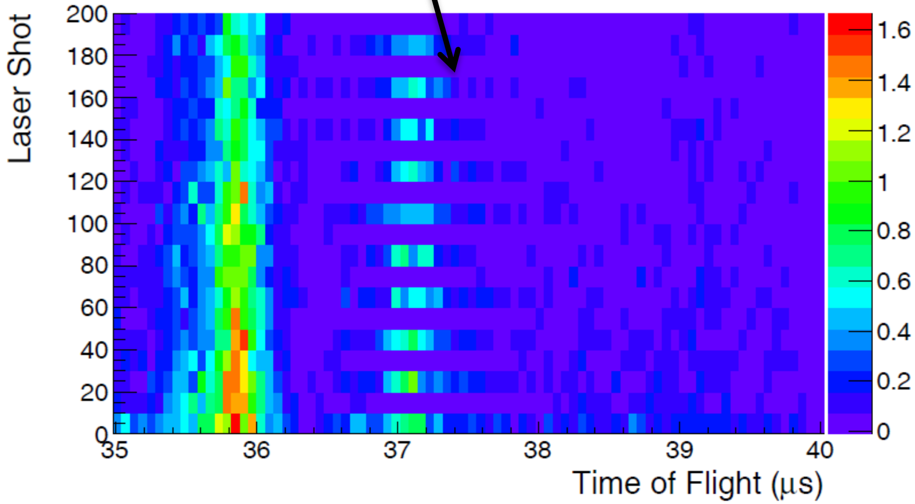
Concept:

RIS - selective ionization of only one element with lasers

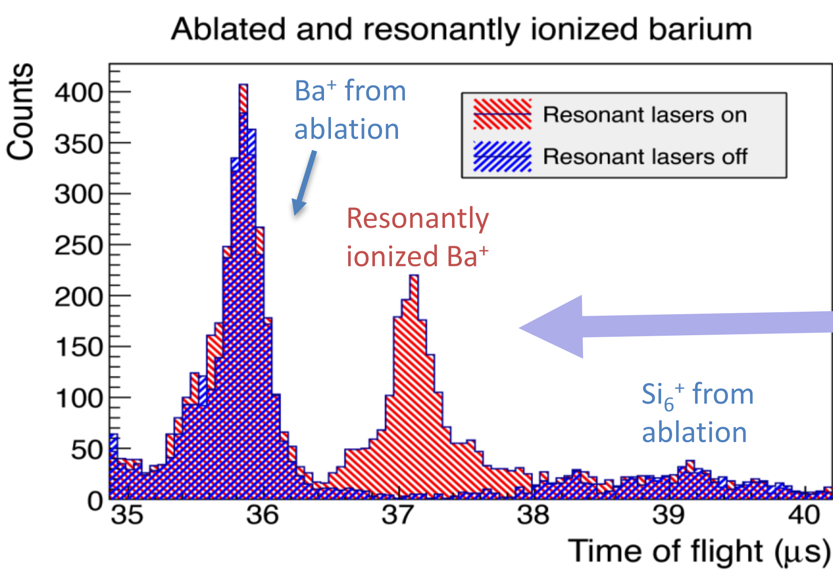
- Move probe close to Ba$^+$ ion in LXe
- Attach Ba$^+$ ion to probe
- Move probe out of LXe
- Laser-ablate Ba atom from probe
- Laser-ionize Ba$^+$ by RIS
- Accelerate Ba$^+$ ions and identify by TOF

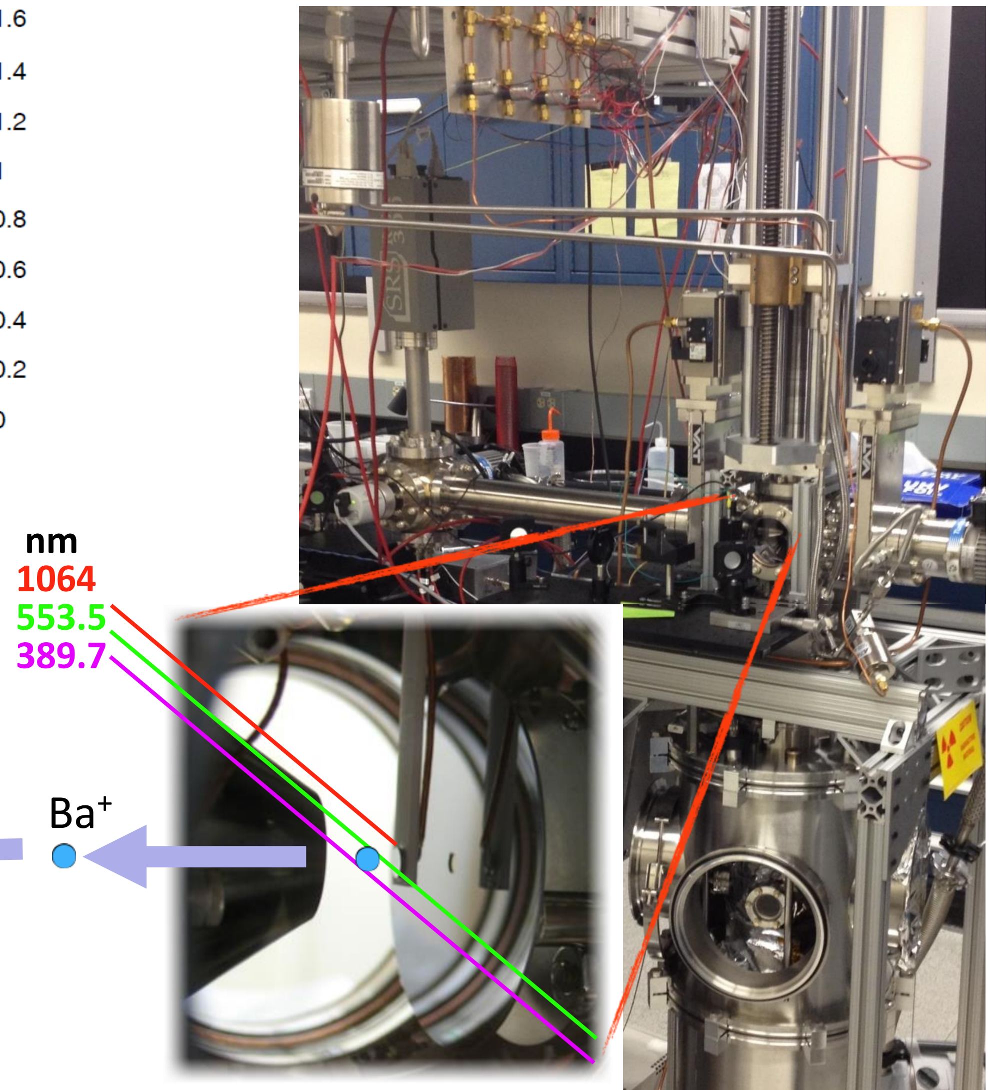
RIS Ba^+ tagging at Stanford

Blank regions are when RIS lasers are blocked



RIS and ablated Ba^+ as well as background ablated ions separated by time-of-flight

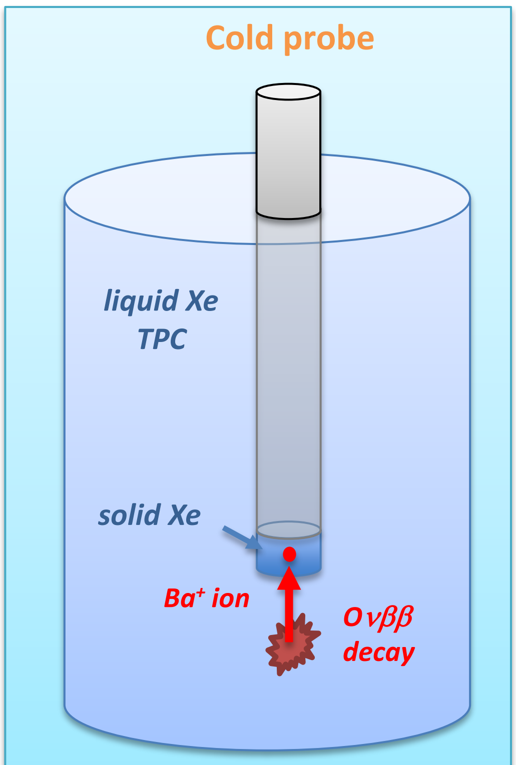




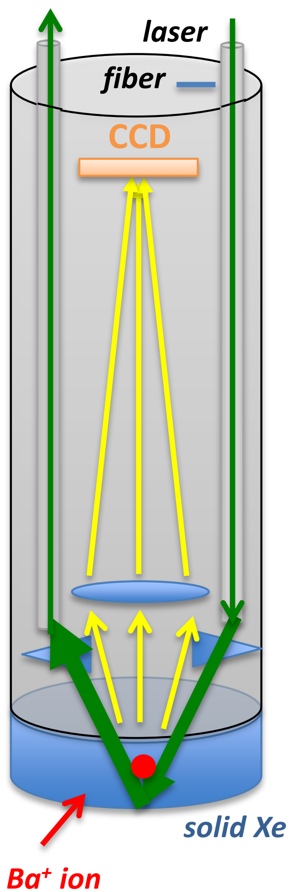
Barium tagging in solid xenon (CSU)

Tagging concept

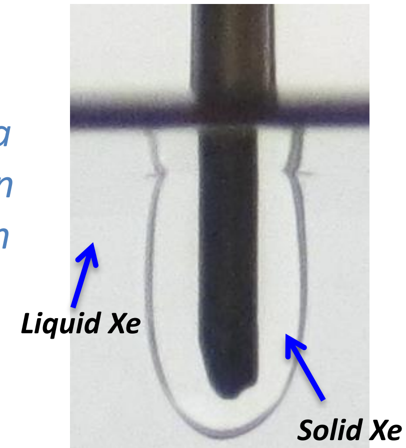
1, Capture Ba^+ daughter in solid xenon on a probe:



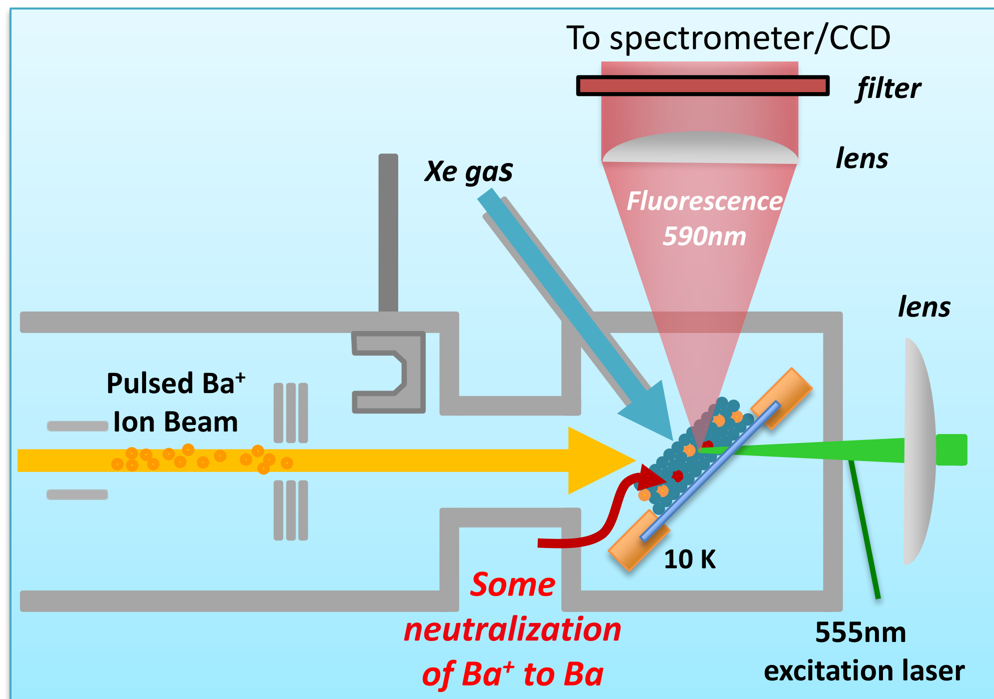
2, Detect single Ba^+ or Ba on probe by fluorescence:



Solid Xe formed on a cryoprobe in liquid xenon



Barium tagging test apparatus

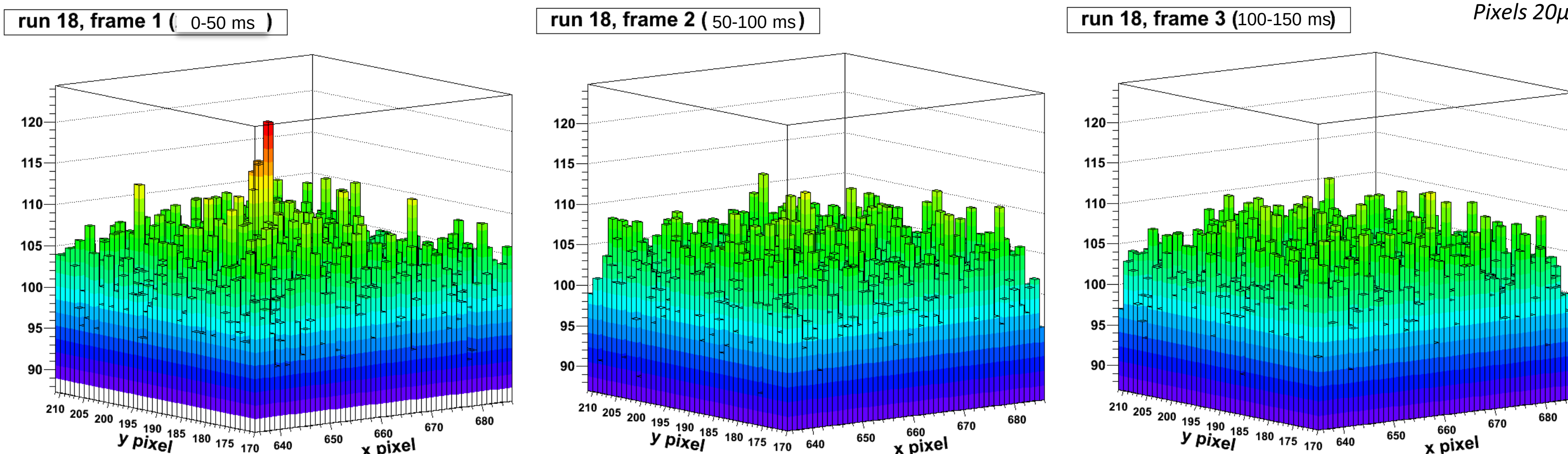


Successful spectroscopy of Ba-ions in sXe (CSU)

50 ms images of deposit of ~10^5 Ba^+ ions in solid xenon

most signal comes in ~5 μs, before optical pumping occurs

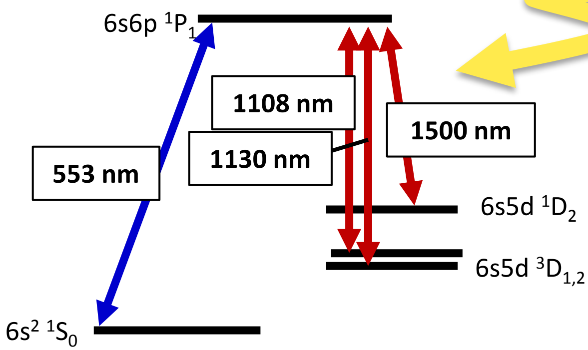
Pixels 20μmx20μm

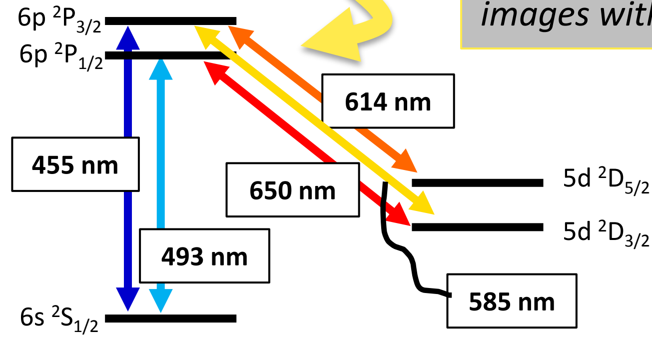


Ba

Ba^+

Need repumping lasers to overcome optical pumping and get single Ba/Ba^+ images with 10^6x or more signal



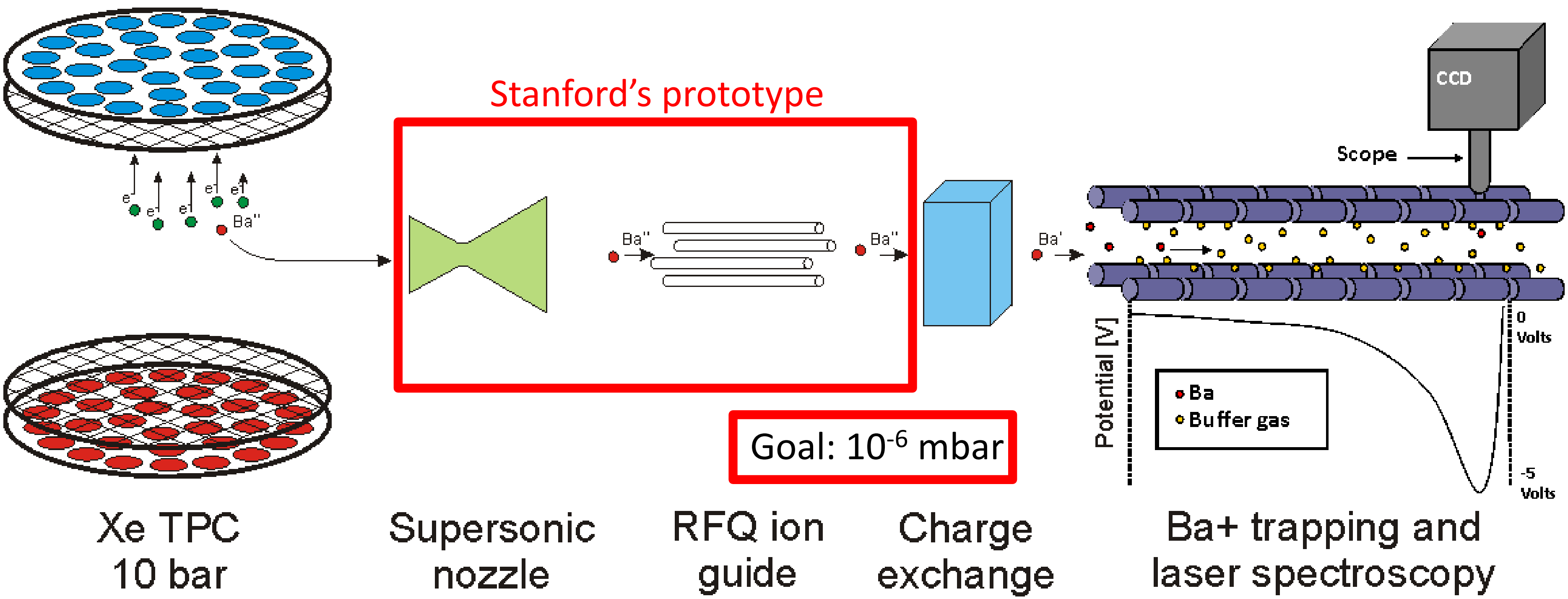


~1 in 350 decays from $^1P_1$ state are into metastable D states

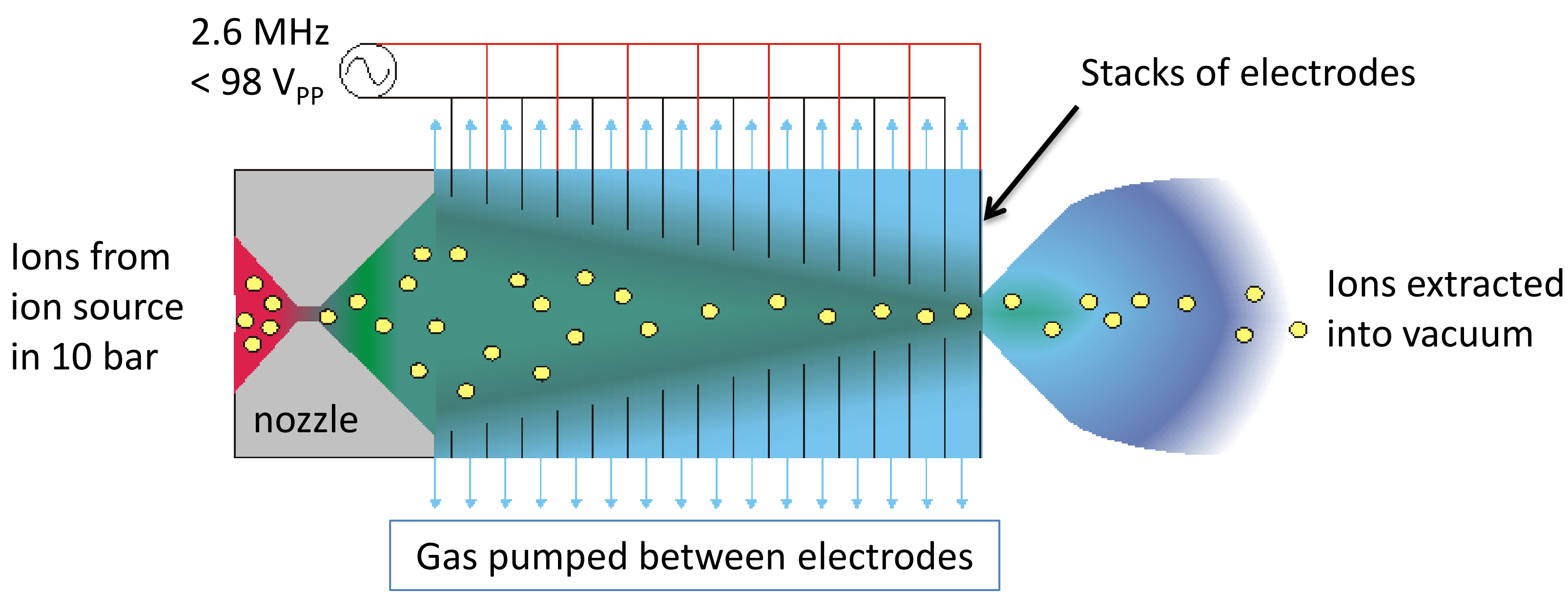
~1 in 4 decays from $^2P_{1/2}$ state are into metastable D state

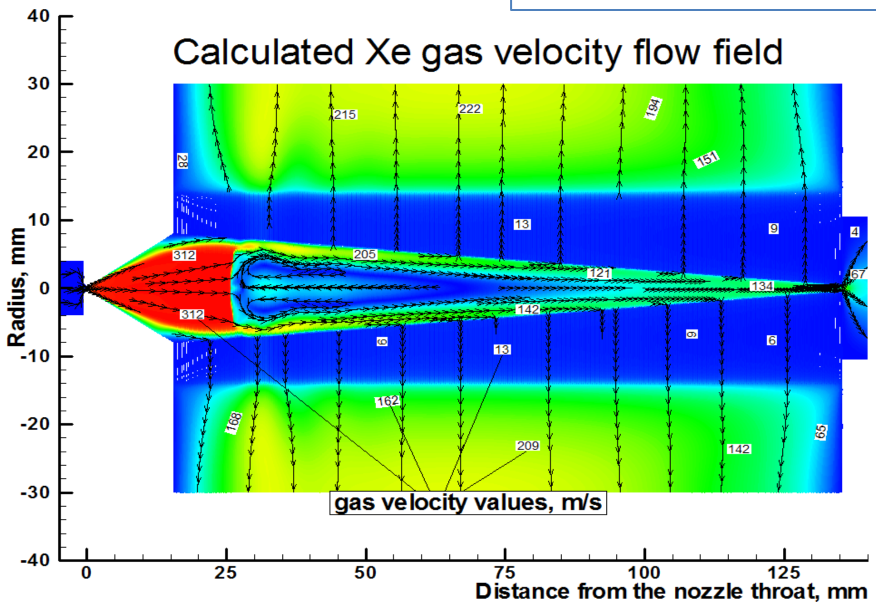
General Concept of Ba^{++} Tagging in gas

- Guide Ba^{++} in high pressure Xe inside the TPC (10 bar) to a nozzle
- Extract Ba^{++} with a Xe gas jet into a low pressure chamber
- After nozzle, pump Xe gas away and guide Ba^{++} to identification



Concept of RF-funnel





- Concept of funnel by V. Varentsov
- Conv.-diverging supersonic nozzle
- 301 RF electrodes (0.1 mm thick)
- 0.25 mm electrode spacing
- RF applied to electrodes
- **P_0 = 10 bar!** to 1 mbar in only one stage
- Simulated extraction efficiency of up to 95%
- Xe gas is recaptured by a cryo pump

arXiv:1302.6940v1

Pictures of RF-funnel

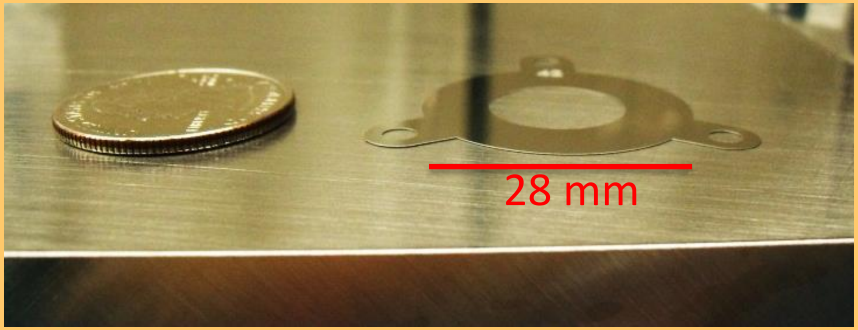
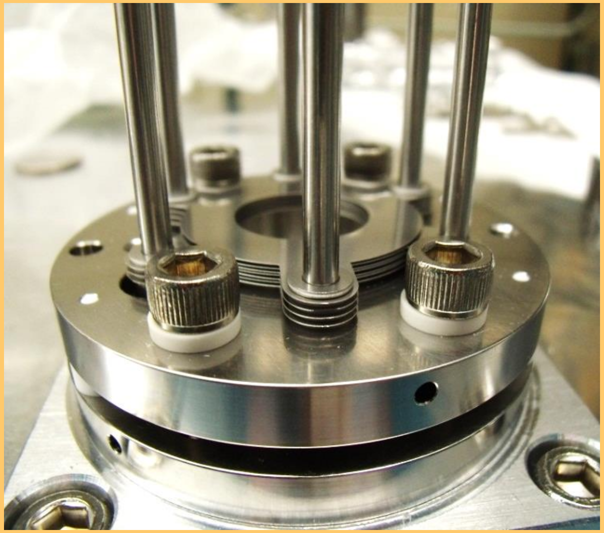
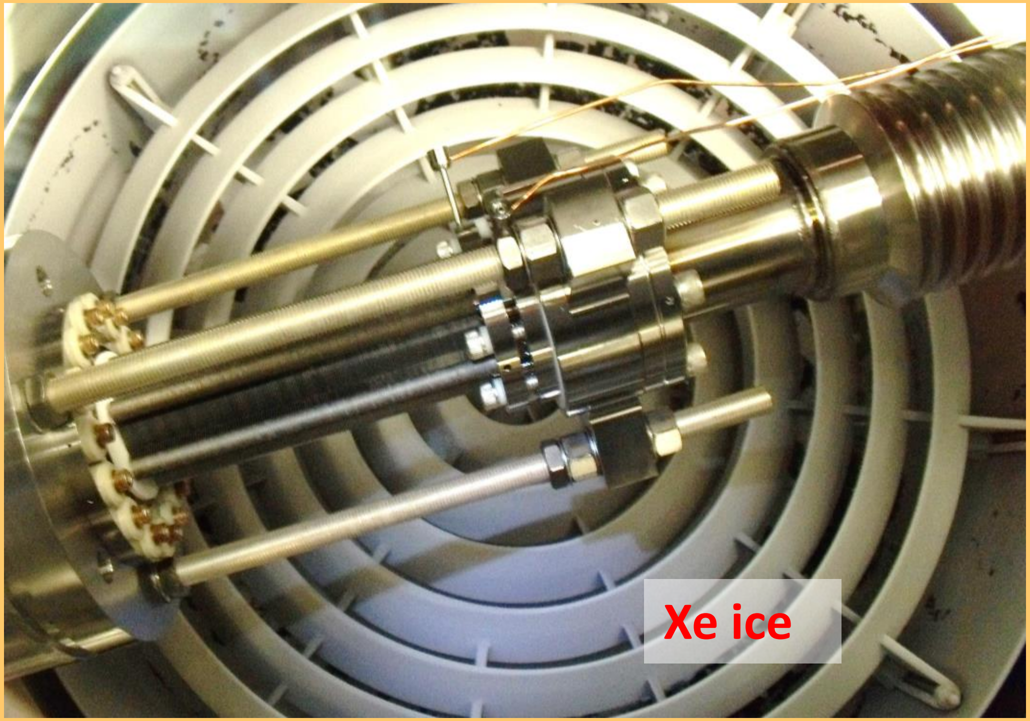


Photo-etched electrodes with decreasing ID

All components
UHV compatible



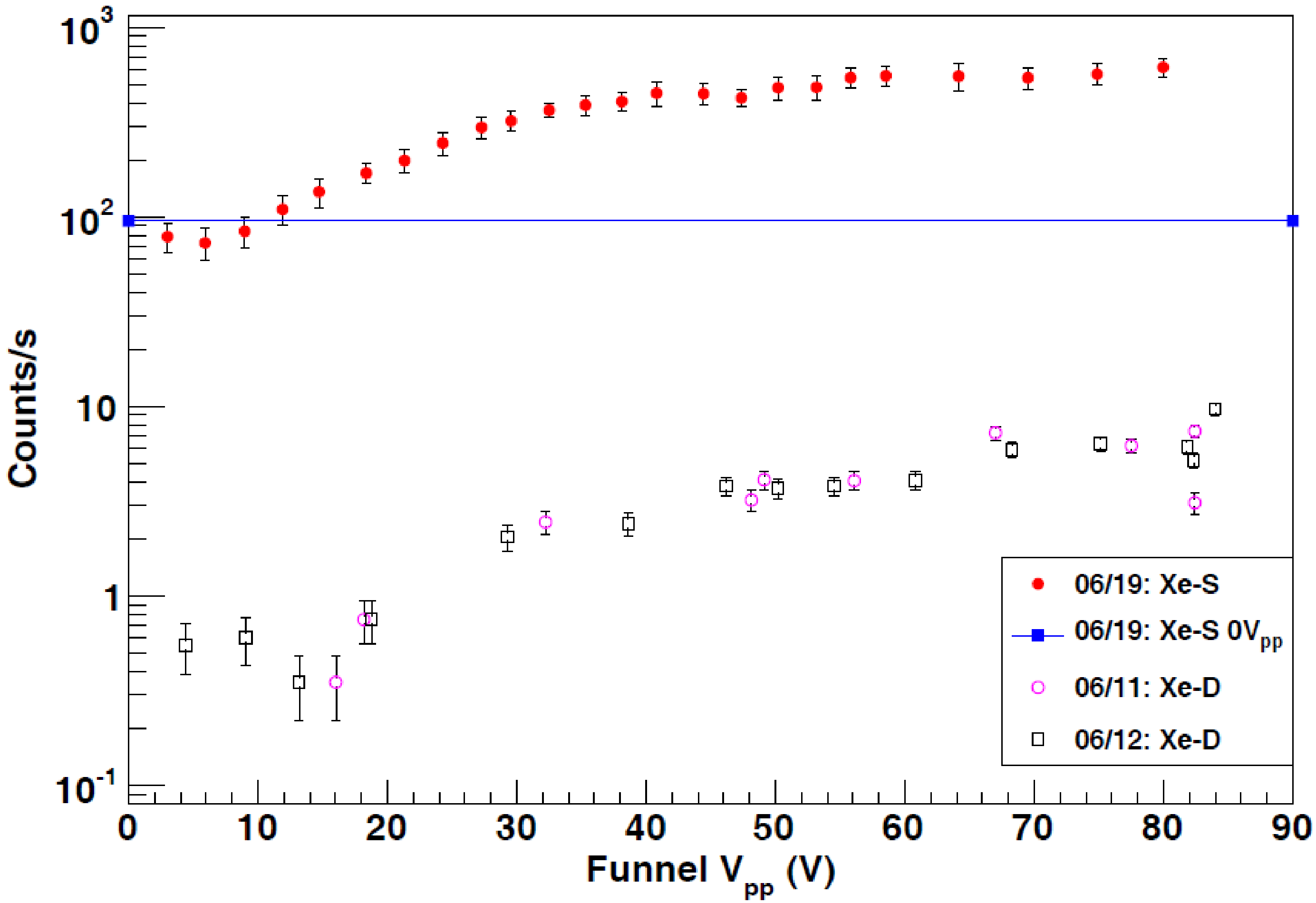
2 electrically insulated stacks



Insalled RF-funnel during a Xe run

RF-funnel and nozzle

Ion extraction from 10 bar Xe gas



Funnel RF at 2.6 MHz

Current status:

- A Xe or Ar gas jet can be operated at up to 12 bar
- Xe gas can be recovered after an experiment
- Ions can successfully be extracted from high-pressure gas environment

For the future:

- Ion identification
- Determination of extraction efficiency

Conclusion

- Development of nEXO, a multi-ton scale detector, well advanced
- Several groups are working on techniques for Ba-ion extraction from Xe, for the nEXO collaboration
- Successful spectroscopy of Ba-ions in Xe ice (CSU).
- Investigating of Ba-ion properties on surfaces.
- First RIS Ba-ion identification.
- Positive ion extraction from high pressure Xe gas and Ar gas.

lXe

gXe

The EXO-200 Collaboration

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Backup slides

Barium tagging by Thermal Ionization (UI, TUM)

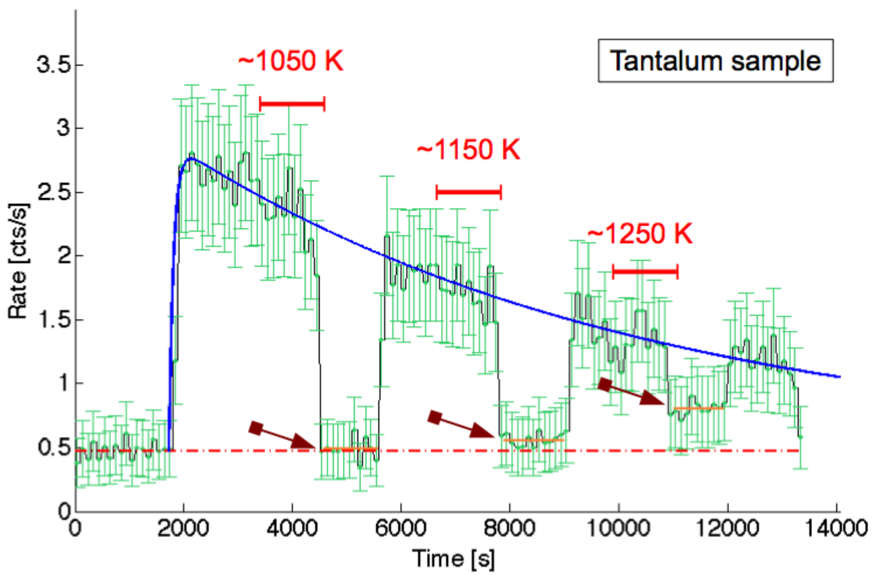
- Study neutralization of Ba in Xenon Ice.
- Study of desorption of Ba from surfaces.

CARIBU beam at Argonne National Lab provides radioactive beams of ^{139}Cs or ^{139}Ba

γ 1283 keV (7%) γ 165.9 keV (24%)

^{139}Cs → ^{139}Ba → ^{139}La

9 min 83 min Stable



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