Barium Tagging for the NEXT Neutrinoless Double Beta Decay Experiment

NICHOLAS BYRNES

Supported By

Moe, M. K. "Detection of neutrinoless double-beta decay." Physical Review C 44.3 (1991): R931.

^{136}Xe Double Beta Decay

- NEXT (Neutrino Experiment with a Xenon TPC) uses high-pressure enriched xenon-136 gas as both the source of the decay and the detection medium.
- When ^{136}Xe decays, the only possible daughter ion is ^{136}Ba.
- Detecting this barium daughter in tandem with electron energy measurement techniques will result in background free double beta decay detection

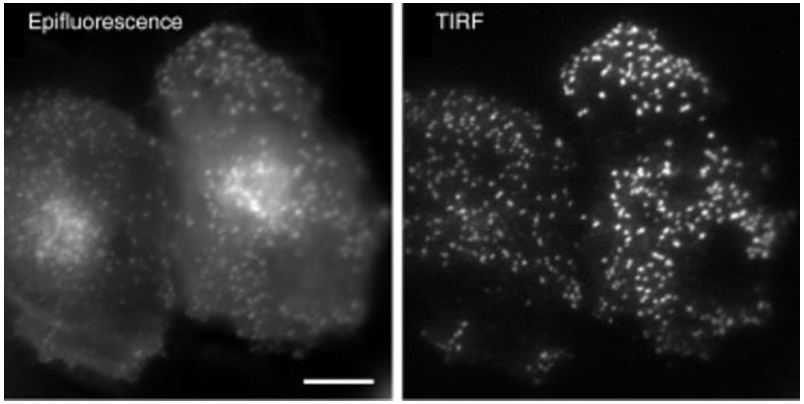
$$^{136}_{54}Xe \rightarrow \ ^{136}_{56}Ba + \ 2e^{-} + 2\bar{\nu}$$

NEXT-NEW Vessel in its housing at Canfranc, Spain

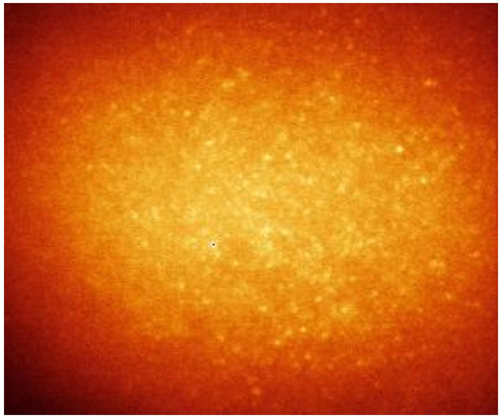
Mattheyses, A. L., Simon, S. M., & Rappoport, J. Z. (2010). Imaging with total internal reflection fluorescence microscopy for the cell biologist. *Journal of cell science*, *123*(Pt 21), 3621–3628. doi:10.1242/jcs.056218

Single Molecule Fluorescent Imaging

- In biological imaging, fluorescent dyes are used to tag specific ions in cells, primarily calcium.
- By using Total Internal Reflection Single Molecule Fluorescence Imaging (TIR-SMFI) these molecules can be imaged at the single ion level.



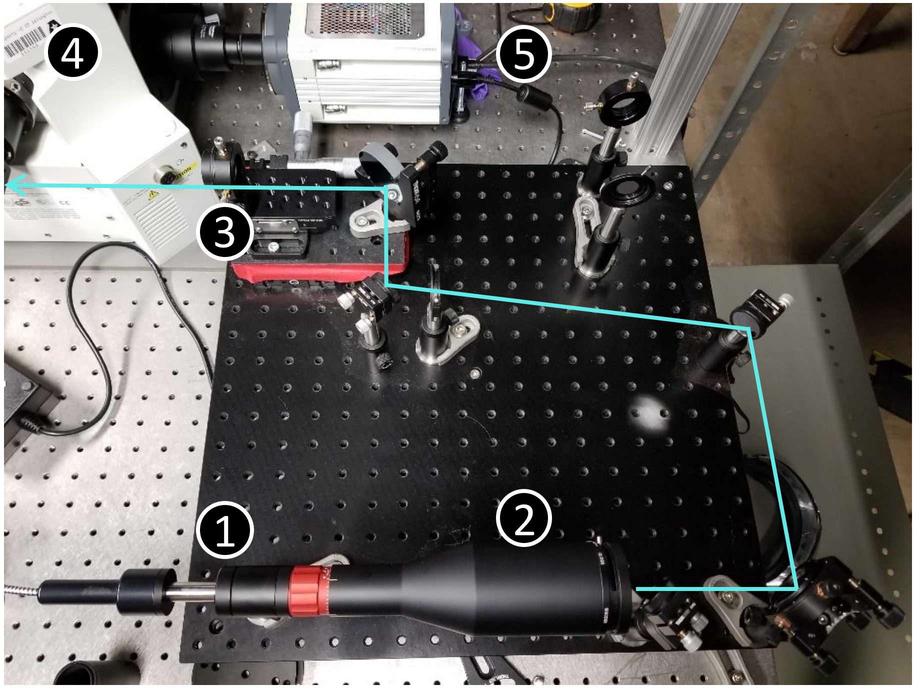
Cells, focused on the plasma membrane, in EPI and TIRF modes*



Individual Fluo-4 + Ca molecule imaged at UTA

- At UTA, we are applying these techniques to tagging the Barium Daughter of ^{136}Xe double beta decay.

Optics and Microscope Assembly



1. Excitation Laser Output
2. Beam Expander
3. TIRF Lens
4. Microscope Assembly
5. EM-CCD Camera

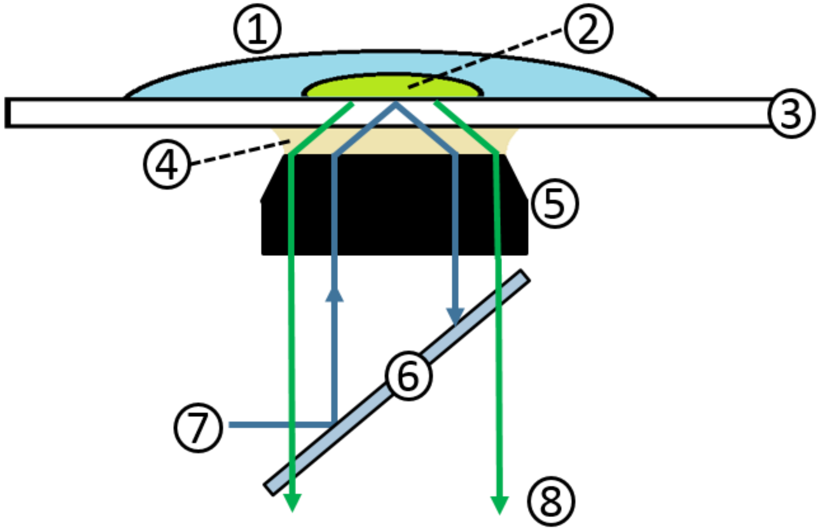
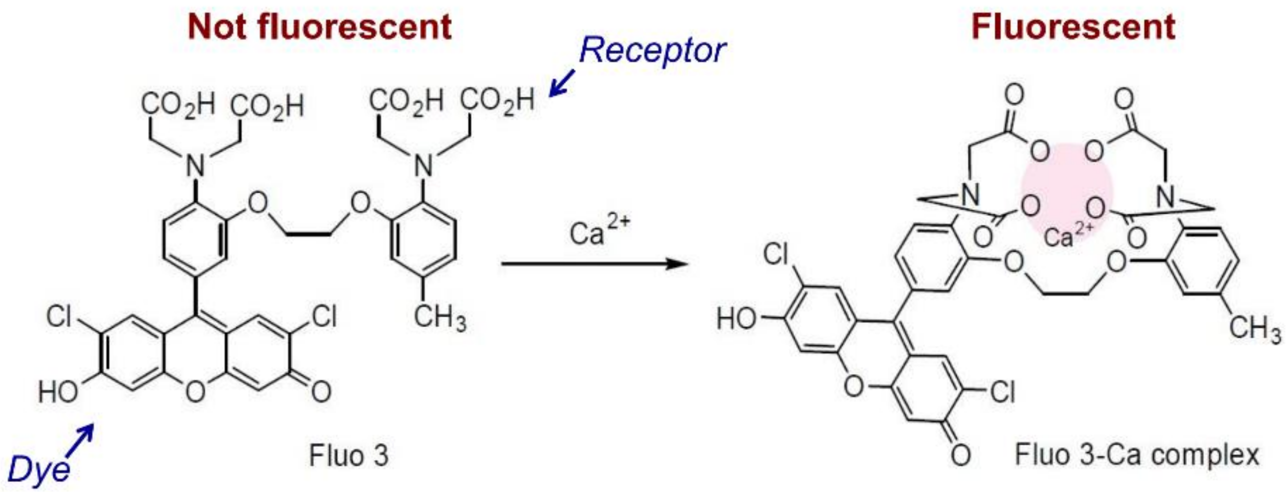


Diagram showing the inner workings of a TIRF Microscope.

1. Sample
2. Evanescent Field
3. Cover glass
4. Immersion oil
5. Objective
6. Dichroic Mirror
7. Excitation laser
8. Emitted Fluorescence

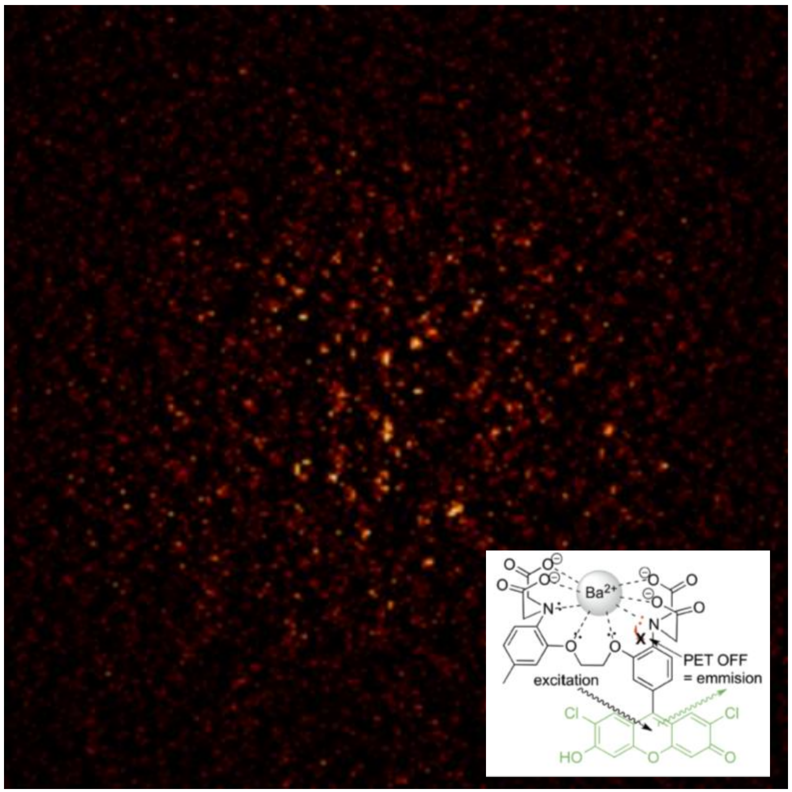
Single Ion Chelation



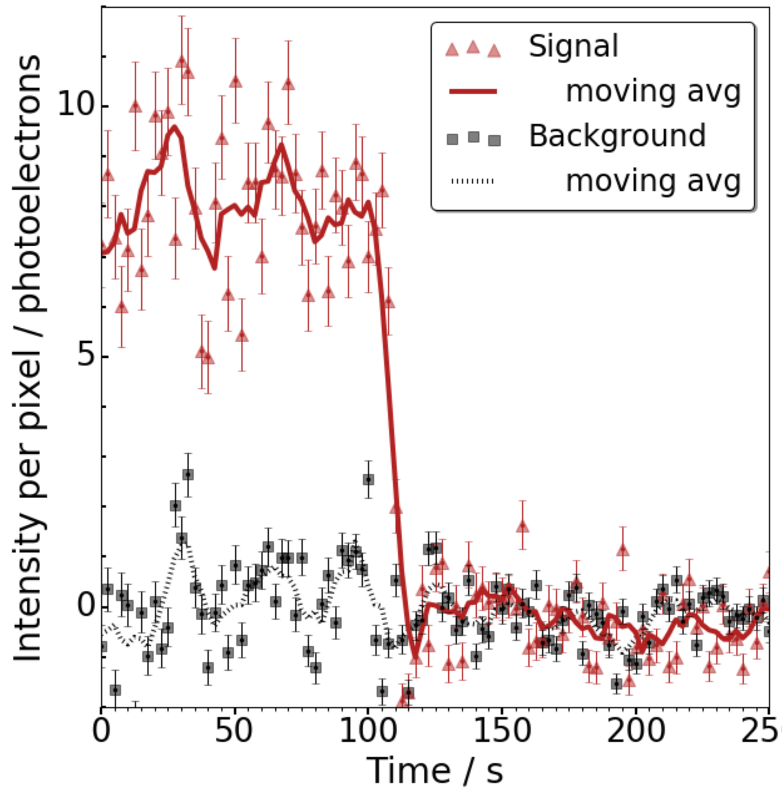
Chelation process, where an "off state" dye binds a metal cation and becomes fluorescent, or, "on."

A. D. Mcdonald et al., "Demonstration of Single-Barium-Ion Sensitivity for Neutrinoless Double-Beta Decay Using Single-Molecule Fluorescence Imaging," *Physical Review Letters*, vol. 120, no. 13, 2018.

Single Molecule Images



First picture showing fluorescent response from barium in PVA solution, using commercially available Fluo-3, treated with BAPTA.

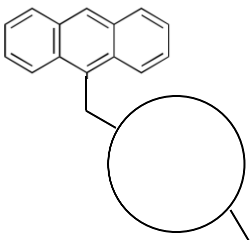


The single step photobleaching process of a barium ion chelated by commercial Fluo-3 dye

Pawan Thapa et al., “Barium Chemosensors with Dry-Phase Fluorescence for Neutrinoless Double Beta Decay,” Submitted to Nature Scientific Reports

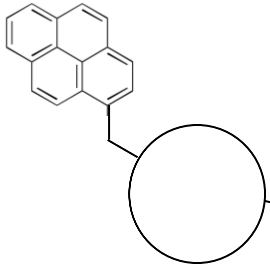
Custom Barium Chemosensors

Anthracene

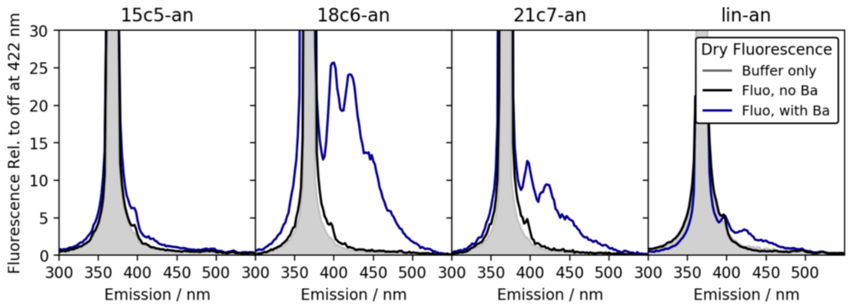


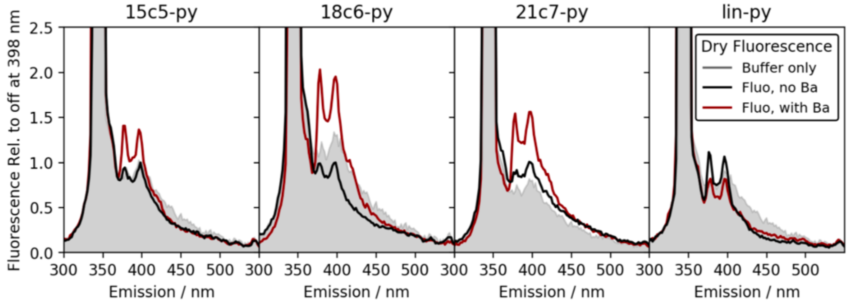
Receptor

Pyrene

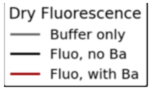


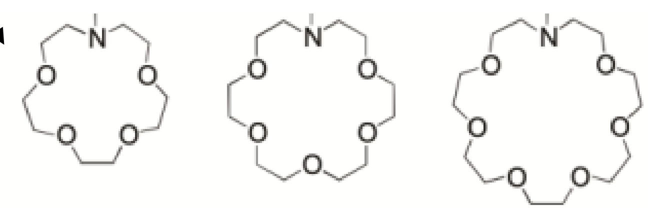
Receptor





Fluorescence response of dried films of fluorescent barium sensing molecules in buffer

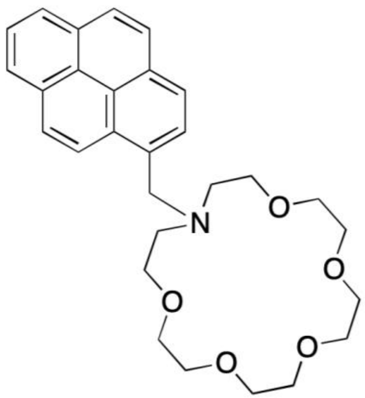




15c5 18c6 21c7

Pawan Thapa et al., “Barium Chemosensors with Dry-Phase Fluorescence for Neutrinoless Double Beta Decay,” Submitted to Nature Scientific Reports

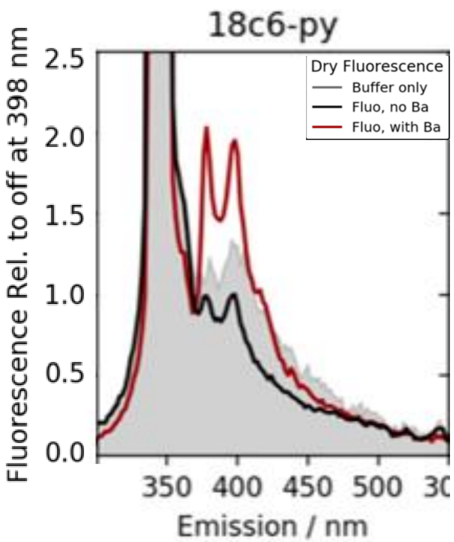
Custom Barium Chemosensors (Cont.)

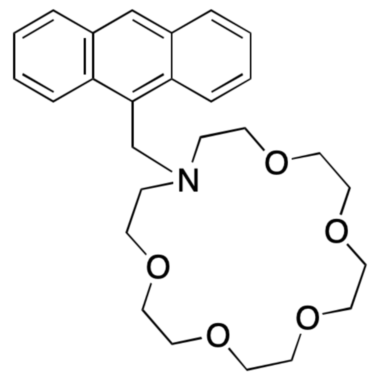


18c6 Pyrene

λ_{abs} = 345 nm

λ_{ems} = 400 nm

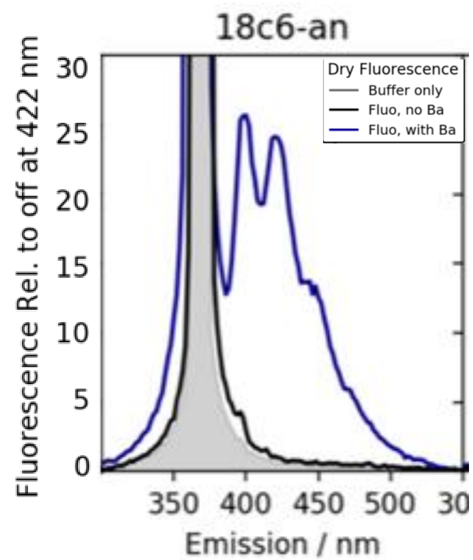




18c6 Anthracene

λ_{abs} = 375 nm

λ_{ems} = 410 nm

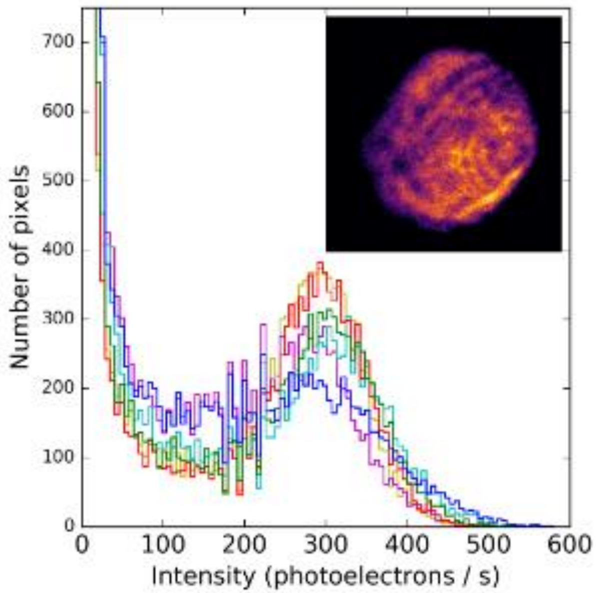


18c6 proved the most promising receptor for barium in these studies

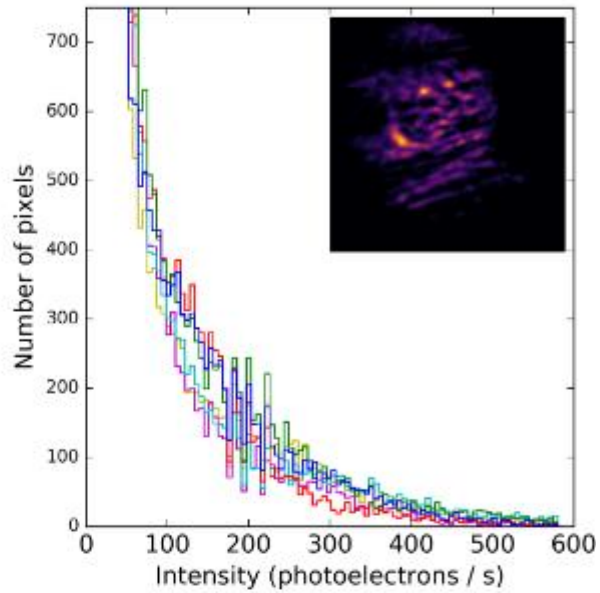
Pawan Thapa et al., "Barium Chemosensors with Dry-Phase Fluorescence for Neutrinoless Double Beta Decay," Submitted to Nature Scientific Reports

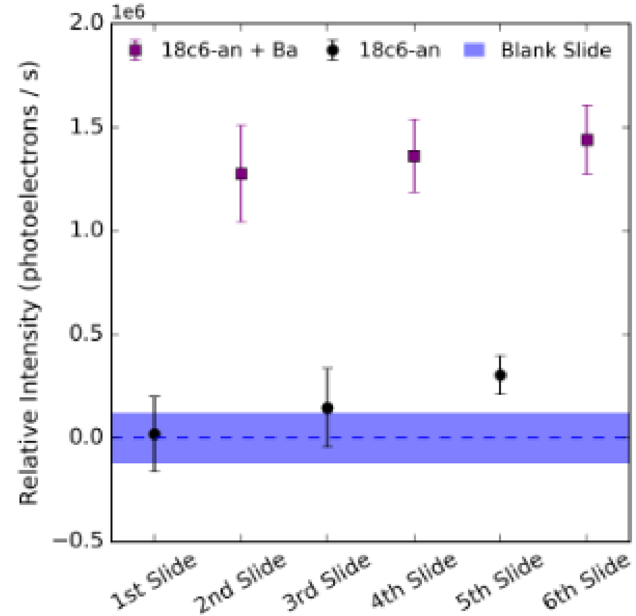
Custom Barium Chemosensors (Cont.)

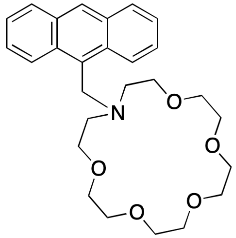
w/ Ba



w/o Ba



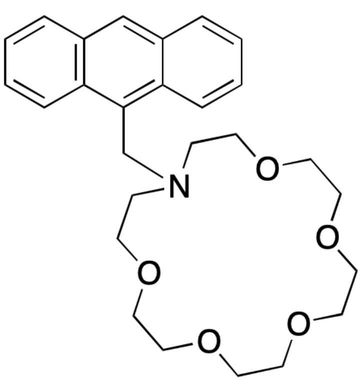




18c6 Anthracene showing fluorescent response when exposed to barium ions. Excitation wavelength of 375nm.

Custom Barium Chemosensors (Cont.)

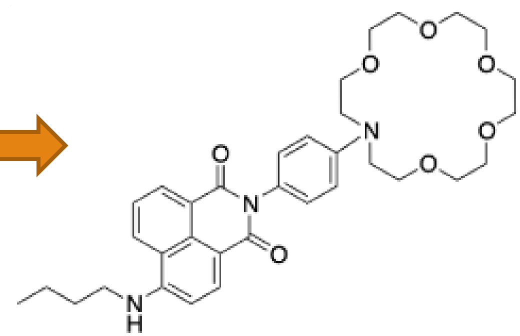
- Despite these early successes, Anthracene was still not the fluorophore of the future.
- It responded in the UV spectrum, meaning that:
  - It was invisible and therefore very hard to adjust the beam path, TIRF settings, etc.
  - Many substances fluoresce under UV light, introducing large backgrounds
- A new fluorophore has since been found; Naphthalimide,



18c6 Anthracene

$\lambda_{abs} = 375$ nm

$\lambda_{ems} = 410$ nm

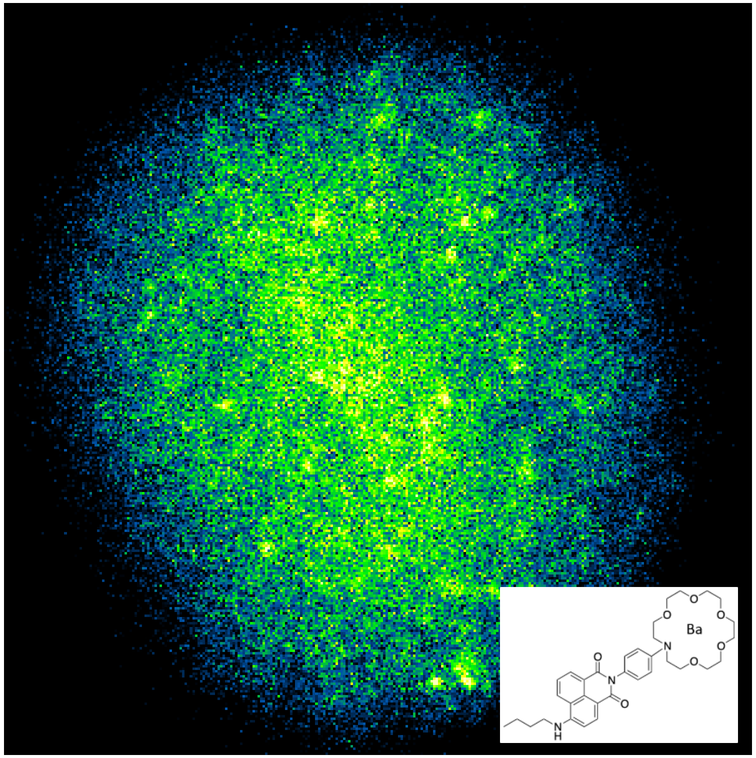


18c6 Naphthalimide

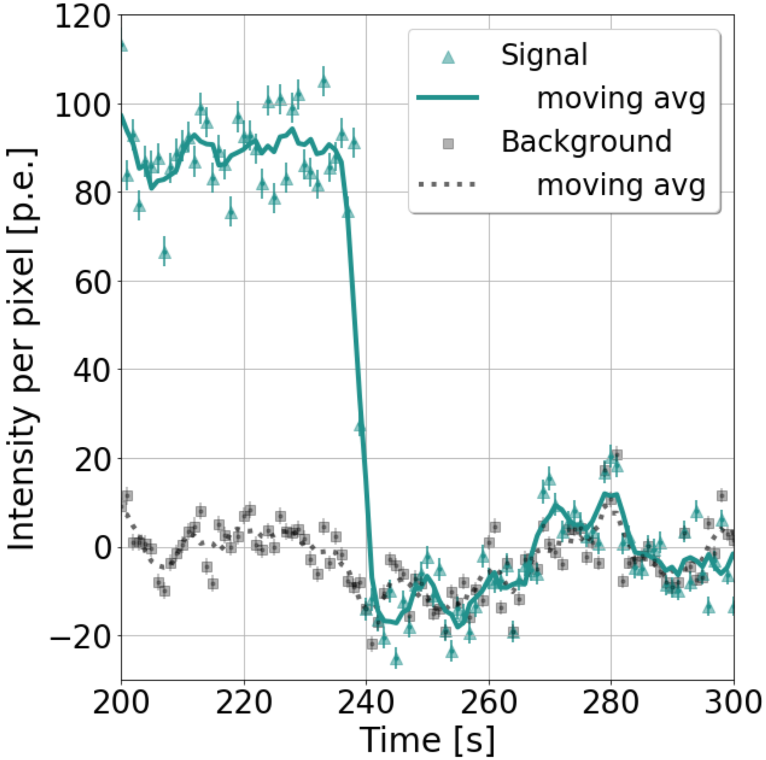
$\lambda_{abs} = 465$ nm

$\lambda_{ems} = 560$ nm

Custom Barium Chemosensors (Cont.)

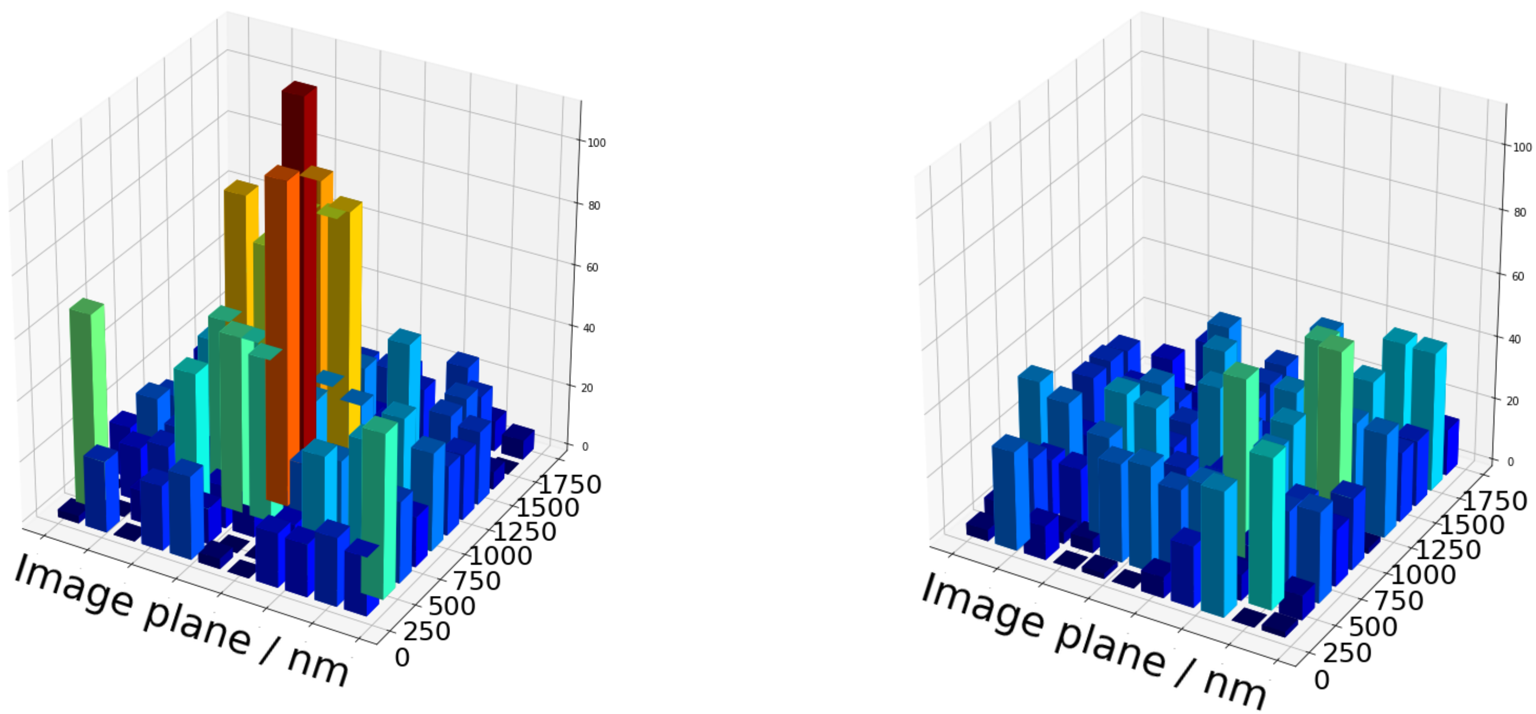


Current image showing fluorescent response from barium, now using our newest molecule, 18c6-Naphthalimide, in PVA solution



The single step photobleaching process of a barium ion chelated to 18c6-Naphthalimide

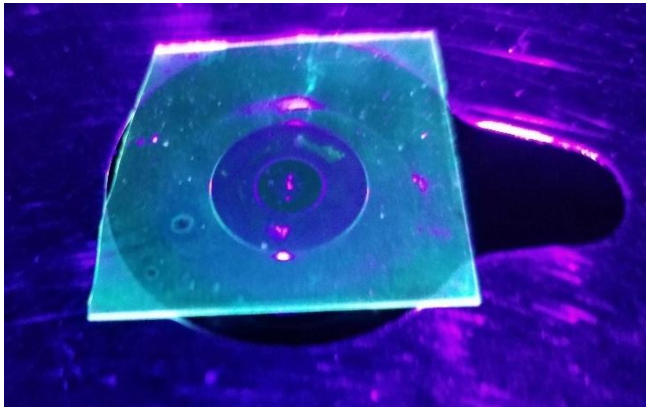
Custom Barium Chemosensors (Cont.)



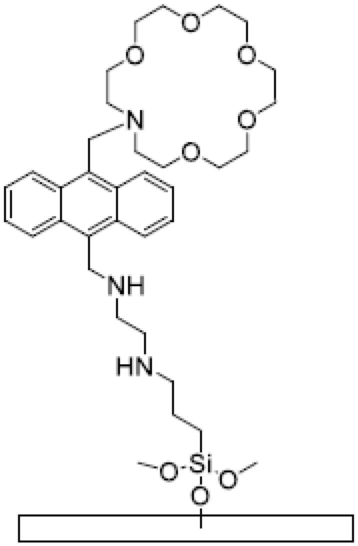
Pixel intensity histogram of a single barium + 18c6-Naphtalamide molecule before and after photobleaching.

Barium Chelating Monolayer

- There is a need to move away from PVA and bulk depositions in order to observe barium tagging processes.
- Self Assembling Monolayers (SAMs) provide a viable route to realize this.
- Using linkers, the molecules are tethered to the glass surface, resulting in uniform surface coverage and control in spacing.

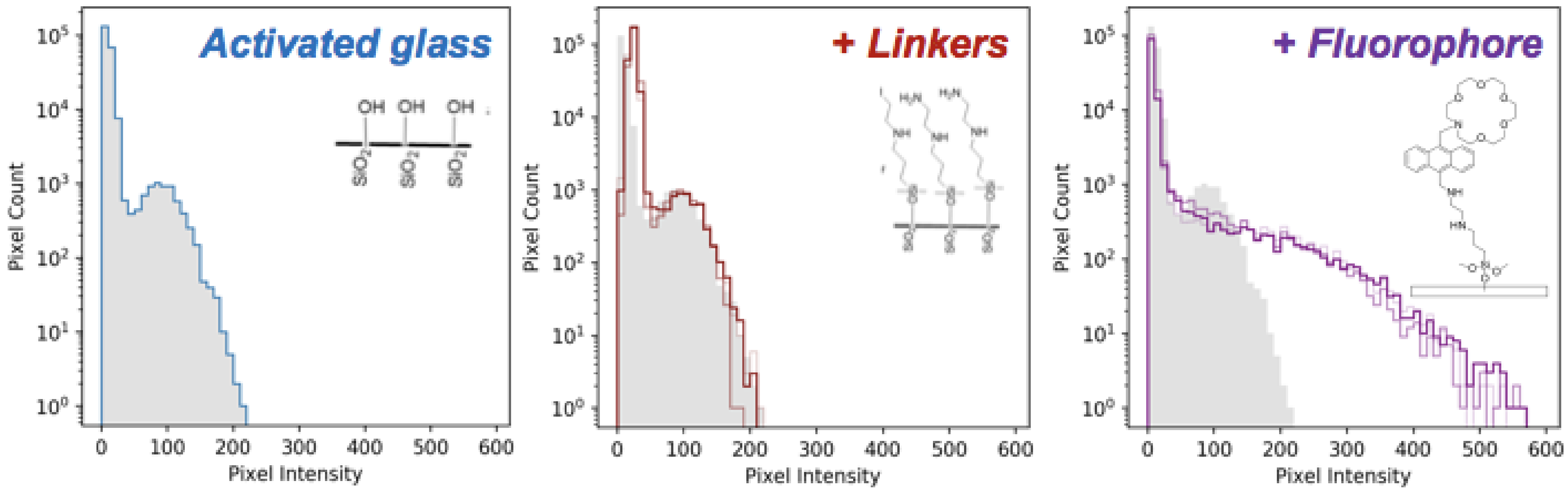


Glass substrate coated with an excess of 18c6 anthracene glowing strongly under UV light. Early sign that a coating of this type is promising



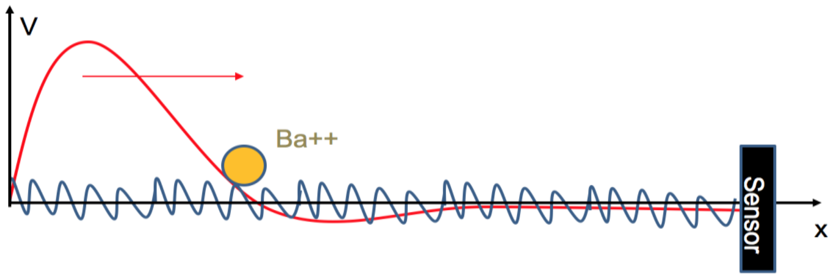
18c6 Anthracene linked to an oxidized glass substrate

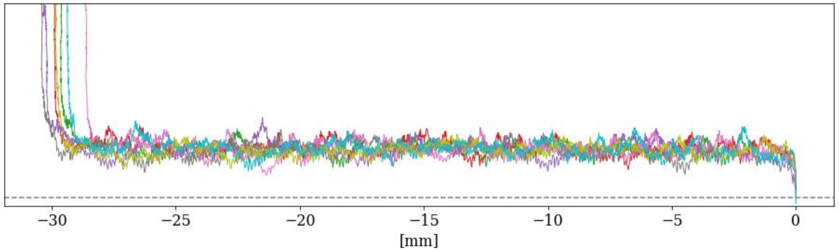
Barium Chelating Monolayer (Cont.)



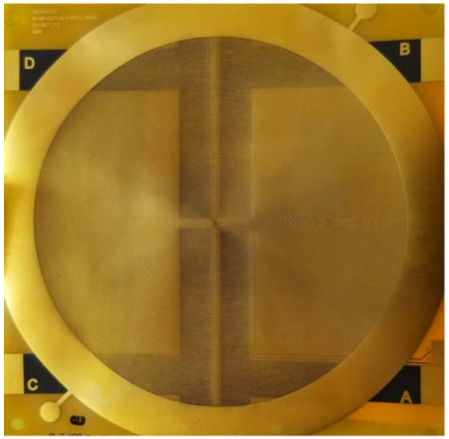
Pixel count vs. Intensity histograms showing the pixel intensity increase when fluorophores are bound to a glass substrate and analyzed using TIRF imaging.

Ion Surfing Mechanism



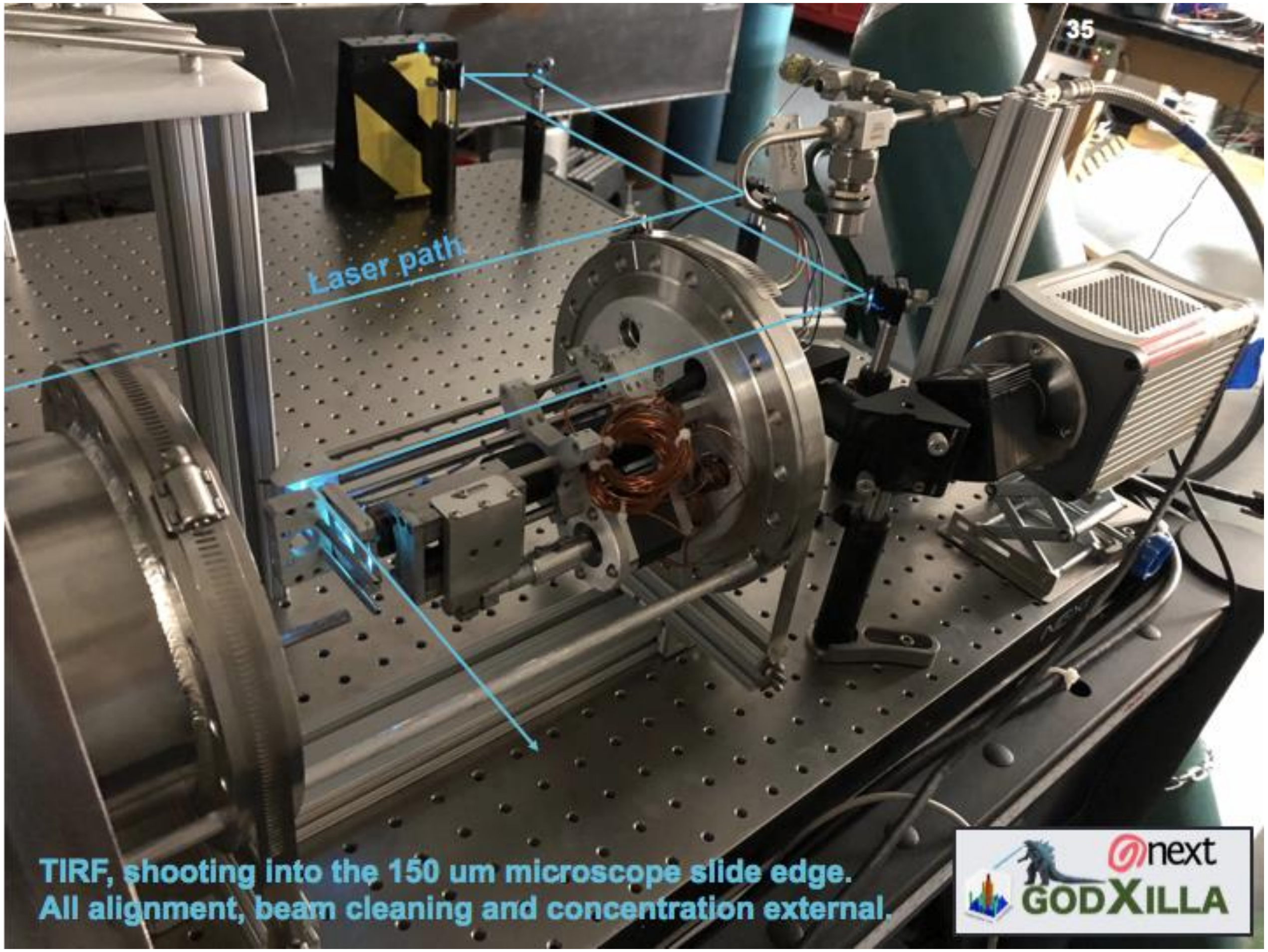


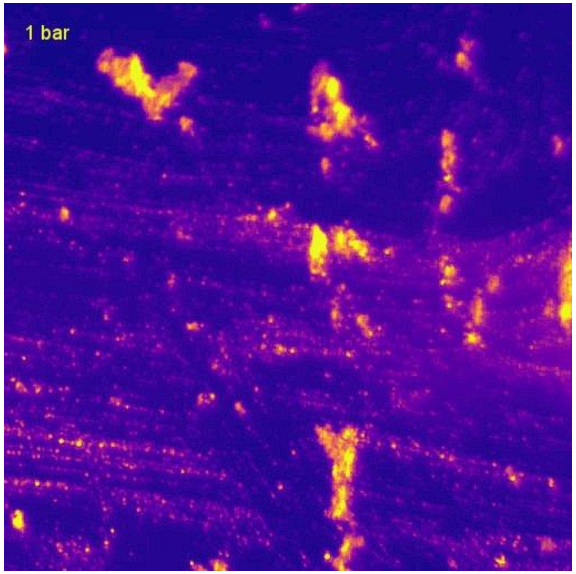
Graphic and Simion simulation showing the projected path Ba^{++} should follow. Work is under way to make an RF carpet work under high pressure.

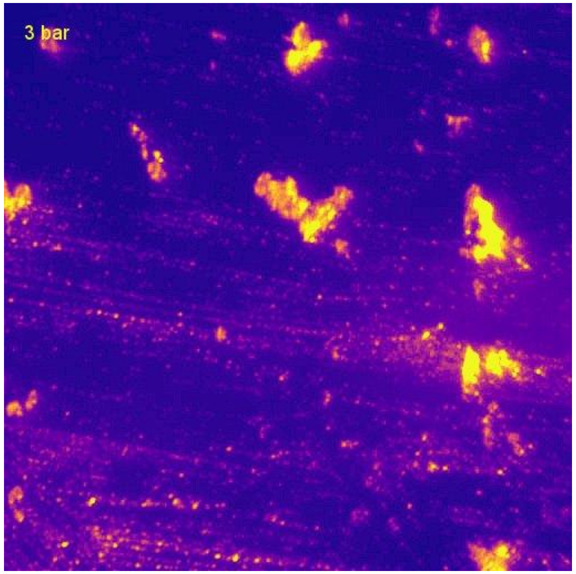


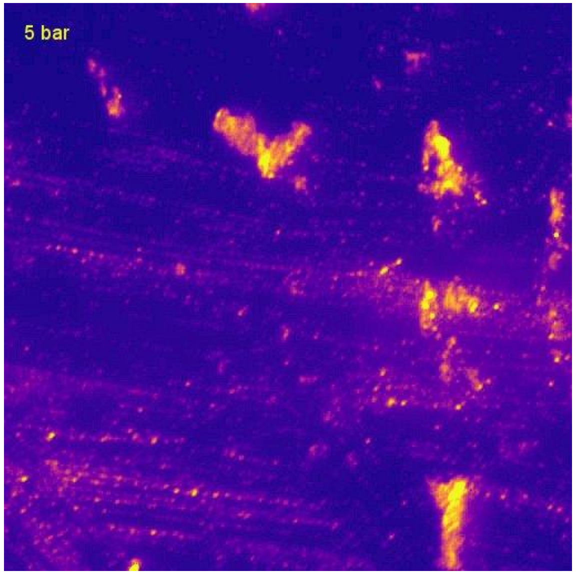
The RF carpet that will levitate and 'sweep' the ion towards the center. Will soon be tested at ANL using Ba ions produced by CARIBU

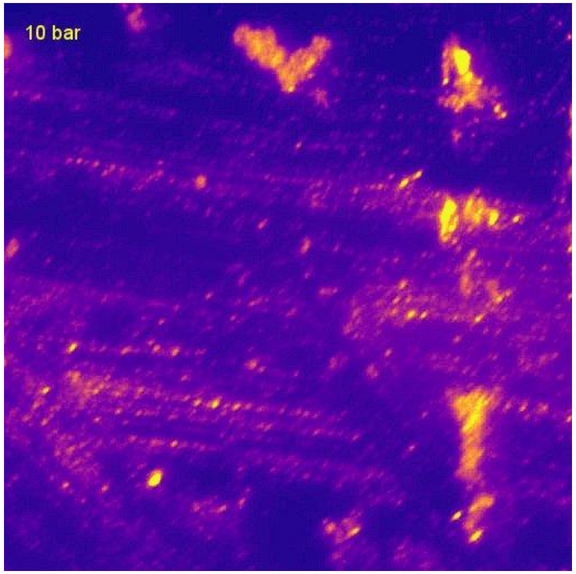
Pressure Microscope Assembly

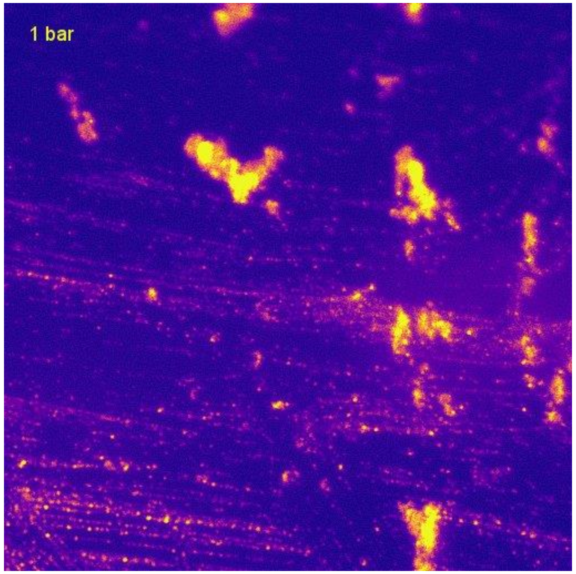



1 bar


3 bar

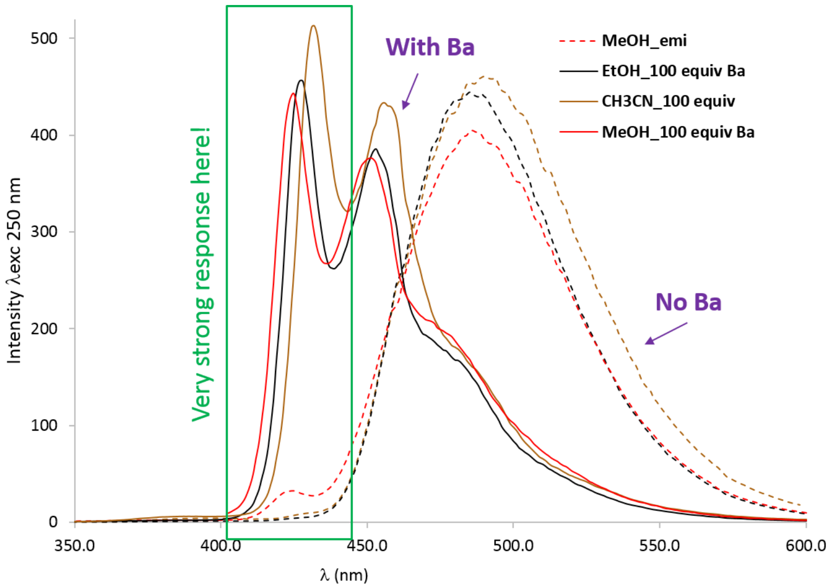

5 bar


10 bar


1 bar

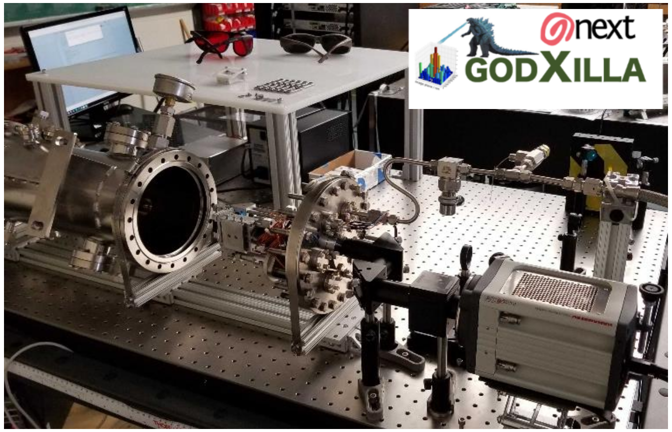
Other Advancements in NEXT

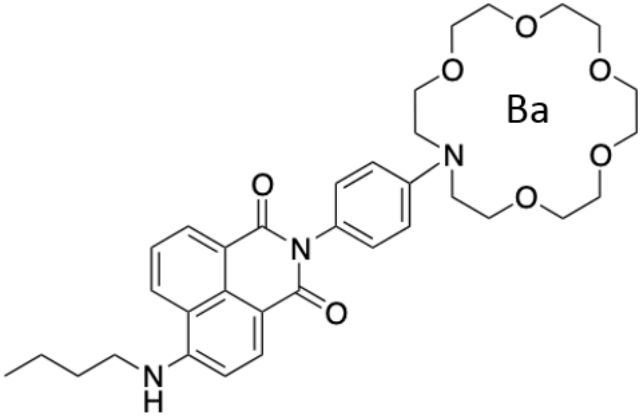
- Single ion sources in development at Ben Gurion University, Israel
- Barium Assay of surfaces/materials continuing at Pacific Northwest National Lab
- An alternate approach to this technique is underway at DIPC in Spain, using a color-shift two photon fluorophore detection techniques.



Conclusions

- New Fluorescent Barium Tagging Molecules have been developed by the University of Texas Arlington, eclipsing any commercially available dyes we previously used for this task.
- A new pressure-microscope has been successfully tested and shown to allow for the collection of images at least 10 bar.
- These advancements bring us closer to the development of an in-situ barium detection mechanism, which will allow NEXT to have far and away the most effective double beta decay sensitivity



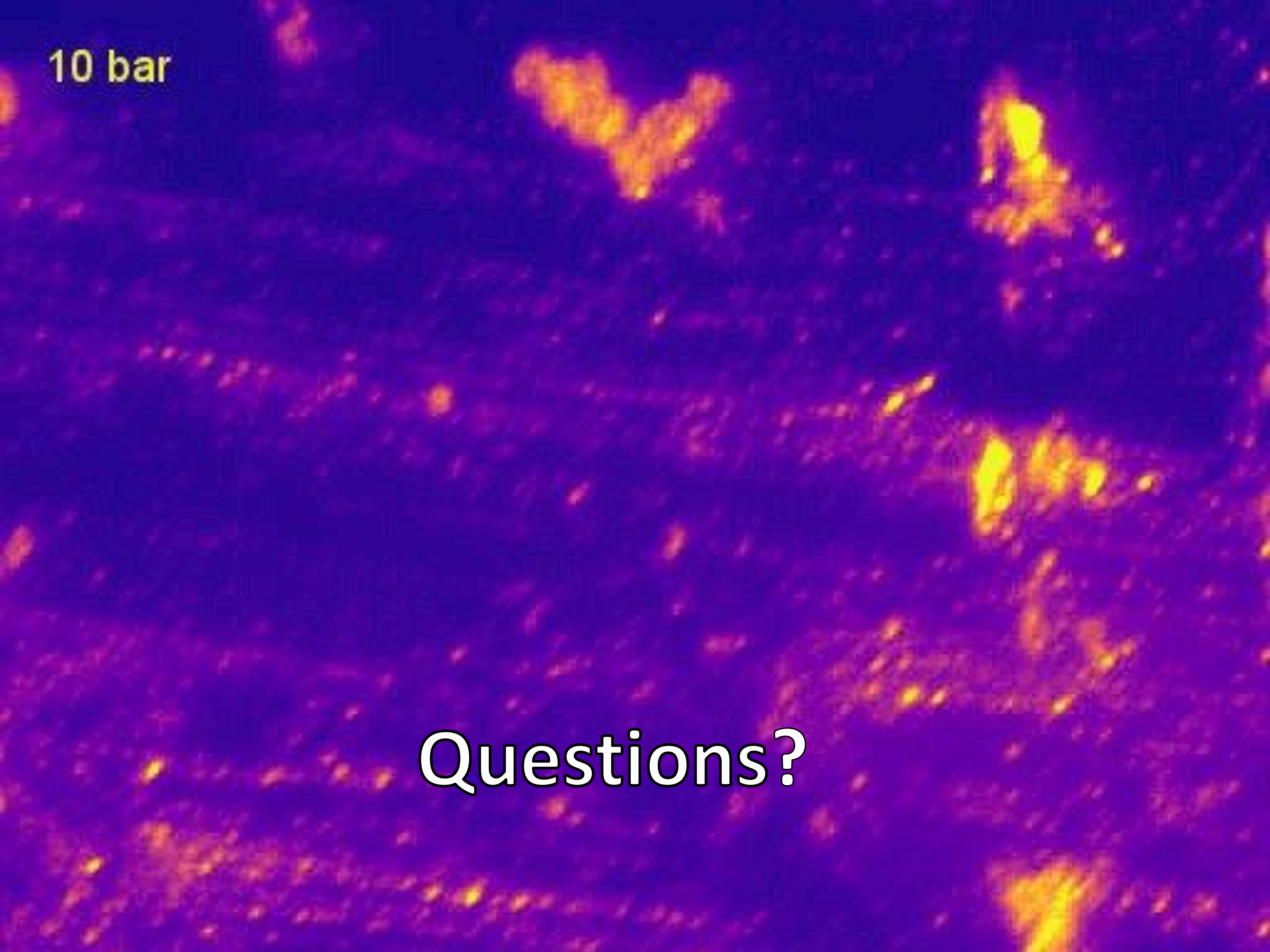


Acknowledgements

I would like to thank the NEXT collaboration, with special thanks to Dr. Frank Foss Jr., Dr. Ben Jones, Austin McDonald, Dr. David Nygren, Dr. Pawan Thapa, Alena Trinidad, Dr. Katherine Woodruff, and the rest of the UTA REST team.

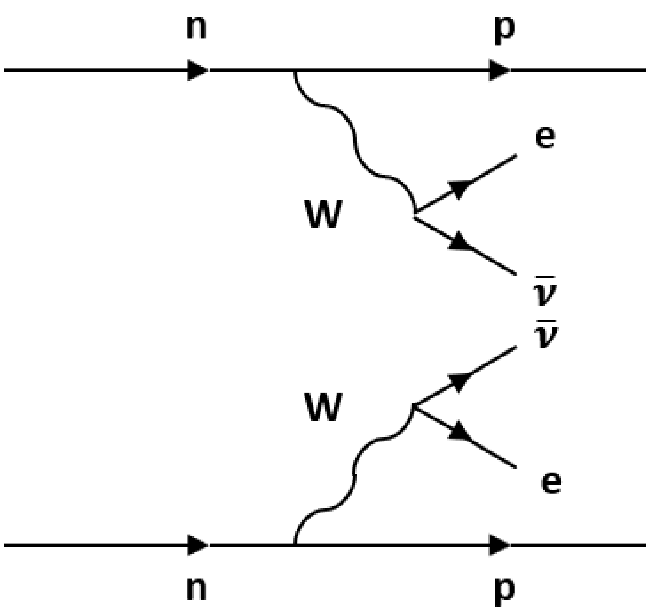
UNIVERSITY OF TEXAS ARLINGTON

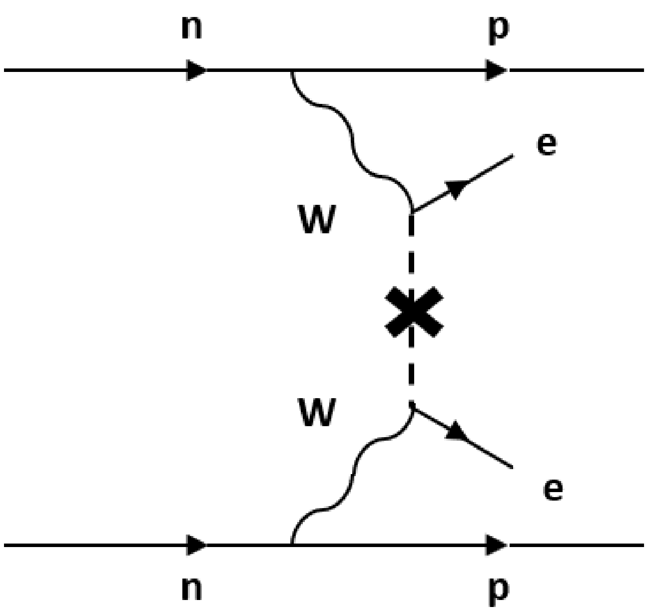
next



Questions?

Neutrinoless Double Beta Decay



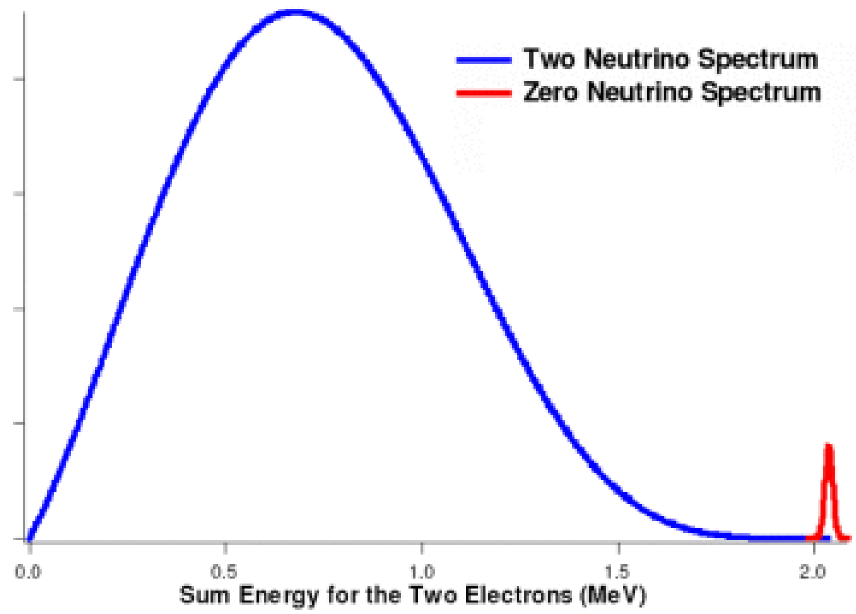


Double Beta Decay-
Two neutrons decays into two protons, electrons and antineutrinos.

Neutrinoless Double Beta Decay-
Two neutrons decays into two protons and electrons, but the antineutrinos annihilate.

Neutrinoless Double Beta Decay Cont.

- Proves that the neutrino is a Majorana Particle i.e. it is its own antiparticle.
- Shows that lepton number is *not* conserved, thereby meeting the first Sakharov Condition
- Is an exceedingly rare process, leading to the need for enhanced detection techniques.



Energy spectra of a standard xenon double beta decay vs. a neutrinoless xenon double beta decay