Development Towards a Camera Readout and Barium Tagging Optical TPC, or CRAB-OTPC, for the NEXT Collaboration

NICHOLAS BYRNES

Supported by

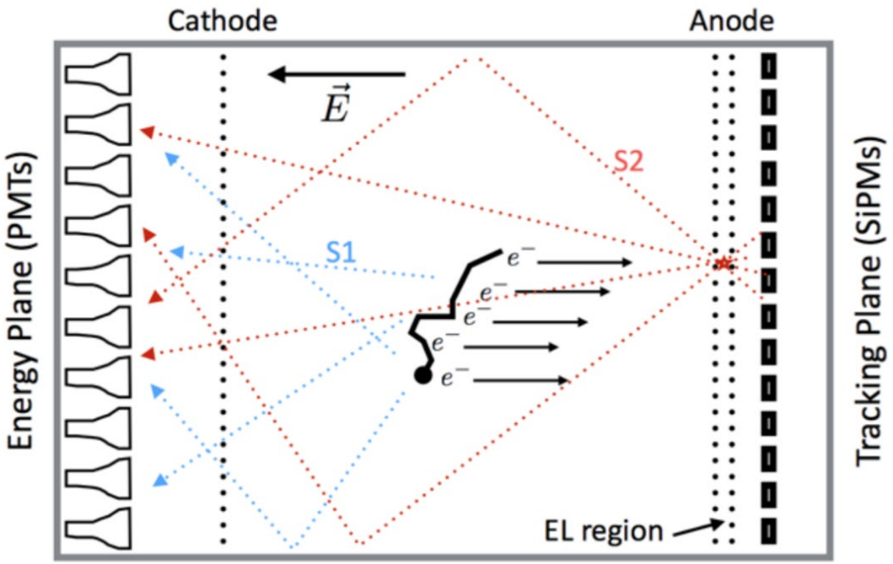
Monrabal, F. et al., “The Next White (NEW) detector,” arXiv:1804.02409

The NEXT Program

- The NEXT collaboration uses a High-Pressure Xenon (HPGXe) TPC with an electroluminescence (EL) region to convert particle tracks into light which is wavelength shifted (WLS), collected, and analyzed.

- Using this technology, NEXT is looking for neutrinoless double beta decay (0νββ) via event energy and topology.

- A new optical visualization technique for event topology in 0νββ will facilitate the implementation of barium daughter identification – a step toward a background-free experiment in high-pressure xenon gas.

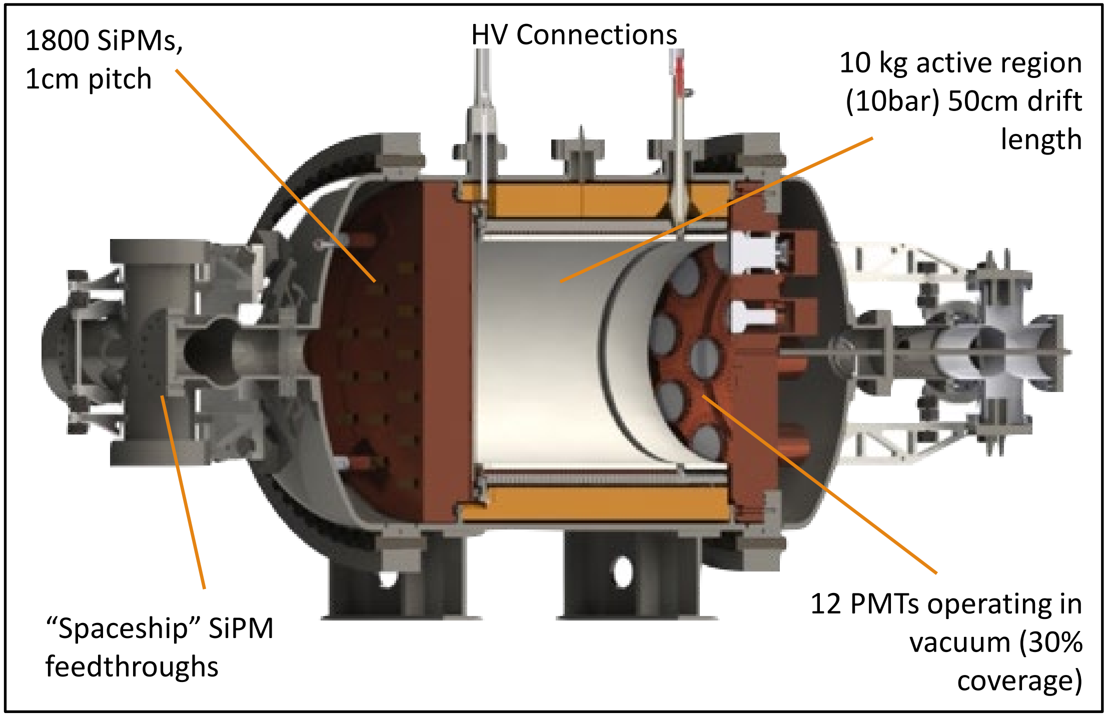


Internal Schematic for the NEXT-White High-Pressure Xenon TPC

The NEXT Program

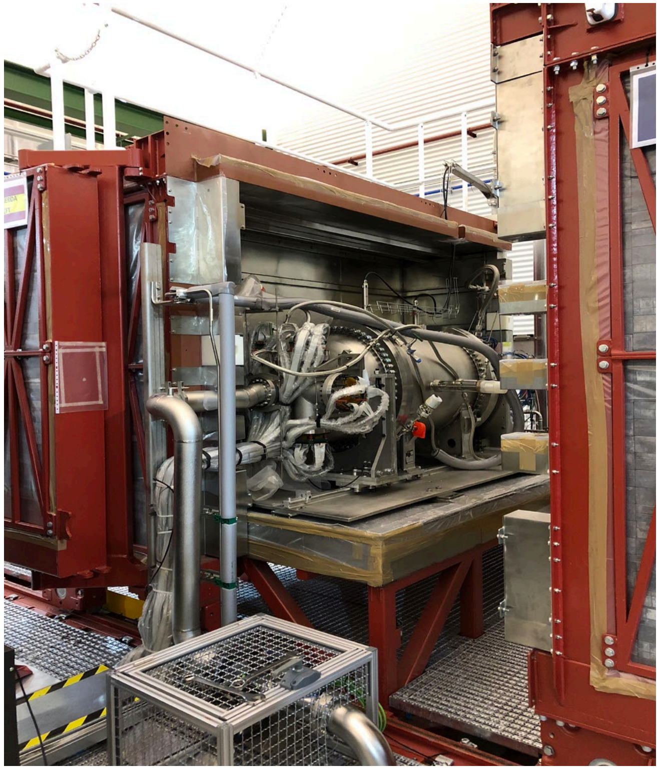
Sequence of HPGXe experiments, focused on achieving big, very low background xenon 0νββ detector

- NEXT-DBDM
- NEXT-DEMO
- NEXT-NEW
- NEXT-100
- NEXT-HD
- NEXT-BOLD



Full-system technology demonstrator to validate background model and demonstrate detector scalability, laying foundation for NEXT-100

0νββ Background Reduction



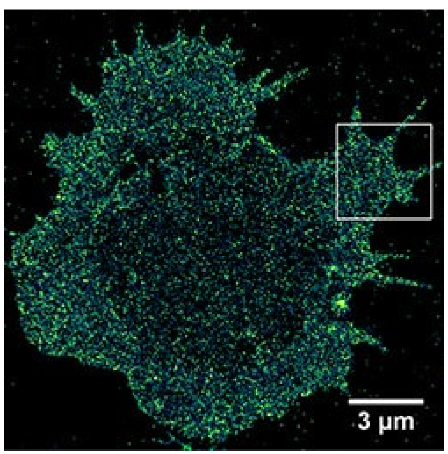
NEXT-White Vessel in its housing at Canfranc, Spain

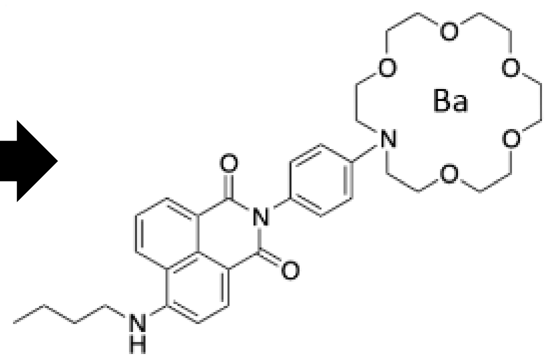
- If observed, 0νββ would be the rarest known nuclear process in the Universe ($T_{1/2} > 10^{26}$yr). This means that any process in the energy range of interest can obfuscate the signal.
- Much of this background comes from natural radioactive decay from materials inside the detector vessel and shielding (primarily from Copper).
- Additionally, data is currently collected using internal SiPM's and PMT's, which make their own background.

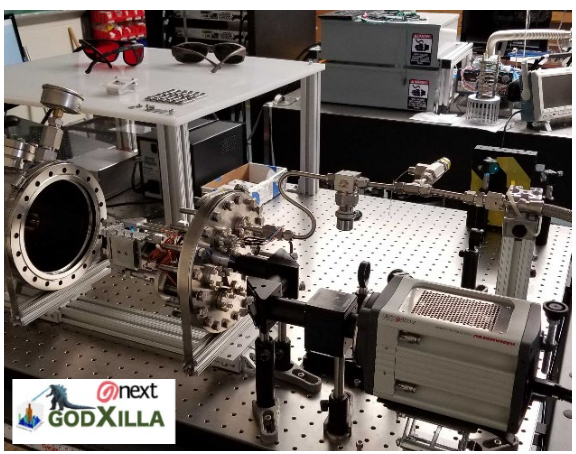
D.R. Nygren, “Detection of the barium daughter in 136Xe→ 136Ba+ 2e- by in situ single-molecule fluorescence imaging,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Barium Tagging For Double Beta Decay

- One of the potentially most powerful ways to reduce backgrounds would be to identify the daughter Ba ion made when ^{136}Xe decays.
- The method currently being explored by the NEXT collaboration is to use custom barium-sensitive molecules to fluoresce while chelated with Ba^{++} via Single Molecule Fluorescence Imaging (SMFI).



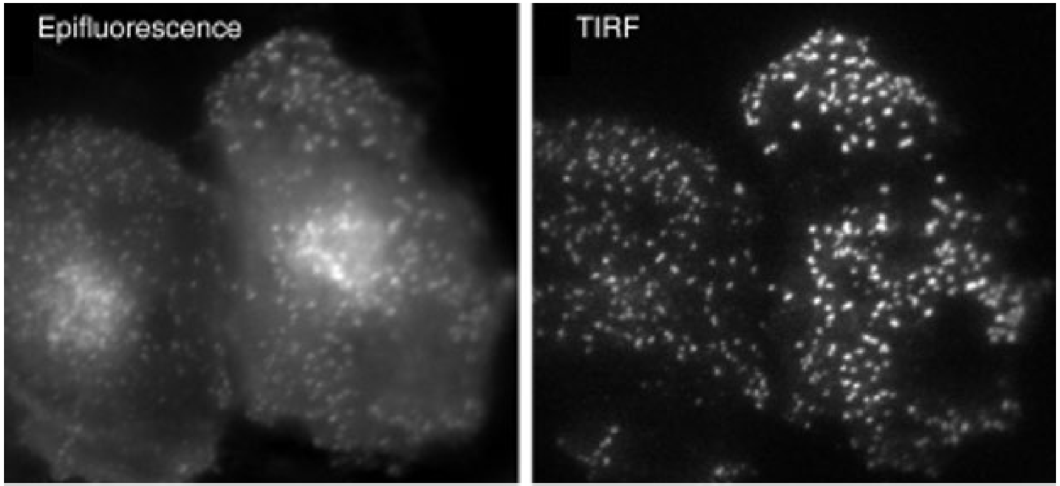




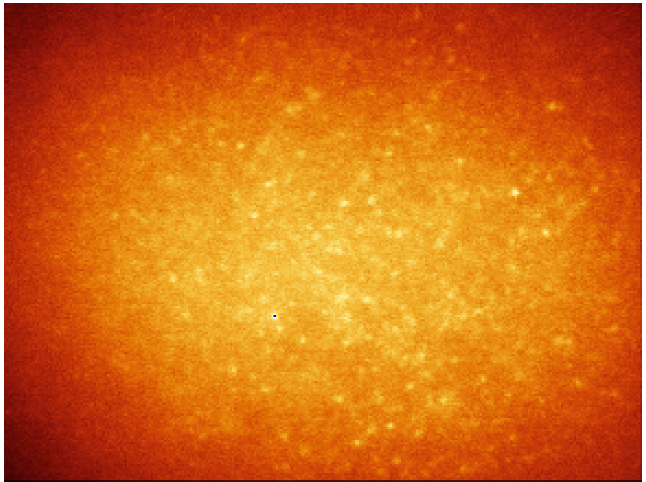
Single Molecule Fluorescent Imaging

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

- In biological imaging, fluorescent dyes are used to tag specific ions in cells, primarily calcium.
- By using Single Molecule Fluorescence Imaging (SMFI), individual ion-molecule complexes can be imaged.
- We are applying these Bio-chem techniques to tagging the Barium Daughter of ^{136}Xe double beta decay.



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



Individual Fluo-4 + Ca ion complex imaged at UTA

Complementary Ba-Tagging R&D

McDonald A D et al. 2018 Phys. Rev. Lett. 120132504 (Preprint1711.04782)

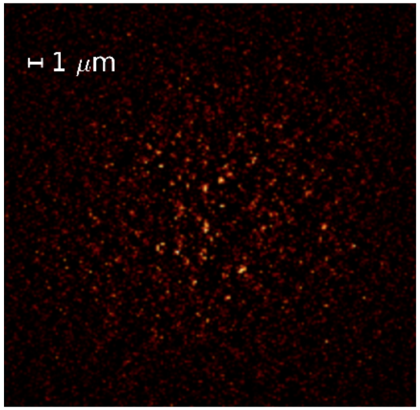
Rivilla, I. et al. Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments. Nature 583, 48–54 (2020). https://doi.org/10.1038/s41586-020-2431-5

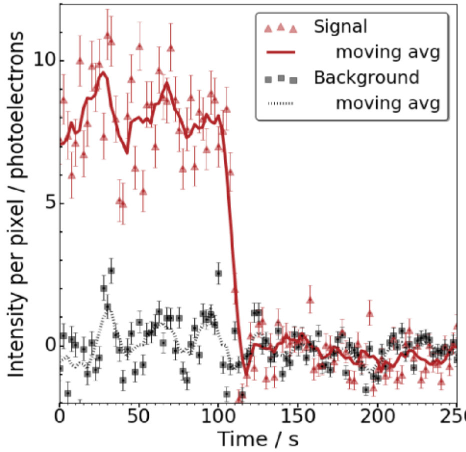
US R&D activities

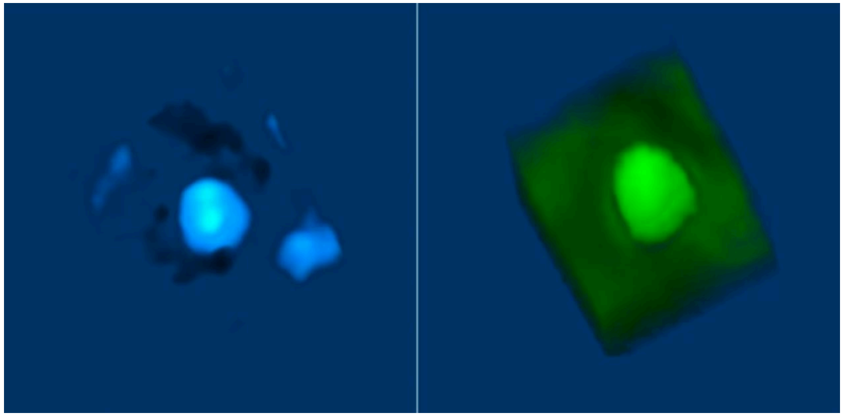
- Turn-on fluorophores with dry single molecule imaging
- High pressure microscopy in epi- and TIRF-modes
- RF carpets for ion concentration
- Camera-based tracking to accommodate tagging systems

European R&D activities

- Fluorescent bicolor indicators (FBI)
- TPA microscopy
- Metalenses







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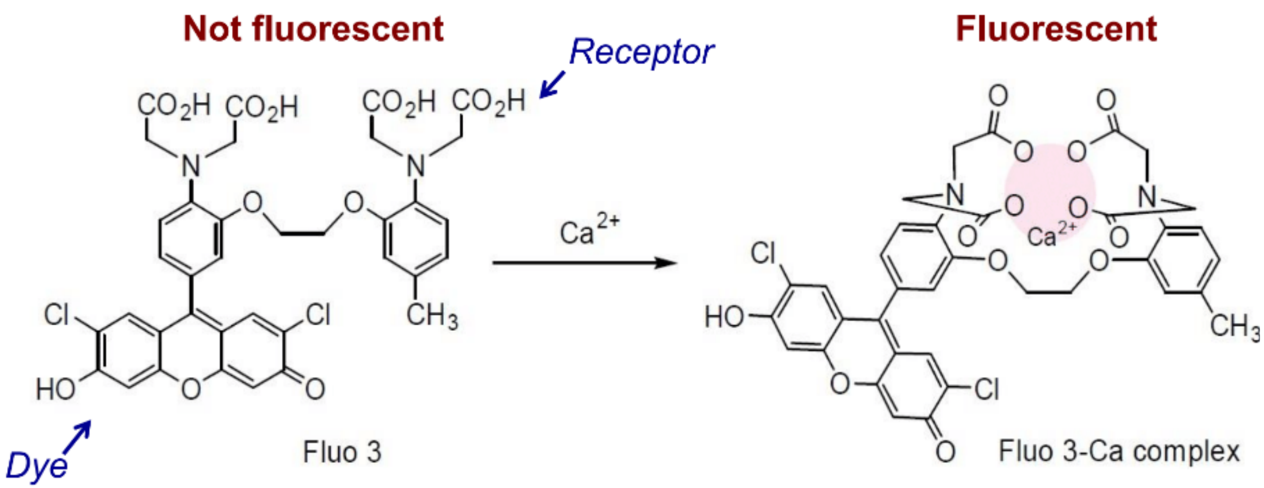
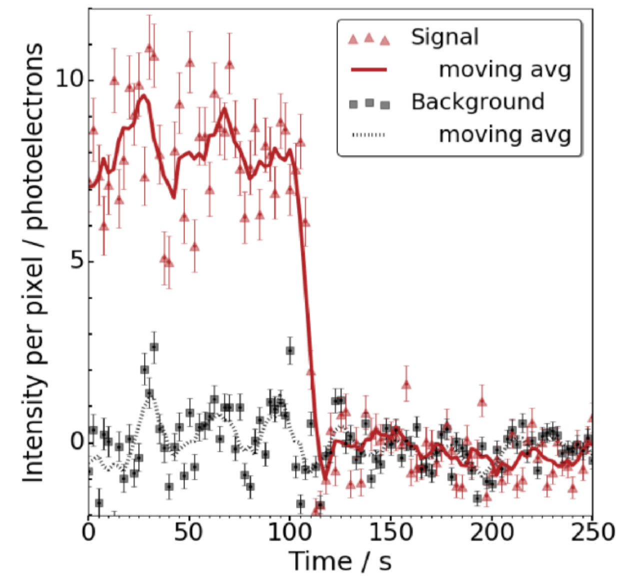
Single Molecule Fluorescent Imaging



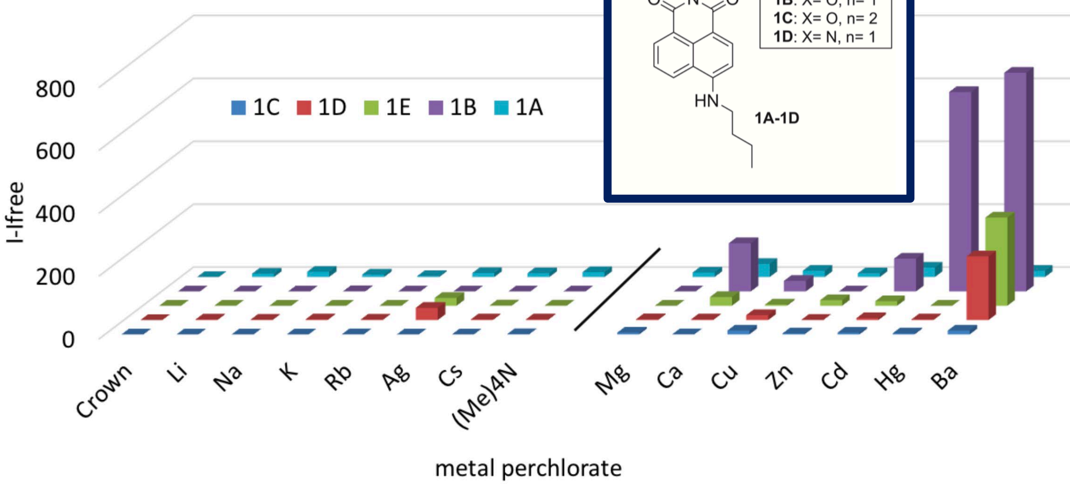


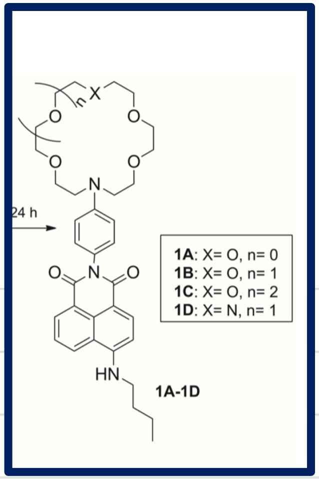
Chelation process, where an "off state" dye binds a metal cation and becomes fluorescent, or "on."

Signature 'single-step' fluorescent trajectory indicating individual ions.

N.K. Byrnes et al., "Barium Tagging with Selective, Dry-Functional Single Molecule Sensitive On-Off Fluorophores for the NEXT Experiment," APS DPF 2019 Proceeding, arXiv:1909.04677

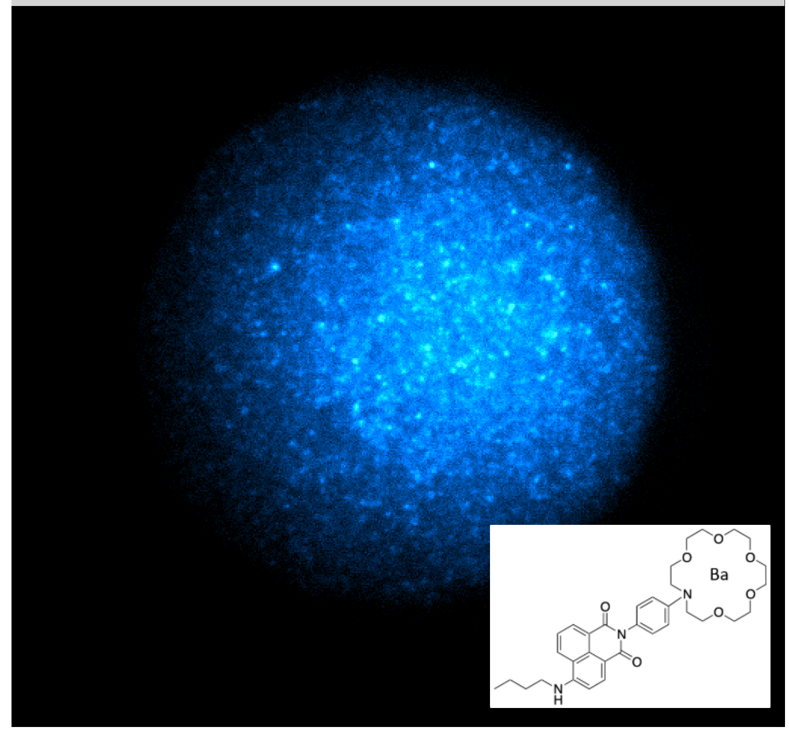
Custom Barium Chemosensors





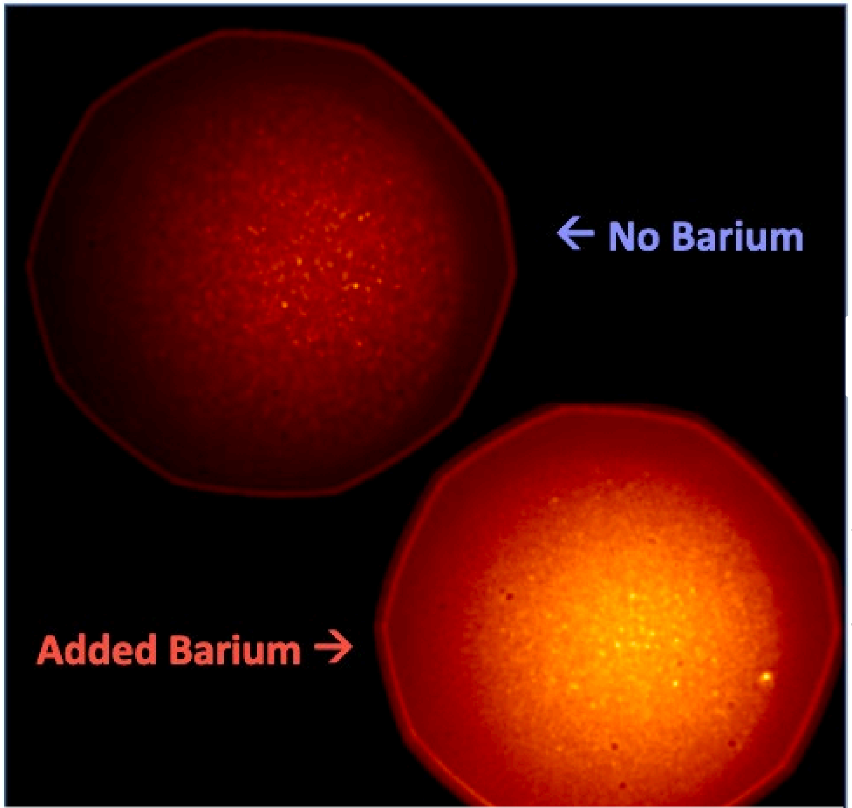
Selectivity of 18c6-Nap variations to various metal ions

Fluorescent 18c6-Nap molecules in PVA, taken over 300s



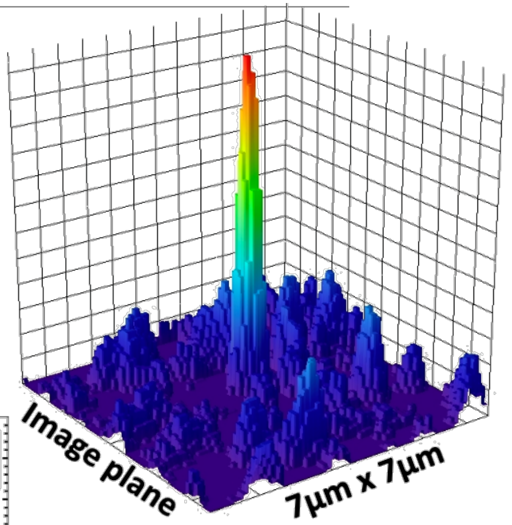
Barium Tagging Progress

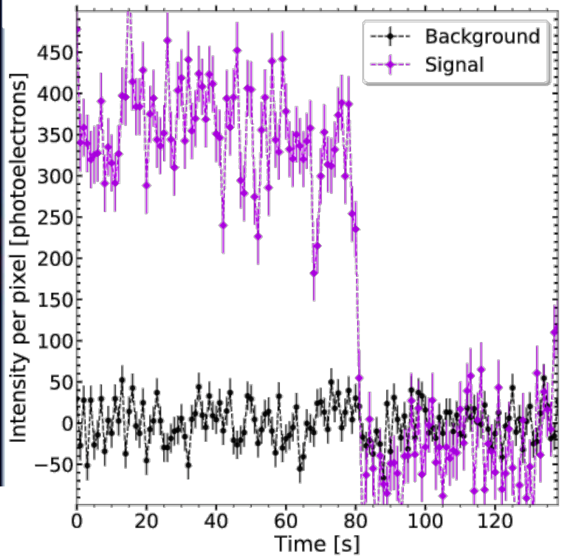
P. Thappa, N.K. Byrnes et al., "Demonstration of Selective Single-Barium Ion Detection with Dry Diazacrown Ether Naphthalimide Turn-on Chemosensors," ACS Sensors 2021 6 (1), 192-202. DOI: 10.1021/acssensors.0c02104



Dry, solid 18c6Nap in cyanoacrylate before/after Ba Saturation

3D histogram of a single 18c6Nap complex before photobleaching.

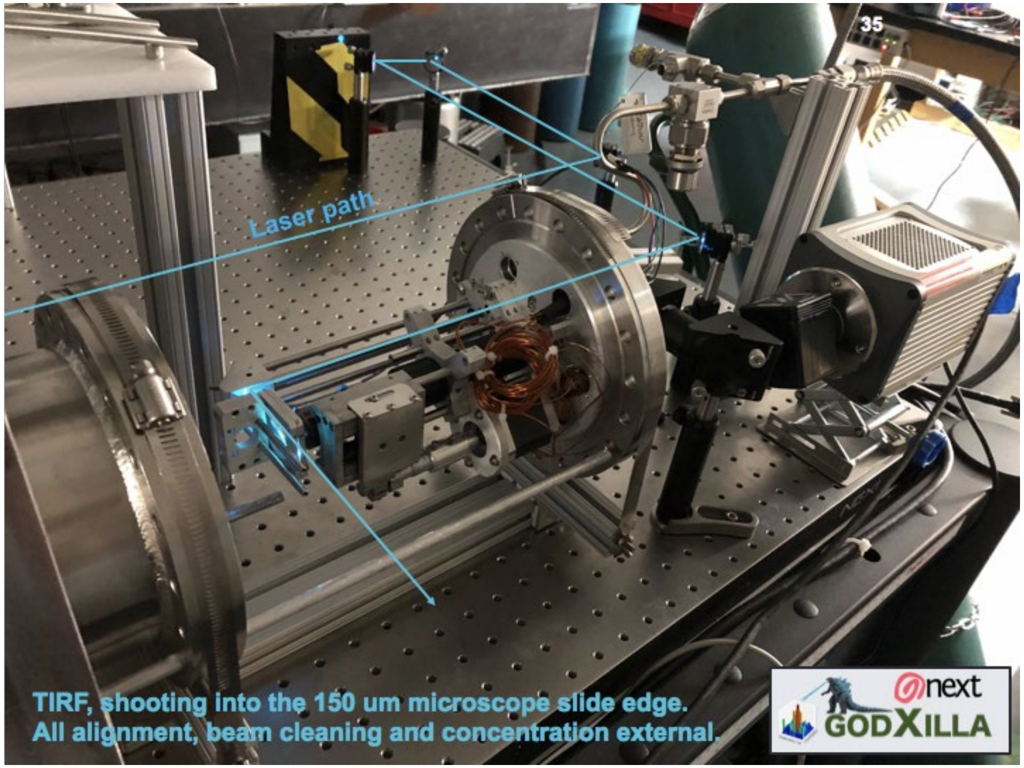


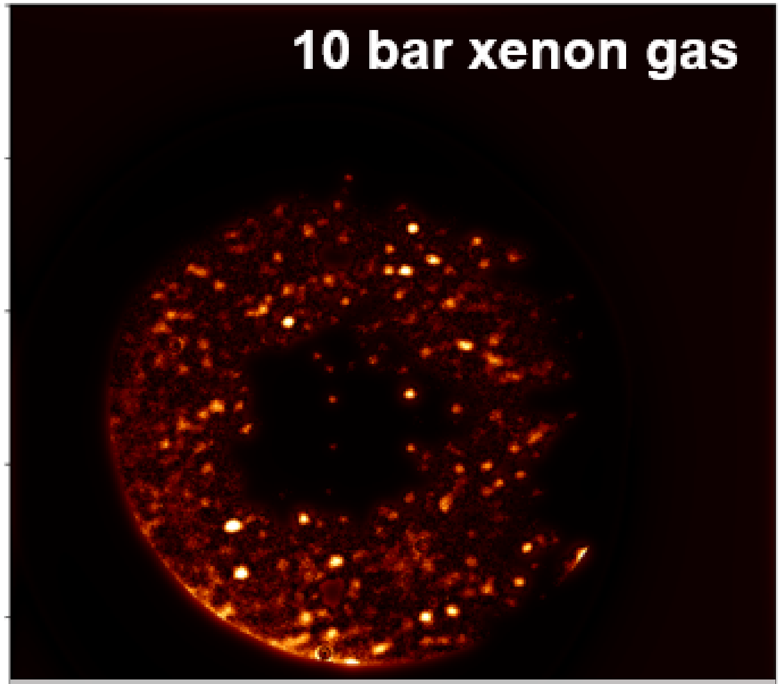


Fluorescent trajectory of a dry 18c6Nap complex photobleaching in one discreet single step.

Barium Tagging Progress

N.K. Byrnes et al., "Barium Tagging with Selective, Dry Functional Single Molecule Sensitive On-Off Fluorophores for the NEXT Experiment," APS DPF 2019 Proceeding, arXiv:1909.04677



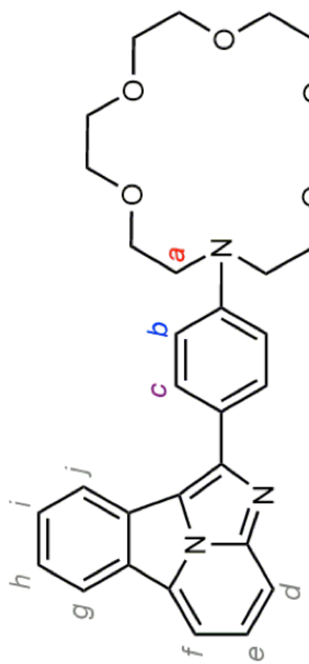


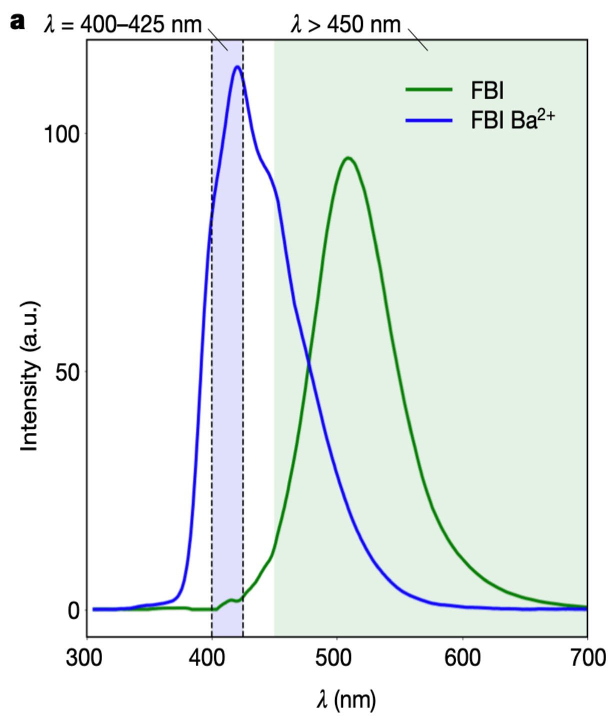
First ever fluorescent image of single chelated 18c6-Nap complexes taken in High Pressure xenon gas

Rivilla, I., Aparicio, B., Bueno, J.M. *et al.* Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments. *Nature* **583,** 48–54 (2020). https://doi.org/10.1038/s41586-020-2431-5

Bi-color sensors

A parallel line of R&D is exploring bi-color chemosensors which switch green → blue upon binding with barium ions.



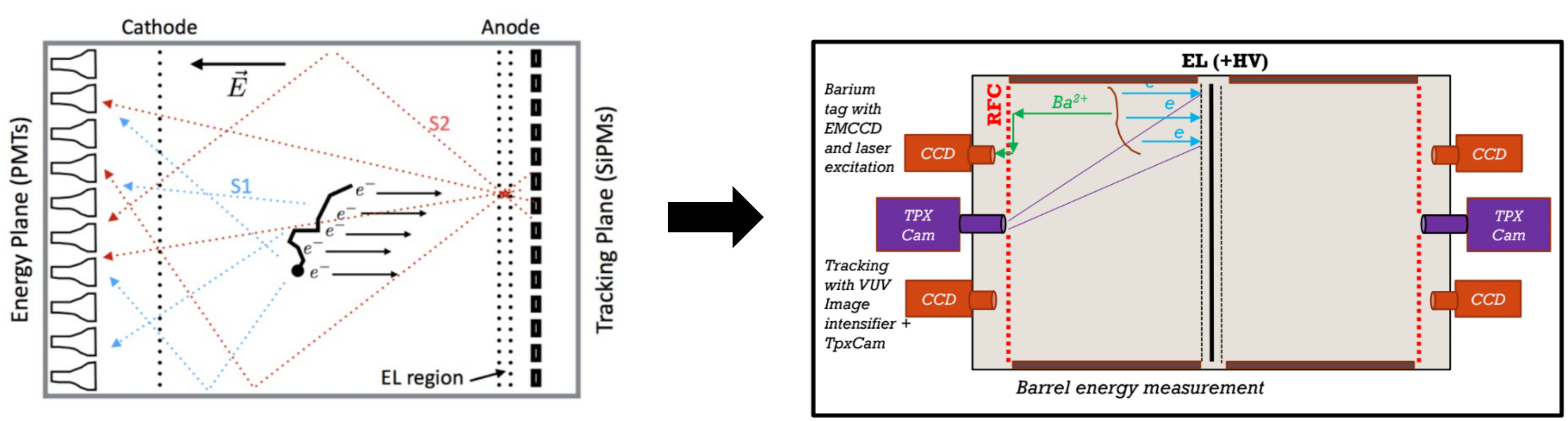


← **No Ba^{2+}**

← **With Ba^{2+}**

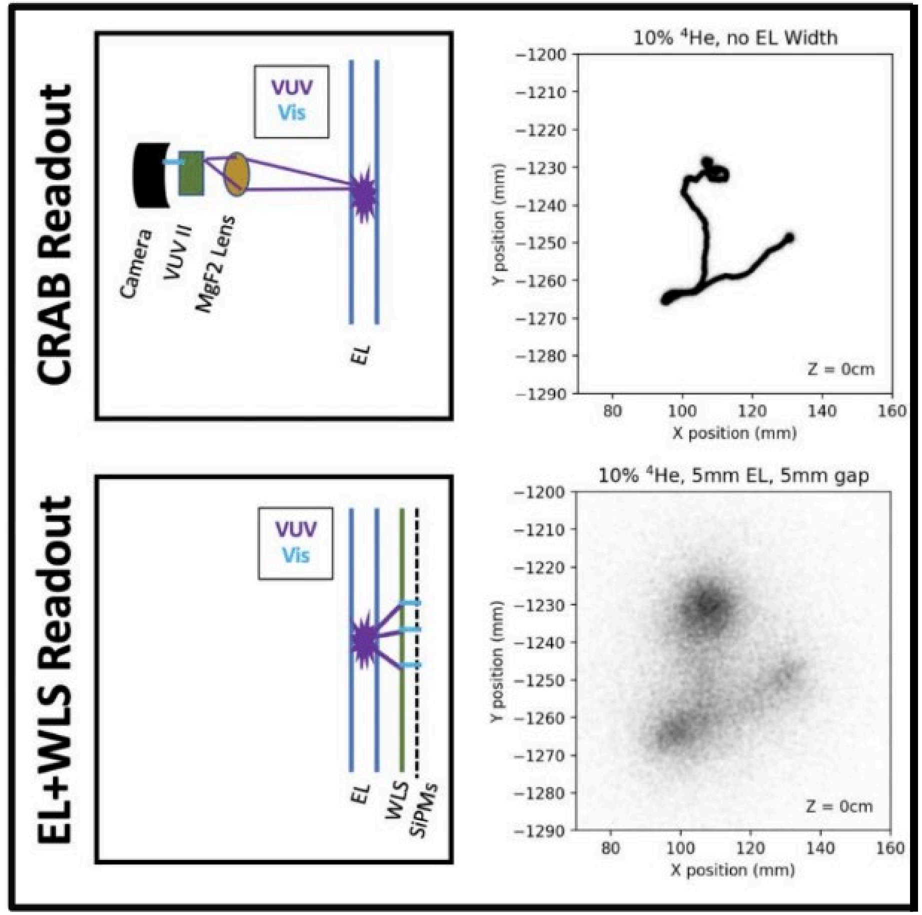
Camera Readout Optical TPC

- An important consideration in a Ba-Tagging TPC is where the energy/charge sensing elements can be placed, given a Ba-sensing cathode.
- One approach to make room is to implement tracking-plane readout using an external camera in lieu of SiPM's, creating the requisite space for barium tagging.
- This also allows us to move the EL region to the center of the detector, removing the need for a buffer region to step down HV, which wastes xenon gas.
- This also removes the complexity, heat-load, and radioactivity associated with a dense, pixelated tracking plane.



Track Sharpness

- And additional advantage to camera-based direct VUV tracking is an improvement in track sharpness.
- With a proper choice of optics, the VUV light made by tracks can be observed directly without the need for a WLS plane.
- This, combined with the improved resolution of a camera over a SiPM grid, will drastically improve track shape.



Camera Readout HPGXe TPC

- A prototype Camera Readout TPC is currently being designed and tested by researchers at UTA and ANL. UTA will be prototyping the optical path design primarily.
- All optical components must be transparent at 175nm to see scintillation light from xenon. These optics are being designed and built in-house at UTA.
- Our image intensifier must also be operated in a N_2 filled vessel to prevent the 175nm light from scattering in atmospheric gas.

A

B

A Photonis Image Intensifier (a) and the Hamamatsu imagem X2 EMCCD Camera used in our detector (b)

Image Intensification

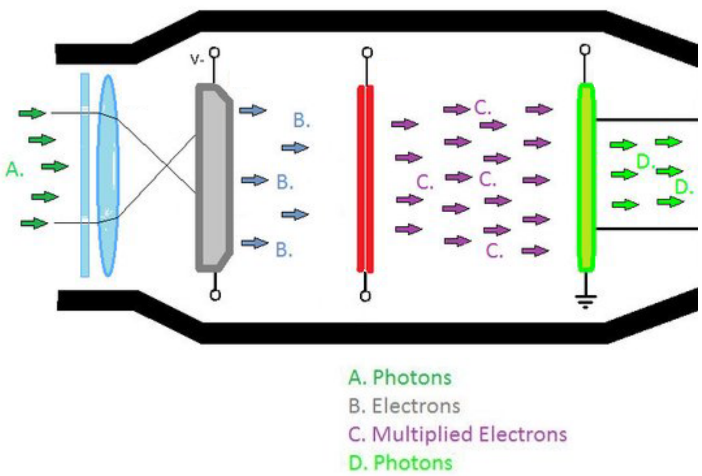
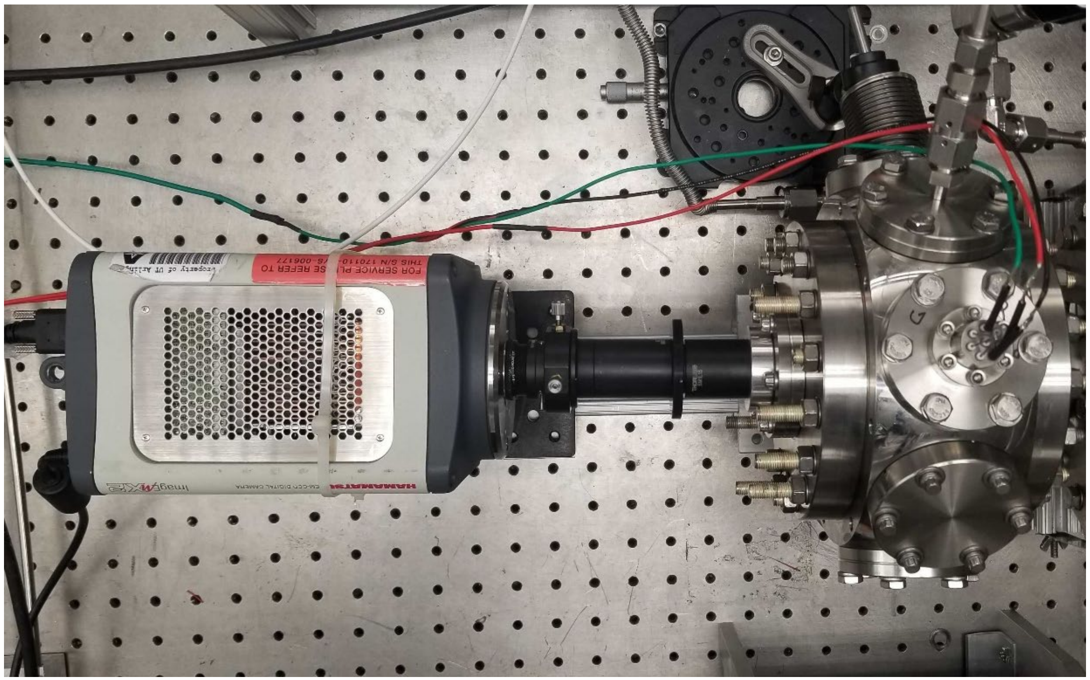


Image Intensifier Diagram

- The Image Intensifier, a crucial part of making the Camera Readout, works as follows:
  - Incoming photons strike a photocathode and are converted to electrons.
  - These electrons are then multiplied via an MCP.
  - The electrons then finally collide with a phosphor plane, ionizing it and emitting photons.
- These devices have enormous light amplification (3000x), perfect for the low-light UV track light made in a TPC.

Camera Readout
HPGXe TPC

NEXT
Camera
Readout
And
Barium-Tag

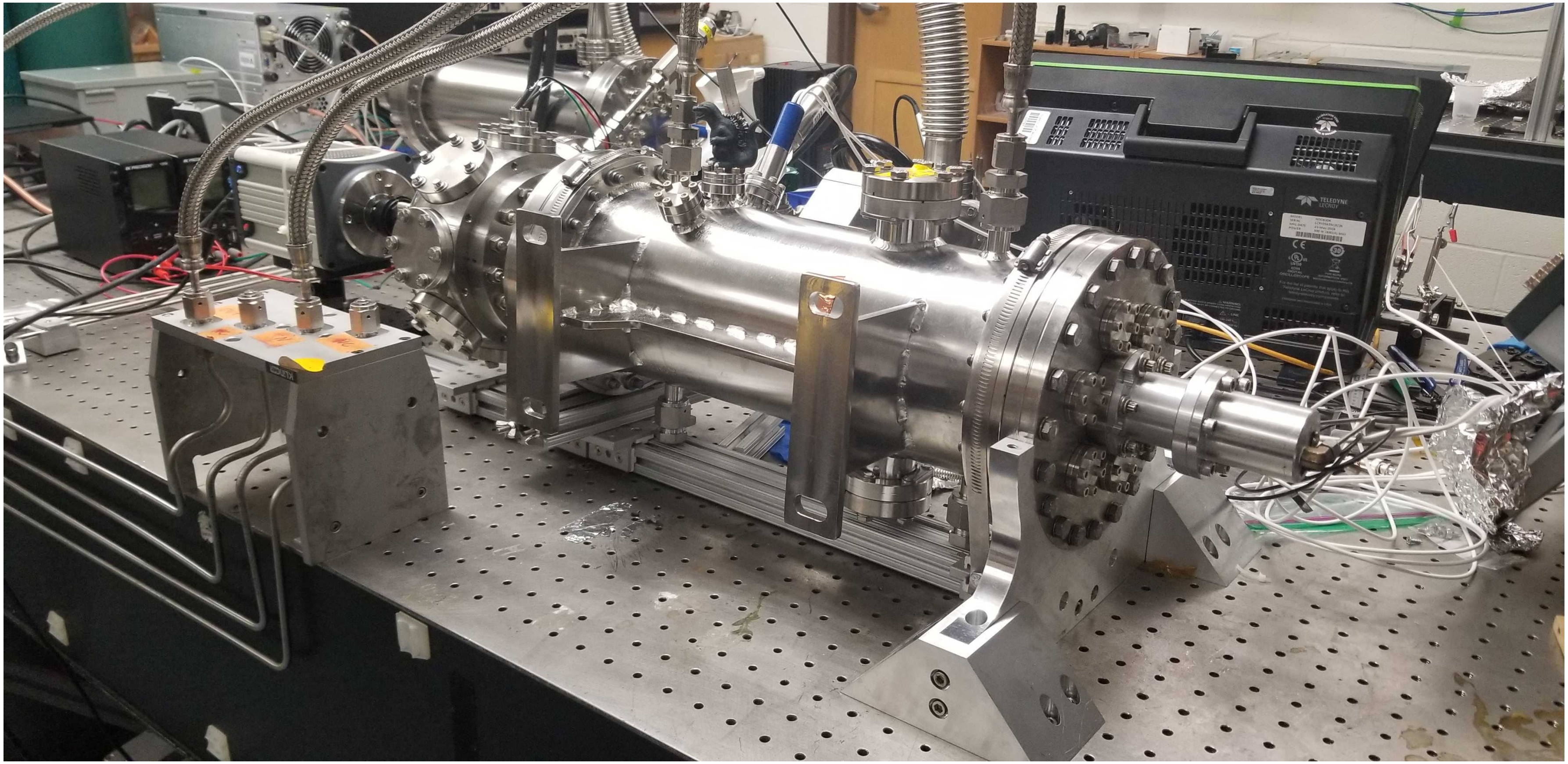


Tracking electronics: EMCCD Camera (left) and Image Intensifier Vessel (right)

Internal Field Cages and EL Region

Camera Readout HPGXe TPC

NEXT
Camera
Readout
And
Barium-Tag



D.R. Nygren., “The Time-Projection Chamber- A new 4π detector for charged particle,” *eConf* C740805 (1974) 58

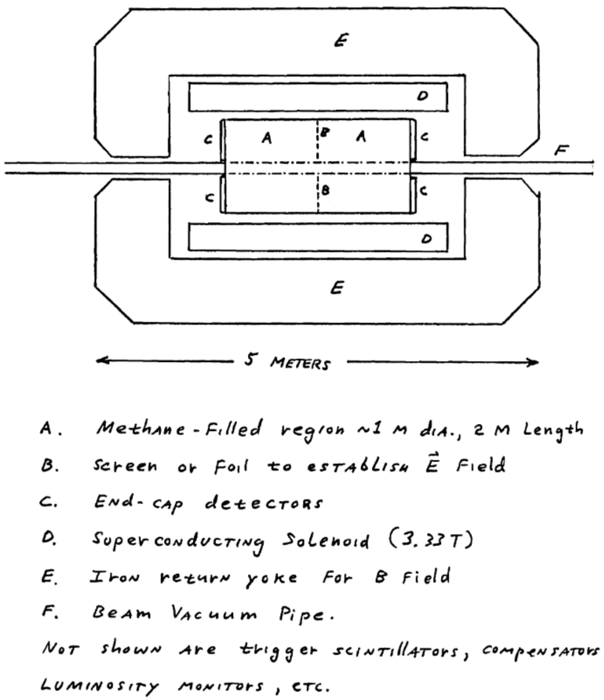
Conclusions

- For rare events like 0νββ, TPC backgrounds are one of the greatest challenge to overcome.

- Ba Tagging, a technique to identify the daughter ion made in 0νββ, has the potential to reduce backgrounds to almost zero when coupled with stringent energy cuts.

- Work is underway to design a novel HPGXe Optical Time Projection Chamber to allow for Ba Tagging implementation and direct track observation

- In concert with other R&D ongoing within the NEXT collaboration, this may lead to a normal-ordering-class method for testing the Majorana nature of the neutrino



Schematic drawing for the first TPC from 1974

References

1. Nygren D R 2016 Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 8242–5

2. Jones B, McDonald A and Nygren D 2016 Journal of Instrumentation 11P12011

3. McDonald A D et al. 2018 Phys. Rev. Lett. 120132504 (Preprint1711.04782)

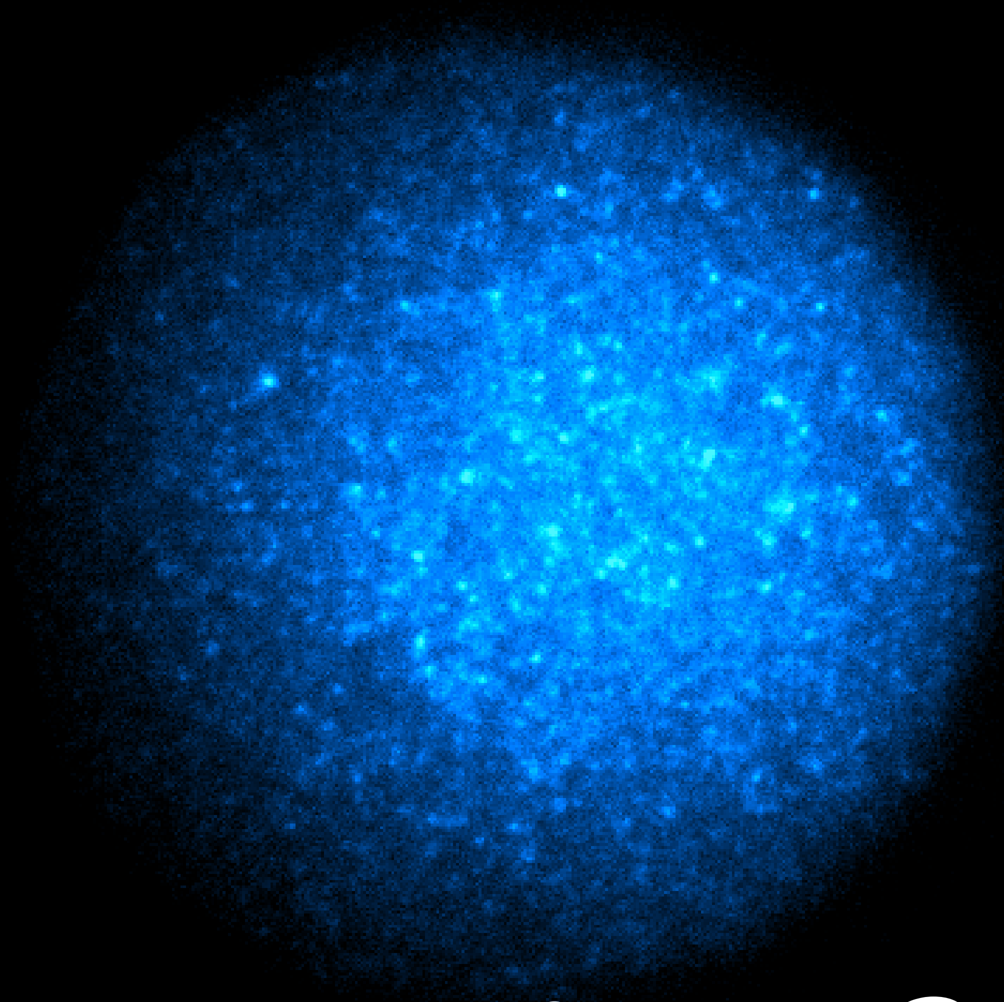
4. Mattheyses, A. L., Simon, S. M., & Rappoport, J. Z. (2010). Imaging with total internal reflection fluorescence microscopy for the cell biologist. *Journal of cell science*, *123*(Pt 21), 3621–3628. doi:10.1242/jcs.056218

5. N.K. Byrnes et al., “Barium Tagging with Selective, Dry-Functional Single Molecule Sensitive On-Off Fluorophores for the NEXT Experiment,” APS DPF 2019 Proceeding, arXiv:1909.04677

6. P. Thappa, N.K. Byrnes et al., “Demonstration of Selective Single-Barium Ion Detection with Dry Diazacrown Ether Naphthalimide Turn-on Chemosensors,” *ACS Sensors* 2021 *6* (1), 192-202. DOI: 10.1021/acssensors.0c02104

7. Rivilla, I., Aparicio, B., Bueno, J.M. *et al.* Fluorescent bicolour sensor for low-background neutrinoless double β decay experiments. *Nature* **583,** 48–54 (2020). https://doi.org/10.1038/s41586-020-2431-5

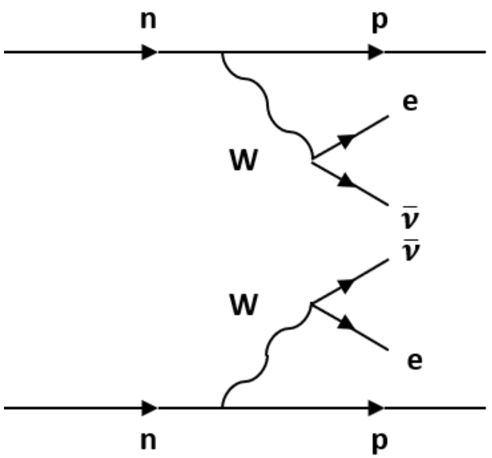
8. D.R. Nygren., “The Time-Projection Chamber- A new 4π detector for charged particle,” *eConf* C740805 (1974) 58

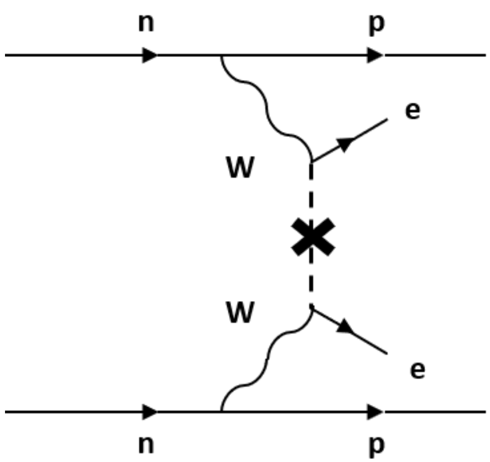


Questions?

Backup Slides

Neutrinoless Double Beta Decay



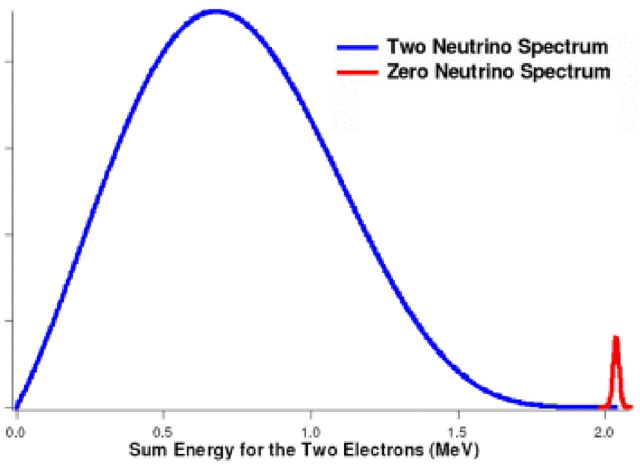


Double Beta Decay-
Two neutrons decays into two protons, electrons and antineutrinos.

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

Neutrinoless Double Beta Decay Cont.

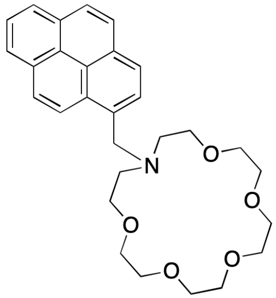
- Proves that the neutrino is a Majorana Particle i.e. it is its own antiparticle.
- Shows that lepton number is *not* conserved, thereby meeting the first Sakharov Condition
- Is an exceedingly rare process, leading tc the need for enhanced detection techniques.



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

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

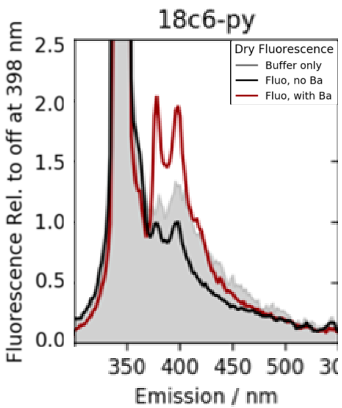
Custom Barium Chemosensors

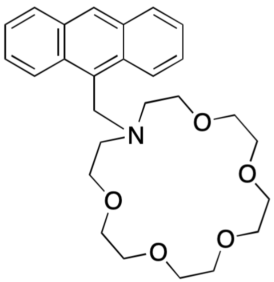


18c6 Pyrene

λ_{abs} = 345 nm

λ_{ems} = 400 nm

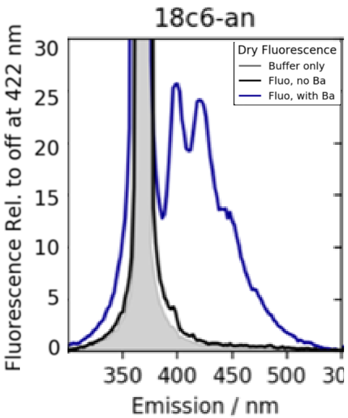




18c6 Anthracene

λ_{abs} = 375 nm

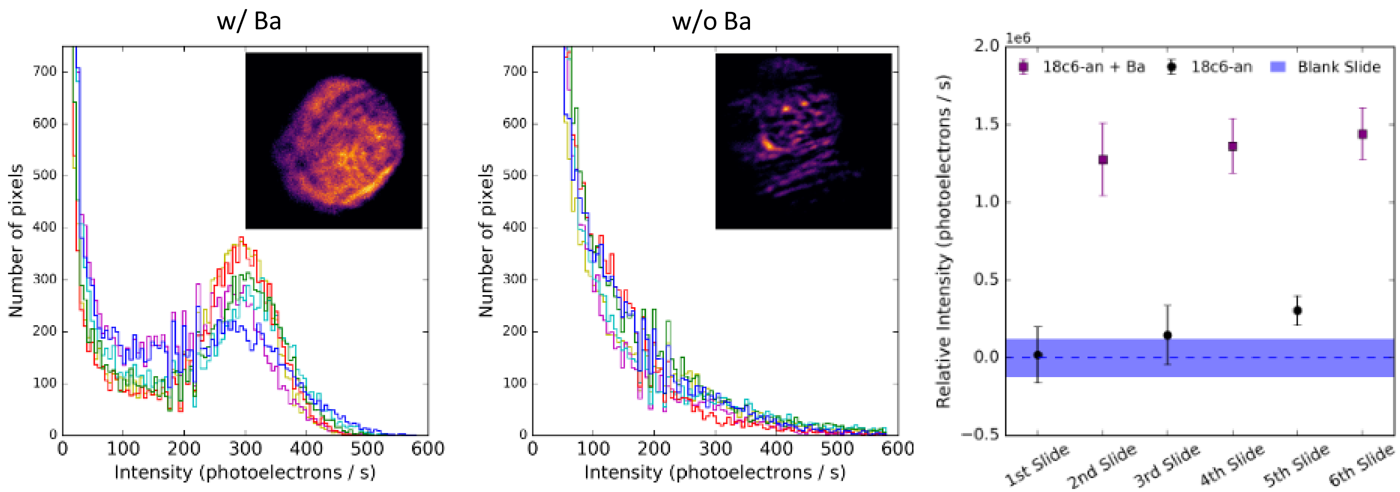
λ_{ems} = 410 nm

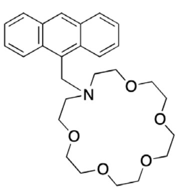


18c6 proved the most promising receptor for barium in these studies

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

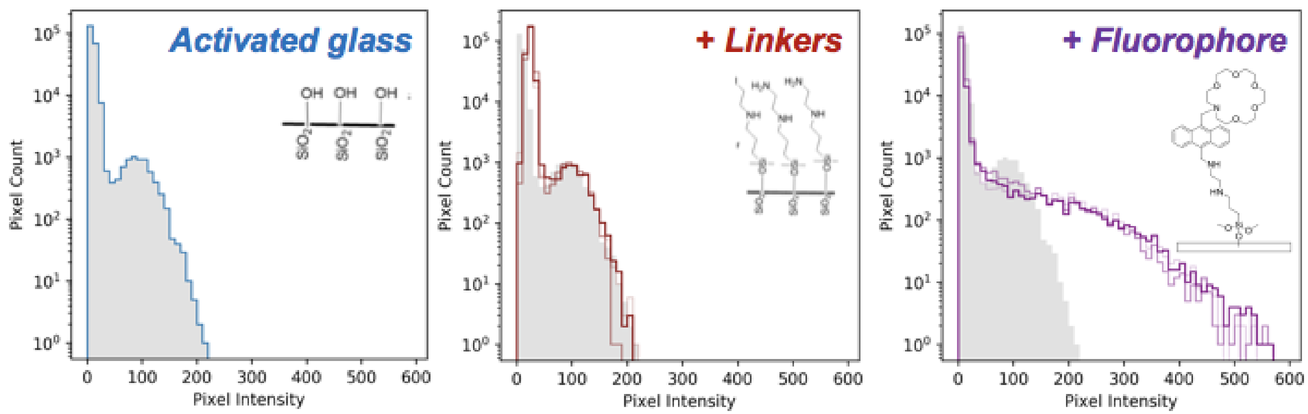
Custom Barium Chemosensors





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

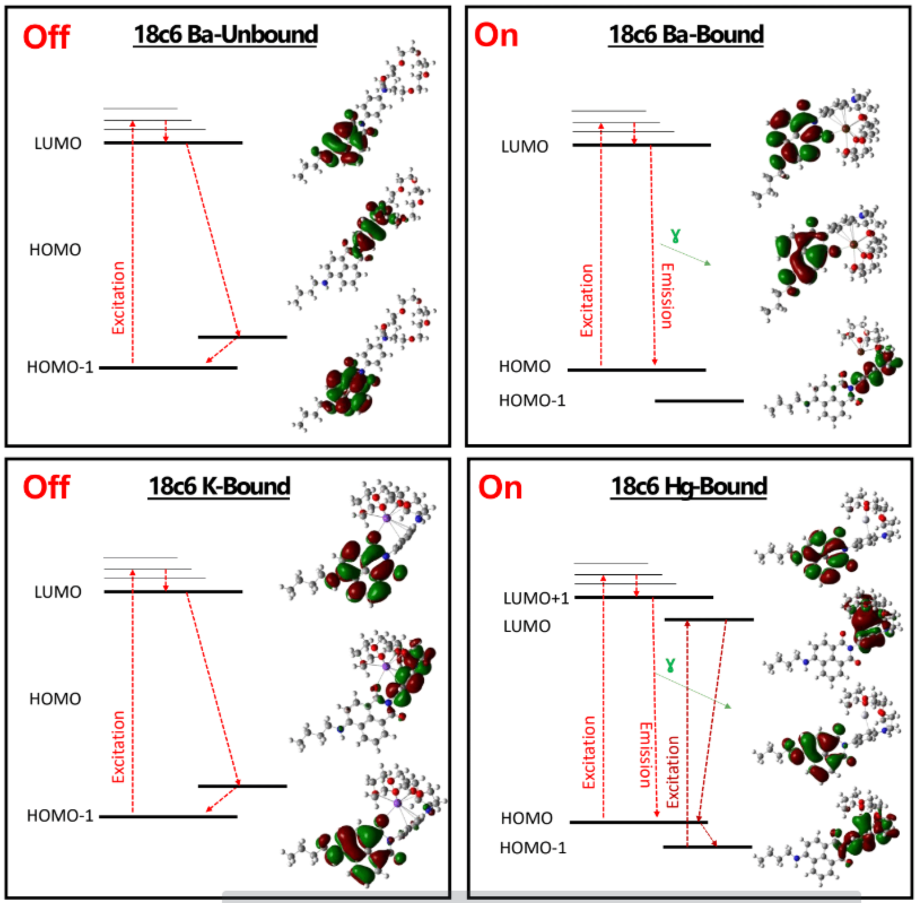
Barium Chelating Monolayer

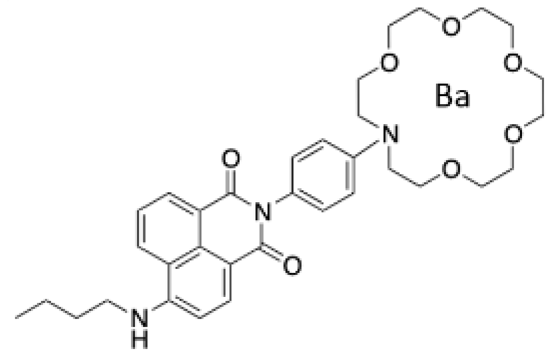


Pixel count vs. Intensity histograms showing the pixel intensity increase when fluorophores are bound to a glass substrate and analyzed using TIRF imaging.

P. Thappa, N.K. Byrnes et al., “Demonstration of Selective Single-Barium Ion Detection with Dry Diazacrown Ether Naphthalimide Turn-on Chemosensors,” ACS Sensors 2021 6 (1), 192-202. DOI: 10.1021/acssensors.0c02104

Custom Barium Chemosensors

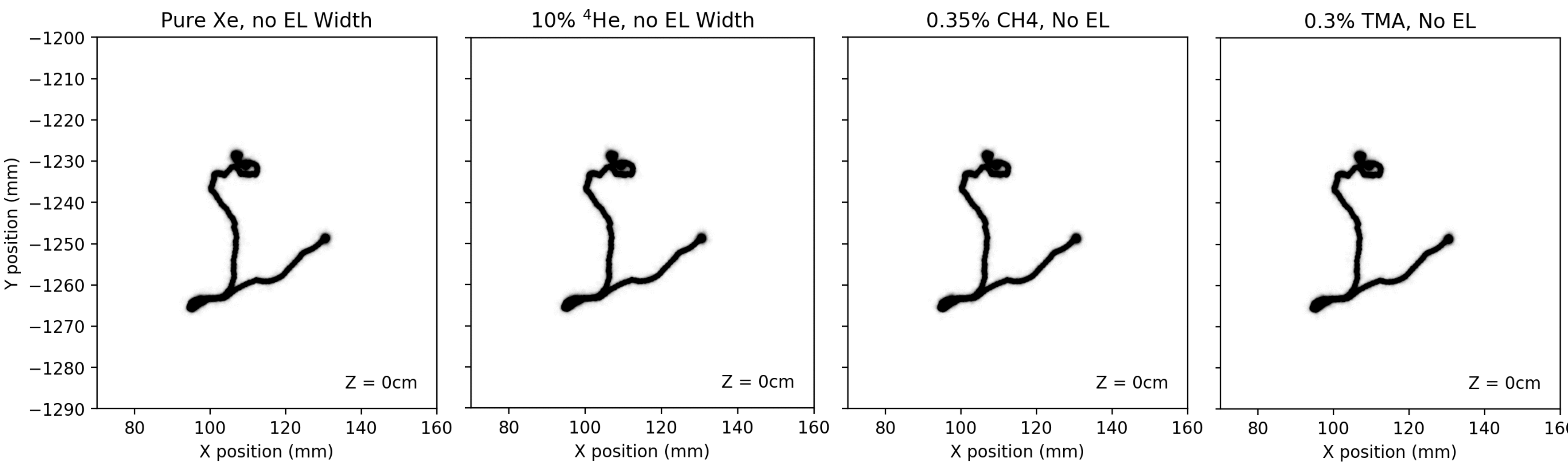




- We have computational models predictive of the fluorescence processes we see in the lab
- Orbital structures of 18c6-Nap unbound and chelated with Ba, K, Hg.
- Note the intermediary states present in the ‘off’ and missing in the ‘on’ configurations responsible for quenching the photon emission.

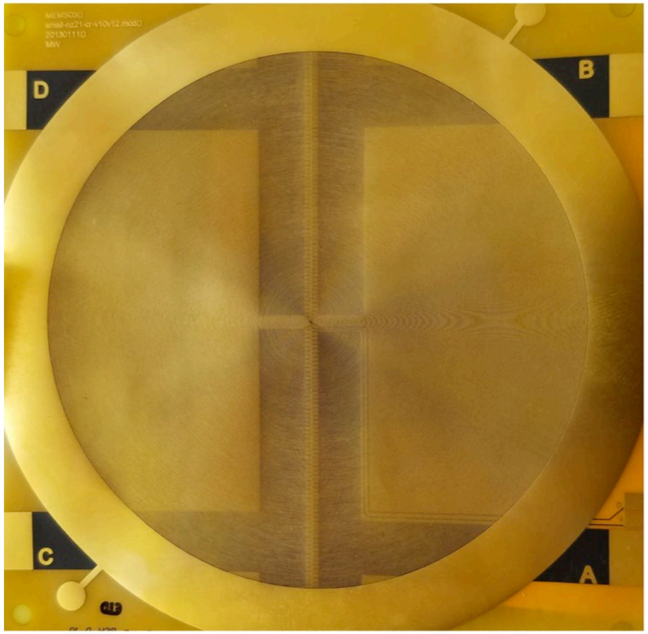
Diffusion Reduction

- Use of an additive, either light or molecular, can wick energy away from electron swarm leading to cooling.
- This reduces the effective transverse diffusion and sharpens topology.



Concentrations here are picked qualitatively where the additive hits roughly “diminishing returns.”

Ion Surfing Mechanism

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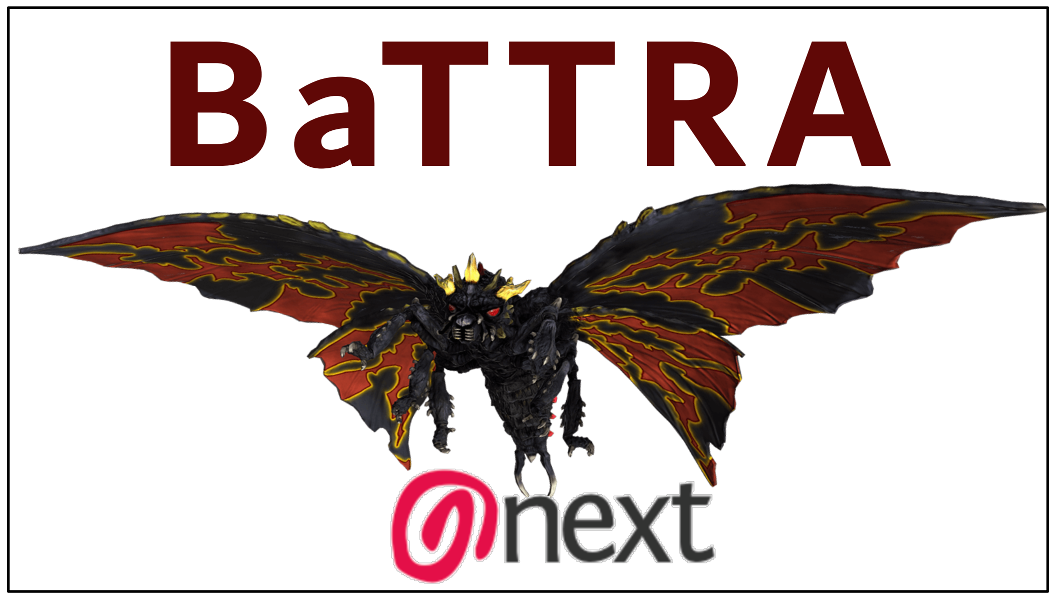
EBIIRAH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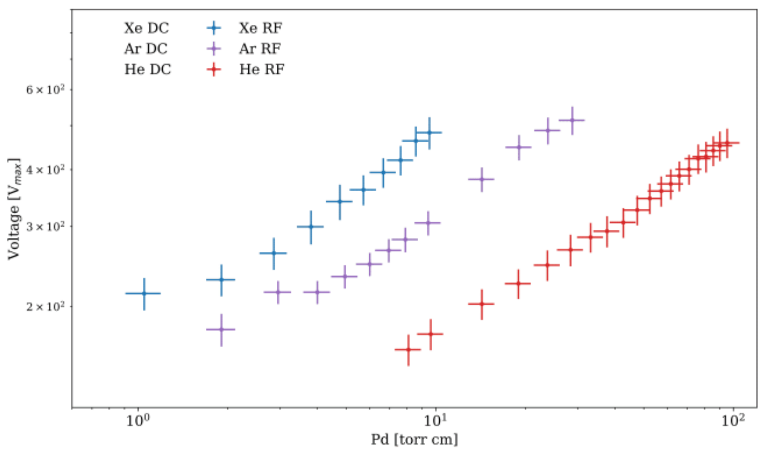
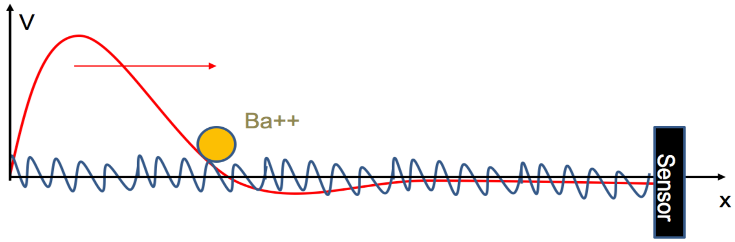
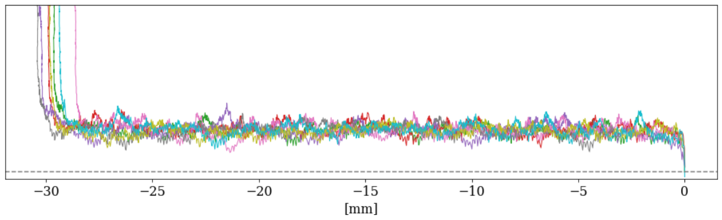
Ion Surfing Mechanism

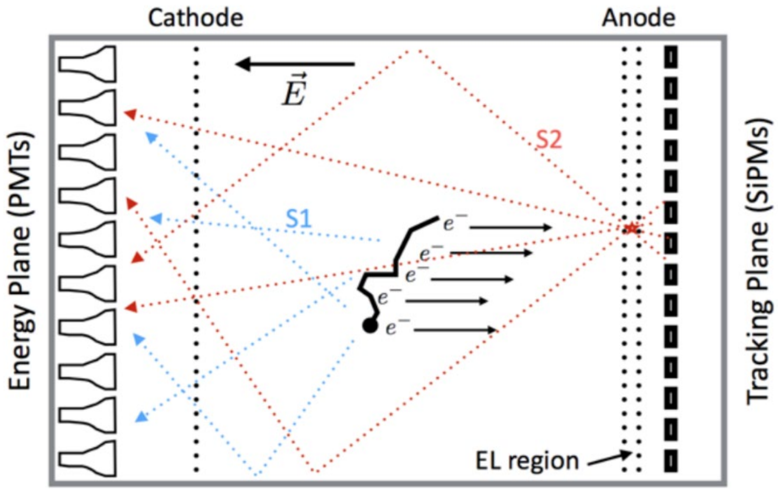






Camera Readout Optical TPC

- One major hurdle to eventually implementing barium tagging is the spatial requirement.
- Currently both ends of the TPC are occupied with light collection devices where we would need to collect the barium daughter.
- One approach is to implement tracking-plane readout using an external camera in lieu of SiPM's, creating the requisite space for barium tagging.

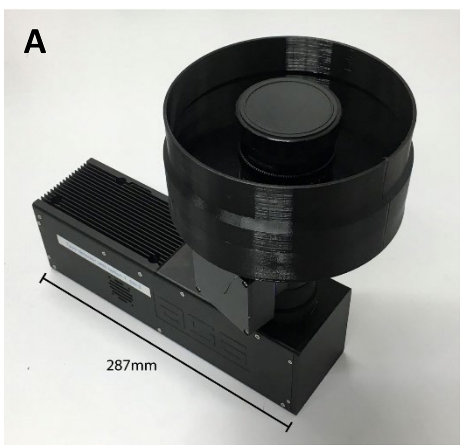


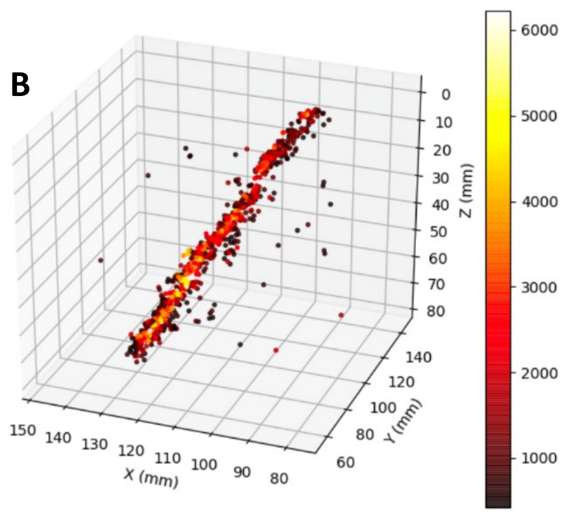
The current configuration of the NEXT experiment, with tracking SiPM's on the right taking topological event data and the PMT's on the left collecting energy data.

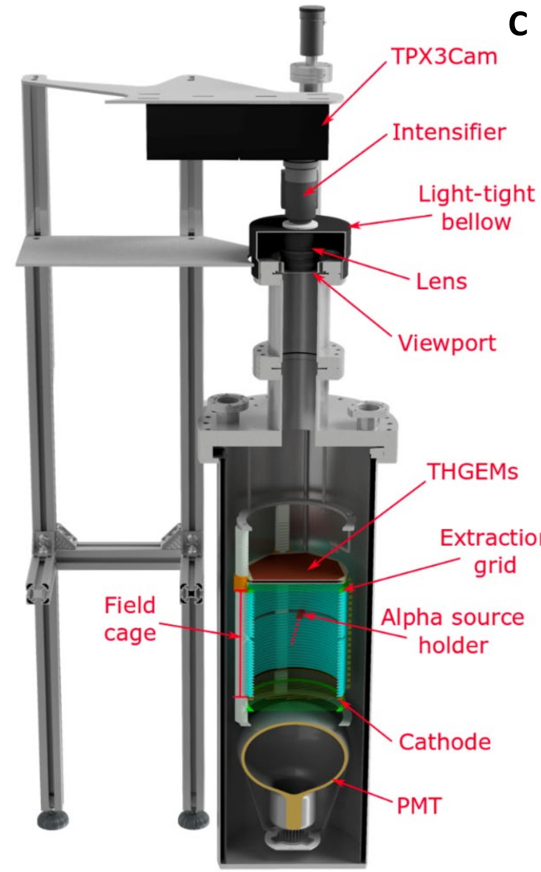
A. Roberts et al., “First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera,” arXiv:1810.09955

ARIADNE

- Recently, the ARIADNE Camera Readout TPC provided a strong proof of concept for this technique.
- By using an Image Intensifier and a high-speed, high quantum efficiency camera, ARIADNE was able to image Alpha Tracks
- This design inspired our group at UTA to design our own HPGXe TPC







The Ariadne TPX3Cam with Image Intensifier (A), a reconstructed Alpha particle track (B), and the full detector schematic (C)