Ion Extraction Tests for Barium Tagging

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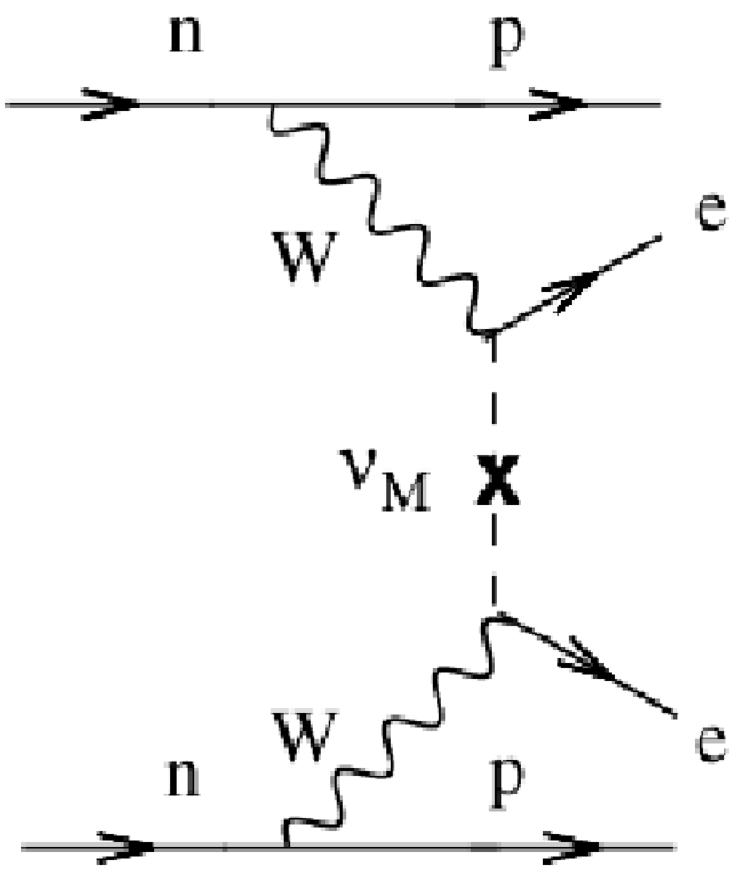
CAP 2024

Neutrinoless double-beta decay (0vββ)

- 2n --> $2p^+ + 2e^- + 0\bar{\nu}$

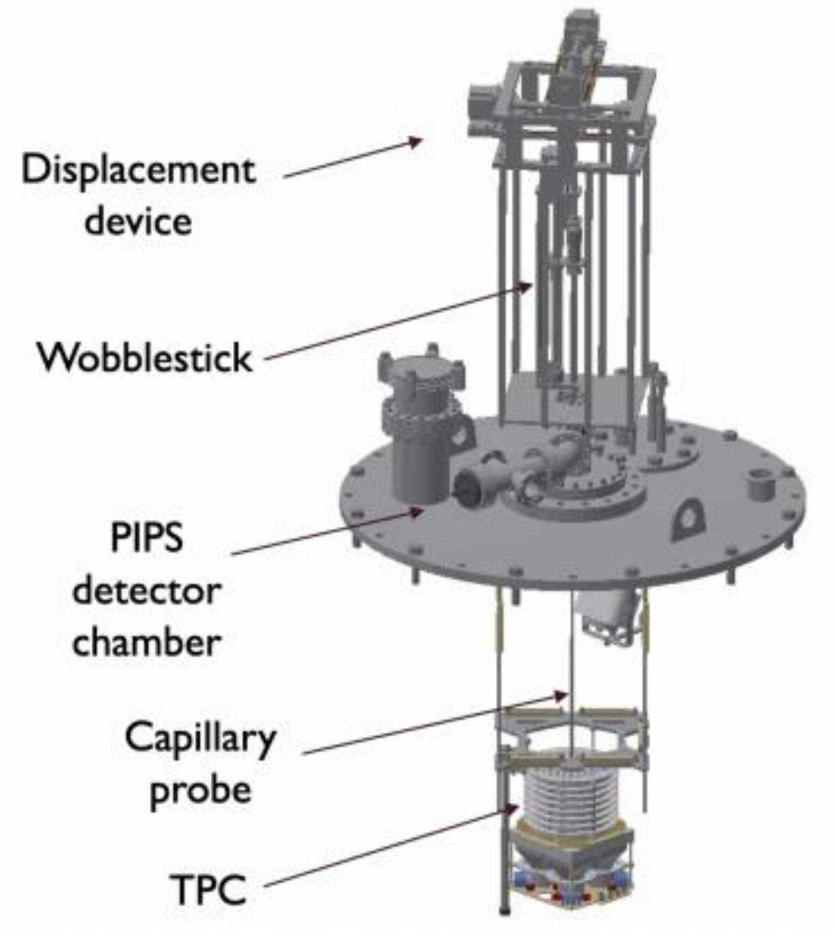
- If 0vββ is observed, neutrinos must be their own antiparticle (Majorana fermion)
- Half-life of the 0vββ process will also tell us the effective majorana mass of neutrinos



F.T. Avignone III et al., Double Beta Decay, Majorana Neutrinos, and Neutrino Mass

Barium Tagging

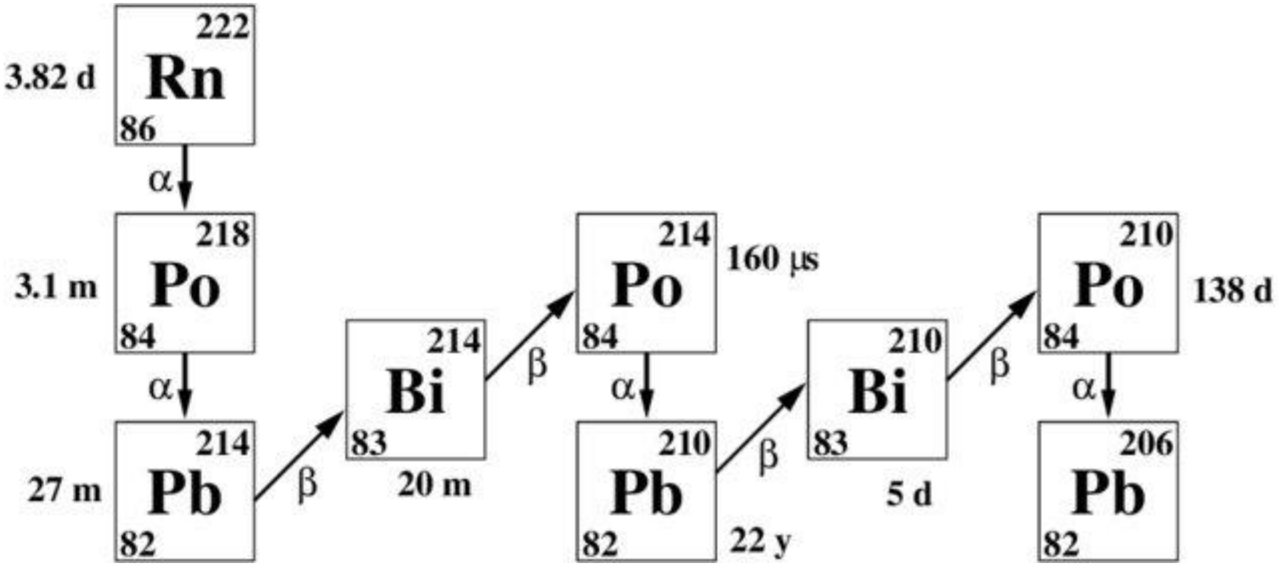
- EXO: Enriched Xenon Observatory : Liquid Xe in Time Projection Chamber (TPC)
- Looking for $^{136}Xe \rightarrow {}^{136}Ba^{2+} + 2e^{-}$ (+ 0$\bar{\nu}$)
- Presence of Barium ion rules out all non-double beta decay backgrounds!
- @Carleton: Displacement device manoeuvres a capillary probe to the decay location and quickly extracts LXe volume with the Ba ion
- Capillary delivers the Ba ion to detection/identification apparatus (McGill, TRIUMF)



Development of a Displacement Device for Ion Extraction from Liquid Xenon. R. Elmansali, 2023

Species to be Tested

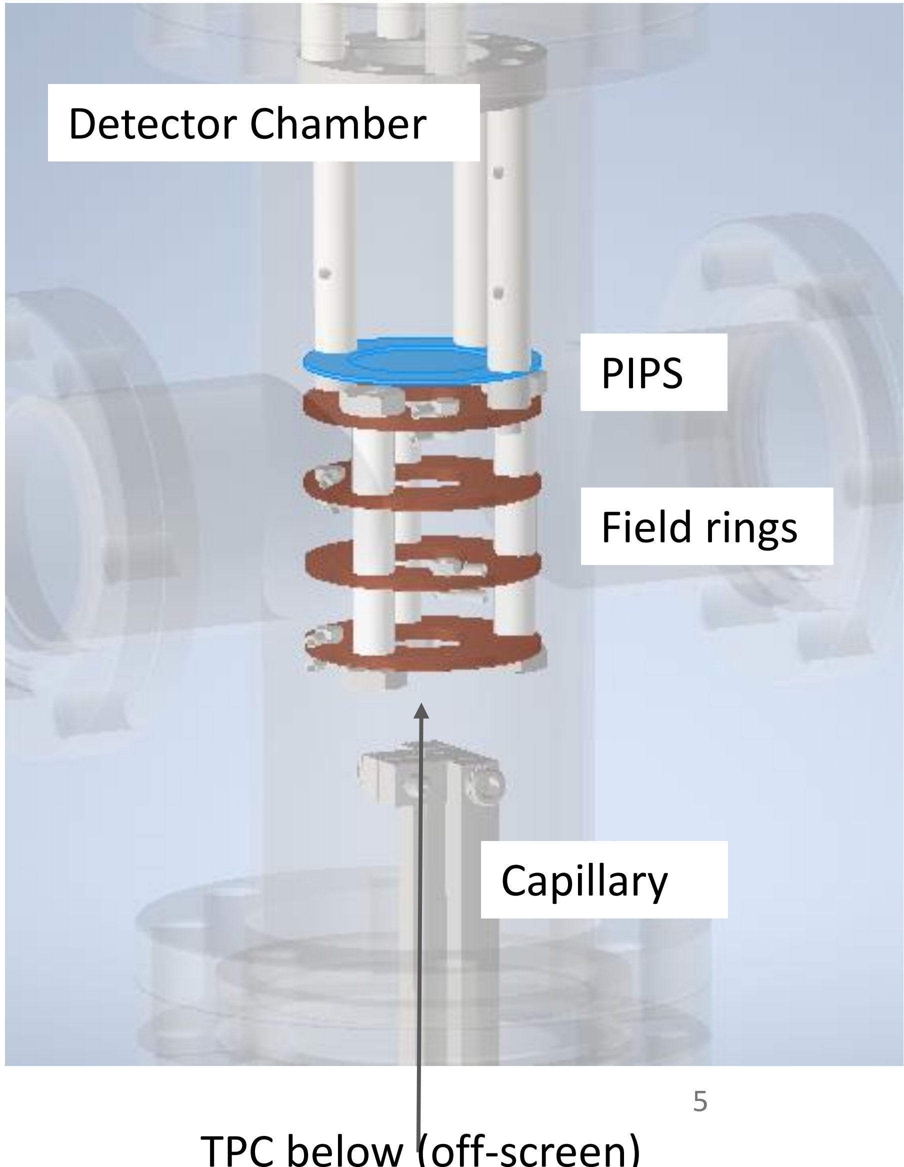
- Barium identification is its own problem. Initial studies focused on just transferring ions
- Rn-222 source: radioactive decays are easy to detect
- Po-218 and Po-214 are the ions to look for (α-decay)



Guiseppe, V. E., et al. "A radon progeny deposition model."

Untargeted ion extraction

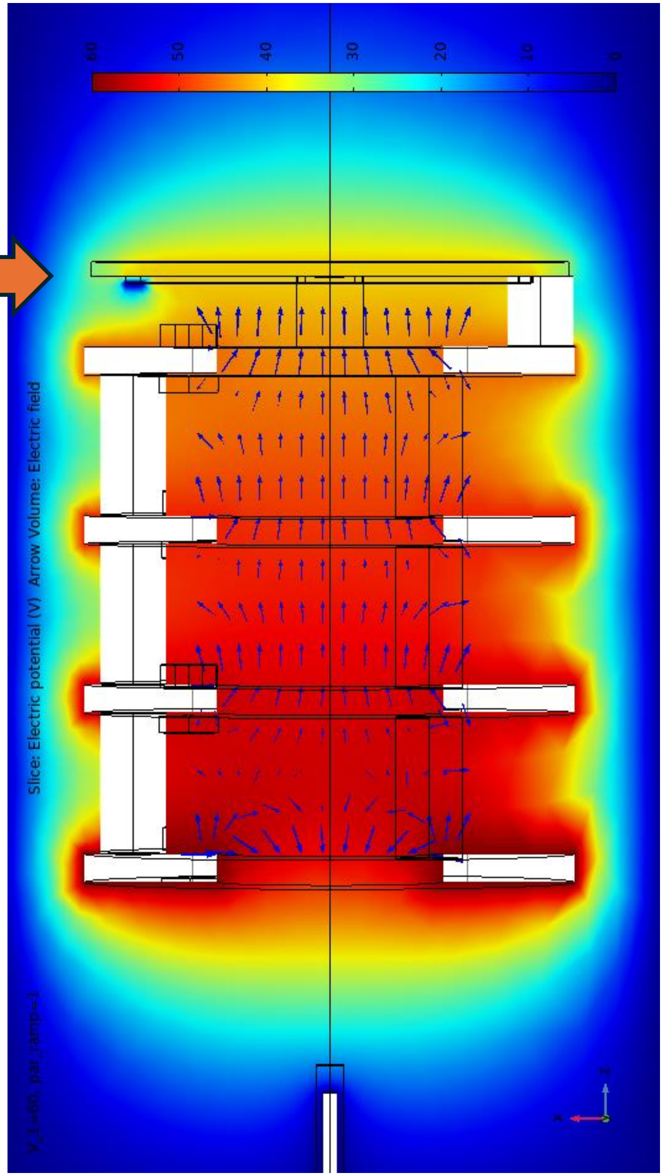
- Initial testing of the setup with Rn-222 in argon gas (less technically demanding than LXe, so suitable for prototype test)
- Inject TPC with Rn, attempt to transfer ionic decay products to a detector chamber via capillary
- Pressure differential to maintain gas flow from TPC to detector chamber: 1.2 bar and 0.8 bar respectively
- Electric field guides ions onto a Passivated Implanted Planar Silicon (PIPS) detector
- When ions decay, PIPS detects energy from the resulting alpha particle



Electric field

- Radon-222 is a neutral atom, diffuses throughout
- Polonium-218 and Polonium-214 are ions:
  - If they were outside the field, they stay outside
  - If they are brought inside the field, they get swept down to the PIPS and stay there
  - "Brought inside" meaning riding the gas flow from the capillary
  - Another possibility: radon decaying inside the field...

(COMSOL) Electric field and Gas flow simulations: Dr. R. Collister



Background problem

- PIPS sees (decay energy of) ions from two sources:
  - Ions transferred from the TPC through the capillary (signal)
  - Ions resulting from the progeny of radon that was already present in the detector chamber (background)
- To properly interpret ion transfer results, we need an understanding of this background

Simulation

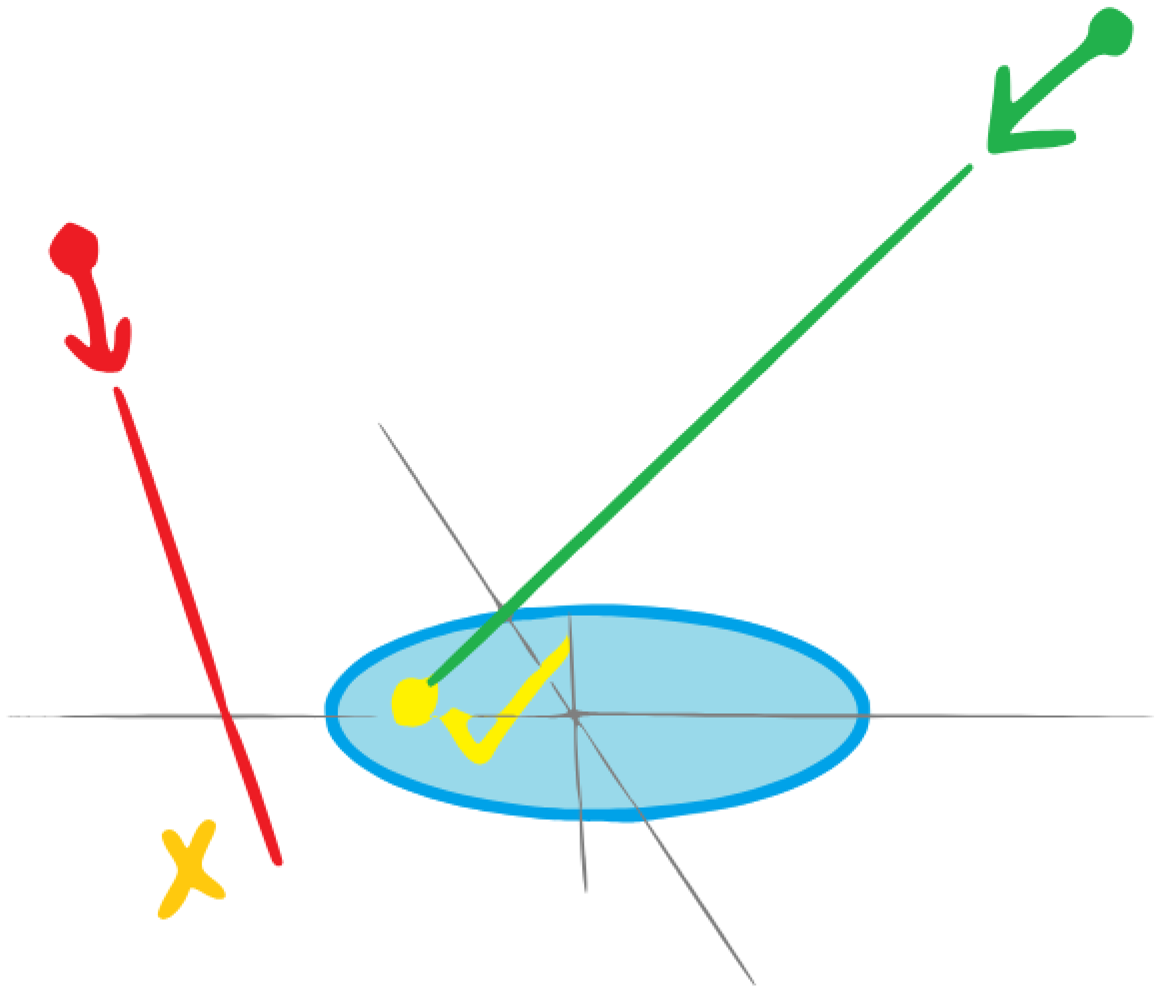
- Due to geometry and obstructions, the visible solid angle to the PIPS detector is difficult to calculate
- Monte-Carlo simulation of creation and movement of alpha particles in the detector chamber
  - How many events will be detected?
  - What should the observed energy spectrum look like?

Method

- Make a 3d model of the interior of the detector chamber
- Populate the space with Rn and Po decay events, with random locations
- Each decay produces alpha particle in a random direction
- Check whether this alpha particle successfully hits the PIPS detector or not
- Compute what fraction of decays are successfully detected
- Compile a list of distances that they traveled through argon, and thence derive the energy spectrum seen on PIPS

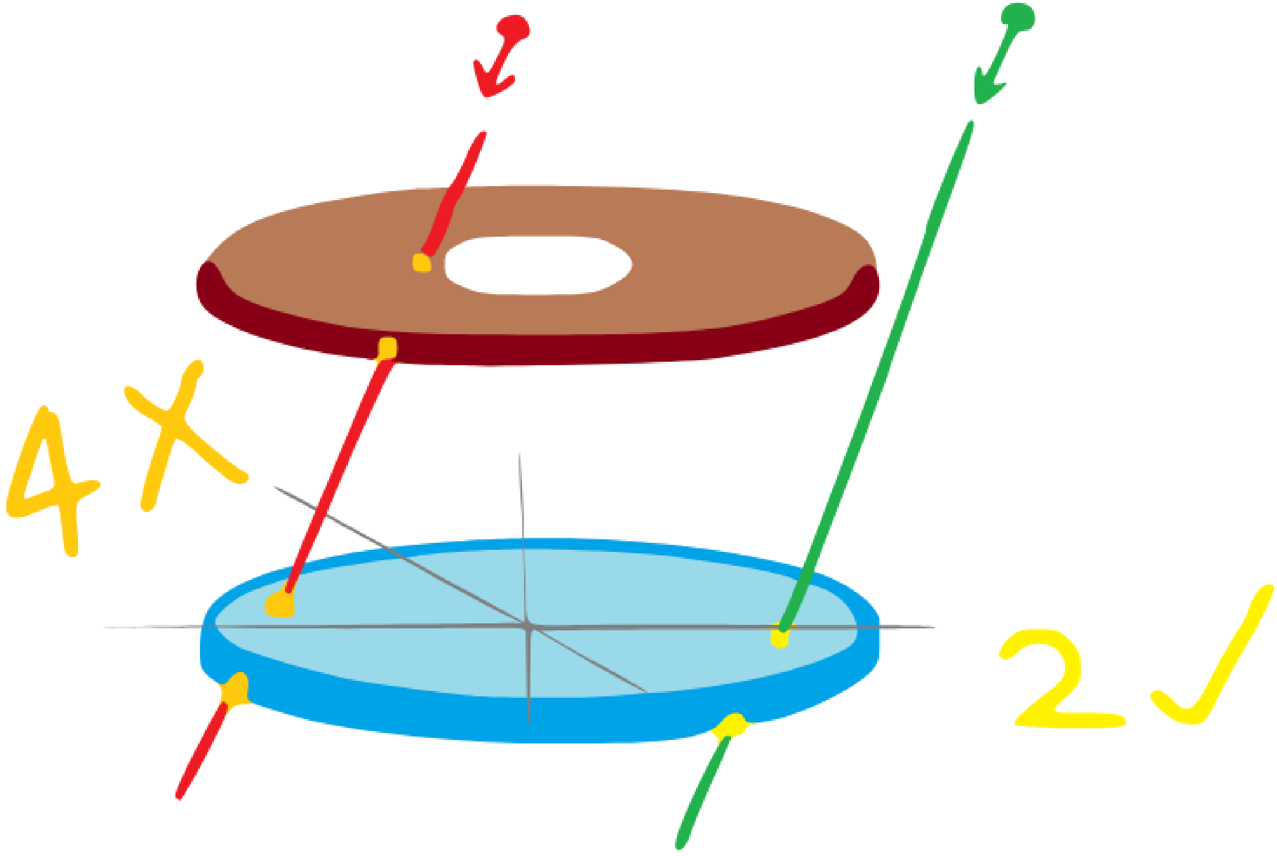
Collision detection (1)

- First 'cut':
- Is the alpha particle headed in the right direction overall?
- PIPS located on z=0 plane with radius 1cm
- Find xy position that alpha would have at z=0
- Reject if >1cm from origin



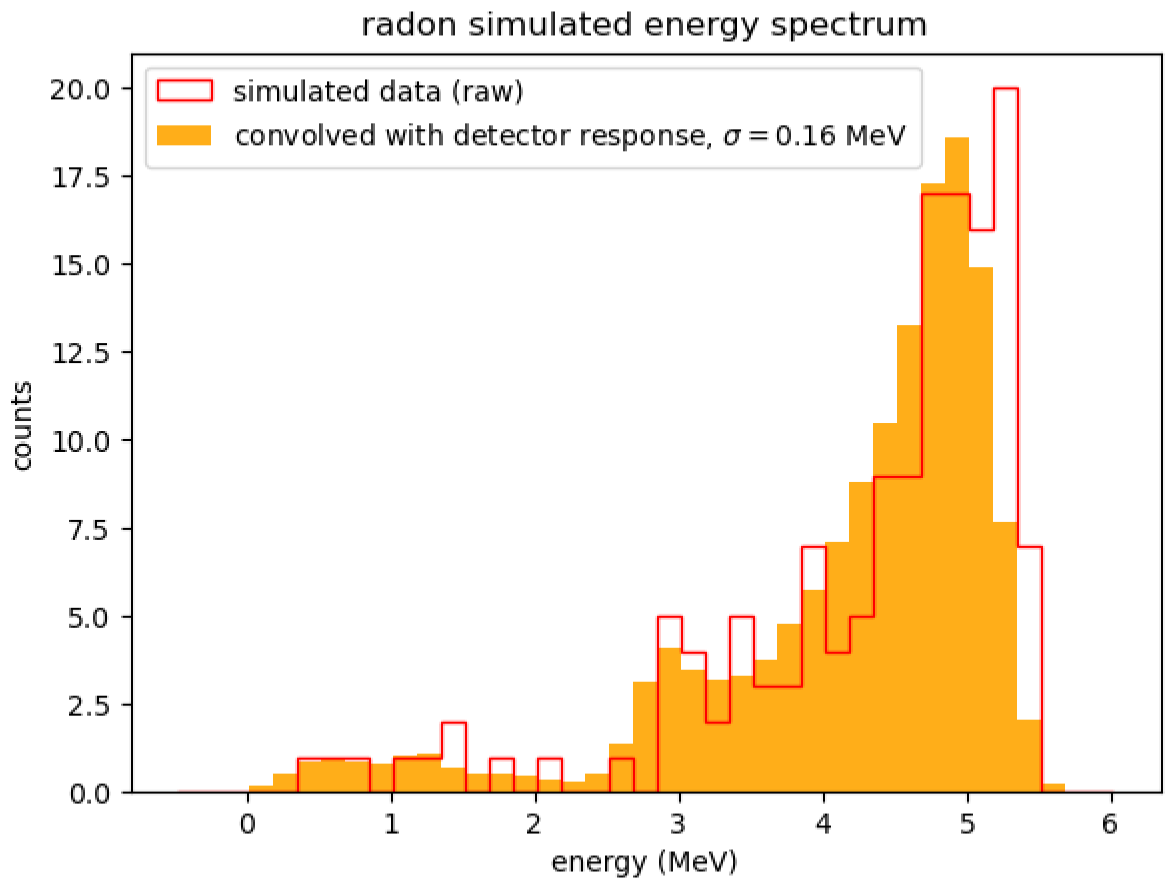
Collision detection (2)

- Next step:
- Export detector chamber model as STL, solid surfaces are represented as polygons
- Import into Python (numpy-stl)
- For each decay event, for each surface polygon, check if they intersect (ray-tracing algorithm e.g. Moeller-Trumbore)
- Iff the ray intersects exactly two polygons (top and bottom of PIPS) then it is a 'success'



Energy loss

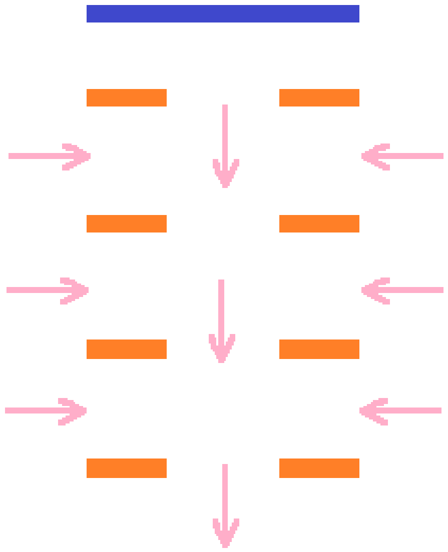
- From earlier calculation we get a list of lengths the decay alphas had to trudge through (in 0.8 bar Argon)
- From ASTAR we get dE/dx
- Numerically integrate to get energy lost as function of length
- Apply this function to the list of lengths to get a list of observed energies
- Radon depicted here: sharp cutoff at 5.5 MeV with low-energy tail, as expected
- Some Poloniums stuck to PIPS, have monoenergetic spectrum

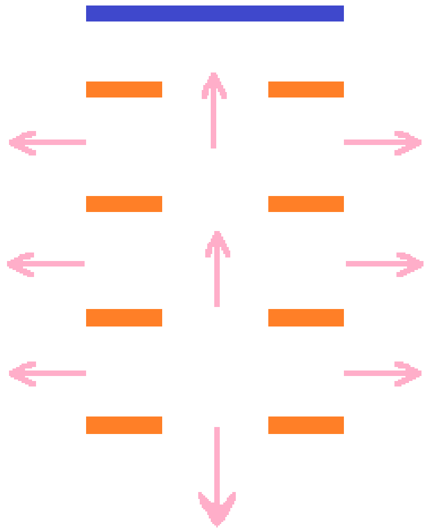


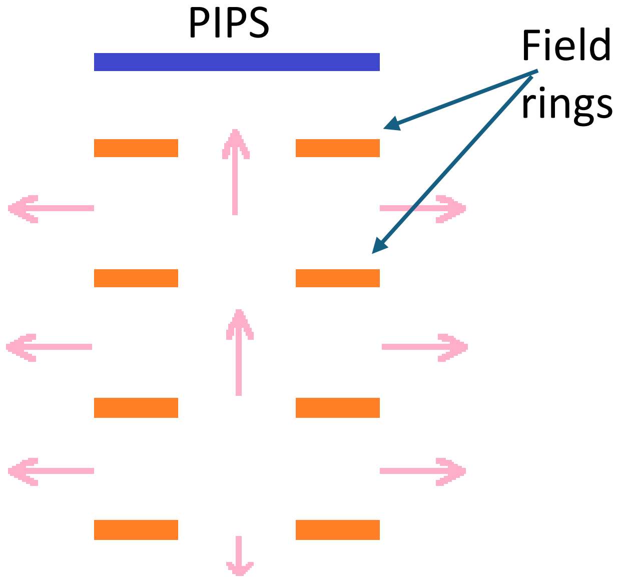
Detector has a resolution ~160 keV, simulated results must be convolved with a gaussian to account for this spread

Experimental study of Background

Background processes to study with simulation and compare







Reverse Field

Field direction is reversed. Ions cannot enter, and any ions formed inside are directed away from the PIPS

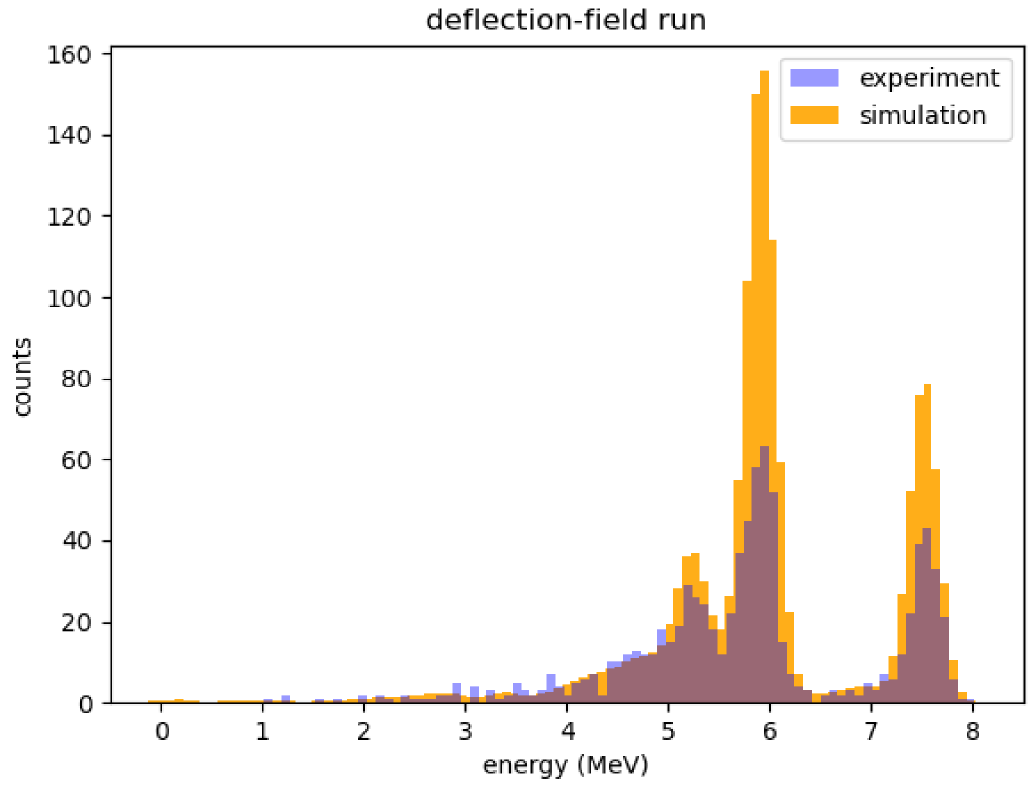
Deflection Field

Ions formed inside the field are collected, but ions coming from the capillary cannot enter the field region and bounce away

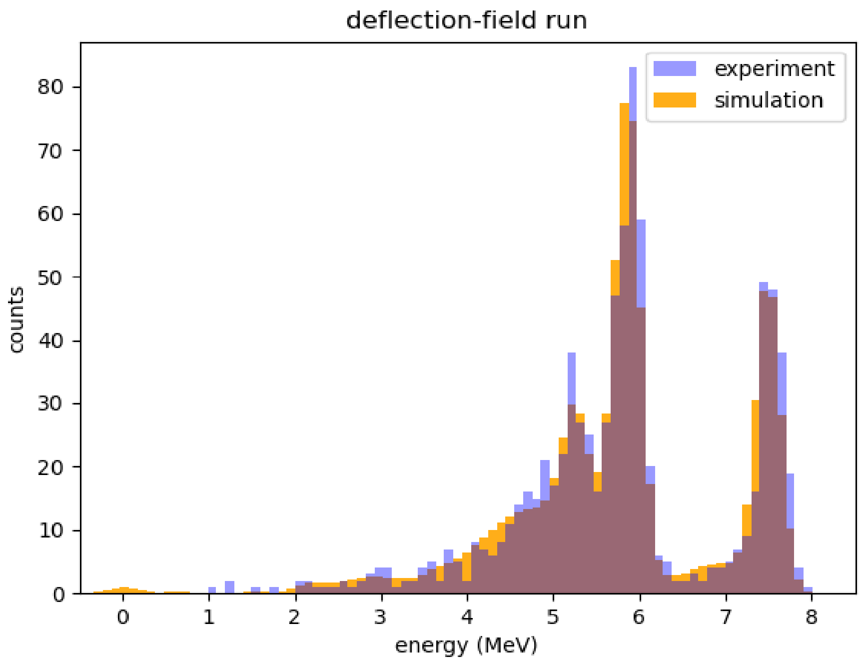
Transfer field

Ions that make it through the capillary enter the field region and are directed onto the PIPS for collection

Deflection field



Adjusted by hand



Discrepancies:

- Polonium monoenergetic peaks lower than expected – perhaps due to inefficient collection by the field
- Not all of the Polonium daughters are ions

Summary

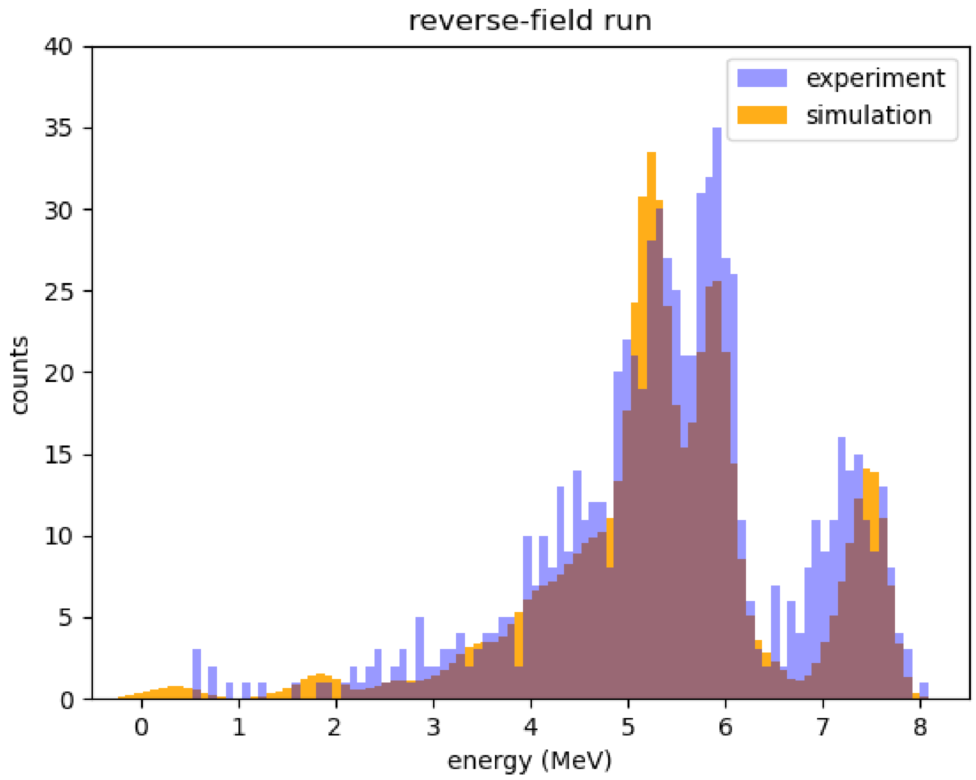
- Barium tagging provides good background rejection for neutrinoless double-beta decay
- To extract Barium efficiently, ion transfer through capillary being studied
- Simulation developed to model the test setup
- Discrepancies indicate we need to improve our understanding of the processes involved

Thank you for listening!

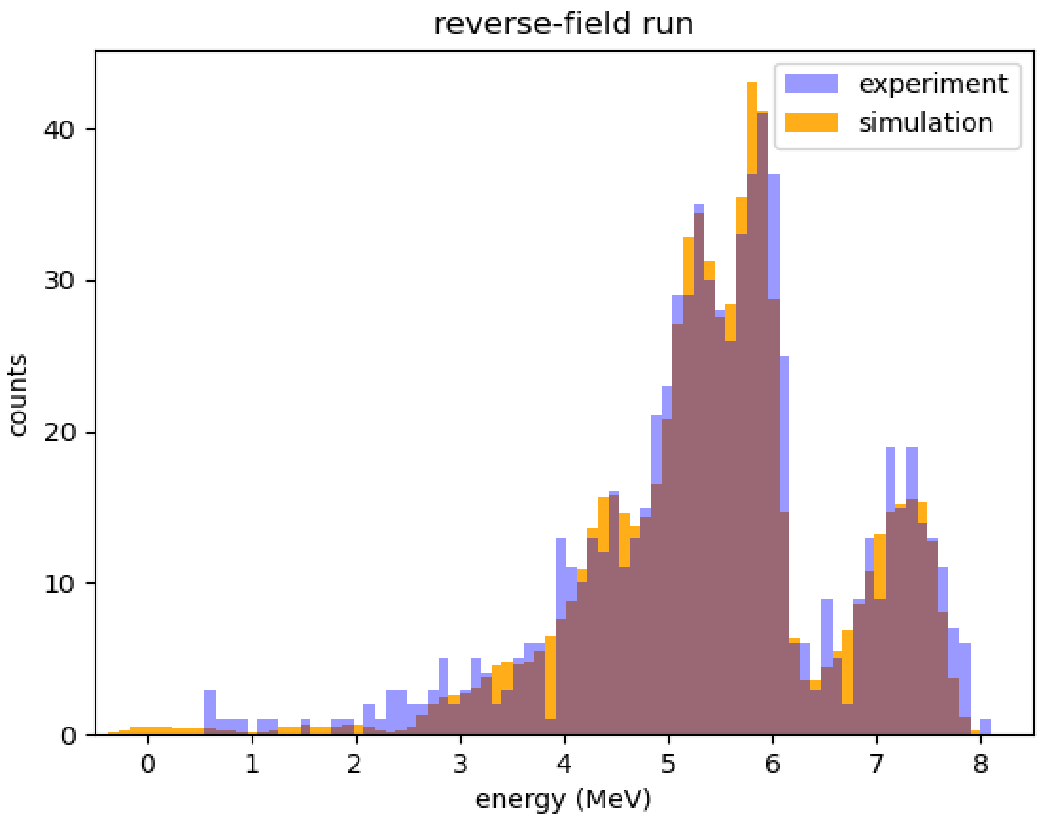
- Carleton Ba-Tagging Team:
  - Supervisor: Dr. Razvan Gornea
  - Lab members: Dr. Robert Collister, Mr. Ryan Elmansali

Reverse field

- Simulation vs experimental observations

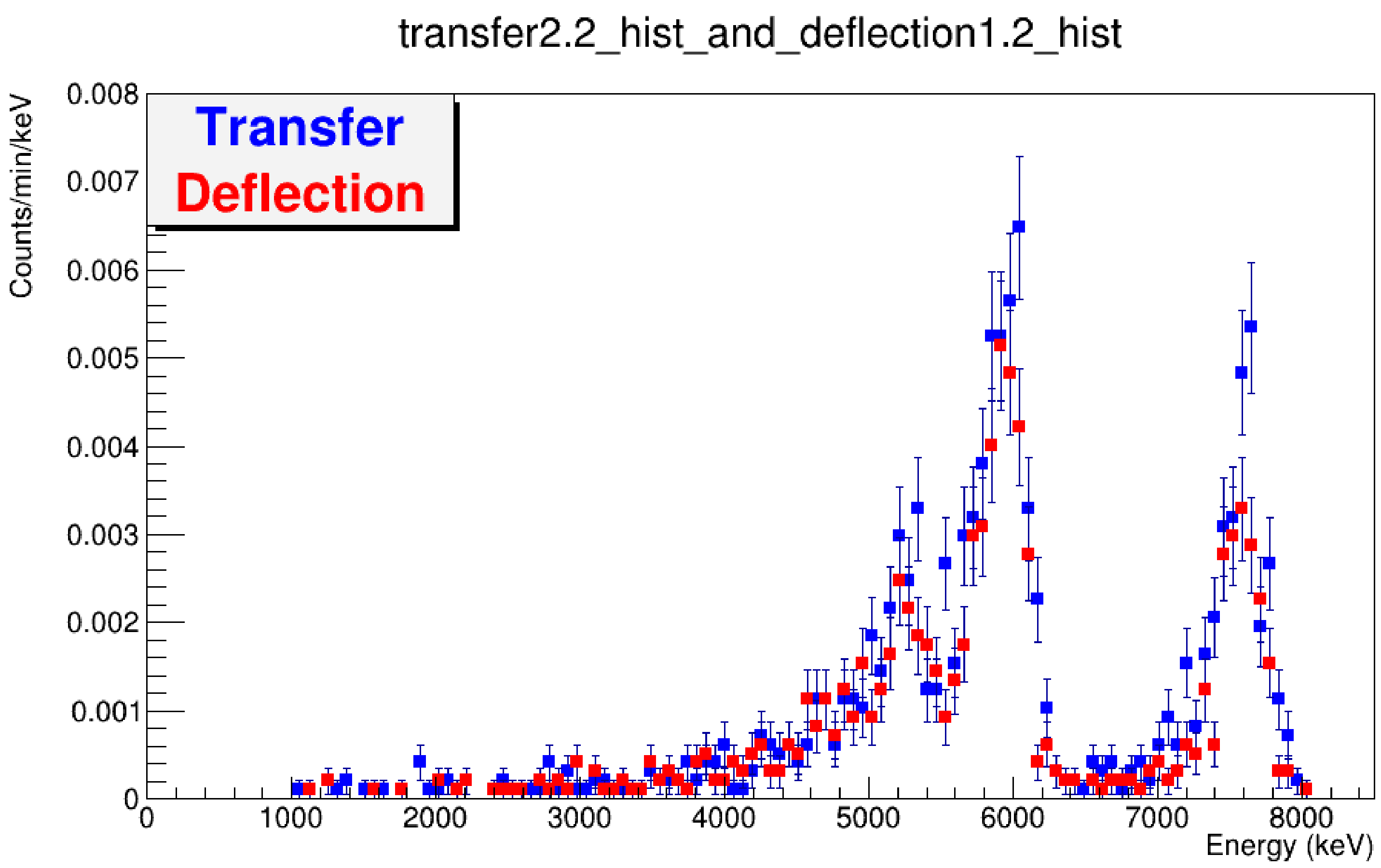


Adjusted



Discrepancies:

- Po214 has a relatively high-energy tail, modeled as due to plating out on the field rings
- Po218 monoenergetic peak higher than expected, not understood



transfer2.2_hist_and_deflection1.2_hist
Transfer
Deflection
Counts/min/keV
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
1000
2000
3000
4000
5000
6000
7000
8000
Energy (keV)

Neutrinos – why study them?

- Neutrinos oscillate between flavours: hence they must have mass
- Major blow to otherwise splendid Standard Model (where they are massless)
- Investigate neutrinos further – e.g. how much mass exactly?

MissMJ (Wikimedia)