Ion Extraction Tests for Barium Tagging

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Neutrinoless double-beta decay (0νββ)

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

• If $0\nu\beta\beta$ is observed, neutrinos must be their own antiparticle (Majorana fermion)

• Half-life of the $0\nu\beta\beta$ 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 $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{2+} + 2\text{e}^- (+ 0\bar{\nu})$
• 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 ($\alpha$-decay).

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:
  o If they were outside the field, they stay outside
  o If they are brought inside the field, they get swept down to the PIPS and stay there
  o "Brought inside" meaning riding the gas flow from the capillary
  o Another possibility: radon decaying inside the field...
Background problem

• PIPS sees (decay energy of) ions from two sources:
  o Ions transferred from the TPC through the capillary (signal)
  o 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
  o How many events will be detected?
  o 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 $\sim 160$ 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

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:
  o Supervisor: Dr. Razvan Gornea
  o Lab members: Dr. Robert Collister, Mr. Ryan Elmansali
Reverse field

• Simulation vs experimental observations

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
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?