Linear Paul Trap for Ba-tagging

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Motivation for $0\nu\beta\beta$ searches

- Double beta decay are rare nuclear decay observed only in about 12 nuclei.
- Involves 2 simultaneous decay beta decays.

$$^{A}X_{z} \rightarrow ^{A}Y_{z+2} + 2e^{-} + 2\overline{\nu}_{e}$$

Neutrinoless double beta decay is special case of double beta decay.

$$^{A}X_{z} \rightarrow ^{A}Y_{z+2} + 2e^{-} + 0\overline{\nu}_{e}$$

Motivation for 0νββ searches

Motivation for 0νββ searches

\[ {^{A}X_z} \rightarrow {^{A}Y_{z+2}} + 2e^- + 0\bar{\nu}_e \]

Consequences of 0νββ observation:

• Neutrino is its own antiparticle
• Lepton number violation
• Absolute neutrino mass scale
• Matter-Antimatter asymmetry

{arXiv:hep-ph/0611243}

{arXiv:0708.1033}

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nEXO Experiment

- Searches for $0\nu\beta\beta$ events in liquid xenon (LXe) enriched in Xe-136 isotope (90%).

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

- Uses large time projection chamber (TPC), holding 5000kg of LXe.
- Charge collection pads used at the anode.
- VUV-SiPM line the curved face of TPC.
- Refrigerant (maintain xenon as liquid)
- Water tank for shielding.
- nEXO is anticipated to be located at SNOLAB.
Backgrounds limit the projected sensitivity of the experiment.

Solution: Barium tagging

- Required for the unambiguous detection.
- Detect Ba-136 ion at the position of 0νββ decay.

\[ ^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2e^- \]
Ba-tagging technique (Canadian approach)

Stage 1: Extraction of detector volume around the location of the decay to gas phase.

Stage 2: RF funnel facilitates separation of xenon accompanying the Barium ion.

Stage 2*: Serves as source of Barium ion for testing assembly.

Stage 3: The Linear Paul trap for detection of barium ion via laser fluorescence spectroscopy.

Stage 4: Multiple Reflection TOF Spectrometer for systematic studies and determination of ion mass.

{K. Murray, et al., Hyperfine Interact. 240 (2019) 1, 97}
Single Barium ion detection

- Uses ion trap for confining ions and laser induced fluorescence for barium ion detection.
- Single ion detection has been demonstrated by collaborators at Carleton University.
- Demonstrated first by M. Green et. al by studying 493nm fluorescence intensity from single barium ion.

- Manipulation of ions using electric fields.
- Radial confinement using radio-frequency (RF) potentials.
- DC field for directing and confining axial motion.
Linear Paul trap for Ba-tagging

- Custom designed for the purposes of Barium tagging by Yang Lan, TRIUMF/UBC.
- Composed of a quadrupole mass filter (QMF), precooler, cooler and an ion buncher.
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• Composed of a quadrupole mass filter (QMF), precooler, cooler and an ion buncher.
Ion cooling

- RF potential confines ion radially.
- Buffer gas cools the ions, ions get thermalized by the time they reach towards the end.

(Retrieved from: Emittance and phase space measurement, A. Cianchi University of Rome)

Schematic showing evolution in phase space. (Liouville theorem), the phase space density doesn't change under the action of conservative forces.
Axial drift and trapping

- Injected ions entering from x = 0mm travel down the potential towards the buncher.
- Trapped ions are then cooled collisional with helium gas.
- Equilibrium is established between buffer gas cooling and RF heating.
Components in the LPT

QMF:
- Perform filtering of incoming ions based on their mass-charge ratio.

Precooler:
- Required for differential pumping.
- Acts as ion guide for filtered ions.

Cooler:
- Helium buffer axially cools incoming ions.
- Tapering electrode provide axial drift field.

Buncher:
- Trapped ions are further cooled down and bunched.
- Perform laser spectroscopy on stored ions.
Ba-tagging status at McGill

- In-gas Ion source: M. Medina Peregrina
- Linear Paul trap:  Y. Lan, H. Rasiwala,  X. Shang
- MR-TOF:  K. Murray
- Rail system:  C. Chamber

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• nEXO is a next generation 0νββ detector with a projected sensitivity for Xe-136 half-life of close to $10^{28}$ yr.

• Ba-tagging as an upgrade to nEXO for explicit detection of barium ion.

• Upgrade activities and goals following restart of research at McGill:
  - Upgrade current RF funnel to a 3-stage RF funnel
  - Begin commissioning of the LPT and MR-TOF

• Next year, we will be able to show results once assembling is done.
Quadrupole mass filter

DC coupled RF frequency voltages filter ions based on \((m/q)\) ratio.

\[
q = q_y = -q_z = \frac{4eV}{m\Omega^2 r_0^2} \quad a = a_y = -a_z = \frac{8eU}{m\Omega^2 r_0^2}
\]

• Based on selection of trajectory parameters \((a, q)\), DC and RF amplitudes are scaled for selective passage on specific ions.

• Pre filter facilitates ramping of RF field to avoid track instabilities due to fringing fields.
Ion cooling

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 Injected ions

![Diagram showing ion cooling process](image_url)
Ba-tagging technique

Recent nEXO Ba-tagging publications:
- Imaging individual Ba atoms in solid xenon for barium tagging in nEXO
- An RF-only ion-funnel for extraction from high-pressure gases
- Spectroscopy of Ba and Ba⁺ deposits in solid xenon for barium tagging in nEXO
- An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe

Details:
Image of trapped barium ion