Prototypes of an ion trap for the Barium tagging of nEXO

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nEXO: next Enriched Xenon Observatory

- Search for neutrinoless double beta decay (0νββ)
- 2νββ: $^{136}Xe \rightarrow ^{136}Ba^{++} + 2e^- + 2\bar{\nu}_e$
- 0νββ: $^{136}Xe \rightarrow ^{136}Ba^{++} + 2e^-$

- If 0νββ detected,
  - Validate neutrinos to be their own anti-particles (Majorana)
  - Lepton numbers do not conserve
  - Neutrinos’ absolute mass scale?

- Challenge: 0νββ half-life > $10^{25}$ yrs
  - Requires low background
    - Underground detector
    - Radiation shielding
  - Barium tagging
Barium tagging: the ultimate method for background rejection

- A potential upgrade for nEXO
- Multiple approaches
  - Stanford U: laser resonance ionization, mass spectrometry
    “An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe”
  - Colorado State U: cold probe, laser spectroscopy
    “Imaging individual Ba atoms in solid xenon for barium tagging in nEXO”
  - McGill, Carleton, TRIUMF: RF funnel, ion trap, laser spectroscopy, mass spectrometry
    “An RF-only ion-funnel for extraction from high-pressure gases”
**Ion trap requirements**

- Continuously capture all the extracted ions
- Cool ions and store them for laser spectroscopy identification
  - Low temperature to avoid Doppler broadening
- Found contaminant ions in offline experiments, purify ions with $m/\Delta m > 80$
- Eject ions as fine bunches to a Multi-Reflection Time-of-Flight (MR-TOF) mass spectrometer
  - Small energy spread and time spread

**Needs to develop a special linear Paul trap (LPT)**
Linear Paul Trap (LPT)

- **Major components**
  - Quadrupole mass filter (QMF): ion purification according to ion mass-to-charge ratio
  - Cooler: ion cooling with helium buffer gas
  - Laser spectroscopy ion trap (LSIT): barium ion identification
  - Buncher: ion ejection for the MR-TOF mass spectrometer

- **Needs different pressures**
  - QMF: $< 1 \times 10^{-5}$ mBar
  - Cooler: $\sim 0.1$ mBar
  - Laser spec. ion trap: $< 1 \times 10^{-3}$ mBar
  - Buncher: $< 7 \times 10^{-3}$ mBar

![Diagram of Linear Paul Trap](image)

- Ions from RF funnel
- Ions to MR-TOF

**Longitudinal confinement**
Final LPT design

- Pre-cooler for effective differential pumping:
  - Mechanical precision and alignment
    - QMF: <50 μm positional precision, others ~ 0.1 mm
  - Differential pumping channel
Experiments

- Experiments with prototypes at TRIUMF
  - Made prototypes of LPT
  - Developed electronics, control and DAQ systems

- Final LPT at McGill
Prototypes

- 100+ happy hours in machine shop
Quadrupole mass filter prototype QMF2.2

- Third iteration of QMF prototypes
  - ~30 hours each

- Quadrupole electrodes have positional precision around 10 \( \mu \text{m} \)
  - except one mistake of 150 \( \mu \text{m} \)
QMF2.2 results

- Ion transmission matches Mathieu stability diagram

- Measured isotopic ratio consistent with natural abundances:
  - $^{39}\text{K}/^{41}\text{K}=17.0\pm3.9$ (93%/7%=13.3)
  - $^{85}\text{Rb}/^{87}\text{Rb}=3.7\pm1.2$ (72%/28%=2.6)
QMF2.2 results: best achievable $R$

- Detailed measurement around tip of stability diagram
  - Mass resolving power $R$
  - Ion count rate
    $\propto$ transmission efficiency
    $\propto$ ion acceptance
- Compare with simulations
- Best achievable mass resolving power $R_{\text{max}} \approx 140$
  ✓ (>$80$)
  - Limited by a mechanical error
RFQ ion cooler prototype

- 3D printing for complicated geometries
  - Fast and cheap
  - Materials vacuum compatible
  - Mechanical precision of 0.1 mm is sufficient

3D printed tapered aluminum electrodes
3D printed nylon electrode holders
Aperture plate

Ions in
Ions out
Ion cooler prototype tests

- Ions cooled and trapped at potential minimum
- Ions ejected when $V_{ap}$ switched to low

Simulation

- Validated ion cooling
- Successful ion trapping with novel electrodes

Next: Ion time of flight (ToF) measurements
Ion ToF vs. ion temperature: $\sigma_{t_{ToF}} \propto \sqrt{T_x}$

- Ion ToF measurements qualitatively validated simulations
- Ion temperature simulation for laser spec. ion trap and buncher
  - Longitudinal: $T_x$ close to buffer gas temperature
  - Radial: $T_y$ and $T_z$ below 400 K when $q<0.6$
- Laser spectroscopy: no significant Doppler broadening ✓
- Buncher for MR-TOF: no significant increase in ion energy spread and time spread ✓

- LPT meets requirements. Being commissioned at McGill.
Conclusion and outlook

- **Barium tagging** helps nEXO to reach the ultimate background level

- A special **linear Paul trap** has been designed for barium tagging
  - Ion trapping properties studied and meet requirements

- Prototypes built for experimental studies
  - **QMF prototype** has $R_{\text{max}} \approx 140$, exceeding requirement ($R=80$)
  - **Validated novel cooler for ion trapping, cooling and ejection**
  - Ion ToF measurements agrees qualitatively with simulations
  - Simulated ion temperatures meet requirements for LSIT and buncher

- Final LPT set up and being commisioned at McGill
  - Will be combined with RF funnel and MR-TOF for barium tagging studies
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Also thanks to the TITAN group at TRIUMF for discussions and equipment!
Spare slides
Neutrino physics … without neutrinos

- Neutrinos in beta decay ($\beta$)
  - Missing energy/momentum
  - “A particle that cannot be detected”

Neutrino proposed by Wolfgang Pauli in 1930
Neutrino experiments

- First detection in 1956 at a nuclear reactor (Reines and Cowan)
  - Inverse β decay: $\bar{\nu}_e + p \rightarrow n + e^+$

- Solar neutrino problem: 1960s to 2002
  - Detected solar neutrinos only 1/3 of expectation
  - Caused by neutrino oscillation

\[
\begin{bmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{bmatrix} =
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{bmatrix}
\begin{bmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{bmatrix}
\]
Mass scale of neutrinos

- Non-zero mass confirmed by neutrino oscillation experiments
- Absolute mass scale to be measured

Slide courtesy of G. Gratta
Neutrino mass

- Absolute mass scale measurement
  - Direct approach: Beta decay spectrum end point

Figure credit: KATRIN collaboration (2001)
Neutrino mass

- Beta decay spectrum end point
  - Mainz and Troitsk: $m_{\nu_e} \leq 2.2$ eV
  - Next generation experiment: KATRIN
    - Aiming at 0.2 eV
    - 2019 result: $m_{\nu_e} \leq 1.1$ eV

- Neutrinoless double beta decay
  - Sensitive to neutrino mass below 0.01 eV

Science 356 (2017) 6345
Double beta decay (\(\beta\beta\))

- \(\beta\beta\) is a second order process
- Detectable if first order \(\beta\) decay is energetically forbidden

<table>
<thead>
<tr>
<th>Candidate</th>
<th>(Q) (MeV)</th>
<th>Abundance (%)</th>
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<tbody>
<tr>
<td>(^{48})Ca→(^{48})Ti</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>(^{76})Ge→(^{76})Se</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>(^{82})Se→(^{82})Kr</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>(^{96})Zr→(^{96})Mo</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>(^{100})Mo→(^{100})Ru</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>(^{110})Pd→(^{110})Cd</td>
<td>2.013</td>
<td>11.8</td>
</tr>
<tr>
<td>(^{116})Cd→(^{116})Sn</td>
<td>2.802</td>
<td>7.5</td>
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<tr>
<td>(^{124})Sn→(^{124})Te</td>
<td>2.228</td>
<td>5.64</td>
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<tr>
<td>(^{130})Te→(^{130})Xe</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>(^{136})Xe→(^{136})Ba</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>(^{150})Nd→(^{150})Sm</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>
EXO-200

- Located at Waste Isolation Pilot Plant (WIPP), New Mexico
- 655 m underground (1600 m.w.e)
- 175 kg of liquid xenon in a Time Projection Chamber (TPC) cooled to 167 K
EXO-200 TPC

- Measurement of both ionization and scintillation
- Reconstruct events 3D locations
  - Distinguish true $\beta\beta$ decay from backgrounds
  - Locate daughter isotope $^{136}$Ba for tagging (future plan)
EXO-200 energy resolution

- Combining ionization and scintillation to enhance energy resolution
  - Energy resolution $\sim 1.25\%$ at Q value in rotated axis

![Energy spectra graph with data points and lines indicating energy resolution comparison between calibration sources and rotated energy.](attachment:energy_spectra.png)
EXO-200 phase-II data

- Phase-II data taking: May 2016 to December 2018
- Underground shift: December 2017
- Data quality analyzer: from Jan 2017 to Dec 2018
  - Ensured EXO-200 operation and data taking

2019 result from complete dataset: $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25} \text{ yr}$
EXO-200 results and backgrounds

- EXO-200 experiment:
  - 200 kg of liquid xenon
  - Data: phase I: 2011 to 2014, phase II: 2016 to 2018
  - Weekly data quality analysis: Jan 2017 to Dec 2018

- No evidence for $0\nu\beta\beta$
- $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr
  - One of the best results

- nEXO: 5 tonnes xenon
- Lowest background level
  - Barium tagging

\[ ^{136}Xe \rightarrow ^{136}Ba^{++} + 2e^- + 2\bar{\nu}_e \]
\[ ^{136}Xe \rightarrow ^{136}Ba^{++} + 2e^- \]

*Physical review letters, 123(16):161802, 2019*
EXO-200 → nEXO

- Enriched xenon 200 kg → 5000 kg
- Underground: 655 m → 2070 m
- Improved energy resolution
- Barium tagging

\[ 2\nu\beta: \ {^{136}Xe} \rightarrow {^{136}Ba}^{++} + 2e^- + 2\bar{\nu}_e \]

\[ 0\nu\beta: \ {^{136}Xe} \rightarrow {^{136}Ba}^{++} + 2e^- \]
nEXO sensitivity with barium tagging

- $0\nu\beta\beta$ vs. neutrino mass

$$\frac{1}{T^{0\nu\beta\beta}_{1/2}} = G_F M^2 \langle m_{\beta\beta} \rangle^2 \approx 10^{28} \left( \frac{0.01 \text{ eV}}{\langle m_{\beta\beta} \rangle} \right)^2$$

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} m_i U_{ei}^2$$
Electric potential in a LPT

- Spatial harmonics: \( \phi(r, \theta) = \sum_{n=0}^{\infty} A_n \phi_n \)

\[
\phi_0 = A_0
\]

\[
\phi_2 = A_2 \frac{y^2 - z^2}{r_0}
\]

\[
\phi_6 = A_6 \frac{x^6 - 15x^4y^2 + 15x^2y^4 - y^6}{r_0^6}
\]

\[
\phi_{10} = A_{10} \frac{x^{10} - 45x^8y^2 + 210x^6y^4 - 210x^4y^6 + 45x^2y^8 - 7^{10}}{r_0^{10}}
\]
LPT: ion confinement in radial directions

- Radio frequency quadrupole (RFQ) for ion confinement

Ion’s equation of motion:

\[ \frac{d^2 y}{dt^2} = \frac{-2ey}{r_0^2} (U - V \cos \Omega t) \]
\[ \frac{d^2 z}{dt^2} = \frac{2ez}{r_0^2} (U - V \cos \Omega t) \]

Mathieu equation:

\[ \frac{d^2 u}{d\xi^2} + (a - 2q \cos 2\xi) u = 0 \]

Mathieu parameters:

\[ a \propto U, \quad q \propto V \]

\[ \beta \approx \sqrt{(a + \frac{1}{2}q^2)} \quad (\beta \ll 4) \]

Micromotion: \( \Omega \)

Macromotion: \( \omega = \beta \Omega / 2 \)

Figure credit: Molhave (2000)
Mathieu equation: analytical solution from first principles

\[ u(\xi) = A \sum_{n=-\infty}^{\infty} C_{2n} \cos[(\beta + 2n)\xi] + B \sum_{n=-\infty}^{\infty} C_{2n} \sin[(\beta + 2n)\xi], \quad \xi = \frac{\Omega t}{2} \]

- Stable solution & ion confinement: \( \beta \) is a real and non-integer number

\[ \beta = \sqrt{a - \frac{q^2}{a-(\beta-2)^2} - \frac{q^2}{a-(\beta+4)^2} - \cdots} \]

- \( \beta \): no analytical solution
  - Only approximations in literature

- New approach: iterative method
  - \( \beta_0 = 1 + 0j, \; \beta_{n+1} = \beta(a, q, \beta_n) \)
  - \( n = 1000 \), convergence \(< 10^{-15} \)
  - Analytical solution of \( \beta \) for any \((q, a)\)

- First detailed Mathieu stability diagram
  - Exact analytical solution of beta
  - Analytical solution for ion motion
Ion motion and ion acceptance ellipses $\epsilon$

- **Analytical solution of Mathieu equation**
- Ion acceptance $\epsilon$: area of ellipses in phase space
- **Analytical solution of acceptance for any $(q,a)$**
- Maximum ion transmission: $a=0$, $q \approx 0.6$
Phase-independent ion acceptance $\epsilon_{PI}$

- To capture all extracted ions
  - Accept ions at any RF phase
  - $\epsilon_{PI}$: overlapped ion acceptance

LPT design parameters:
- $q=0.45$, $r_0=3.51$ mm, $f=1$ MHz, $V_{RF}=77$ V:
  - $\epsilon_{PI}=2.44$ mm·mm/μs,
  - can captures $\geq 99\%$ of extracted ions
- 2D Gaussian distributed
- $\epsilon_{PI} \approx \epsilon_{4rms}$
- Meets requirement
Ion acceptance of quadrupole mass filter (QMF)

- Ion acceptance $\epsilon$ analytically calculated for any $(q,a)$
- For validating simulations and experiments
  - Mass resolving power $R (m/\Delta m)$
  - Ion transmission rate $T$

When ions are abundant and uniformly distributed, ion transmission rate $T$ is proportional to $\epsilon$: $T \propto \epsilon$
Novel electrode geometry for ion cooler

- **Classical design**
  - Segmented quadrupole electrodes to form potential gradient

- **Novel design**
  - Tapered electrodes
    - Varying electric field penetration to form potential gradient
  - Simplified electrical connections
A realistic LPT: electrode geometries

- Hyperbolic shape is ideal but mechanically difficult

- Round electrodes are easier to machine and assemble
  - Studied electric potential
    - Purity of quadrupole potential
    - Effects on ion transmission
  - Optimum parameter: $r_e/r_o=1.13$
Truncated hyperbolic electrodes

- Ideal quadrupole potential when truncated at $> 1.8r_0$
Round electrodes

- “Magic ratio” $r_e/r_0 = 1.14511$ for $A_6 = 0$
- However, not best for ion transmission
Novel electrodes for cooler

- Tapered quadrupole to also provide DC potential gradient
- Varying electric field penetration
LPT conceptual design

- Ensure mechanical precision and alignment
  - QMF needs $<50 \ \mu m$ positional precision, others $\sim 0.1 \ mm$

- Effective differential pumping:
  - Apertures and long channels
QMF design
Pre-cooler design
Ion cooler design
Laser spectroscopy ion trap design
Ion buncher design

Pulse drift tube

(a)

(b)
Vacuum design

- Different pressure requirements
- Differential pumping through apertures and channels
Vacuum simulation

- Tool: Molflow+ (https://molflow.web.cern.ch)
  - Molecular flow simulation using ray-tracing
  - Simplified geometry
Vacuum simulation

- Tool: Molflow+ ([https://molflow.web.cern.ch](https://molflow.web.cern.ch))
- Molecular flow simulation using ray-tracing

Avoid gas buildup

- Pump

Helium gas in

5 cm

$1 \times 10^{-5}$ mbar

$6 \times 10^{-4}$ mbar

$5 \times 10^{-4}$ mbar

$6 \times 10^{-2}$ mbar
QMF stability diagram
QMS mass scan

- Voltage scan vs. Frequency scan
Quadrupole electrode simulations for QMF

$r_e/r_0 = 1.145$

Simulation $v_x = 2 \text{mm/\mu s}$
Simulation $v_x = 5 \text{mm/\mu s}$

Acceptance $\alpha_{\text{coll}}$ [\text{rad}^2/	ext{cm}]

$r_e/r_0 = 1.13$

Simulation $v_x = 2 \text{mm/\mu s}$
Simulation $v_x = 5 \text{mm/\mu s}$

Acceptance $\alpha_{\text{coll}}$ [\text{rad}^2/	ext{cm}]
QMF2.2 results: best achievable $R$

- A problem in assembly:
  - Performance of QMF2.2 limited by the mechanical problem
  - Best achievable mass resolving power $R_{\text{max}} \approx 140 \checkmark (>80)$
RFQ ion guide acceptance simulation

- $r_e/r_0=1.13$ is optimum
Ion emittance from RF funnel

- $\epsilon_{3\text{rms}} = 1.44 \text{ mm}\cdot\text{mm}/\mu\text{s}$
Experimental preparation

- Electronics, control and DAQ systems
- Vacuum
- Ion source
- Ion detector
Quadrupole Mass Filter (QMF) prototypes

- Acrylic QMF (V1.0)
  - Novel design
  - Mechanical tolerance ~ 0.2 mm
  - Tested as an ion guide
    - Saw optimum ion transmission at 20 Vpp, 530 kHz
    - Things are working: electronics, DAQ, ion source, ion detector …

0.02 mm (20 μm) tolerance needed
Mechanical tolerance $\sim 50 \mu m$ (0.002"")

RF amplitude: 20 Vp-p, frequency 0.3 to 0.9 MHz

Figure credit: Niessen (2017)
RF cooler prototype

- More complicated geometries
- Less tolerance requirement: 0.3 mm
- Try 3D printing for rapid prototyping
  - Tolerance ~ 0.1 mm ✓

- Tested vacuum compatibility
  - Below $10^{-6}$ Torr within 10 hours of pumping ✓

- Ongoing experiment with ion cooler:
  - Ion trapping and ion ejection
QMS performance simulation

- Transmission efficiency
  - acceptance
- Mass resolving power
- Validate mechanical tolerance
Measure QMS electrode tolerance

- Use the digital readout on a lathe
Novel rectangular electrode for cooler

Width: 4 mm

Width: 2 mm
Laser spectroscopy

- Initial study at Stanford (~2005)
- now at Carleton University