Design of a Multiple-Reflection Time-of-Flight Mass-Spectrometer for Barium-tagging with nEXO

Kevin Murray
Supervisor: Thomas Brunner

McGill University

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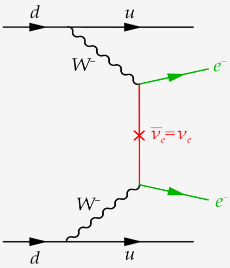
Neutrinoless Double Beta Decay

Neutrino properties are still quite poorly understood...



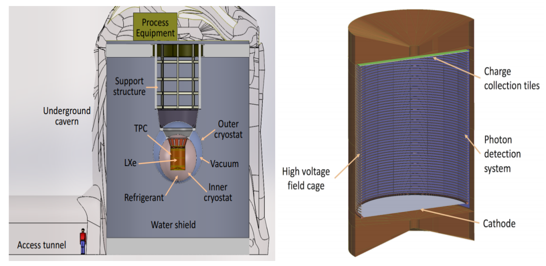
- Is the Neutrino Dirac or Majorana (is it its own antiparticle)?
- Why is the neutrino mass so small relative to other leptons?
  - If Majorana there is a potential solution through the see-saw mechanism.

A Majorana neutrino violates conservation of lepton number $\Longrightarrow$ Search for lepton number violating process. BSM physics!

Barium-tagging with nEXO

Based on the success of EXO 200 [1].

nEXO:



- Planned neutrinoless double beta decay experiment.
- $\sim$ 5t of liquid Xe enriched to $\sim$ 90% in ^{136}Xe.
- Anticipated at SNOLAB.

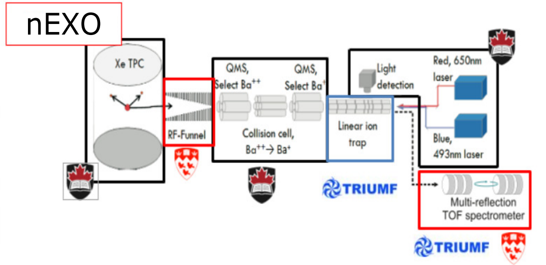
Barium-tagging: The process of extracting and identifying the daughter Barium ion of double beta decay, in order to eliminate backgrounds and verify the signal.

Barium-tagging in Canada

Ba-tagging:

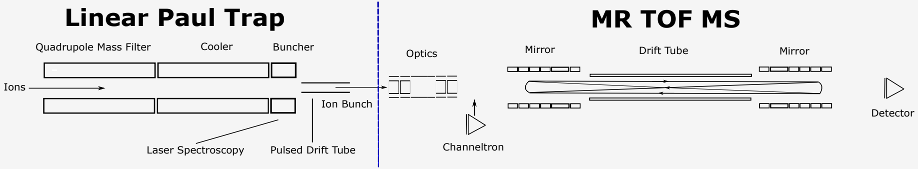
- Identify if event is of interest (energy/characteristics).
- Localize the Event.
- Extract decay volume from the detector volume.
- Probe for Barium.

Canadian approach:



Ion Identification

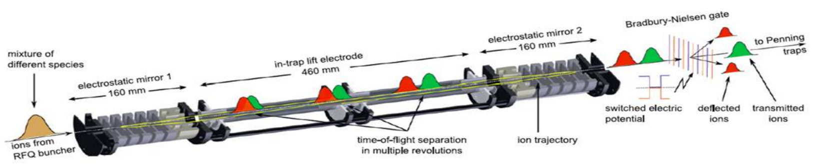
Linear Paul Traps (LPTs) and Multiple-Reflection Time-of-Flight Mass-Spectrometers (MR TOFs) are a popular combination!



- Ions are cooled with Helium buffer-gas and trapped in the LPT.
- The Barium is then identified with laser spectroscopy.
- Ion bunches are ejected and accelerated by a pulsed drift tube.
- The bunch is injected into the MR TOF.
- The MR TOF is sensitive to all ion species, it is mainly to be used for systematic studies.

The MR TOF

Each mirror consists of 6 electrodes, 2 accelerating and 4 retarding.

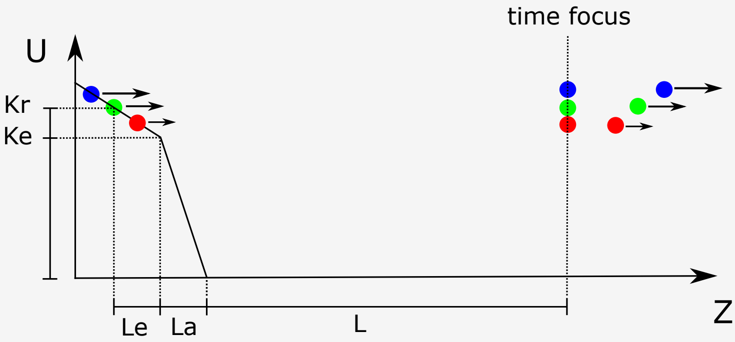


Mass-resolving power:

$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$

Time Focus: A point in space at which ions of the same m/q will arrive at the same time, even though they have slightly different kinetic energies.

Where is the Time Focus?

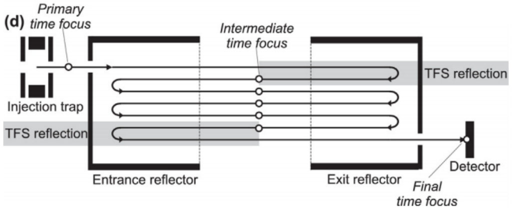


$$L = 2L_e \left(\frac{K_r}{K_e}\right)^{\frac{3}{2}} - 2L_a \sqrt{\frac{K_r}{K_e}} \frac{1}{1 + \sqrt{K_e/K_r}} \quad (1)$$

For the current trap configuration this places the primary time focus about $\sim$ 3cm from the exit of the LPT.

Can it be moved?

Yes! Reflections in the MR TOF mirrors can be used to move the position of the time-focus.

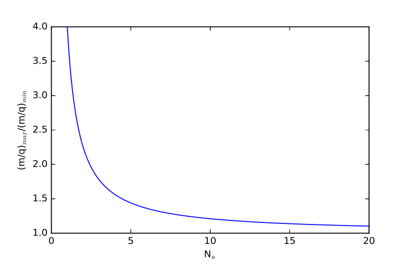


(d) Dynamical TFS with the analyzer; for all reflections except for the first and the last, the focus length of each reflector is that of a half-turn and in the first and last reflections different reflector settings are used such that the primary time focus is imaged on the first intermediate time focus and that the last intermediate time focus is imaged onto the detector (Section 2.4).

- For the original design the time focus was shifted over many reflections.
- Can also be shifted in one reflection to avoid re-tuning. Allowing the mass range to be easily adjusted.

Unambiguous Mass Range

Ions will start to overlap each other. Advantageous to be able to adjust the number of reflections for desired range.



The MR TOF mass acceptance range is approximated roughly as [2]:

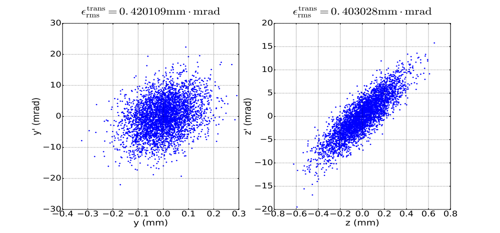
$$\frac{(\mathrm{m/q})_{\mathrm{max}}}{(\mathrm{m/q})_{\mathrm{min}}} \approx \frac{(N_a + 1)^2}{N_a^2}$$

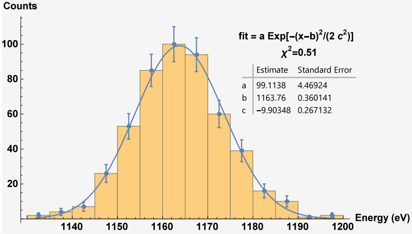
Where m/q is the mass-to-charge ratio and N_a is the number of turns in the MR TOF.

Good motivation for turn independence for low revolution numbers. With precise control of time-of-flight aberrations.

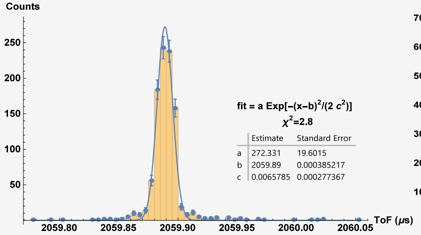
Simulation Results

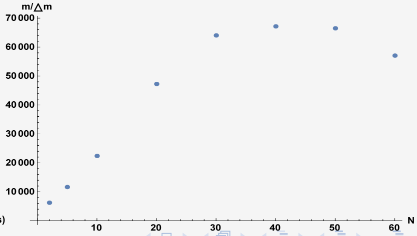
Emittance (left) and Energy (right):



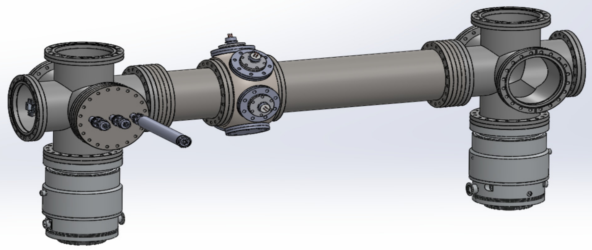


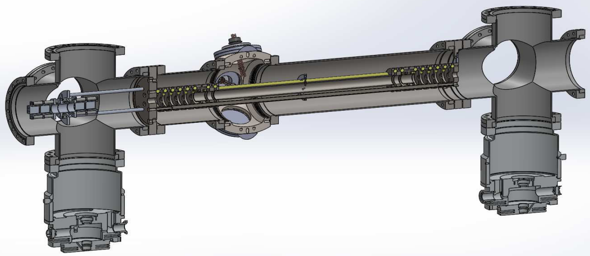
Sample spectrum for 50 reflections (left), mass resolving-power (right):





SolidWorks Drawings

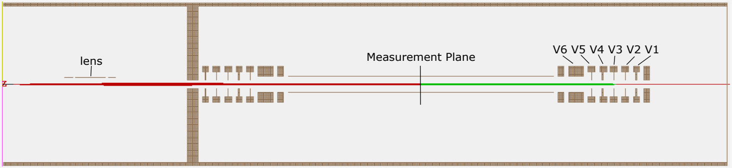




Machine Learning for Ion-Optics?

The MR TOF is difficult to optimize...

Can machine-learning predict how the MR TOF should be operated for a single reflection? For more information see back-up slides.



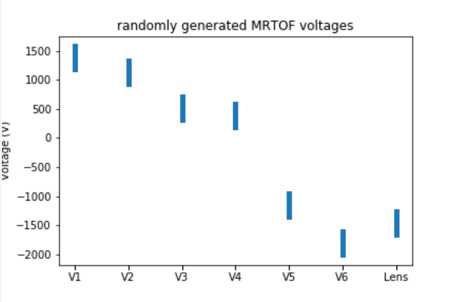
Simion:

$$\text{V1, V2, V3, V4, V5, V6, lens} \rightarrow (x|x), (y|y), (t|\delta), (t|\delta\delta), (t|\delta\delta\delta)$$

Keras:

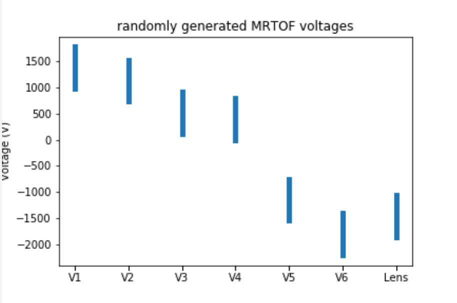
$$(x|x), (y|y), (t|\delta), (t|\delta\delta), (t|\delta\delta\delta) \rightarrow \text{V1, V2, V3, V4, V5, V6, lens}$$

A narrow guess for the operational voltages seems to perform fairly well.

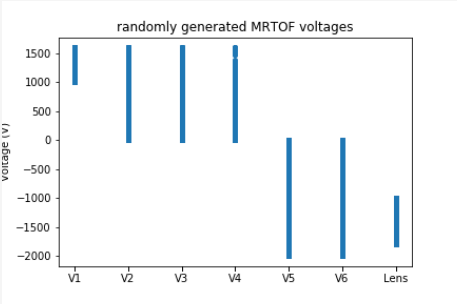


Loss: residual sum of squares between predicted and true values.

As the initial guess starts to widen the performance starts to decrease.

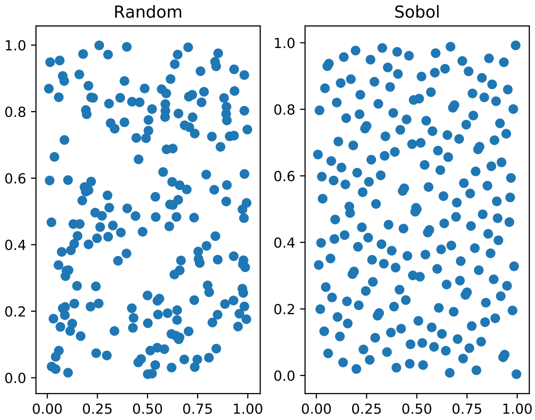



train/test = 80%/20%, bunch size = 200, total runs = 11578
Loss
Accuracy
test loss = 77.85%
test accuracy = 50.04%
Percentage (%)
Epoch


randomly generated MRTOF voltages
voltage (V)
V1
V2
V3
V4
V5
V6
Lens

Sobol Sequence

Perhaps the input voltages should be pseudo-random to avoid gaps in the parameter space?



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JB Albert et al.
Search for majorana neutrinos with the first two years of exo-200 data.
Nature, 510(7504):229, 2014.

Mikhail I Yavor et al.
Ion-optical design of a high-performance multiple-reflection time-of-flight mass spectrometer and isobar separator.
International Journal of Mass Spectrometry, 381:1–9, 2015.

Optical properties of the MR TOF

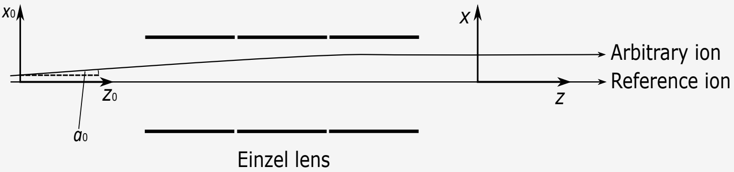
Equations from initial to final conditions for the MR TOF.

$$
\begin{aligned}
x =& (x|x)x_0 + (x|a)a_0 + (x|x\delta)x_0\delta + (x|a\delta)a_0\delta + \dots \\
a =& (a|x)x_0 + (a|a)a_0 + (a|x\delta)x_0\delta + (a|a\delta)a_0\delta + \dots \\
y =& (y|y)y_0 + (y|b)b_0 + (y|y\delta)y_0\delta + (y|b\delta)b_0\delta + \dots \\
b =& (b|y)y_0 + (b|b)b_0 + (b|y\delta)y_0\delta + (b|b\delta)b_0\delta + \dots \\
t' =& (t|\delta)\delta + (t|xx)x_0^2 + (t|xa)x_0 a_0 + (t|aa)a_0^2 + (t|yy)y_0^2 + (t|yb)y_0 b_0 \\
& + (t|bb)b_0^2 + (t|\delta\delta)\delta^2 + (t|\delta\delta\delta)\delta^3 + (t|\delta\delta\delta\delta)\delta^4 + (t|xx\delta)x_0^2\delta \\
& + (t|xa\delta)x_0 a_0\delta + (t|aa\delta)a_0^2\delta + (t|yy\delta)y_0^2\delta + (t|yb\delta)y_0 b_0\delta
\end{aligned}
$$

For an arbitrary ion

$$\delta = \frac{K - K_0}{K_0}, t' = t - t_0, a = \frac{vx}{vz}, b = \frac{vy}{vz}$$

Where K_0 and t_0 are the kinetic energy and time of flight of a reference ion.



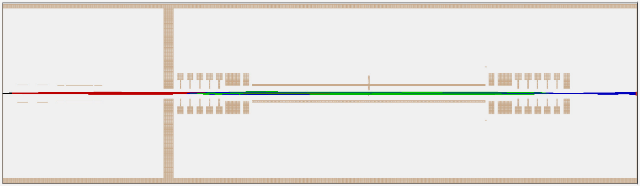
x, y, a and b are transverse displacements and angles from a reference ion trajectory.

To place the first time focus optimization goals are:

$$(x|x) = (y|y) = (t|\delta) = (t|\delta\delta) = (t|\delta\delta\delta) = 0$$

Mass Selector

Mass Selector Off



Mass Selector On