The Nab Experiment: Precision Measurements of Correlation Parameters in Neutron Beta Decay

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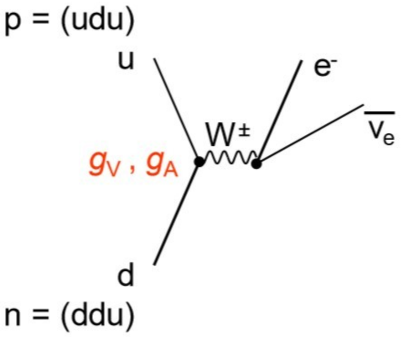
Talk Overview

- Coupling Constants in Neutron Beta Decay
- Neutron beta decay parameters
- Nab Spectrometer and Measurement Technique
- Large Segmented Silicone Detector
- Manitoba Proton MCP Tests

Neutron Beta Decay



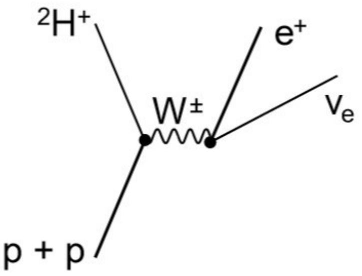
$n \rightarrow p + e^- + \overline{\nu}_e$

Precise and accurate measurements of fundamental coupling constants are desired for quantitative analysis of sub-atomic phenomena.

Quark-Quark Vertex Factor:

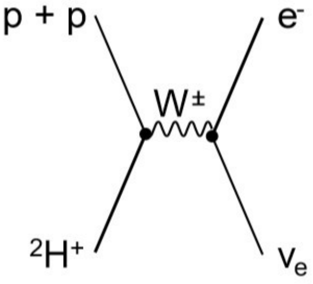
$$\mathcal{K}^\mu \rightarrow -\frac{i g_w}{2\sqrt{2}} \gamma^\mu (g_V - g_A \gamma^5)$$

Many astrophysical processes depend on weak-coupling constants.



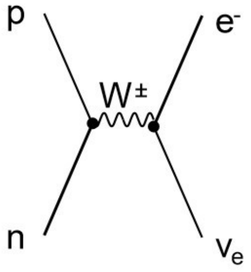
$p + p \rightarrow {}^2H^+ + e^+ + \nu_e$

Solar Neutrino Production



$\nu_e + {}^2H^+ \rightarrow p + p + e^-$

Neutrino Capture Efficiency



$n + \nu_e \leftrightarrow p + e^-$

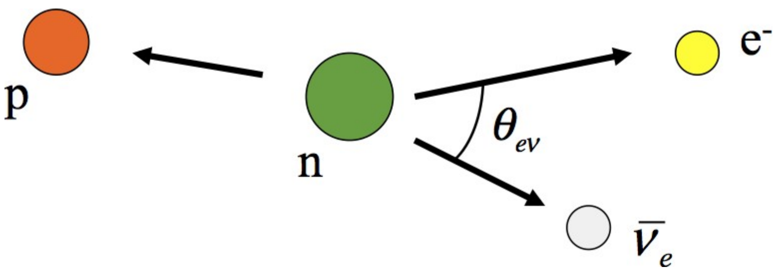
Big Bang Nucleosynthesis

The Nab Experiment and Neutron Beta Decay Correlation Parameters

Electron-Neutrino Correlation Parameter ≡ a

Fierz Interference Term ≡ b (b = 0 in standard model)

Triple Differential Decay Rate from QFT:



$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \simeq p_e E_e (E_0 - E_e)^2$$

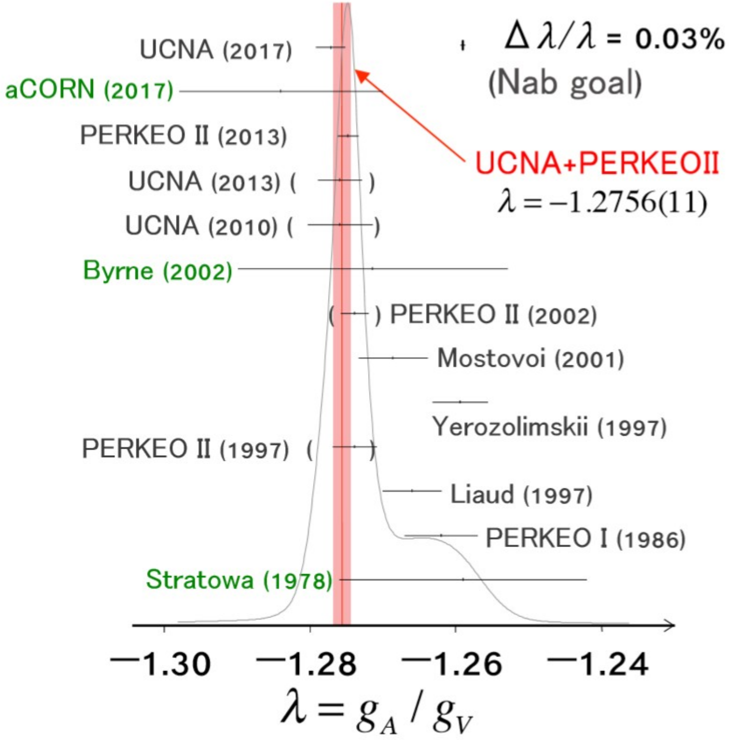
$$\times \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} \right) + \ldots \right]$$

Measuring a gives us λ.

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad \lambda = \frac{G_A}{G_V}$$

Where λ is the ratio of the axial vector to vector coupling constants

Measurements of Electron-Neutrino Correlation Parameter, a



Previous measurements of a:

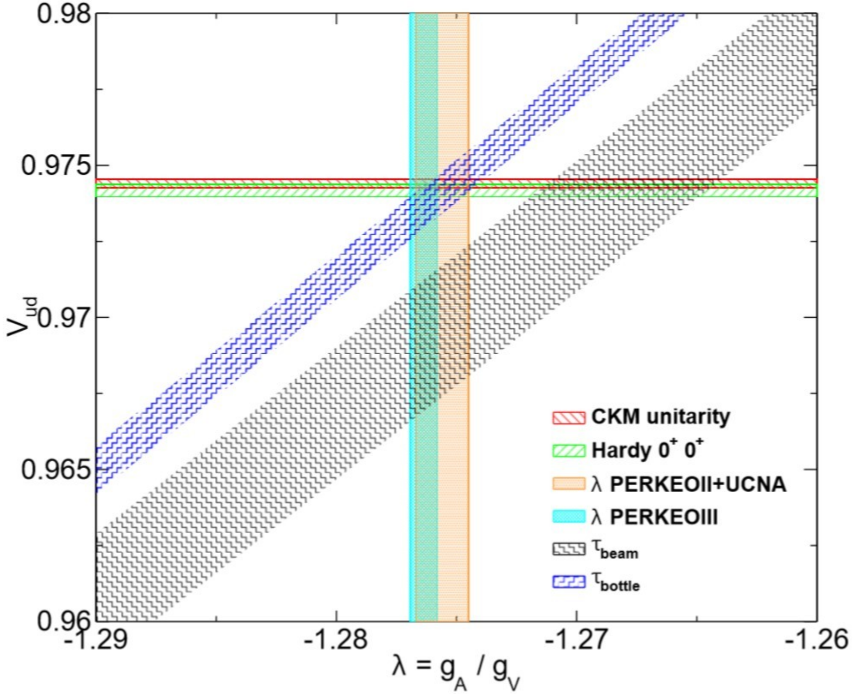
−0.1090±0.0041 Darius et al, 2017 (aCORN)
−0.1054±0.0055 Byrne et al, 2002

The Nab experiment is reaching for relative uncertainties in a and b, $\Delta a/a \leq 10^{-3}$ and $\Delta b \leq 3 \cdot 10^{-3}$, respectively.

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2}$$

Testing Unitarity in the Cabibbo-Kobayashi-Maskawa Matrix

Neutron decay rate: $\Gamma = 1/\tau_n \propto |V_{ud}|^2 |g_V|^2 G_F^2 (1 + 3|\lambda|^2)$



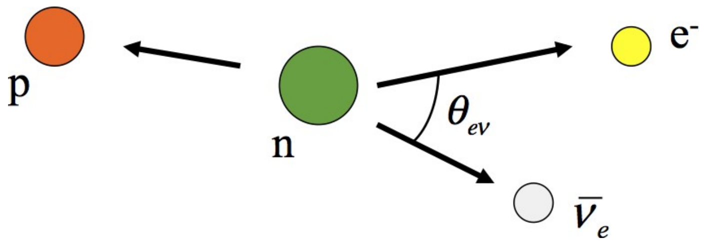
Unitary CKM matrix describes the mixing of quark generations:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$|V_{ud}| = 0.97420 \pm 0.00021$$

How do we measure a?



Applying 4-Momentum Conservation:

$$p_p^{\ 2} = p_e^{\ 2} + p_\nu^{\ 2} + 2 p_e p_\nu \cos\theta_{e\nu} \qquad E_\nu = E_{e,max} - E_e$$

The cosine term can be solved in terms of proton momenta and electron energy.

$$\cos\theta_{e\nu} = \frac{1}{2}\left[\frac{p_p^2 - (2E_e^2 + E_0^2 - 2E_0 E_e)}{E_e(E_0 - E_e)}\right]$$

We arrive at a linear relation in which the only unknown is a, the electron-neutrino correlation parameter.

$$p_p^{\ 2} \propto \ 1 + a\frac{p_e}{E_e}\cos\theta_{e\nu}(p_p^{\ 2})$$

Measuring for different fixed values of E_e we construct a distribution in p_p^2 which is used to back out a.

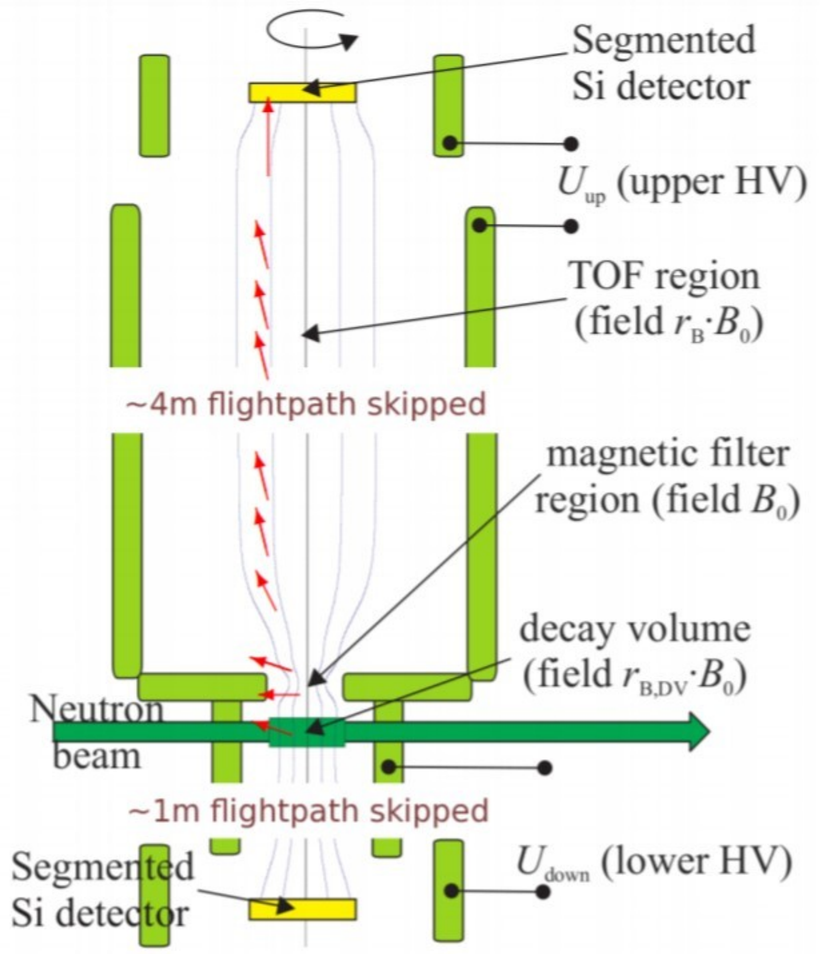
Nab Spectrometer

Static electric and magnetic fields are azimuthally symmetric about the z-axis.

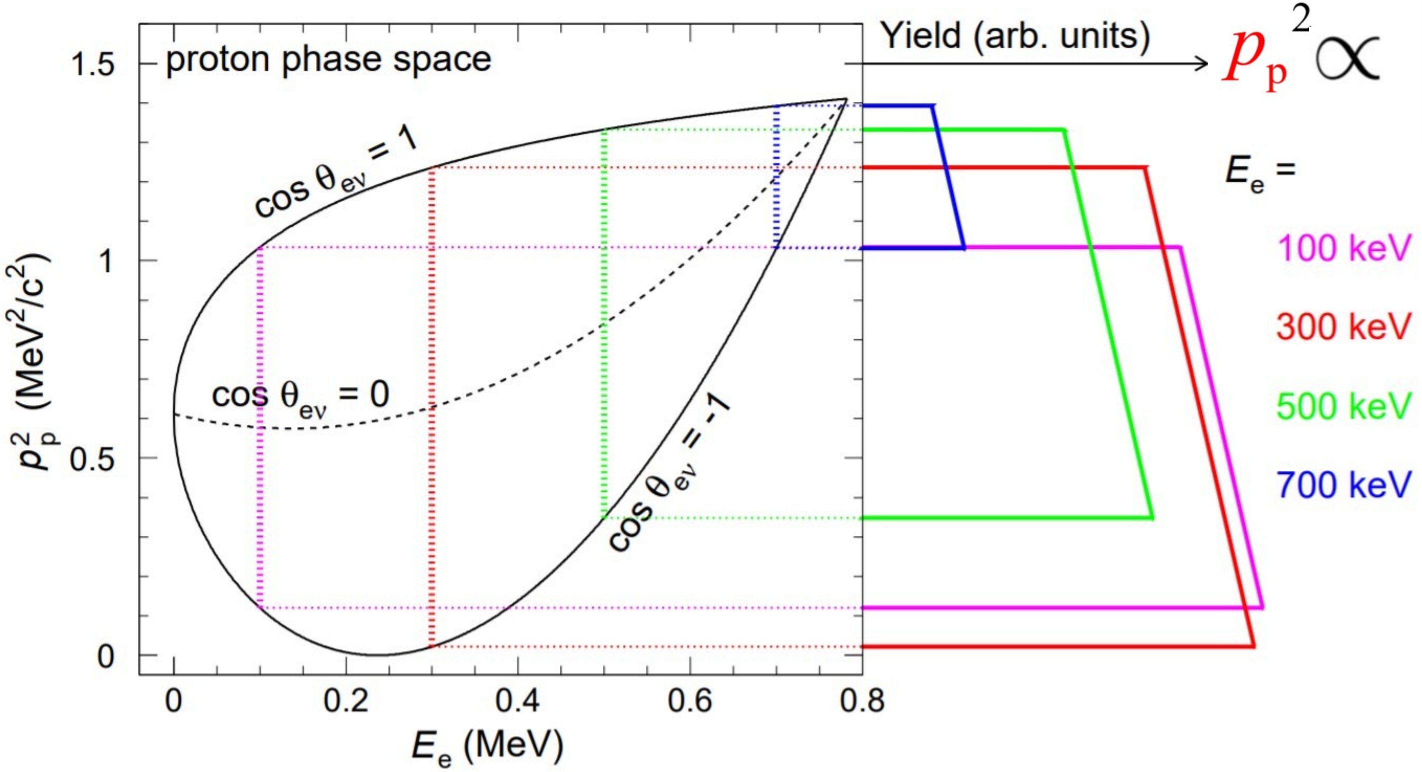
Neutrons decay in a region of large B(4T).
Proton and electron spiral around magnetic field lines as they travel toward the detector.

An electric field at the end of the proton TOF region accelerates the proton to 30 keV*(from~1keV)* into a silicon detector.

Proton momentum must me rapidly longitudinalized order to ensure the time of flight obeys $t_p \propto 1/p_p$.



$$p_p{}^2 \propto \; 1 + a\frac{p_e}{E_e}\cos\theta_{ev}\,(p_p{}^2)$$



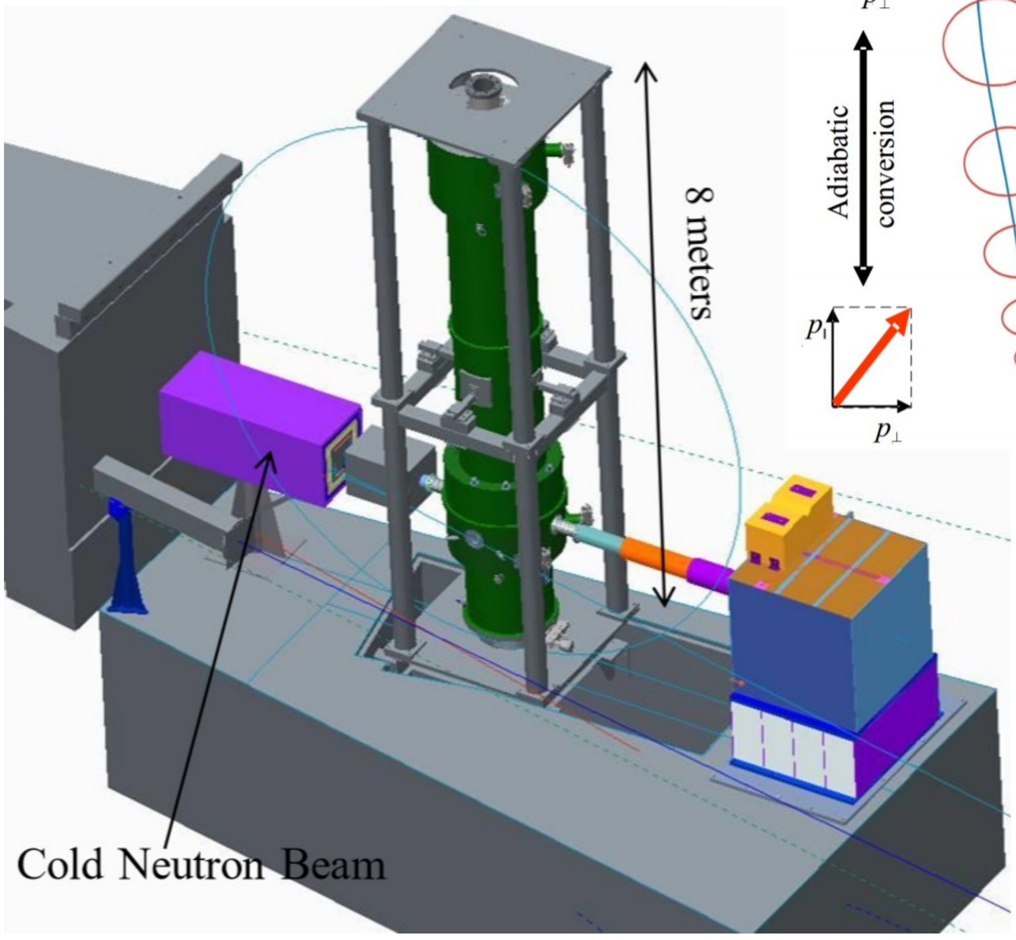
Free Proton Time of Flight:

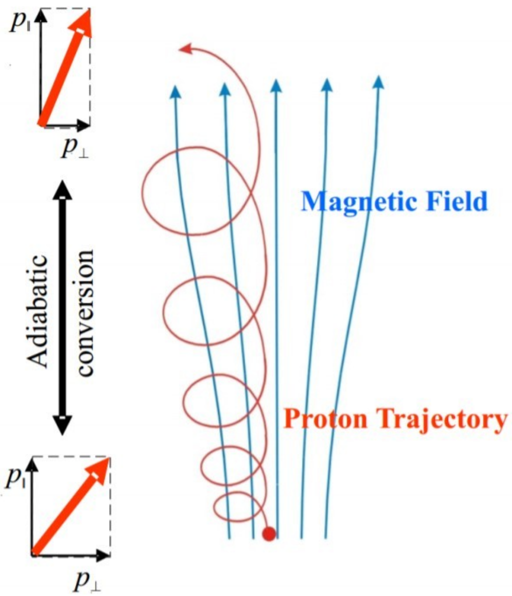
$$t_p = L\frac{m_p}{p_p}$$

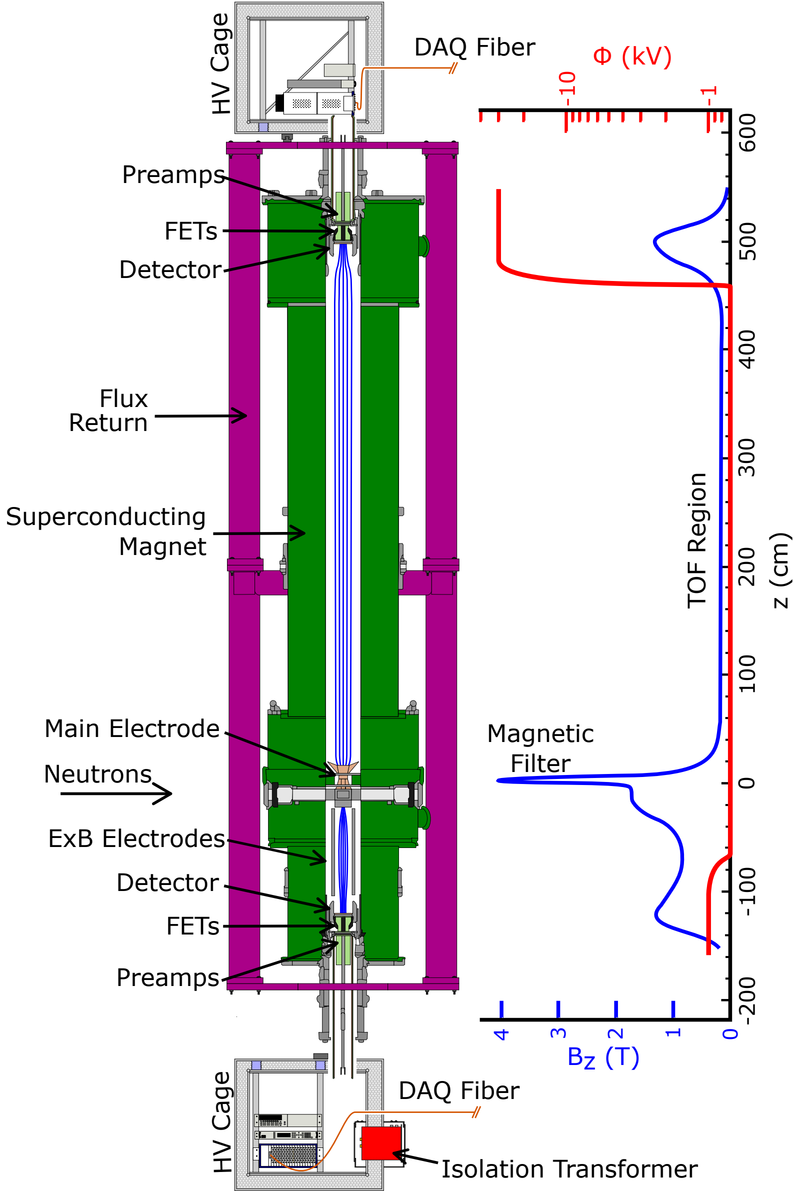
where L is the path length

Decay parameters a and b are uniquely determined by proton momenta and electron energy. In the Nab experiment, the proton momenta are measured by their time-of-flight and the electron energies are measured directly from pulse height spectra.

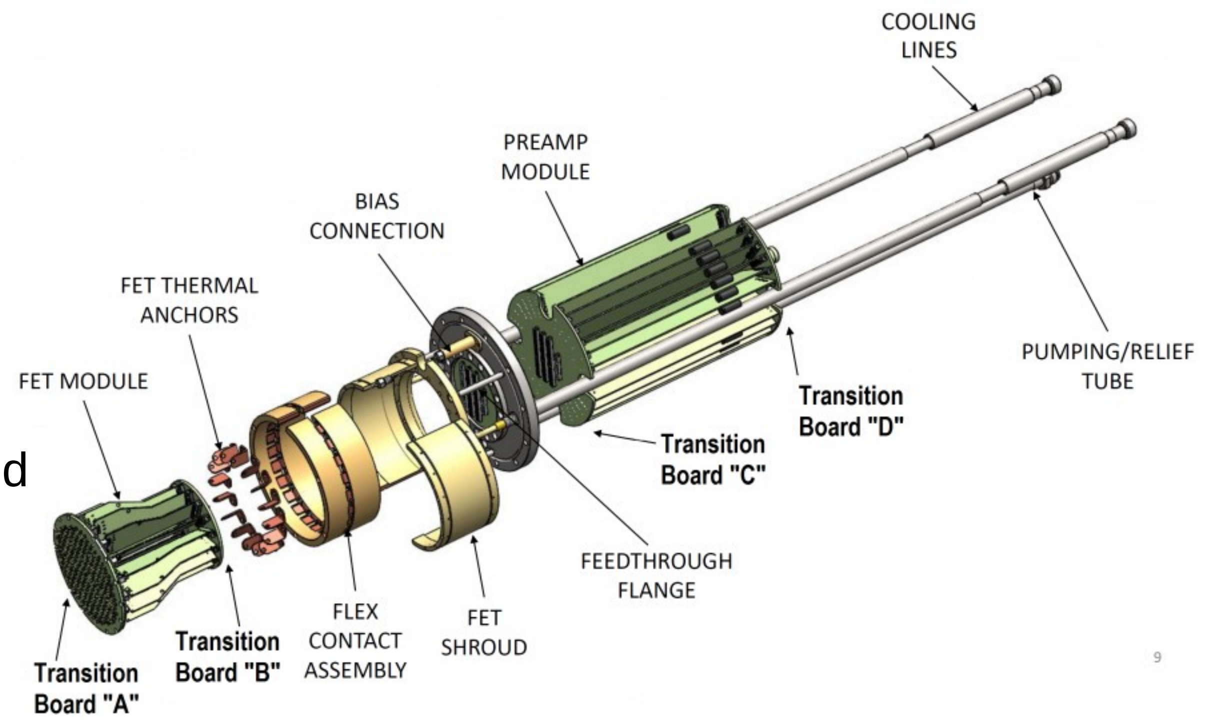
Adiabatic Magnetic Field Expansion







Large Area Segmented Silicon Detector

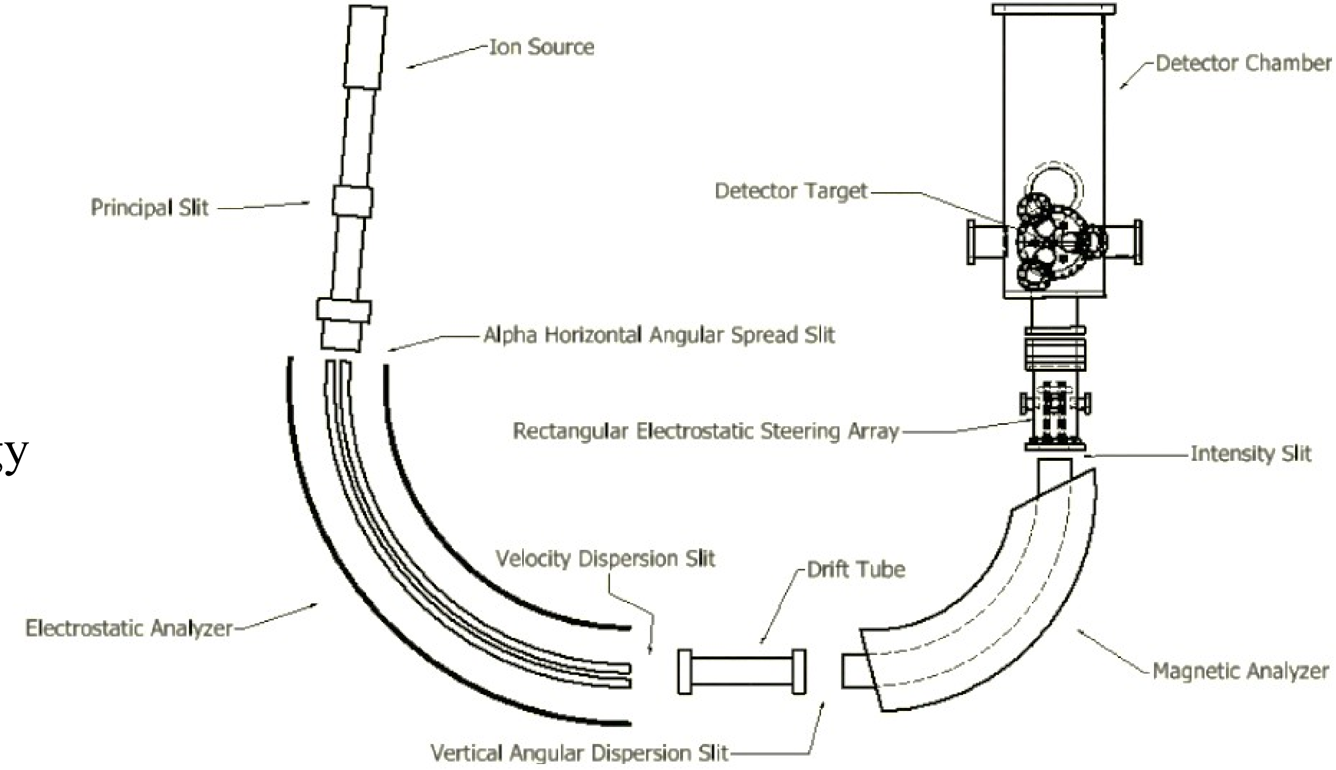


Two detectors will measure proton and electron events,respectively.

Specifications:
Active area: 100cm^2
Dead layer: <100nm
Pixel Count: 127
Thickness: 2mm
Estimated detection rate: ~200protons/second

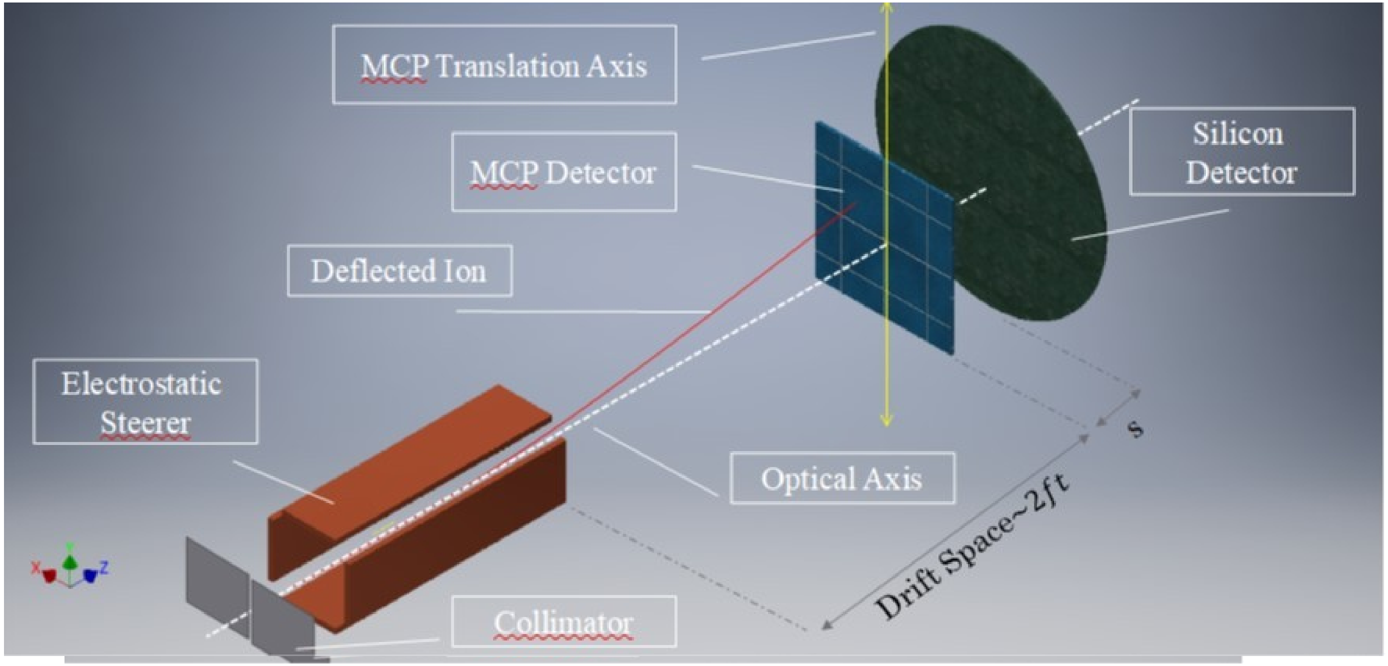
Manitoba II Proton Source

- Double focussing mass spectrometer: energy and momentum focusing
- Penning Ion Gauge Hydrogen-Argon Gas Discharge Source
- Accelerate protons to 30keV
- Electrostatic analyzes ion energy
- Magnetic analyzer selects ion momentum
- Electrostatic steerer deflects beam to detection location



Detector Testing for Nab and The Manitoba 2 Proton Source

- Nab will use large area segmented silicon detectors that will be characterized to proton detection using the Manitoba II Proton Source.
- Test requirements: Test each pixel independently, search for pixel cross talk and perform relative efficiency measurement to secondary large area segmented multi-channel plate(MCP) detector.



Summary

- Measure a and b; $\Delta a/a \leq 10^{-3}$ and $\Delta b \leq 3 \cdot 10^{-3}$
- Unitary test in the CKM matrix
- Comparison of measured λ to lattice calculations
- Search for scalar-tensor interactions through b