Updates of the Nab Experiment: A Precise Measurement of Unpolarized Neutron Beta Decay

Jason Fry, for the Nab Collaboration

Eastern Kentucky University

April 15, 2023

APS April Meeting 2023

Oak Ridge National Laboratory

NSF

NSF-PHY 2213411

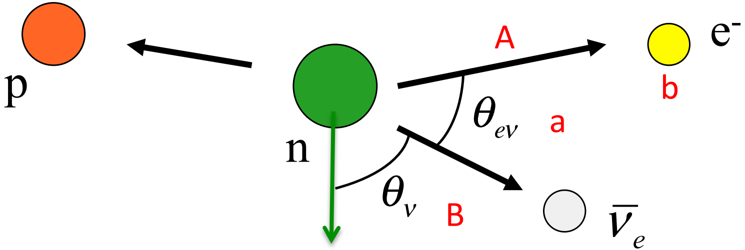
The Nab collaboration

Nab collaborating institutions:

University of South Carolina,
Universität Karlsruhe (TH),
Universidad Nacional Autónoma de México,
Western Kentucky University

Main project funding:

Neutron Beta Decay Correlations



- Along with the neutron lifetime, neutron beta decay correlations provide input into standard model $\rightarrow V_{ud}$ and CKM unitarity (**quark mixing**)
- Correlations are all related to a single parameter in the SM: $\lambda = \frac{G_A}{G_V}$
  - Neutron decay rate: $\Gamma = 1/\tau_n \propto |V_{ud}|^2 |g_V|^2 G_F^2 (1 + 3|\lambda|^2)$
  - **Sensitively tests the standard model!** Is there additional physics?
  - Different correlations provide multiple checks with different systematics

Free neutron beta decay rate

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

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

where in SM:

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2\frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}$$

$$B = 2\frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2} \qquad \lambda = \frac{G_A}{G_V} \text{ (with } \tau_n \Rightarrow \text{CKM } V_{ud}\text{)}$$

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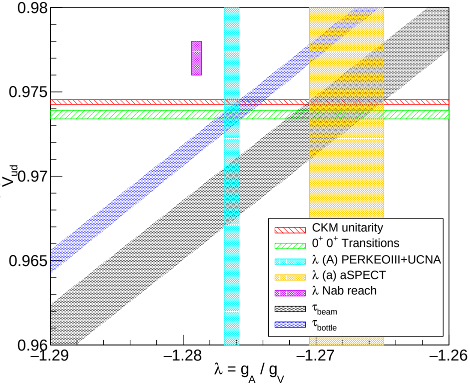
- Measurements of a, A, B contain different systematics, independent determinations of λ
- Fierz interf. term b adds sensitivity to non-SM processes! (b = 0 in SM)

Status of λ and V_{ud} in n decay: CKM Unitarity?

- Data + theoretical radiative corrections generate some tension with CKM Unitarity
- New physics at the TeV level? $\Delta\lambda/\lambda = 3\times10^{-4}$ and $\tau_n = 0.3$ s for neutrons to competitively test CKM
- Nab will measure $\frac{\Delta a}{a} \simeq 10^{-3}$ and $\Delta b \simeq 3\times10^{-3}$



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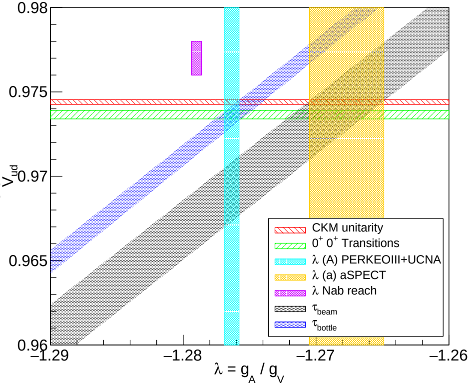
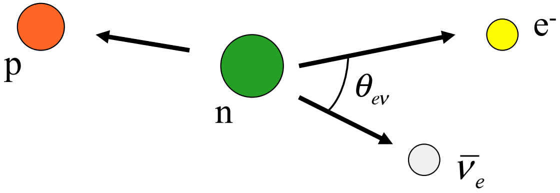


- Independent measurements of λ are necessary in order to entangle V_{ud} from the neutron lifetime, $1/\tau_n \propto |V_{ud}|^2|g_V|^2 G_F^2(1+3|\lambda|^2)$
- **N***ab*+pNab $\Rightarrow$ independent $\sim 0.03\%$ determinations of λ

N*ab*: How do we determine "*a*"?



the angular decay rate $w \propto 1 + a\beta\cos\theta_{e\nu}$

- Considering conservation of momentum in **n** beta decay along with neglecting proton recoil energy, $E_e + E_\nu = E_0$, we can arrive at

$$\cos\theta_{e\nu} = \frac{1}{2}\left[\frac{p_p^2 - (2E_e^2 + E_0^2 - 2E_0E_e)}{E_e(E_0 - E_e)}\right].$$

$\cos\theta_{e\nu}$ is uniquely determined by measuring E_e and p_p.

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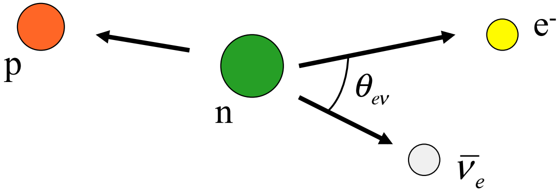

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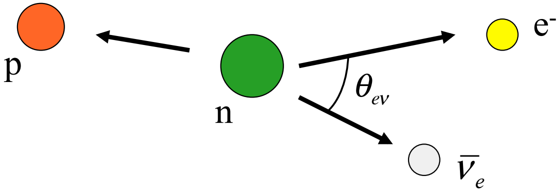

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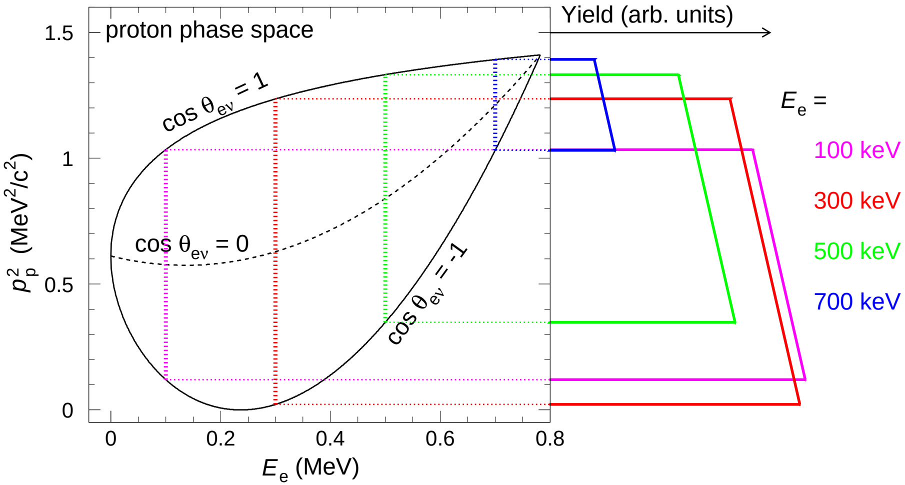
Neutron beta decay phase space: determination of *a*



For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

Multiple measurements of *a* for each E_e slice

Courtesy Dinko Pocanic

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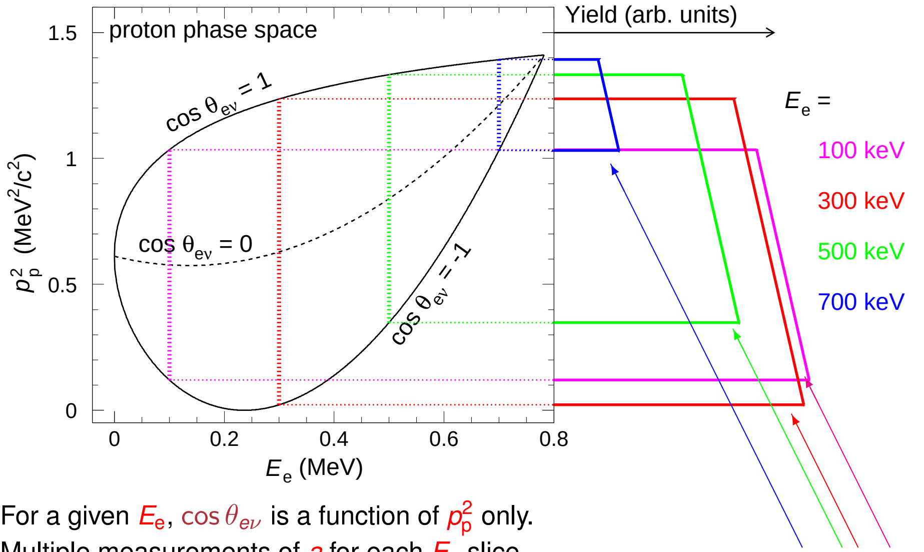

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Slope of $p_p^2 \propto a$

N*ab* spectrometer and measurement

- **In order to extract p_p practically within N*ab*, we use a long spectrometer that measures t_p to determine p_p**

- Detect electrons directly, in upper or lower Si detector $\rightarrow E_e$

- Detect protons, **after acceleration**, in upper Si detectors $\rightarrow t_p$ determine p_p

Nab spectrometer and measurement

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A complex magneto-electrostatic apparatus is required to guide particles (nearly) adiabatically to detectors.

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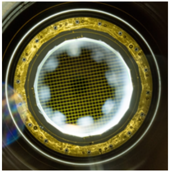
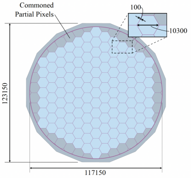
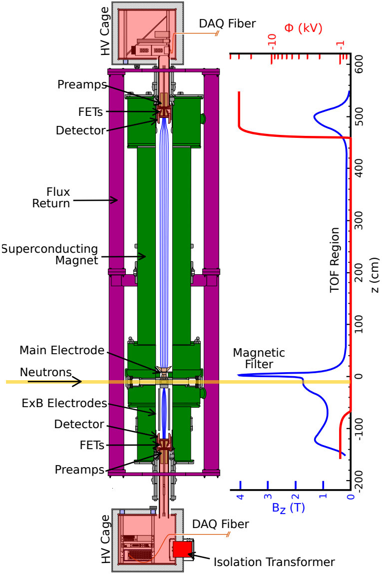




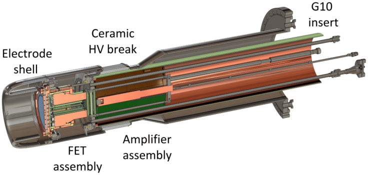
David Mathews



Aaron Jezghani

N*ab* Si detectors: measurement and calibration

- 15 cm diameter, full thickness: 2 mm
- 127 pixels, dead layer $\leq$100 nm
- Energy resolution a few keV, 10 keV proton threshold



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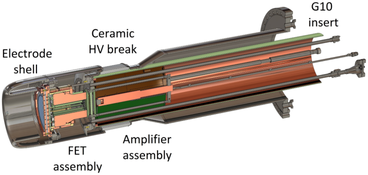
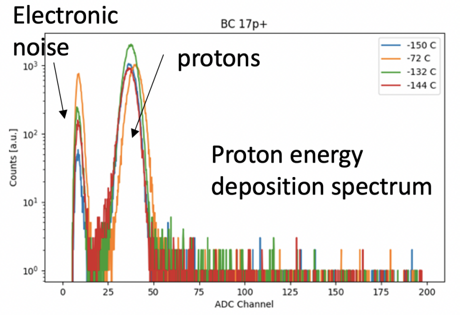
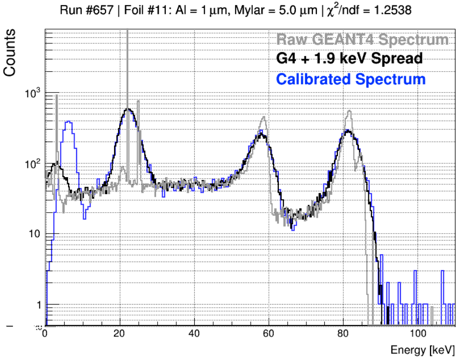


Initial protons and radioactive source data at University of Manitoba

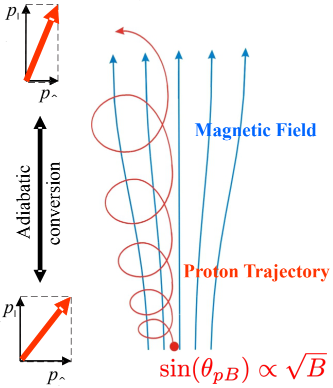


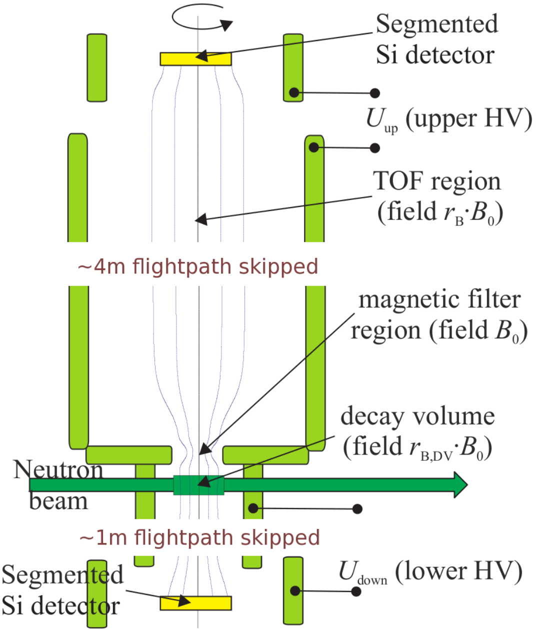


Jin Ha Choi, Leendert Hayen, Nick Macsi, David Mathews, Leah Broussard, others!

How do we collect low energy protons? Max energy 800 eV

A strong magnetic filter accepts protons with a narrow upward cone $\cos(\theta_{0,min}) > 0.7$





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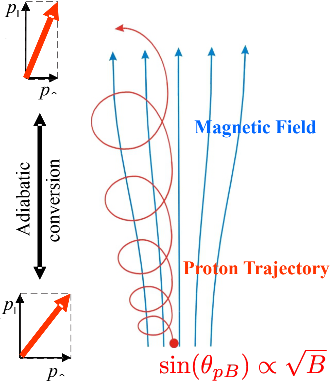

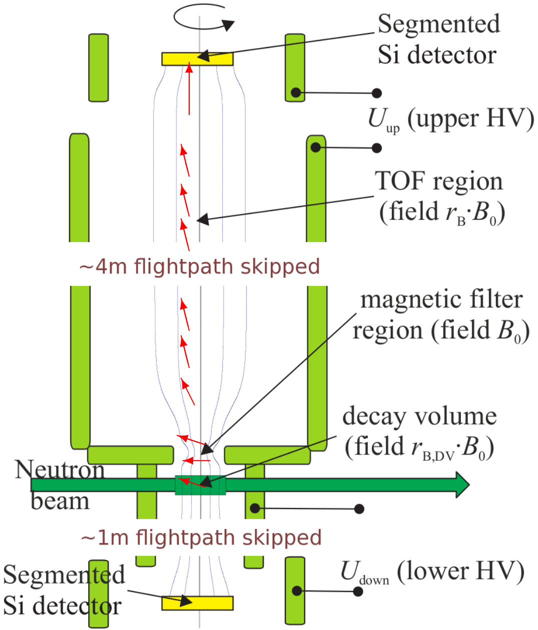

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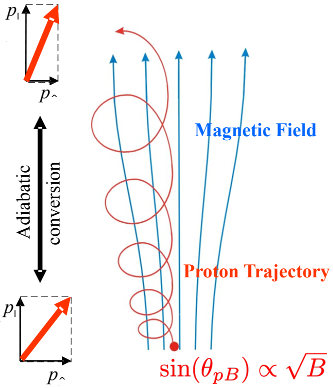
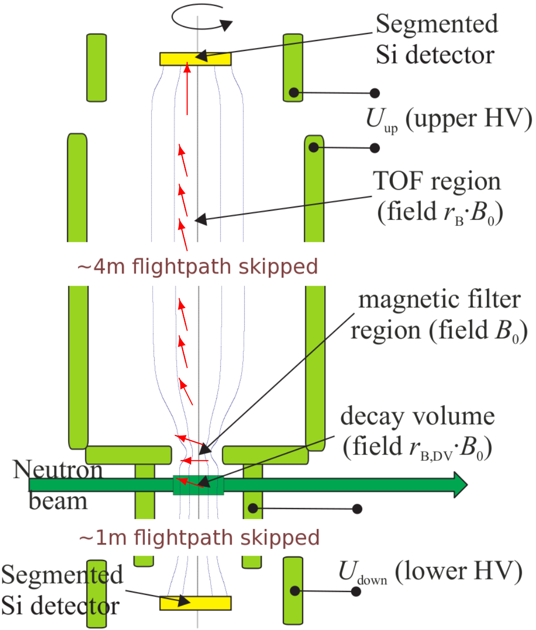
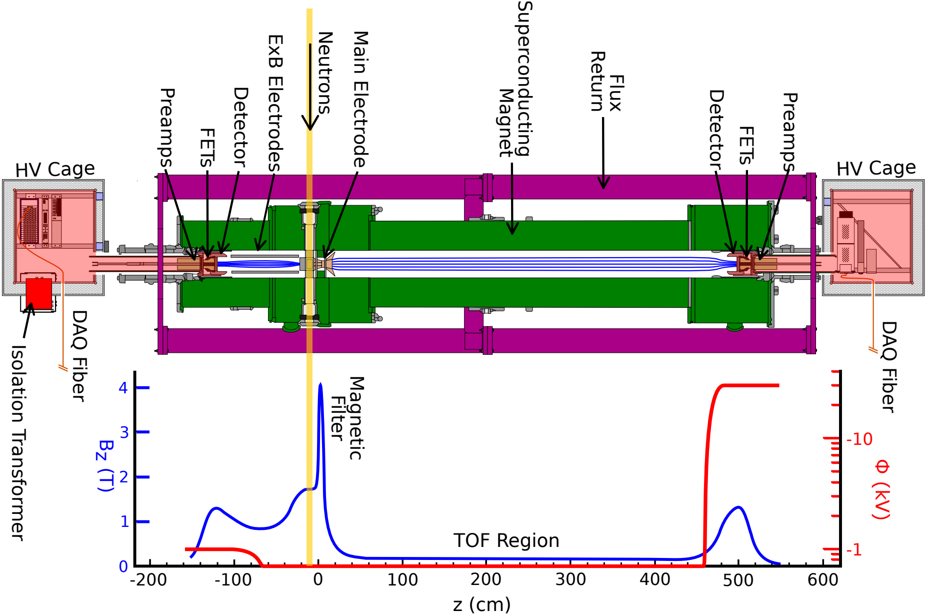




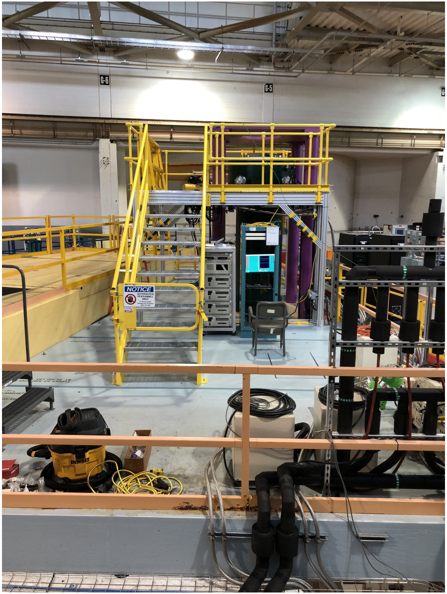
$\Rightarrow$ longitudinalize $\vec{p}$ early, followed by a long drift path!

Nab Spectrometer Magnet



The **N***ab* Magnet on the FNPB at the SNS

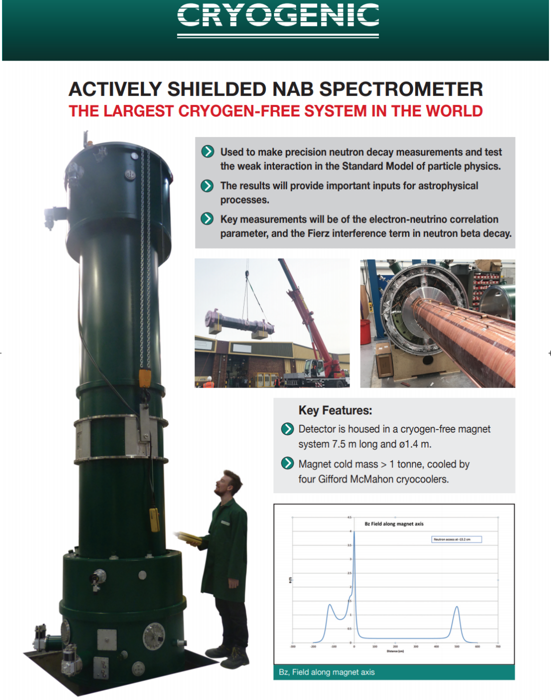
Spectrometer first mounted on the beamline in 2018



Shielding and stairs to upper detector in 2019

The Nab Ma

Spectrometer first n



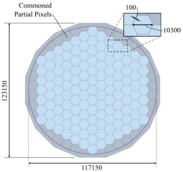
detector in 2019

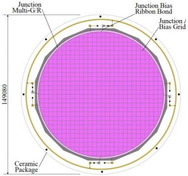
N_ab_ Si detectors: modeling and simulation

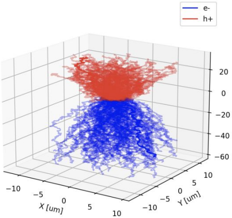
Precision pulse shape simulation for proton detection at the Nab experiment

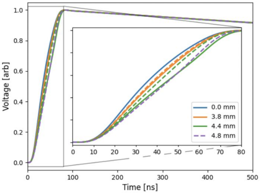
https://arxiv.org/abs/2212.03438

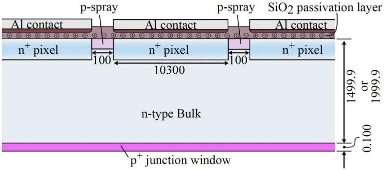
Leendert Hayen,[1,2,*] Jin Ha Choi,[1,2] Dustin Combs,[1,2] R.J. Taylor,[1,2] Stefan Baeßler,[3,4] Noah Birge,[5] Leah J. Broussard,[6,†] Christopher B. Crawford,[6] Nadia Fomin,[5] Michael Gericke,[7] Francisco Gonzalez,[3] Aaron Jezghani,[6] Nick Macsai,[7] Mark Makela,[8] David G. Mathews,[6] Russell Mammei,[9] Mark McCrea,[9] August Mendelsohn,[7] Austin Nelsen,[6] Grant Riley,[8] Tom Shelton,[6] Sky Sjue,[8] Erick Smith,[8] Albert R. Young,[1,2] and Bryan Zeck[1,2,8]







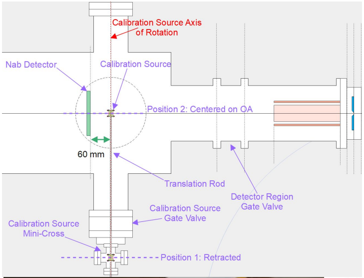




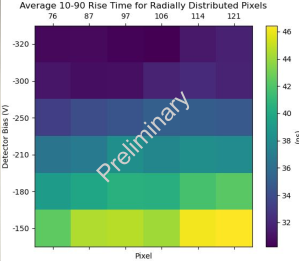
Full realistic detector model with

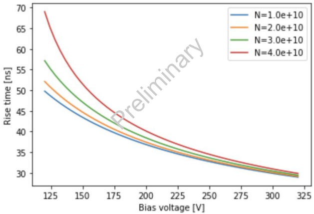
- Bulk profile and Junction and contact implantation.
- Charge carrier transport with pixel weighting potential, electric field profiles, impurity density.
- Carrier transport simulation with continuous interaction, drift and diffusion.
- Precision pulse shape simulation from geant4 and SRIM deposit ranges, SPICE.
- Detailed detector impurity density models

N*ab* Si detectors: Calibration Work at Manitoba



- A low energy (25 keV - 35 keV) proton source is used for detector testing
- An electro-static steerer directs proton trajectories onto pixel targets.
- A Cd-109 and Sn-113 calibration source package are used for energy calibration.
- Average waveform rise times imply radially decreasing density
  - Less impurities lead to weaker electric field for a fixed detector bias.

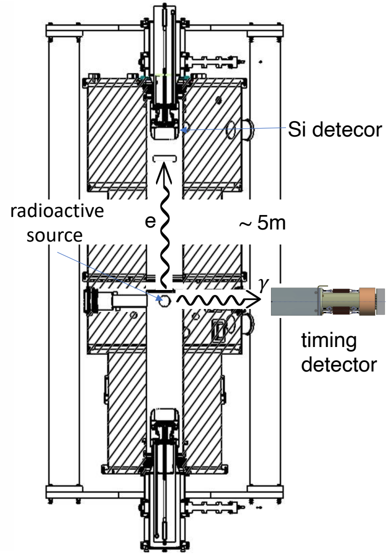




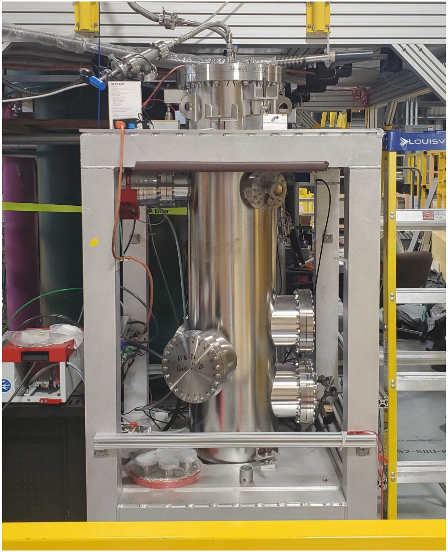
August Mendelsohn

Nab Experimental Detector Timing Calibrations

In-situ timing (EKU, ORNL)



Ex-situ test stand (ORNL)



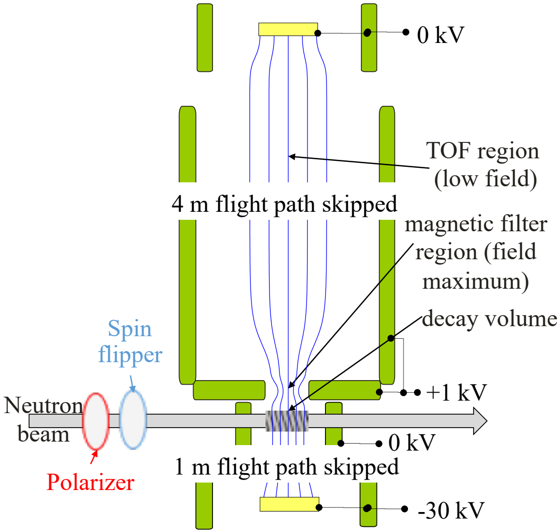
Updated Experimental schedule

- Early this year, magnet wasn't cooling as expected - cold heads serviced, x-ray radiography performed to "see" possible problematic features
- Manufacturer visited, identified possible places in which there could be a touch (loose tie rods, loose super insulation, or loose magnet coil cladding connects coils to warmer parts) or a thermal link that was not intended.

Cooling the magnet now to verify the fix and hopefully a full cooldown later in the summer followed by data taking

- **After cooldown, plan to take data this year through 2025**

Outlook - proposed pNab



Stefan Baessler

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- Different set of systematic errors! Well motivated by the CKM picture at the moment

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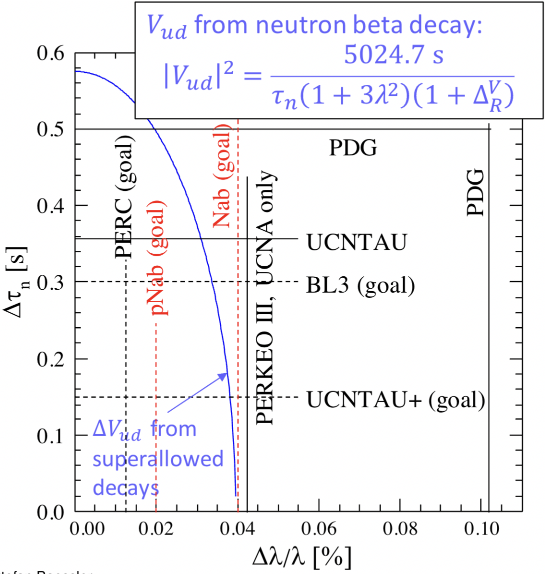

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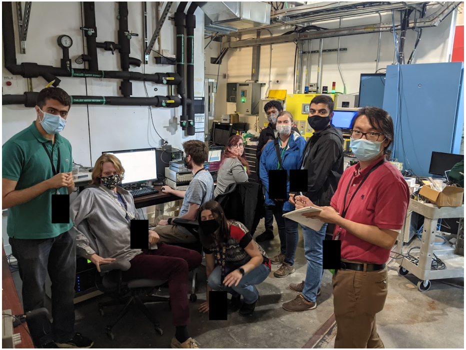
Nab Summary

- Nab offers an independent measurement of $\lambda = g_A/g_V$ with competitive precision, approaching superallowed decays
- Many collaboration efforts underway to pin down remaining systematic effects
- Calibrations underway, data taking and systematic studies through 2025



The Nab collaboration

Nab collaborating institutions:

Oak Ridge National Laboratory
Los Alamos National Laboratory
University of Virginia
The University of Tennessee Knoxville
Arizona State University
NC State University
Massachusetts Institute of Technology
UK University of Kentucky
University of Michigan
EKU Eastern Kentucky University
The University of Tennessee Chattanooga
University of Manitoba
The University of Winnipeg

University of South Carolina,
Universität Karlsruhe (TH),
Universidad Nacional Autónoma de México,
Western Kentucky University

Main project funding:

NSF
U.S. Department of Energy Office of Science
Oak Ridge National Laboratory
University of Virginia

Extras

How do we relate proton momentum p_p to time of flight t_p?

- Proton time of flight in B field:

$$t_p = L\frac{m_p}{p_p}, \quad \text{but...}$$

How do we relate proton momentum p_p to time of flight t_p?

- Proton time of flight in B field:

$$t_p = L\frac{m_p}{p_p}, \quad \text{but...}$$

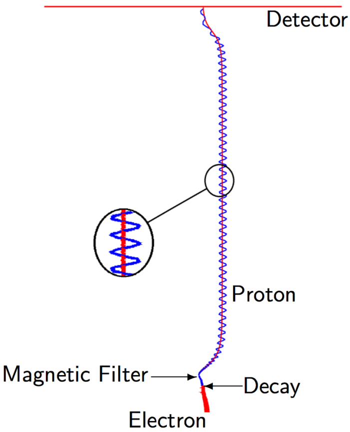
L depends on point at birth and the direction of momentum and field!

$$\cos\theta_{p,0} = \left.\frac{\vec{p}_{p0}\cdot\vec{B}}{p_{p0}B}\right|_{\text{decay pt.}} .$$

- For an adiabatically expanding field,

$$t_p = \frac{m_p}{p_p}\int_{z_0}^{l}\frac{dz}{\sqrt{1-\frac{B(z)}{B_0}\sin^2\theta_{p,0}+\frac{q(V(z)-V_0)}{E_{p0}}}}$$

Geant4 simulation:



One of our Analysis Strategies

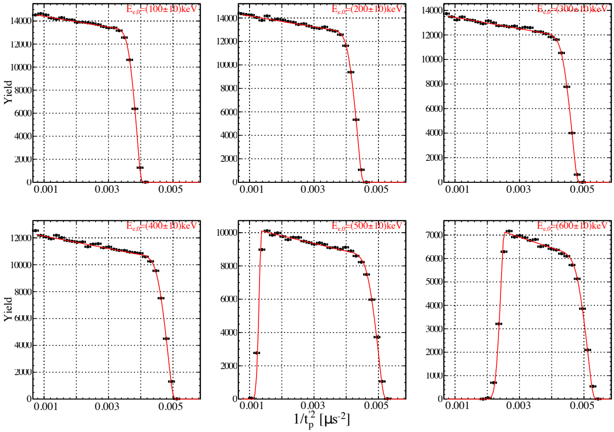
- Expand the integral into Taylor series parameters neglecting $\vec{E}$ contributions, and fit to these parameters using simulation and data
- put in corrections for $\vec{E}$ contributions in fitting parameters
- Knowing the field is **critical** to determining t_p and thus ***a***

$$p_p = \frac{m_p}{t_p} \int \frac{dz}{\sqrt{1 - \frac{B(z)}{B_0} sin^2(\theta_0)}}$$

$$= \frac{m_p}{t_p} \left[L - \eta \ln \frac{cos(\theta_0) - cos(\theta_0)_{min}}{1 - cos(\theta_0)_{min}} \right.$$

$$\left. + \alpha(1 - cos(\theta_0)) + \beta(1 - cos(\theta_0))^2 + \gamma(1 - cos(\theta_0))^3 \right]$$

One of our Analysis Strategies



- Checked using detailed GEANT4 simulations
- Use central part of trapeziums to extract ***a*** (slope!).

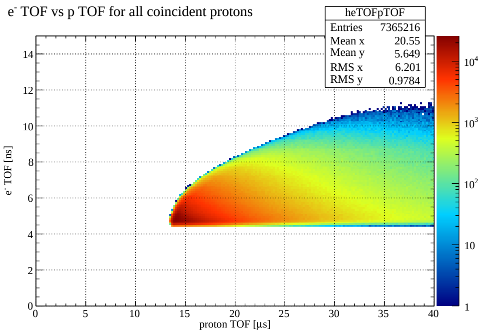
$$p_p = \frac{m_p}{t_p} \int \frac{dz}{\sqrt{1 - \frac{B(z)}{B_0} sin^2(\theta_0)}}$$

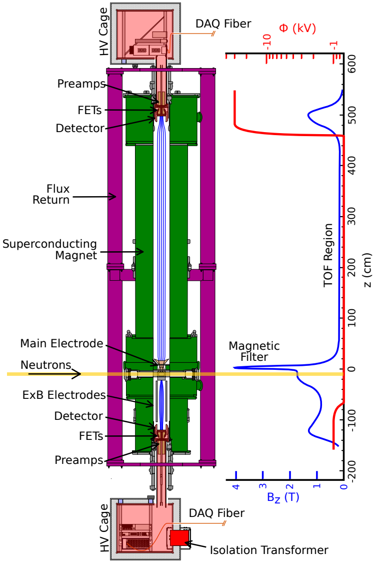
$$= \frac{m_p}{t_p} \left(L - \eta \ln \frac{cos(\theta_0) - cos(\theta_0)_{min}}{1 - cos(\theta_0)_{min}} + \alpha(1 - cos(\theta_0)) + \beta(1 - cos(\theta_0))^2 + \gamma(1 - cos(\theta_0)) \right.$$

N*ab* systematic uncertainties

Experimental parameter		$(\Delta a/a)_{\text{SYST}}$
Magnetic field:	curvature at pinch	5.3×10^{-4}
	ratio $r_B = B_{\text{TOF}}/B_0$	2.2×10^{-4}
	ratio $r_{B,DV} = B_{\text{DV}}/B_0$	1.8×10^{-4}
L_{TOF}, length of TOF region		fit parameter
U inhomogeneity:	in decay / filter region	5×10^{-4}
	in TOF region	2.2×10^{-4}
Neutron Beam:	position	1.7×10^{-4}
	width	2.5×10^{-4}
	Doppler effect	small
	unwanted beam polarization	1×10^{-4}
Adiabaticity of proton motion		1×10^{-4}
Detector effects:	E_e calibration	2×10^{-4}
	shape of E_e response	4.4×10^{-4}
	Proton trigger efficiency	3.4×10^{-4}
	TOF shift (Δt_p)	3×10^{-4}
TOF in acceleration region	$r_{\text{electrodes}}$ (prelim)	3×10^{-4}
electron TOF	analytic correction	small
Accidental coincidences/Background		small
Residual gas	$P < 2 \times 10^{-9}$ (prelim)	3.8×10^{-4}
Sum		1.2×10^{-3}

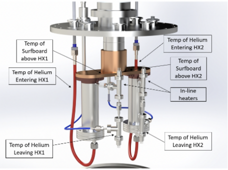
- The Nab spectrometer designed to measure both the electron energy E_e and proton the proton TOF (t_p).
- At **1.4** MW SNS beam power there will be ∼1600 decays/s, or ∼**200** p/s in upper detector.



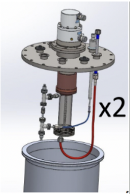


Detector Cooling updates

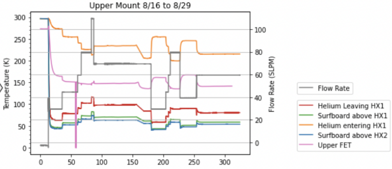
Helium circulating detector cooling system update:



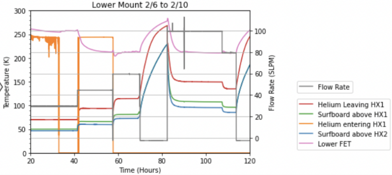
Previously, one cold head serviced both loops (upper and lower) (left). Now working on splitting the system to have a designated cold head for each (right).



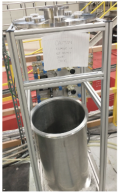
Upper mount FET min temp reached ~140K



Lower mount FET min temp reached ~210K (Room temp magnet)

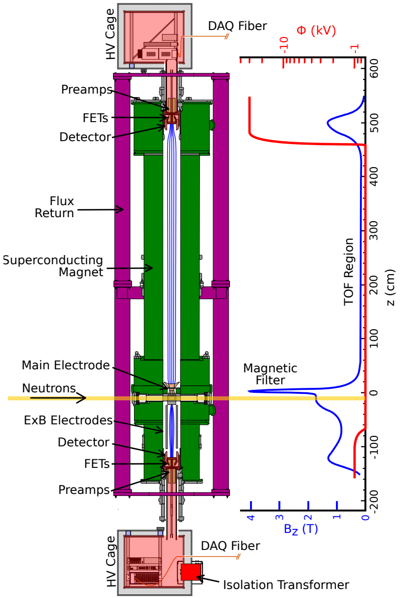


The first cold head is transitioned to servicing only one loop (left).

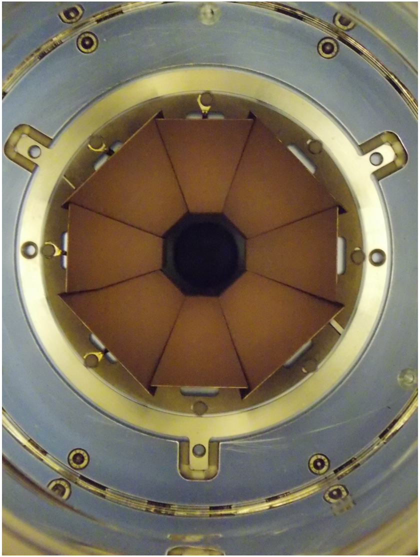


The stand for the second cold head is installed (right).

Electrode Installation

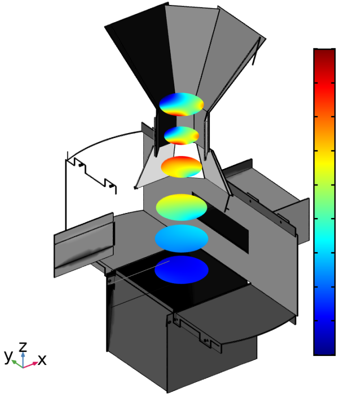


Installed 2020



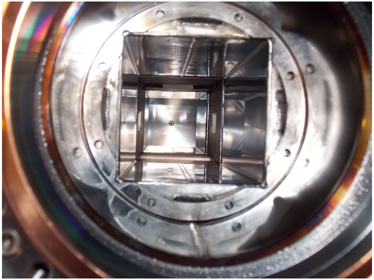
Electrode Installation

Uniform electrostatic potential is needed to reconstruct p_p from t_p! knowledge of potential difference between the decay volume and filter to 10 mV $\rightarrow$ fulfilled!

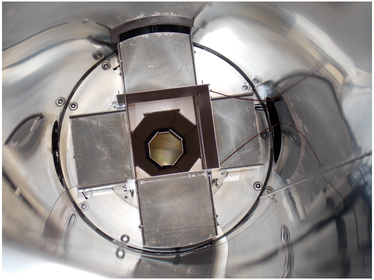


PRELIMINARY

Beam view



Bottom view



Activities in the next couple years

- beam polarization
- more detector characterization with radioactive sources
- Electron energy response (tail, $\Delta E \sim$ few 100 eV),
- proton detection efficiency (variation < 100 ppm/keV) ,
- timing response (Δt_p $\Delta t_e < 0.3$ ns)
- Parallel work on cooling system upgrade, two Faraday cages, Electronics redesign, 3rd mount