The Nab Experiment: Examining Unpolarized Neutron Beta Decay Correlations

Jason Fry, for the Nab Collaboration

Department of Physics, Geosciences, and Astronomy,
Eastern Kentucky University

EKU

October 13, 2021

APS DNP 2021 Meeting

OAK RIDGE
National Laboratory

See talks D. Mathews ML00002, L. Christie ML00003, M. Gervais ML00004 next!

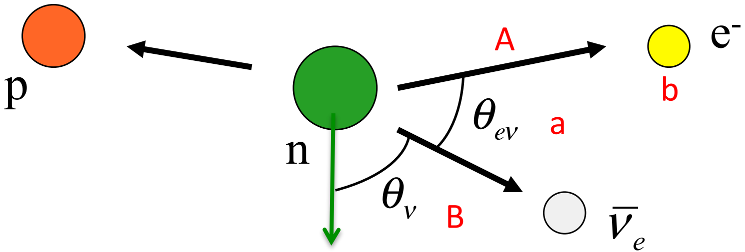
The Nab Collaboration

R. Alarcon[a], A. Atencio[k], S.Baeßler[b,c] (Project Manager), S. Balascuta, L. Barrón Palos[n], T.L. Bailey[m], K. Bass[i], N. Birge[i,k], A. Blose[f], D. Borissenko[b], M. Bowler[b], J.D. Bowman[c] (Co-Spokesperson), L. Broussard[c], A.T. Bryant[b], J. Byrne[d], J.R. Calarco[c,i], J. Choi[m], J. Caylor[i], L. Christie[i], T. Chupp[o], T.V. Cianciolo[c], C.B. Crawford[f], M. Cruz[i], X. Ding[b], George Dodson[s], W. Fan[b], W. Farrar[b], N. Fomin[i], E. Frlež[b], J. Fry[q], M.T. Gericke[g], M. Gervais[f], C. Gilbert[c], F. Glück[h], R. Godri[i], F. Gonzalez[c], G.L. Greene[c,i], R.K. Grzywacz[i], V. Gudkov[j], J. Hamblen[e], L. Hayen[m], C. Hayes[m], C. Hendrus[o], K. Imam[i], T. Ito[k], A. Jezghani[f], H. Li[b], M. Makela[k], N. Macsai[g], J. Mammei[g], R. Mammei[l], M. Martinez[a], D.G. Mathews[f], M. McCrea[f], P. McGaughey[k], C.D. McLaughlin[b], J. Mirabal-Martinez[k], P.E. Mueller[c], A. Nelsen[f], I. Novikov[p], D. van Petten[b], S.I. Penttilä[c] (On-site Manager), D.E. Perryman[i], J. Pierce[r], D. Počanić[b] (Co-Spokesperson), H. Presley[i] , Yu Qian[b], J. Ramsey[c], G. Randall[a], G. Riley[i,k], K.P. Rykaczewski[c], A. Salas-Bacci[b], S. Samiei[b], A. Saunders[c], E.M. Scott[i], T. Shelton[f], S.K. Sjue[k], A. Smith[b], E. Smith[k], E. Stevens[b], L. Tinius[b] , J. Thomison[c], J.W. Wexler[m], R. Whitehead[i], W.S. Wilburn[k], A.R. Young[m], B.Zeck[m], M. Zemke[i]

[a] Arizona State University, Tempe, AZ 85287-1504
[b] University of Virginia, Charlottesville, VA 22904-4714
[c] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
[d] University of Sussex, Brighton BN19RH, UK
[e] University of Tennessee at Chattanooga, Chattanooga, TN 37403
[f] University of Kentucky, Lexington, KY 40506
[g] University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada
[h] KIT, Universität Karlsruhe (TH), Kaiserstraße 12, 76131 Karlsruhe, Germany
[i] University of Tennessee, Knoxville, TN 37996
[j] University of South Carolina, Columbia, SC 29208
[k] Los Alamos National Laboratory, Los Alamos, NM 87545
[l] University of Winnipeg, Winnipeg, Manitoba R3B2E9, Canada
[m] North Carolina State University, Raleigh, NC 27695-8202
[n] Universidad Nacional Autónoma de México, México, D.F. 04510, México
[o] University of Michigan, Ann Arbor, MI 48109
[p] Western Kentucky University, Bowling Greene, KY
[q] Eastern Kentucky University, Richmond, KY 40475
[r] Neutron Technologies Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
[s] Massachusetts Institute of Technology, Cambridge, MA 02139

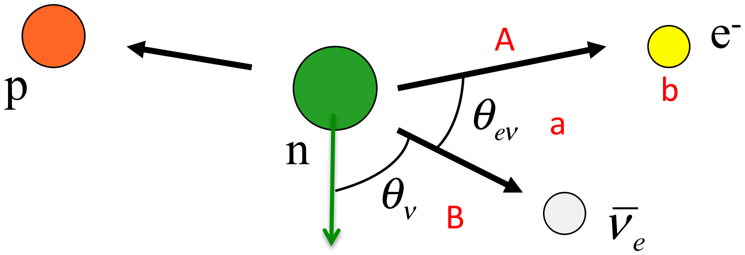
Main Project Funding:

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**)
  - **Sensitively tests the standard model!** Is there additional physics?
  - Different correlations provide multiple checks with different systematics
- Correlations are all related to a single parameter in the SM: $\lambda = \frac{G_A}{G_V}$

Neutron Beta Decay Correlations



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

CKM Matrix (**strength of the flavor-changing weak interaction**):

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

Free neutron beta decay rate

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

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

where in SM:

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

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

Free neutron beta decay rate

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

Un-polarized

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

where in SM:

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

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

Free neutron beta decay rate

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

Un-polarized

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

where in SM:

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

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

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

Free neutron beta decay rate

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

Un-polarized

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

where in SM:

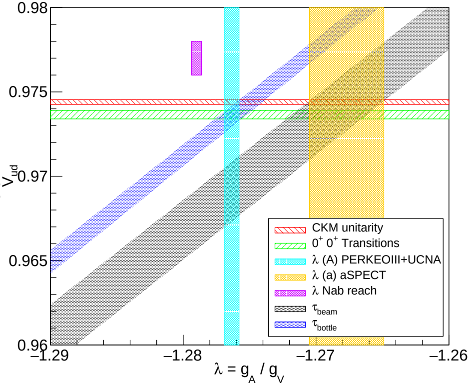
$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2\frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}$$

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

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

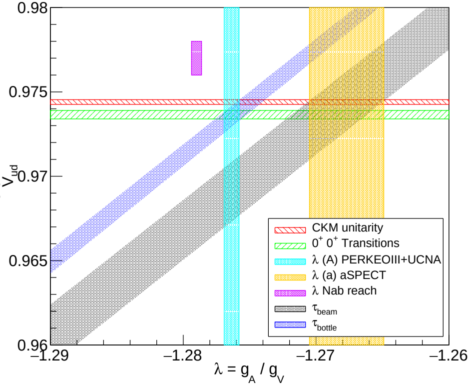
- Measurements of a, A, B contain different systematics, independent determinations of λ
- Fierz interf. term b adds sensitivity to non-SM processes! (b = 0 in SM)

- Data + new 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 $\Delta b \simeq 3\times10^{-3}$



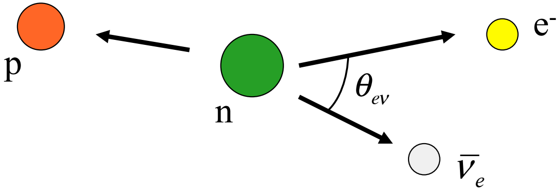
Status of λ and V_{ud} in n decay: CKM Unitarity?

- Data + new 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 $\Delta b \simeq 3 \times 10^{-3}$



- 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 $\Rightarrow$ several independent $\sim 0.03\%$ determinations of λ

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



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

- Conservation of momentum in **n** beta decay results in:

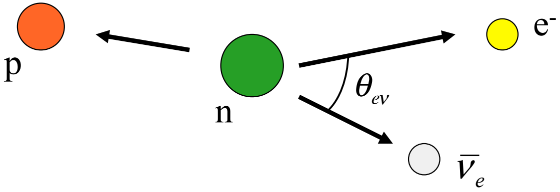
$$\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0\,, \qquad p_p^2 = p_e^2 + 2p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

- Neglecting proton recoil energy, $E_e + E_\nu = E_0$, we can see

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

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

Nab: How do we determine "a"?



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

- Conservation of momentum in **n** beta decay results in:

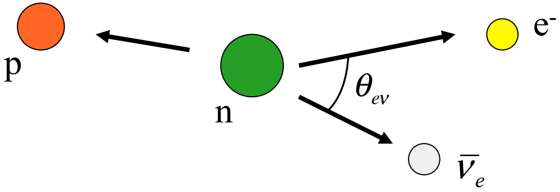
$$\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0\,, \quad p_p^2 = p_e^2 + 2p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

- Neglecting proton recoil energy, $E_e + E_\nu = E_0$, we can see

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

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

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



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

- Conservation of momentum in **n** beta decay results in:

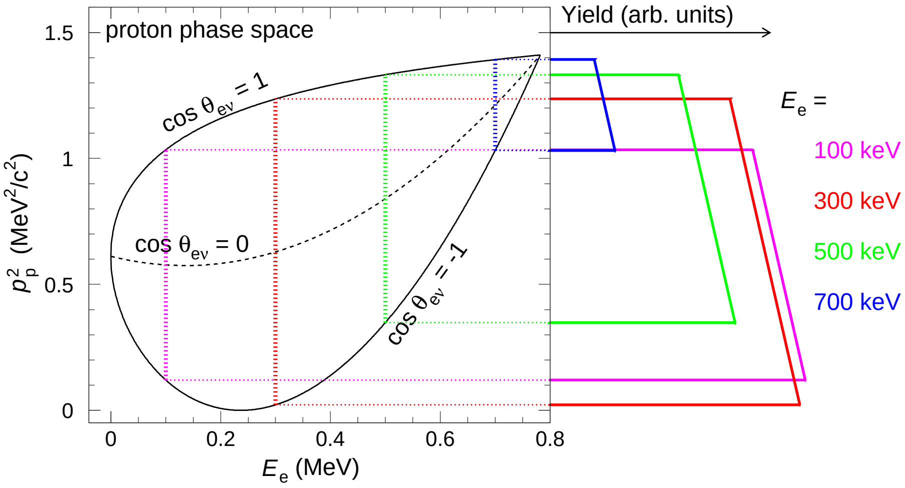
$$\vec{p}_{\rm p} + \vec{p}_{\rm e} + \vec{p}_{\nu} = 0\,, \quad p_{\rm p}^2 = p_{\rm e}^2 + 2p_{\rm e}p_{\nu}\cos\theta_{e\nu} + p_{\nu}^2\,.$$

- Neglecting proton recoil energy, $E_{\rm e} + E_{\nu} = E_0$, we can see

$$\cos\theta_{e\nu} = \frac{1}{2}\left[\frac{p_{\rm p}^2 - (2E_{\rm e}^2 + E_0^2 - 2E_0E_{\rm e})}{E_{\rm e}(E_0 - E_{\rm e})}\right]\,.$$

$\cos\theta_{e\nu}$ is uniquely determined by measuring $E_{\rm e}$ and $p_{\rm p}$.

Neutron beta decay phase space: determination of *a*

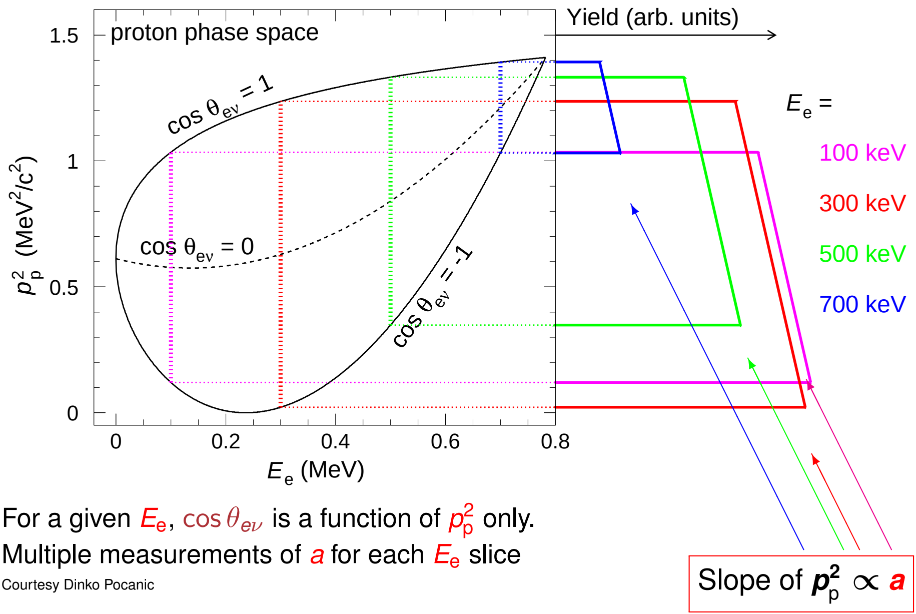


For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

Multiple measurements of *a* for each E_e slice

Courtesy Dinko Pocanic

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

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 $\rightarrow E_{\mathrm{e}}$
- Detect protons, **after acceleration**, in upper Si detectors $\rightarrow t_{\mathrm{p}}$ determine p_{p}

N*ab* spectrometer and measurement

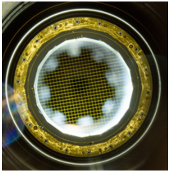
- **In order to extract p_p practically within N*ab*, we use a long spectrometer that measures t_p to determine p_p**
- Detect electrons directly, in upper or lower Si detector $\rightarrow E_\mathrm{e}$
- Detect protons, **after acceleration**, in upper Si detectors $\rightarrow t_\mathrm{p}$ determine p_p

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

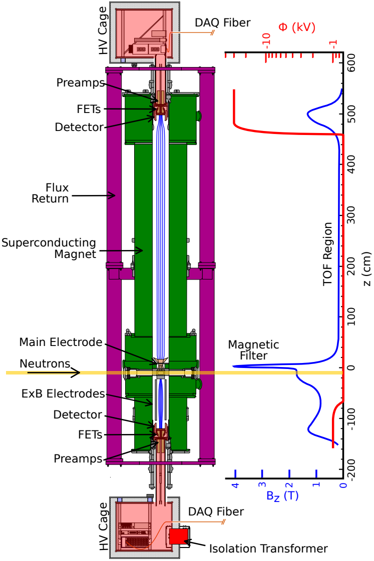
N*ab* spectrometer and measurement

- **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

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



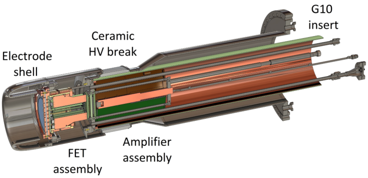
David Mathews



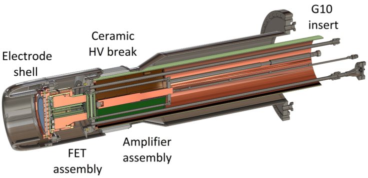
Aaron Jezghani

N*ab* spectrometer and measurement: Si detectors

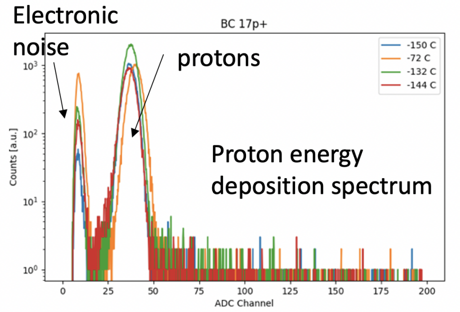
- 15 cm diameter, full thickness: 2 mm
- 127 pixels, dead layer $\lesssim$100 nm
- Energy resolution a few keV, 10 keV proton threshold

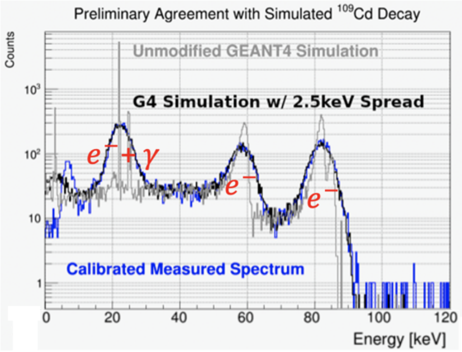


- 15 cm diameter, full thickness: 2 mm
- 127 pixels, dead layer $\leq$100 nm
- Energy resolution a few keV, 10 keV proton threshold



Initial protons and radioactive source data at University of Manitoba



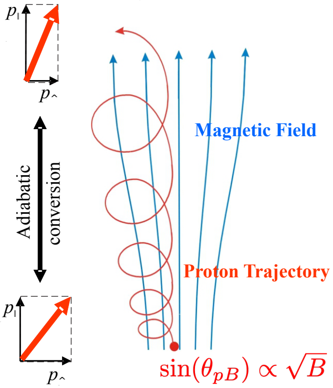


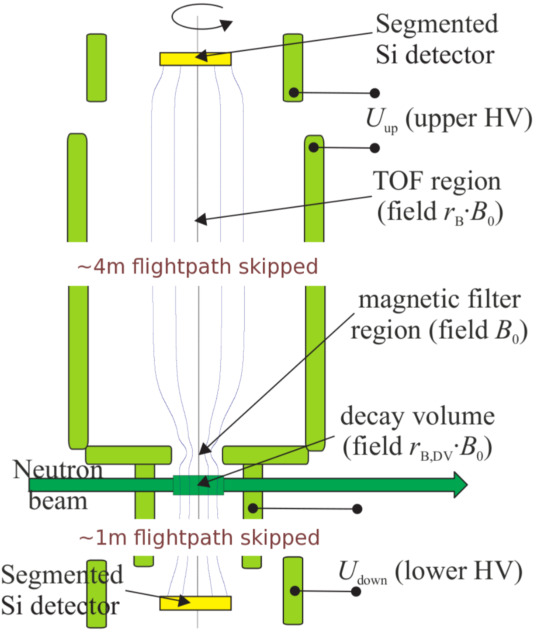
Jin Ha Choi, Leendert Hayen, Nick Macsi, David Mathews, Leah Broussard, others!

See D. Mathews' and L. Christie's talk next!

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

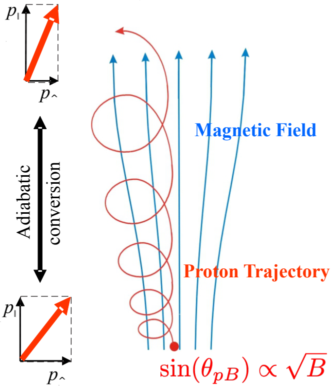
A strong magnetic filter accepts protons with a narrow upward cone $\cos(\theta_{0,min}) > 0.7$

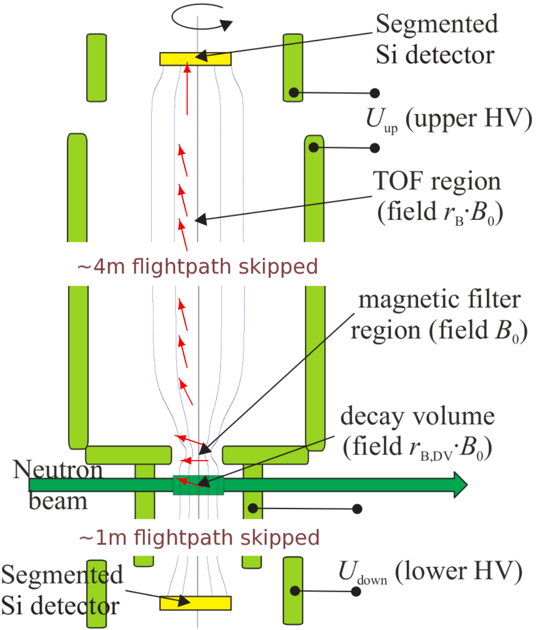




How do we collect low energy protons? Max energy 800 eV

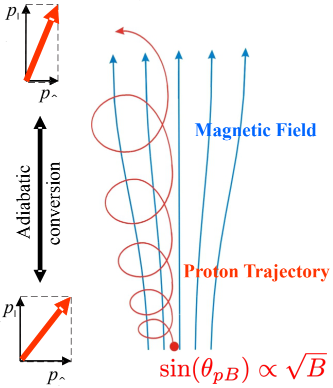
A strong magnetic filter accepts protons with a narrow upward cone $\cos(\theta_{0,min}) > 0.7$



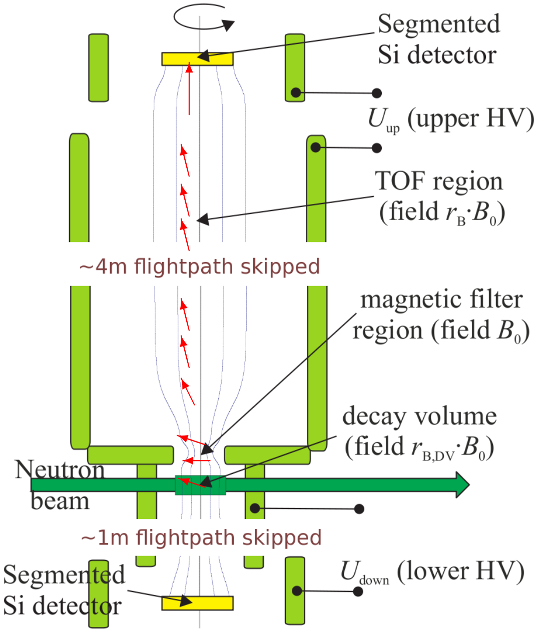


How do we collect low energy protons? Max energy 800 eV

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



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



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:

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

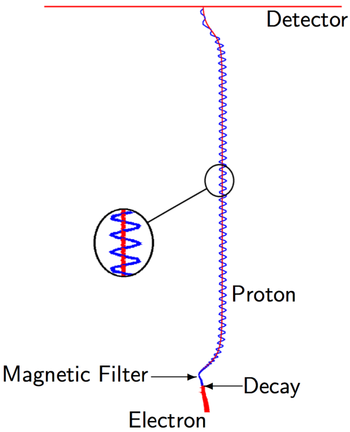
L depends on point at birth and the direction of momentum and field!

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

- For an adiabatically expanding field,

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

Geant4 simulation:

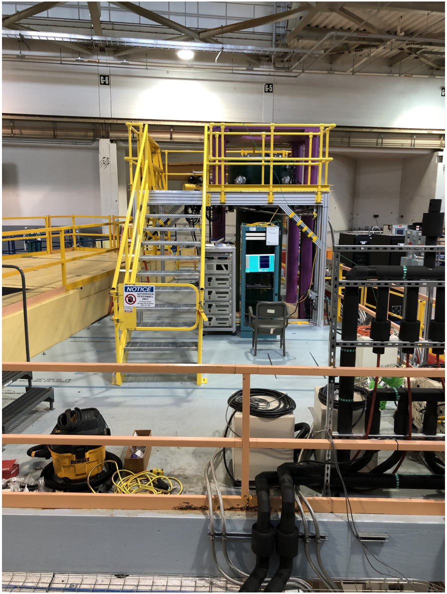


N*ab* systematic uncertainties

Experimental parameter		$(\Delta a/a)_{\mathrm{SYST}}$
Magnetic field:	curvature at pinch	5.3×10^{-4}
	ratio $r_B = B_{\mathrm{TOF}}/B_0$	2.2×10^{-4}
	ratio $r_{B,DV} = B_{DV}/B_0$	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	$r_{\mathrm{electrodes}}$ (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}

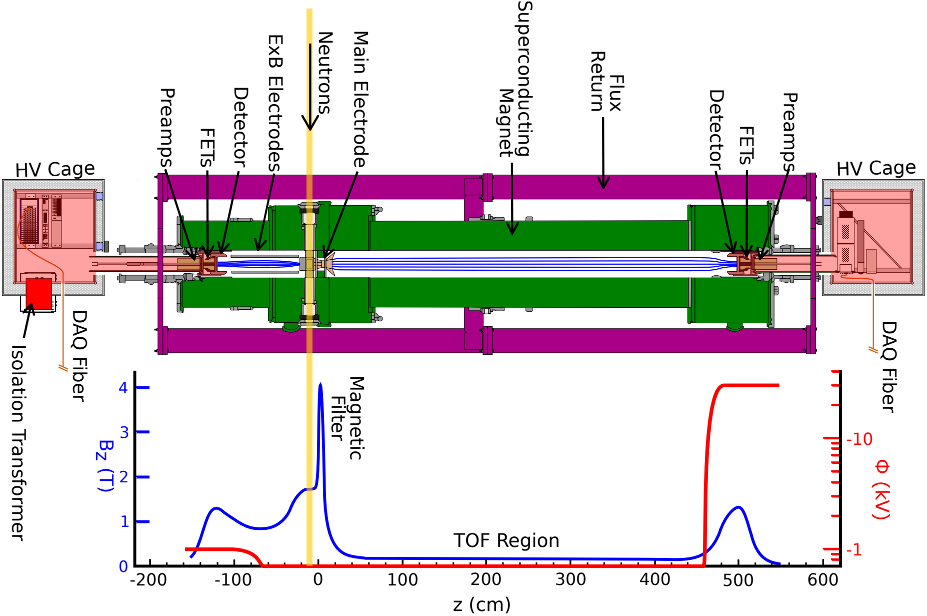
The *Nab* Magnet on the FNPB at the SNS

Spectrometer first mounted on the beamline in 2018

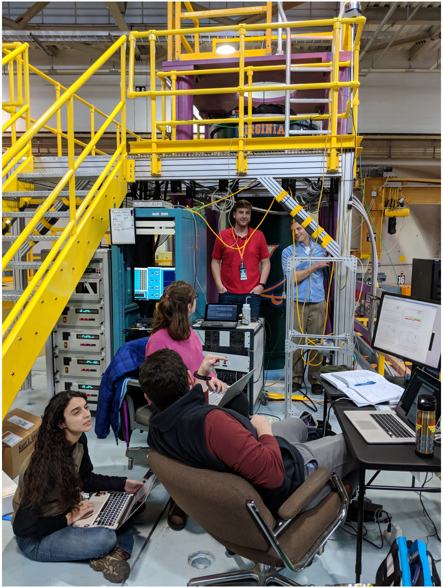


Shielding and stairs to upper detector in 2019

Nab Spectrometer Magnet

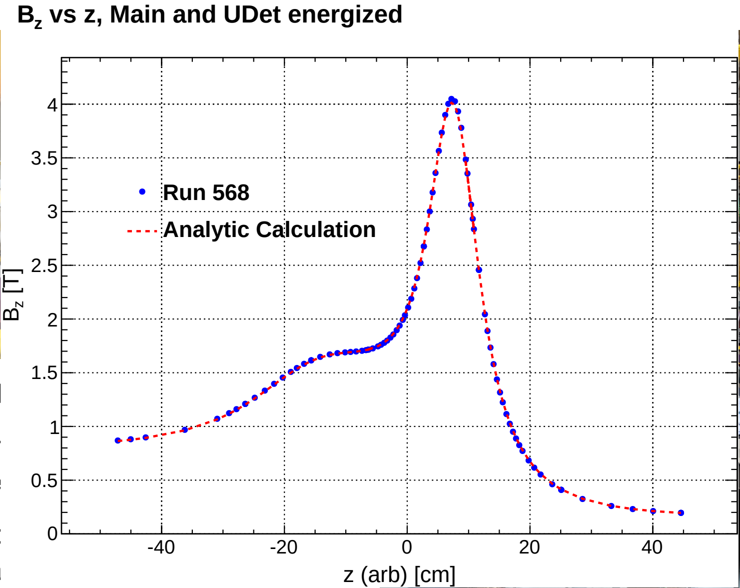


Magnet has been characterized



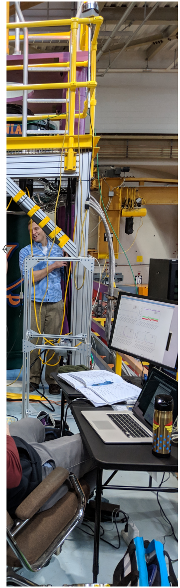
- Stability and Hysteresis
- A mode to operate the field has been established
- Modest requirement of $<1\times10^{-3}$ relative change in the magnetic field over time

Magnet has been characterized



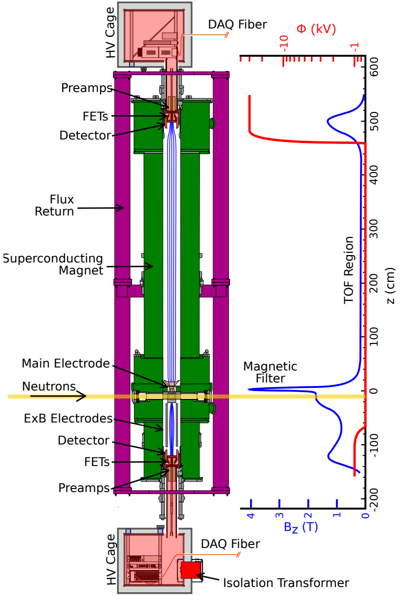
- Stal
- A m
  bee
- Moc
  rela
  field over time

Magnet has

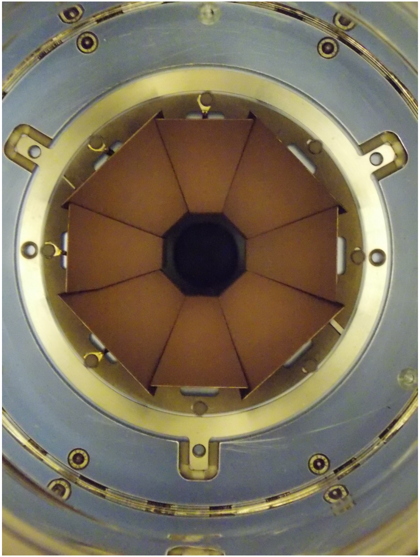


- Stability anc
- A mode to c been establ
- Modest requ relative cha field over tir

Electrode Installation

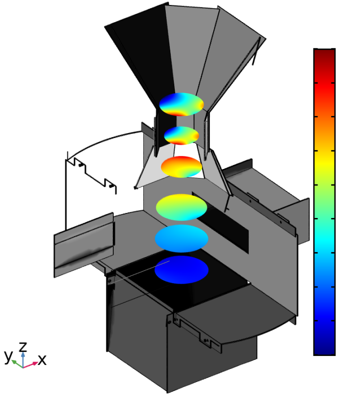


Installed 2020



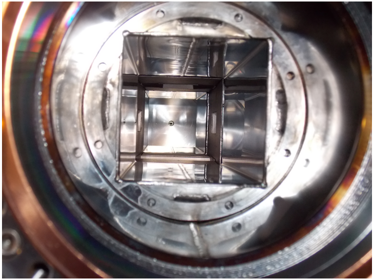
Electrode Installation

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!

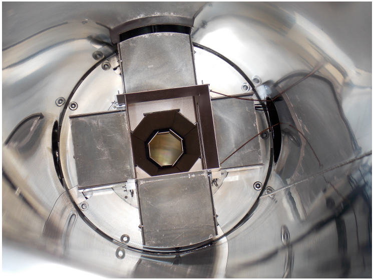


PRELIMINARY

Beam view



Bottom view

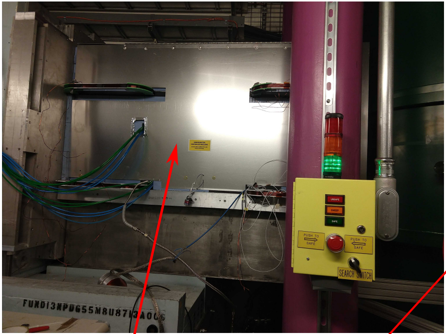


Detector Installation

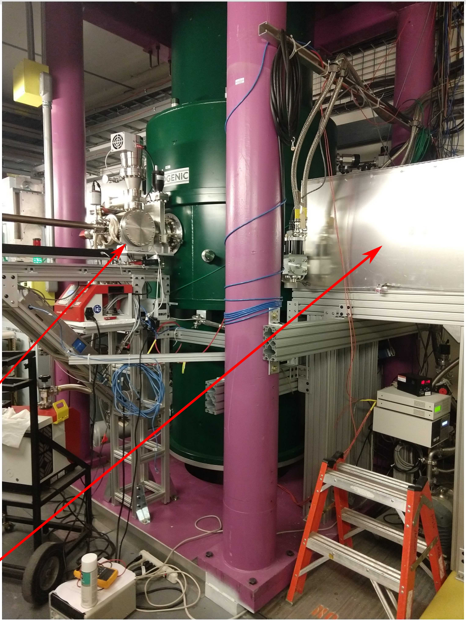
Successful ramp to 30 kV late August!

HV box and upper detector mount installed installed

Beamline Installation



spin flipper

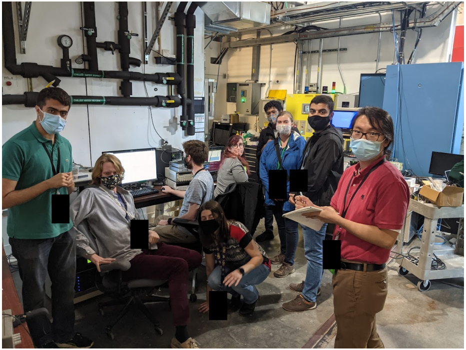


radioactive source insertion system

get lost tube

Nab Summary

- Nab offers an independent measurement of $\lambda = g_A/g_V$ with competitive precision
- **Commissioning underway**, systematic studies and production next
- See ML.00002 (D. Mathews), ML.00003 (L, Christie), ML.00004 (M. Gervais) next!



The Nab Collaboration

R. Alarcon[a], A. Atencio[k], S.Baeßler[b,c] (Project Manager), S. Balascuta, L. Barrón Palos[n], T.L. Bailey[m], K. Bass[i], N. Birge[i,k], A. Blose[f], D. Borissenko[b], M. Bowler[b], J.D. Bowman[c] (Co-Spokesperson), L. Broussard[c], A.T. Bryant[b], J. Byrne[d], J.R. Calarco[c,i], J. Choi[m], J. Caylor[i], L. Christie[i], T. Chupp[o], T.V. Cianciolo[c], C.B. Crawford[f], M. Cruz[i], X. Ding[b], George Dodson[s], W. Fan[b], W. Farrar[b], N. Fomin[i], E. Frlež[b], J. Fry[q], M.T. Gericke[g], M. Gervais[f], **C. Gilbert**[c], F. Glück[h], R. Godri[i], F. Gonzalez[c], G.L. Greene[c,i], R.K. Grzywacz[i], V. Gudkov[j], J. Hamblen[e], L. Hayen[m], C. Hayes[m], C. Hendrus[o], K. Imam[i], T. Ito[k], A. Jezghani[f], H. Li[b], M. Makela[k], N. Macsai[g], J. Mammei[g], R. Mammei[l], M. Martinez[a], D.G. Mathews[f], M. McCrea[f], P. McGaughey[k], C.D. McLaughlin[b], **J. Mirabal-Martinez**[k], P.E. Mueller[c], A. Nelsen[f], I. Novikov[p], D. van Petten[b], S.I. Penttilä[c] (On-site Manager), D.E. Perryman[i], J. Pierce[r], D. Počanić[b] (Co-Spokesperson), H. Presley[i] , Yu Qian[b], **J. Ramsey**[c], G. Randall[a], G. Riley[i,k], K.P. Rykaczewski[c], A. Salas-Bacci[b], S. Samiei[b], A. Saunders[c], E.M. Scott[i], T. Shelton[f], S.K. Sjue[k], A. Smith[b], E. Smith[k], E. Stevens[b], L. Tinius[b] , **J. Thomison**[c], J.W. Wexler[m], R. Whitehead[i], W.S. Wilburn[k], A.R. Young[m], B.Zeck[m], M. Zemke[i]

[a] Arizona State University, Tempe, AZ 85287-1504
[b] University of Virginia, Charlottesville, VA 22904-4714
[c] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
[d] University of Sussex, Brighton BN19RH, UK
[e] University of Tennessee at Chattanooga, Chattanooga, TN 37403
[f] University of Kentucky, Lexington, KY 40506
[g] University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada
[h] KIT, Universität Karlsruhe (TH), Kaiserstraße 12, 76131 Karlsruhe, Germany
[i] University of Tennessee, Knoxville, TN 37996
[j] University of South Carolina, Columbia, SC 29208
[k] Los Alamos National Laboratory, Los Alamos, NM 87545
[l] University of Winnipeg, Winnipeg, Manitoba R3B2E9, Canada
[m] North Carolina State University, Raleigh, NC 27695-8202
[n] Universidad Nacional Autónoma de México, México, D.F. 04510, México
[o] University of Michigan, Ann Arbor, MI 48109
[p] Western Kentucky University, Bowling Greene, KY
[q] Eastern Kentucky University, Richmond, KY 40475
[r] Neutron Technologies Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
[s] Massachusetts Institute of Technology, Cambridge, MA 02139

Main Project Funding:

U.S. DEPARTMENT OF ENERGY Office of Science

OAK RIDGE National Laboratory

UNIVERSITY of VIRGINIA