The Nab Experiment: A Precision Measurement of Unpolarized Neutron Beta Decay

Jason Fry, For the Nab Collaboration

Institute of Nuclear and Particle Physics, University of Virginia

May 26, 2018

International Workshop on Particle Physics at Neutron Sources 2018

Free neutron beta decay

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

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

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

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

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

where in SM:

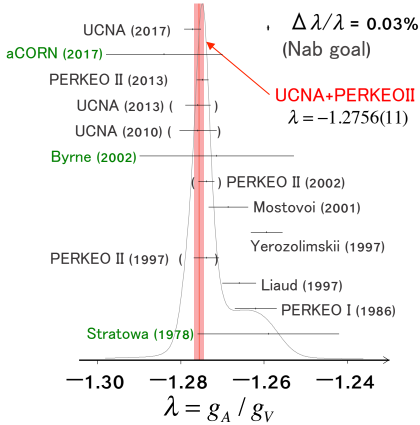
$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2 \frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}$$

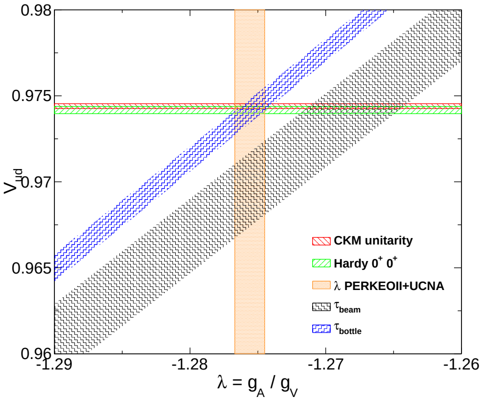
$$B = 2 \frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2} \qquad \lambda = \frac{G_A}{G_V} \text{ (with } \tau_n \Rightarrow \text{CKM } V_{ud}\text{)}$$

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

⇒ Determining *a*, *A*, *B* observables in n beta decay **overconstrains** SM!
Fierz interf. term *b* adds sensitivity to non-SM processes! (*b* = 0 in SM)

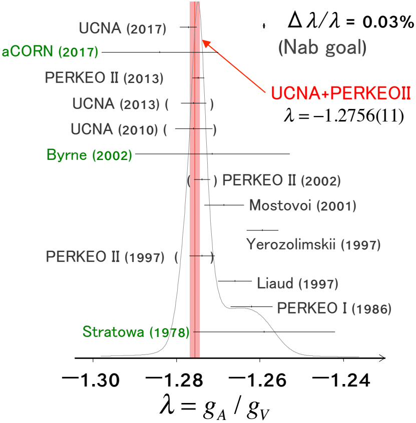
Status of λ and V_{ud} in n decay

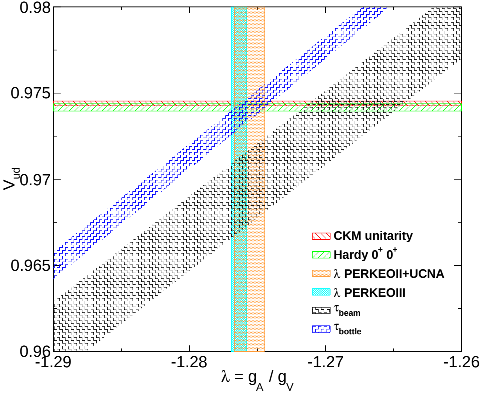




- Independent measurements of λ are necessary in order to entangle V_{ud} from the neutron lifetime, $1/\tau_n \propto |V_{ud}|^2 |g_V|^2 G_F^2 (1 + 3|\lambda|^2)$
- **N***ab*+ABba/PANDA $\Rightarrow$ several independent $\sim$ 0.03% determinations of λ, resolve current conflicts (as well as at least $\Delta\tau_n \sim 0.3$ s for V_{ud})

Status of λ and V_{ud} in n decay





- 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*+ABba/PANDA $\Rightarrow$ several independent $\sim$ 0.03% determinations of λ, resolve current conflicts (as well as at least $\Delta\tau_n \sim 0.3$ s for V_{ud})

Goals of the **N***ab* experiment (at SNS, ORNL)

- Measure the electron-neutrino parameter ***a*** in neutron decay

with precision of $\boxed{\frac{\Delta a}{a} \simeq 10^{-3}}$

current results:

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

Goals of the **N***ab* experiment (at SNS, ORNL)

- Measure the electron-neutrino parameter ***a*** in neutron decay

with precision of $\boxed{\frac{\Delta a}{a} \simeq 10^{-3}}$

current results: -0.1090 ± 0.0041 Darius et al, 2017 (aCORN)

-0.1054 ± 0.0055 Byrne et al, 2002

- Measure the Fierz interference term ***b*** in neutron decay

with accuracy of $\boxed{\Delta b \simeq 3 \times 10^{-3}}$

current results: $0.067^{+0.091}_{-0.061}$ Hickerson et al, 2017 (UCNA)

Goals of the **N***ab* experiment (at SNS, ORNL)

- Measure the electron-neutrino parameter ***a*** in neutron decay

  with precision of $\boxed{\frac{\Delta a}{a} \simeq 10^{-3}}$

  current results: -0.1090 ± 0.0041 Darius et al, 2017 (aCORN)
  -0.1054 ± 0.0055 Byrne et al, 2002

- Measure the Fierz interference term ***b*** in neutron decay

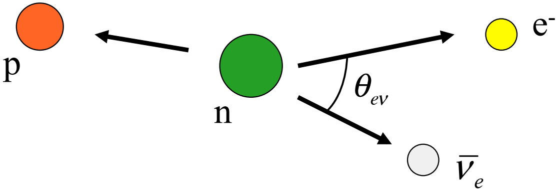
  with accuracy of $\boxed{\Delta b \simeq 3 \times 10^{-3}}$

  current results: $0.067^{+0.091}_{-0.061}$ Hickerson et al, 2017 (UCNA)

Motivation:

- multiple independent determinations of λ (test of CKM unitarity),
- independent and competitive limits on S, T currents (BSM).

Extracting $\cos\theta_{e\nu}$ $\left(\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu}\right)$ from E_e and $p_p \Rightarrow t_p(\mathrm{TOF}_p)$



$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \propto \left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \dots\right]$$

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

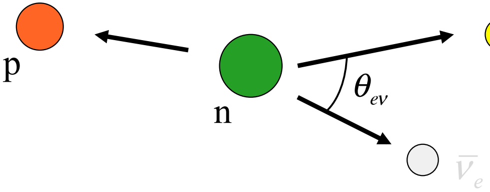
$$\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0\,, \qquad p_p^2 = p_e^2 + 2p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

- Neglecting proton recoil energy, $E_e + E_\nu = E_0$, so that $p_\nu = E_0 - E_e$. This yields

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

$\cos\theta_{e\nu}$ is uniquely determined by measuring E_e and $p_p \Rightarrow t_p(\mathrm{TOF}_p)$.

Extracting $\cos\theta_{e\nu}$ $(\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu})$ from E_e and $p_p \Rightarrow t_p(\mathrm{TOF}_p)$



$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \propto \left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \ldots\right]$$

- Conservation of momentum in n beta decay results in:

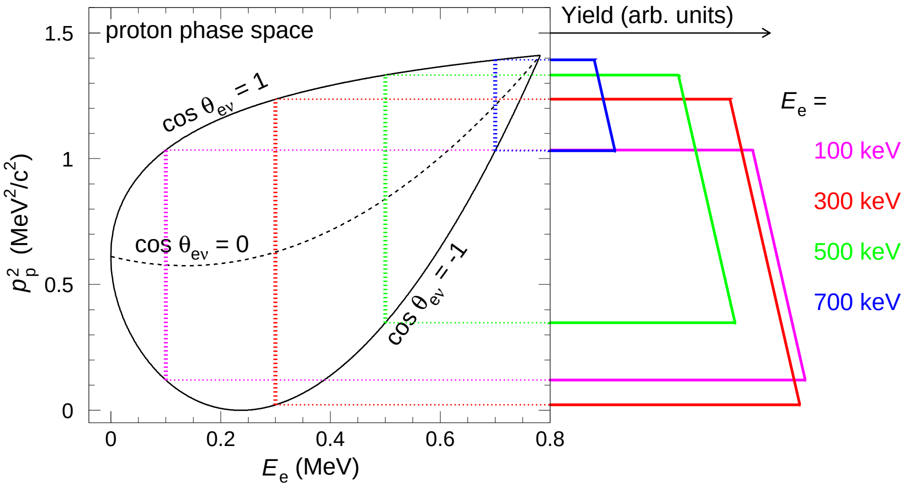
$$\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0\,, \qquad p_p^2 = p_e^2 + 2p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

- Neglecting proton recoil energy, $E_e + E_\nu = E_0$, so that $p_\nu = E_0 - E_e$. This yields

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

$\cos\theta_{e\nu}$ is uniquely determined by measuring E_e and $p_p \Rightarrow t_p(\mathrm{TOF}_p)$.

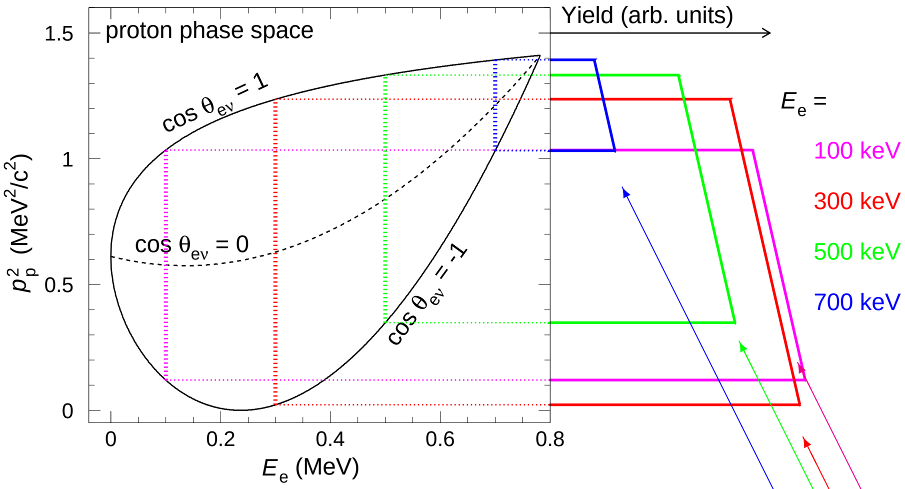
Proton phase space: determination of *a*



For a given E_e, $\cos\theta_{e\nu}$ is a function of $p_p^2 \propto 1/t_p^2$ only.

Multiple measurements of *a* for each E_e slice

Proton phase space: determination of *a*



For a given E_e, $\cos\theta_{e\nu}$ is a function of $p_p^2 \propto 1/t_p^2$ only.

Multiple measurements of *a* for each E_e slice

Slope of $\mathbf{1/t_p^2} \propto \boldsymbol{a}$

How to accomplish the goals of **N***ab*?

$$\boxed{\text{Measure: } \frac{\Delta a}{a} \simeq 10^{-3} \text{ and } \Delta b \simeq 3 \times 10^{-3}}$$

How to accomplish the goals of **N**ab?

$$\boxed{\text{Measure: } \frac{\Delta a}{a} \simeq 10^{-3} \text{ and } \Delta b \simeq 3 \times 10^{-3}}$$

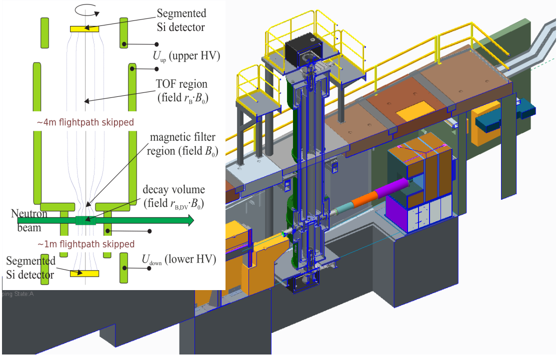
- Detect electrons directly, in Si detectors → E_e
- Detect protons, after acceleration, in Si detectors → determine $p_p \rightarrow t_p(\mathrm{TOF}_p)$

How to accomplish the goals of **N***ab*?

Measure: $\frac{\Delta a}{a} \simeq 10^{-3}$ and $\Delta b \simeq 3 \times 10^{-3}$

- Detect electrons directly, in Si detectors → E_e
- Detect protons, after acceleration, in Si detectors → determine $p_p \rightarrow t_p(\mathrm{TOF}_p)$

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



FnPB at SNS

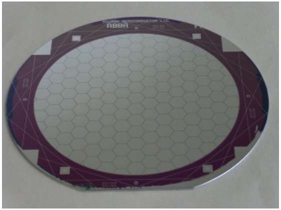
How to accomplish the goals of **N***ab*?

$$\boxed{\text{Measure: } \frac{\Delta a}{a} \simeq 10^{-3} \text{ and } \Delta b \simeq 3 \times 10^{-3}}$$

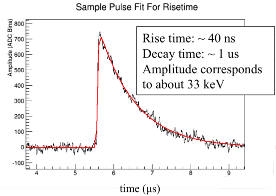
- Detect electrons directly, in Si detectors → E_e
- Detect protons, after acceleration, in Si detectors → determine $p_p \rightarrow t_p(\mathrm{TOF}_p)$

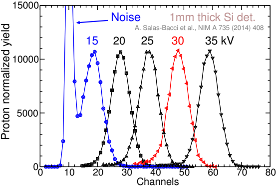
Si Detectors:

- 15 cm diameter
- full thickness: 2 mm
- dead layer ≤100 nm
- 127 pixels



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

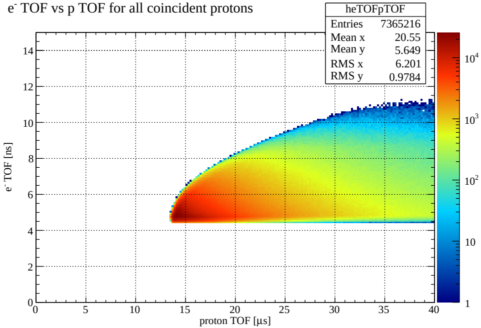


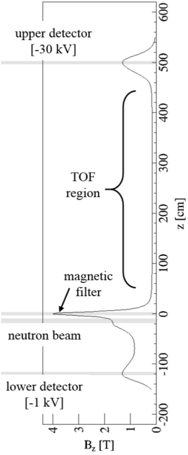


A. Salas-Bacci et al., NIM A 735 (2014) 408

N*ab* spectrometer and measurement

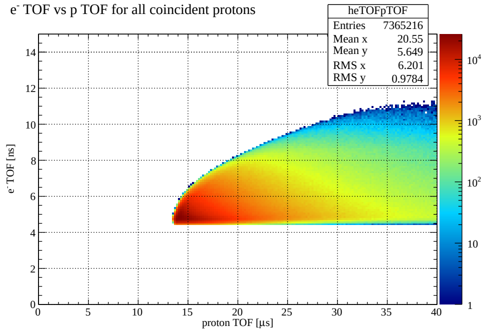
- The Nab spectrometer designed to measure both the electron energy E_e and proton the proton TOF (t_p).
- At **1.4** MW SNS beam power there will be ∼1600 decays/s, or ∼**200** p/s in upper detector.

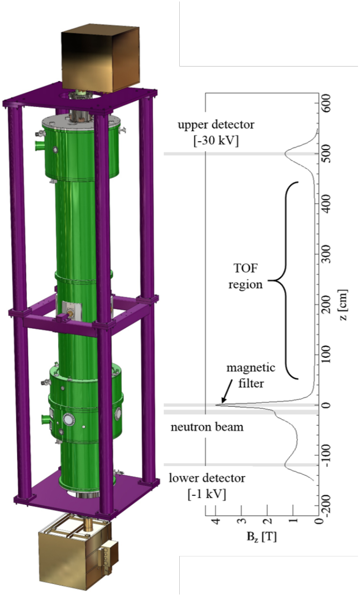




N*ab* spectrometer and measurement

- Specific magnetic field properties
- Electrode system for particle acceleration
- Hermeticity
- Ultra-high vacuum
- Silicon detectors



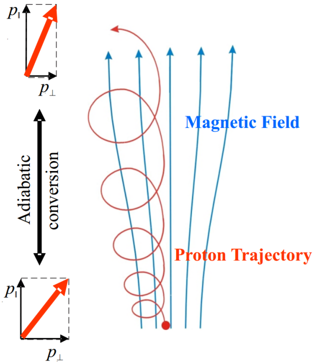


How do we collect protons that fly in all directions?

How do we collect protons that fly in all directions?

Answer: **adiabatic longitudinalization**!

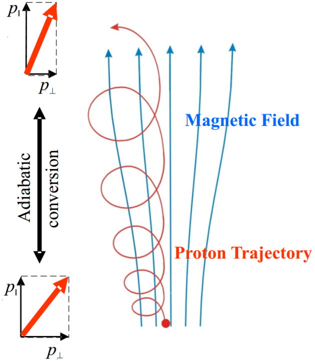
$$\boxed{\sin\theta_{pB} \propto \sqrt{B}}$$



How do we collect protons that fly in all directions?

Answer: **adiabatic longitudinalization**!

$$\boxed{\sin\theta_{pB} \propto \sqrt{B}}$$

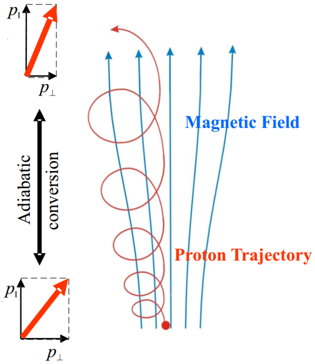


⇒ longitudinalize $\vec{p}$ early, followed by a long drift path!

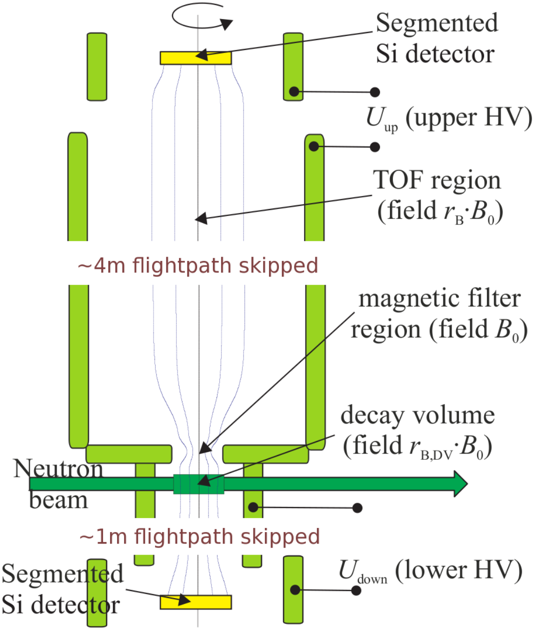
How do we collect protons that fly in all directions?

Answer: **adiabatic longitudinalization**!

$$\boxed{\sin\theta_{pB} \propto \sqrt{B}}$$



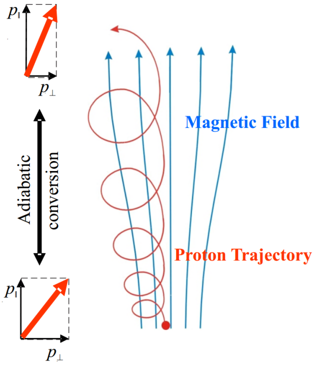
⇒ longitudinalize $\vec{p}$ early, followed by a long drift path!

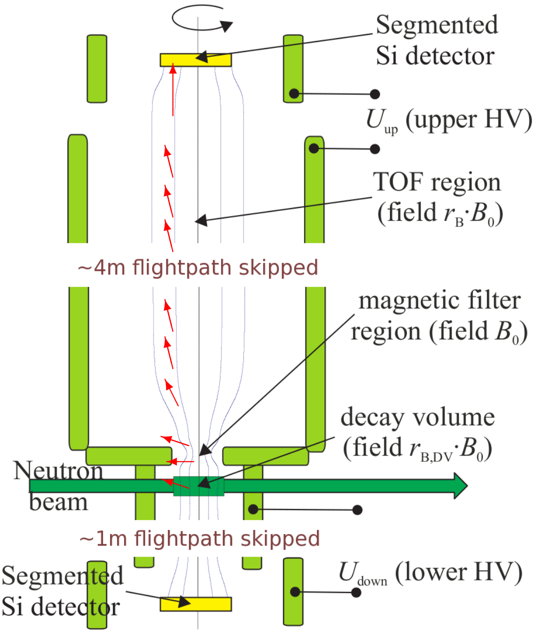


How do we collect protons that fly in all directions?

Answer: **adiabatic longitudinalization**!

$$\boxed{\sin\theta_{pB} \propto \sqrt{B}}$$





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

How do we relate $p_p \Rightarrow$ to $t_p(\mathrm{TOF}_p)$?

- **adiabatic longitudinalization:**

$$\boxed{\sin\theta_{pB} \propto \sqrt{B}}$$

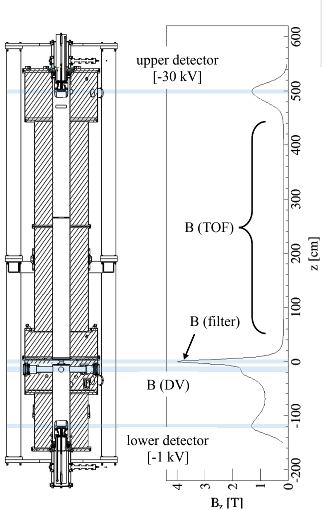
- Proton time of flight in B field:

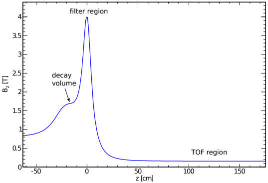
$$t_p = L\frac{m_p}{p_p} = \frac{f(\cos\theta_0)}{p_p} \qquad \text{where}$$

$$\cos\theta_0 = \left.\frac{\vec{p}_0 \cdot \vec{B}}{p_0 B}\right|_{\text{decay pt.}} .$$

- For an adiabatically expanding field,

$$t_p = \frac{m_p}{p_p}\int_{z_0}^{l} \frac{dz}{\sqrt{1 - \frac{B(z)}{B_0}\sin^2\theta_0 + \frac{q(V(z)-V_0)}{E_0}}}$$





How do we relate $p_p \Rightarrow$ to $t_p(\mathrm{TOF}_p)$?

Analysis strategy:

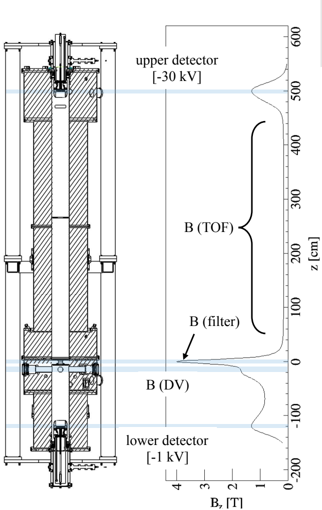
$$t_p = \frac{m_p}{p_p} \int_{z_0}^{l} \frac{dz}{\sqrt{1 - \frac{B(z)}{B_0} \sin^2 \theta_0 + \frac{q(V(z) - V_0)}{E_0}}}$$

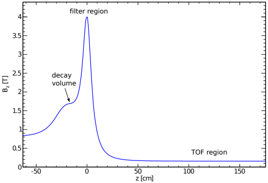
- Note that the magnetic field term in the integral

$$1 - \frac{B(z)}{B_0} \sin^2 \theta_0$$

can be expanded for small angles

- Use GEANT4 simulation to correct for E-field in estimation of $p_p \rightarrow t_p \rightarrow$ then expand and fit to expansion parameters (spectrometer response)

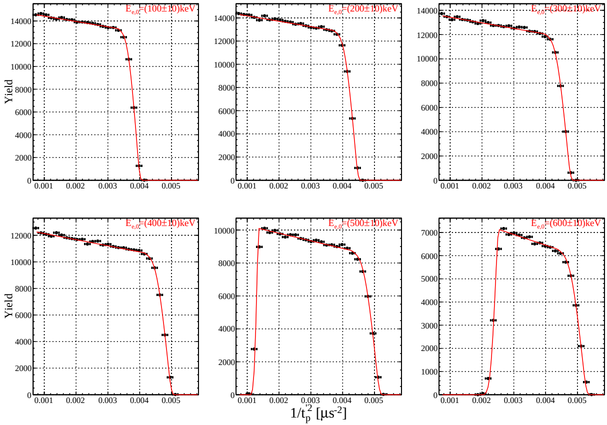




Analysis strategy: Taylor series

- Expand the integral into Taylor series parameters, and fit the edges to these parameters;
- Analysis algorithm demonstrated using GEANT4 simulation;
- Use central part of $P_t(1/t_p^2)$ ($\sim 75\%$) to extract ***a***.

Courtesy Wenjiang Fan

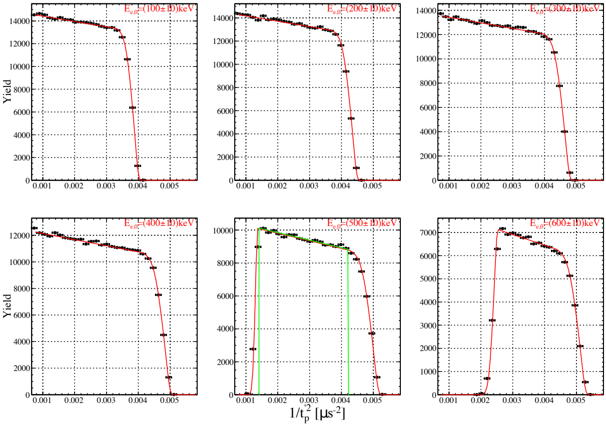


$$p_p = \frac{m_p}{t'_p}\int \frac{dz}{\sqrt{1-\frac{B(z)}{B_0}\sin^2(\theta_0)}}$$

$$= \frac{m_p}{t'_p}\left(L - \eta\ln\frac{\cos(\theta_0)-\cos(\theta_0)_{min}}{1-\cos(\theta_0)_{min}} + \alpha(1-\cos(\theta_0)) + \beta(1-\cos(\theta_0))^2 + \gamma(1-\cos(\theta_0))^3\right)$$

Analysis strategy: Taylor series

Courtesy Wenjiang Fan



$$p_p = \frac{m_p}{t'_p}\int \frac{dz}{\sqrt{1-\frac{B(z)}{B_0}\,sin^2(\theta_0)}}$$

$$= \frac{m_p}{t'_p}\left(L - \eta\ln\frac{cos(\theta_0)-cos(\theta_0)_{min}}{1-cos(\theta_0)_{min}} + \alpha(1-cos(\theta_0)) + \beta(1-cos(\theta_0))^2 + \gamma(1-cos(\theta_0))^3\right)$$

- Expand the integral into Taylor series parameters, and fit the edges to these parameters;
- Analysis algorithm demonstrated using GEANT4 simulation;
- Use central part of $P_t(1/t_p^2)$ ($\sim$ 75%) to extract ***a***.

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 $r_{B,\mathrm{DV}} = B_{\mathrm{DV}}/B_0$	1.8×10^{-4}
L_{TOF}, length of TOF region		(*)
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	measure
Adiabaticity of proton motion		1×10^{-4}
Detector effects:	E_e calibration	2×10^{-4}
	E_e resolution	5.7×10^{-4}
	Proton trigger efficiency	3.4×10^{-4}
	TOF shift (Δt_p)	3×10^{-4}
Accidental coincidences/Background		small
Residual gas	$P < 2 \times 10^{-9}$	3.8×10^{-4}
TOF in acceleration region	$r_{\mathrm{electrods}}$	3×10^{-4} (prelim)
Sum		1.3×10^{-3}

(*) Free fit parameter

The N*ab* Magnet

Testing at Cryogenic Ltd., London UK

The N*ab* Magnet

It arrived late February 2018 in ORNL!

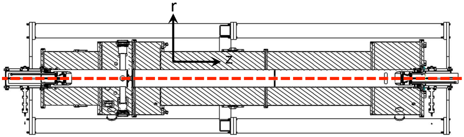
The N*ab* Magnet

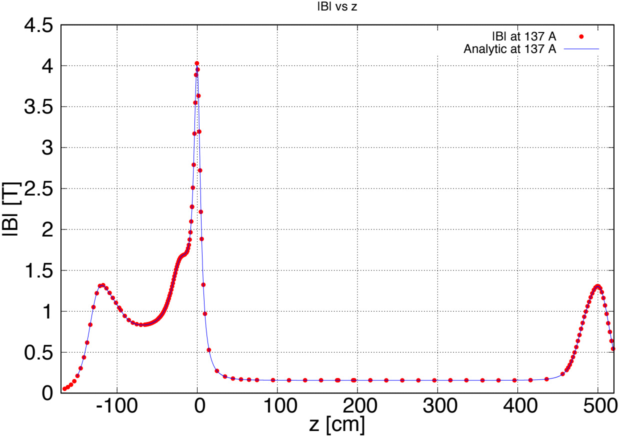
It arrived late February in ORNL!

First measurements of the spectrometer

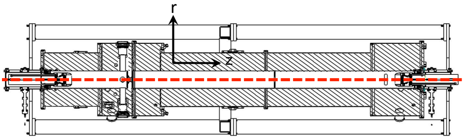
Shortly afterwards: first pump down, cool down, and on-axis field map

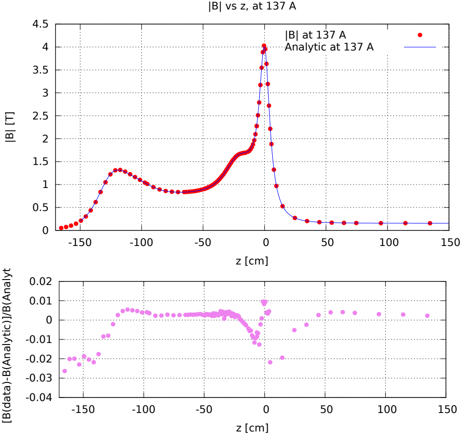
First magnetic field maps, on-axis at SNS

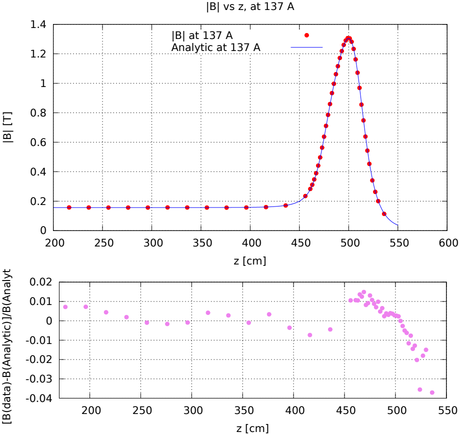




First magnetic field maps, on-axis at SNS







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

Summary

- Nab offers an independent measurement of $\lambda = g_A/g_V$ with competitive precision $\Rightarrow$ hopefully have a determination of V_{ud}, CKM from λ and τ_n
- Nab plans to collect samples of 1 - 2 $\times 10^9$ events in several runs; these runs will take 1 - 2 year's running cycle at SNS.
- Magnet on FNPB at ORNL, first measurements of the $|B|$ field look great
- Installation underway, commissioning to begin late 2018

Active and recent Nab collaborators (as of Oct 2017)

R. Alarcon[a], S. Baeßler[b,c*], S. Balascuta[a§], L. Barrón Palos[e], K. Bass[f§], N. Birge[f§], A. Blose[j§],
D. Borissenko[b§], J.D. Bowman[c†], L. Broussard[d,c], J. Byrne[g], J.R. Calarco[f,c], J. Caylor[f§],
T. Chupp[i], V. Cianciolo[c], J.N. Clement[b§], C. Crawford[j], W. Fan[b§], W. Farrar[b§], N. Fomin[f],
E. Frlež[b], J. Fry[b], M.T. Gericke[k], M. Gervais[j§], F. Glück[ℓ], G.L. Greene[c,f], R.K. Grzywacz[f],
V. Gudkov[m], J. Hamblen[p], C. Hayes[o], C. Hendrus[i§], T. Ito[d], H. Li[b§], C.C. Lu[b§], B. Luffman[j§],
M.F. Makela[d], R. Mammei[k], J. Martin[n], M. Martinez[a§], D.G. Matthews[j§], M. McCrea[j],
P.L. McGaughey[d], C.D. McLaughlin[b§], D. Mitchell[j§], P. Mueller[c], D. Perryman[f§], D. van Petten[b§],
S.I. Penttilä[c‡], D. Počanić[b†], G. Randall[a§], N. Roane[b§], C.A. Royse[o§], K.P. Rykaczewski[c],
A. Salas-Bacci[b], E.M. Scott[f§], T. Shelton[j§], S.K. Sjue[d], A. Smith[b§], E. Smith[d], A. Sprow[j§],
E. Stevens[b§], D. van Petten[b§], J. Wexler[o§], R. Whitehead[f§], W.S. Wilburn[d], A.R. Young[o],
B. Zeck[o].

[a]Arizona State U.
[b]U. of Virginia
[c]ORNL, [d]LANL
[e]UNAM, Mexico
[f]U. Tenn-Knoxville
[g]U. of Sussex
[h]U. New Hampshire
[i]U. of Michigan
[j]U. of Kentucky
[k]U. of Manitoba
[ℓ]Uni. Karlsruhe
[m]U. of South Carolina
[n]U. of Winnipeg
[o]N. Carolina State U.
[p]U. Tenn-Chattanooga
[*]Project Manager
[†]Co-spokesmen
[‡]On-site Manager
[§]Nab students, or recent Nab students/collaborators

Home page: `http://nab.phys.virginia.edu/`

Extras

N*ab* systematic uncertainties

Experimental parameter		$(\Delta a/a)_{\mathrm{SYST}}$
Magnetic field:	curvature at pinch	5.3×10^{-4}
	ratio $r_{\mathrm{B}} = B_{\mathrm{TOF}}/B_0$	2.2×10^{-4}
	ratio $r_{\mathrm{B,DV}} = B_{\mathrm{DV}}/B_0$	1.8×10^{-4}
L_{TOF}, length of TOF region		(*)
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}
	E_e resolution	5.7×10^{-4}
	Proton trigger efficiency	2.5×10^{-4}
	TOF shift (Δt_p)	3×10^{-4}
Accidental coincidences/Background		small
Residual gas		3.8×10^{-4}
Sum		1.2×10^{-3}

(*) Free fit parameter

Requirements of the magnetic field

- To measure a to 10^{-3}, the t_p-a relationship requires a detailed understanding of the effective proton pathlength, L

  ⇒ Imposes specific precision of the magnetic field of the spectrometer

- We require the **relative** uncertainty of the quantities:

$$\frac{\Delta r_B}{r_B} = 10^{-2} \qquad r_B = \frac{B(\mathrm{TOF})}{B(\mathrm{filter})}$$

$$\frac{\Delta r_{B,DV}}{r_{B,DV}} = 10^{-2} \quad \text{where} \quad r_{B,DV} = \frac{B(\mathrm{DV})}{B(\mathrm{filter})}$$

$$\frac{\Delta \gamma}{\gamma} < 2 \times 10^{-2} \qquad \gamma = -\frac{1}{B}\frac{\mathrm{d}^2 B}{\mathrm{d}z^2}$$