The neutron beta decay correlation program at SNS

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NSAC Subcommittee Review
Chicago, IL,
15 April 2011

The FnPB neutron decay program at SNS

- **Nab**: a precise measurement of
  - a, the electron-neutrino correlation in neutron decay, and
  - b, the Fierz interference term (so far not measured in n decay).
- **Polarized program** (abBA/PANDA): precise measurements of
  - A, the electron asymmetry in neutron decay,
  - B, the neutrino asymmetry in neutron decay,
  - C, the proton asymmetry in neutron decay; also

Goal uncertainties: $\delta a/a$, $\delta A/A$, $\delta B/B \le 10^{-3}$, and $\delta b \le 3 \times 10^{-3}$.

Neutron Decay Parameters (SM)

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

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

where:

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

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

also:

$$C = \kappa(A + B) \quad \text{where} \quad \kappa \simeq 0.275\,.$$

Goals of the Nab experiment

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

  with accuracy of $\boxed{\dfrac{\mathbf{\Delta a}}{\mathbf{a}} \simeq \mathbf{10^{-3}}}$

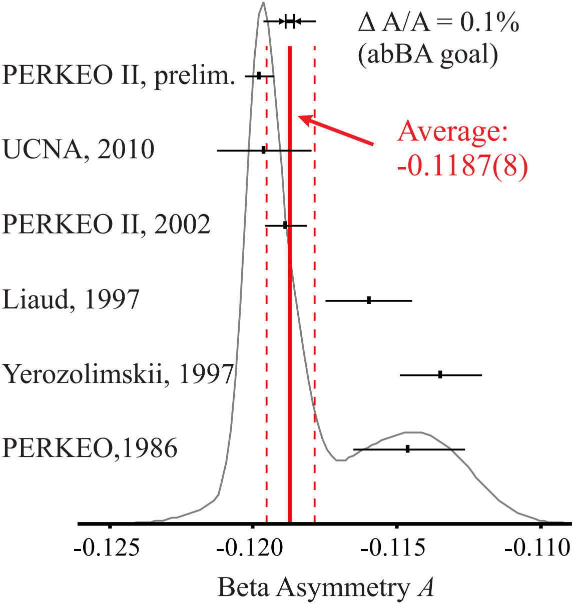
	-0.1054 ± 0.0055	Byrne et al '02
current results:	-0.1017 ± 0.0051	Stratowa et al '78
	-0.091 ± 0.039	Grigorev et al '68

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

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

  current results: **none (in n decay)**

Status of A and λ in n decay

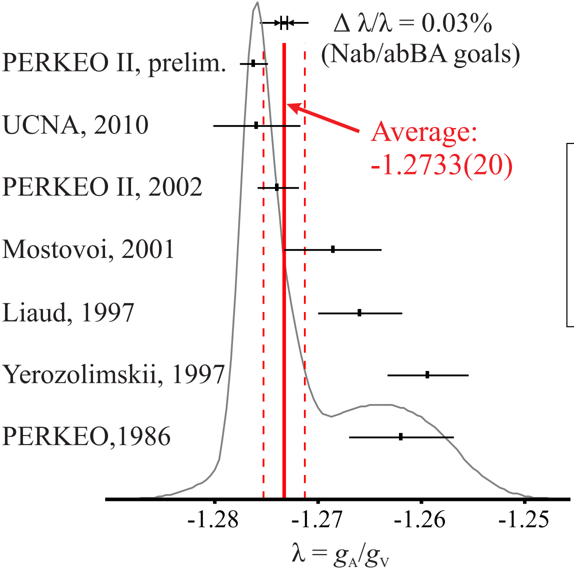


Uncertainty of the average scaled up by factor **2.3×**

Global fit $\chi^2/\text{dof} = 27/5$!

Statistical probability for this χ^2 is 6×10^{-5}.

Status of A and λ in n decay (cont'd)



Goals for Δa, ΔA:

$\Rightarrow \Delta\lambda \simeq 3.5 \times 10^{-4}$

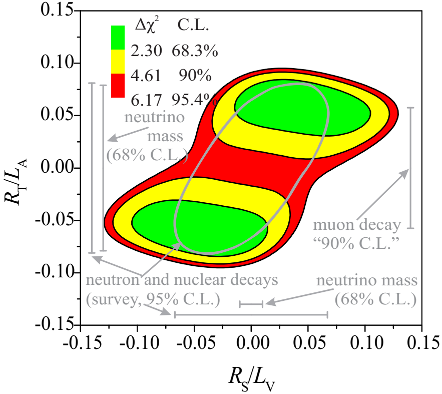
i.e., an order of magn. improvement.

$$\frac{\Delta\lambda}{\lambda} \simeq 0.27\frac{\Delta a}{a} \simeq 0.24\frac{\Delta A}{A}$$

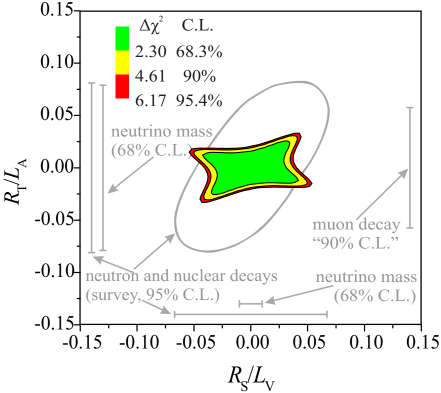
n-decay correlation parameters beyond $\mathbf{V_{ud}}$

- Beta decay parameters constrain L-R symmetric, SUSY extensions to the SM. [Reviews: Herczeg, Prog. Part. Nucl. Phys. **46**, 413 (2001), N. Severijns, M. Beck, O. Naviliat-Čunčić, Rev. Mod. Phys. **78**, 991 (2006), Ramsey-Musolf, Su, Phys. Rep. **456**, 1 (2008)]
- Fierz int. term, never measured for the n, along with B, offers a sensitive test of non-$(V - A)$ terms in the weak Lagrangian (S, T). [S. Profumo, M. J. Ramsey-Musolf, S. Tulin, PRD **75**, 075017 (2007)]
- Measurement of the electron-energy dependence of a and A can separately confirm CVC and absence of SCC. [Gardner, Zhang, PRL **86**, 5666 (2001), Gardner, hep-ph/0312124]
- A connection exists between non-SM (e.g., S, T) terms in $d \to ue\bar{\nu}$ and limits on ν masses. [Ito + Prézaeu, PRL **94** (2005)]

Updated limits for RH S and T currents n decay



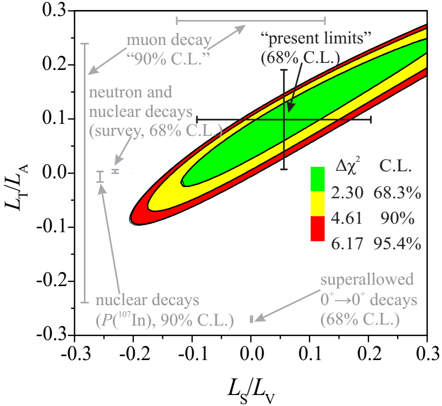
Present limits (*n* decay data)
(SM values at origin of plot.)



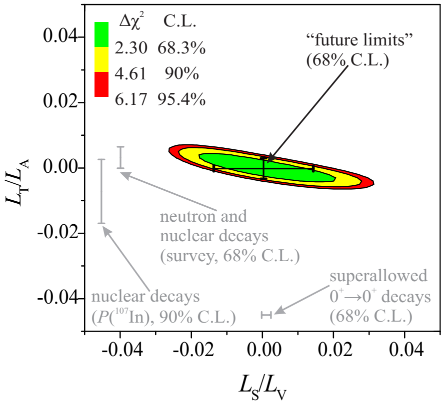
Projected limits based on $a = -0.1030(1)$, $b \equiv 0$, and no improvement in A.

[G. Konrad, W. Heil, S. Baeßler, D. Počanić, F. Glück, arXiv 1007.3027.]

Limits for LH S and T currents n decay



Present limits (n decay data)
(SM values at origin of plot.)



Projected limits assuming $a = -0.1030(1)$; $b = 0 \pm 0.003$: no new A, B measurements.

[G. Konrad, W. Heil, S. Baeßler, D. Počanić, F. Glück, arXiv 1007.3027.]

Correlation parameters with recoil correction

[Gardner, Zhang, PRL **86**, 5666 (2001), Gardner, hep-ph/0312124]

Most general form of hardonic weak current consistent with (V-A):

$$\langle \mathbf{p}(\mathbf{p_p})|\mathbf{J}^\mu|\mathbf{n}(\mathbf{p_n},\mathbf{P})\rangle = \bar{\mathbf{u}}_\mathbf{p}(\mathbf{p_p})\Big(\mathbf{f_1}(\mathbf{q}^2)\gamma^\mu - \mathbf{i}\frac{\mathbf{f_2}(\mathbf{q}^2)}{\mathbf{M_n}}\mathbf{q}^\mu + \frac{\mathbf{f_3}(\mathbf{q}^2)}{\mathbf{M_n}}\mathbf{q}^\mu + \mathbf{g_1}(\mathbf{q}^2)\gamma^\mu\gamma_5 - \mathbf{i}\frac{\mathbf{g_2}(\mathbf{q}^2)}{\mathbf{M_n}}\sigma^{\mu\nu}\gamma_5\mathbf{q}_\nu + \frac{\mathbf{g_3}(\mathbf{q}^2)}{\mathbf{M_n}}\gamma_5\mathbf{q}^\mu\Big)\mathbf{u_n}(\mathbf{p_n},\mathbf{P})$$

$$\mathbf{a},\mathbf{A},\mathbf{B} \Rightarrow \lambda = \frac{\mathbf{g_1}}{\mathbf{f_1}} \qquad \text{while} \qquad \tau_\mathbf{n} \propto (\mathbf{f_1})^2 + 3(\mathbf{g_1})^2$$

However, $\mathbf{f_2}$ (weak magnetism) and SCC's ($\mathbf{g_2}$, $\mathbf{g_3}$), remain unresolved in beta decays (best tested in A=12 system). With recoil corrections, Gardner and Zhang find:

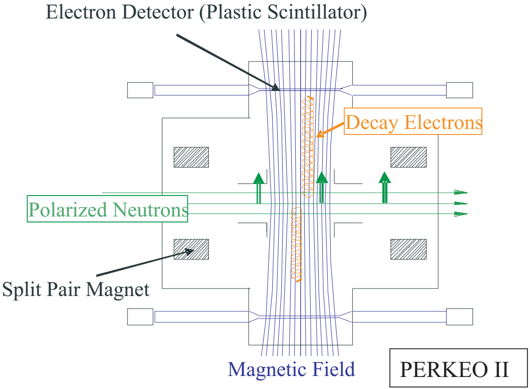
$$\mathbf{a}(\mathbf{E_e}) = \text{func}(\mathbf{f_2}) \qquad \text{while} \qquad \mathbf{A}(\mathbf{E_e}) = \text{func}(\mathbf{f_2},\mathbf{g_2})$$

Current experiments aiming to measure a

1. **Nab**: goal is to measure $\mathbf{\Delta a/a \sim 10^{-3}}$
   - Discussed in this presentation.
2. **aCORN**: goal is to measure $\mathbf{\Delta a/a \sim 0.5 - 2\,\%}$
   - Funded, under way at NIST,
   - Uses only part of neutron decays.
3. **aSPECT**: aims to measure $\mathbf{\Delta a/a \sim 10^{-3}}$
   - Funded and running; recently overcame trapping problems,
   - Stat. sensitivity not as good as Nab due to integration; presently $\sim \mathbf{2}\,\%$/day—will likely improve on publ. results, not $< \mathbf{1}\,\%$ this yr,
   - Determination of detection function relies on theoretical model of spectrometer; if assumptions fulfilled, input param's easy to measure.
   - Singles measurement!
   - will become part of the **PERC** program with improvements.

Current state of the art in **A**: **PERKEO II**

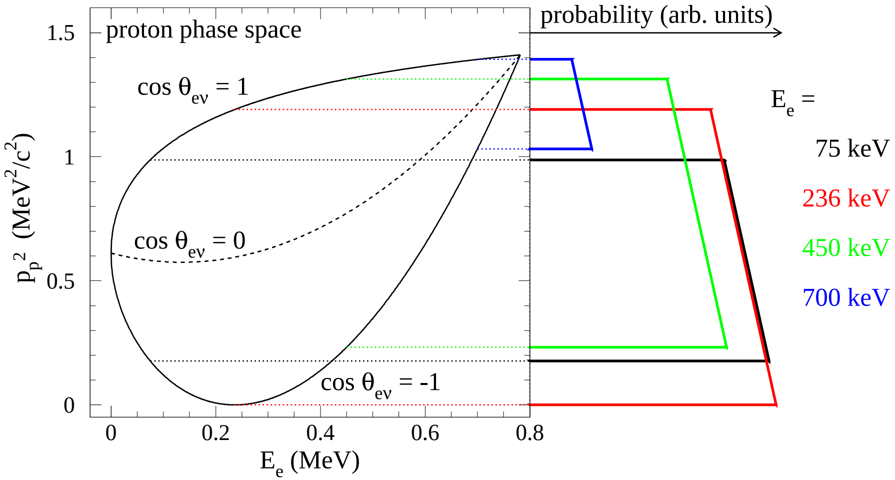
- obtained $\mathbf{A = -0.1189(7)}$ in 2002; $\mathbf{-0.1198(5)}$ current prelim.
- data acquisition finished,
- data analysis of last (3rd) run completed; result not yet published,
- symmetric setup on cold **n** beam, similar to original abBA design,



- singles **e** detection
- benchmark design for all comparisons,
- major uncertainties:
  - statistics,
  - neutron beam polarization,
  - background,
  - electron detection.

1. **abBA:** aim $\boldsymbol{\delta A/A \simeq 1 \times 10^{-3}}$; (discussed in this talk)
    - uses magnetic filter,
    - expected improvements: background (coincidences), electron detection (Si detector), sensitivity to field inhomogeneities,
    - measurements of **C** (**B**) planned
2. **PERKEO III:** aim $\boldsymbol{\delta A/A \simeq 2 \times 10^{-3}}$ in **A**
    - data analysis of second run ongoing, aim to measure **A** and $\mathbf{f_2}$
    - expected improvements: pulsed wide beam (statistics, background)
3. **UCNA:** aim $\boldsymbol{\delta A/A \simeq 2 \times 10^{-3}}$ (discussed at this meeting)
    - achieved $\boldsymbol{-0.11966^{+152}_{-166}}$ in 2010,
    - uses (so far, dedicated) UCN source,
    - major uncertainties: statistics, $\mathbf{P_n}$ (so far: $> \mathbf{99.5\%}$, viz. $\mathbf{99.7(1)\%}$ in PERKEO II), **E** loss in foil, muon veto bgd,
    - further measurements of **B**, **b** planned,
4. **PERC:** aim $\boldsymbol{\delta A/A \simeq 3 \times 10^{-4}}$; (funded, being designed)
    - uses magnetic filter behind a pulsed beam in a neutron guide,
    - main expected improvements: counting statistics, background (singles det'n, but w/pulsed beam), sensitivity to field inhomogeneities;
    - future measurements of **a**, **C**, et al., in planning.

Nab Measurement principles: Proton phase space



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

$\boxed{\text{Slope} = \mathbf{a}}$

Measurement principles: Detection function (I)

Proton time of flight in B field:

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

For an adiabatically expanding field prior to acceleration,

$$f(\cos\theta_{\mathrm{p},0}) = \int_{z_0}^{l} \frac{m_\mathrm{p}\,dz}{\cos\theta_\mathrm{p}(z)} = \int_{z_0}^{l} \frac{m_\mathrm{p}\,dz}{\sqrt{1-\frac{B(z)}{B_0}\sin^2\theta_{\mathrm{p},0}}} .$$

To this we add effects of magnetic reflections and, later, of electric field acceleration.

Measurement principles: Detection function (II)

The proton momentum distribution within the phase space bounds is given by

$$P_p(p_{\mathrm{p}}^2) = 1 + a\beta_e \cos\theta_{e\nu}\,, \qquad [\text{recall: } \cos\theta_{e\nu} = f(p_{\mathrm{p}}^2)]$$

while

$$P_t\left(\frac{1}{t_{\mathrm{p}}^2}\right) = \int P_p(p_{\mathrm{p}}^2)\,\Phi\left(\frac{1}{t_{\mathrm{p}}^2}, p_{\mathrm{p}}^2\right) dp_{\mathrm{p}}^2\,.$$

Detection function Φ relates the proton momentum and time-of-flight distributions! To extract **a** reliably:

- Φ must be as narrow as possible,
- Φ must be understood very precisely.

Two methods ("A" and "B") pursued to specify Φ.

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Measurement principles: Detection function (III)

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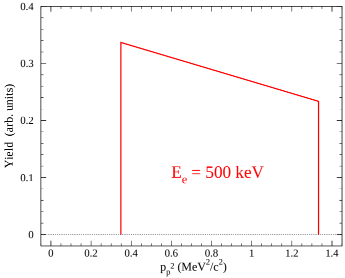
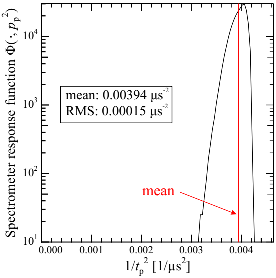
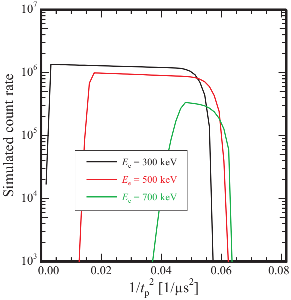
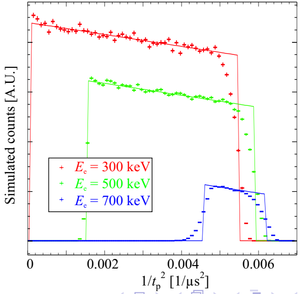




E_p = 500 eV

analyt.
calcul'n

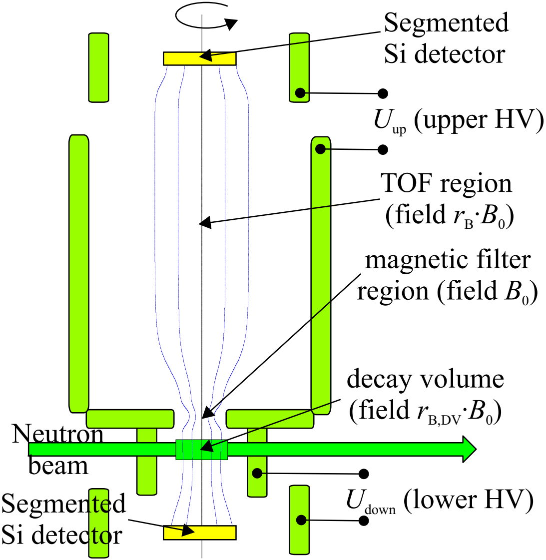




MC
GEANT
simul'n

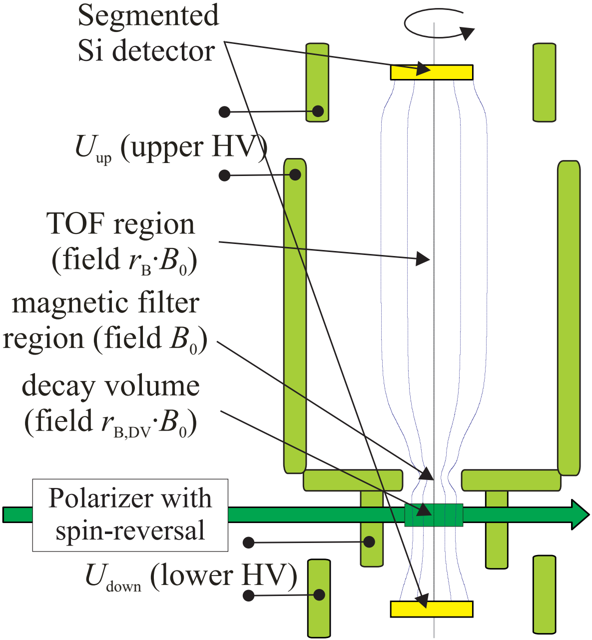
Nab principle of operation

- Collect and detect both electron and proton from neutron beta decay (magnetic field, detectors at both ends)
- Measure electron energy and proton TOF and reconstruct decay kinematics (Magnetic field shape, silicon detectors at both ends).

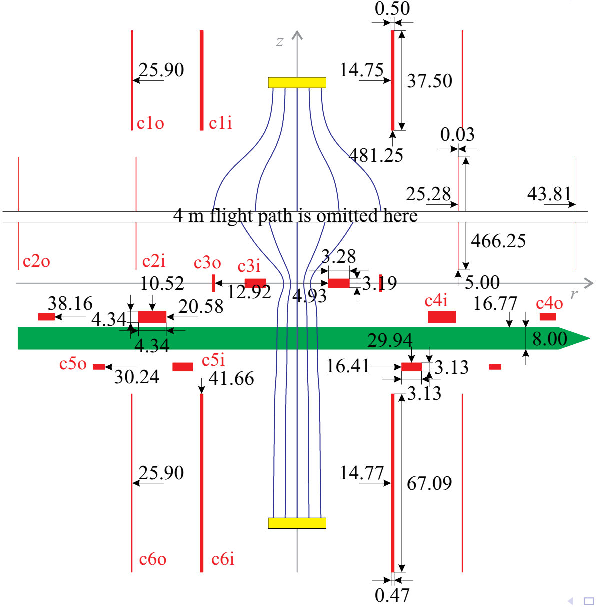


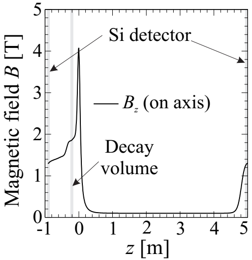
abBA/PANDA configuration:

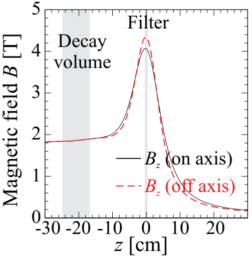
- A: detect electrons in upper, protons in lower detector;
- B/C: detect protons in upper, electrons in lower detector;



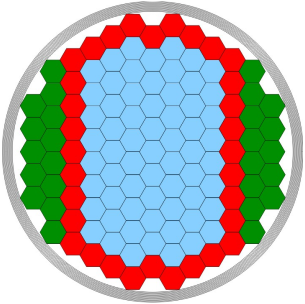
The spectrometer: coil design and magnetic field profile

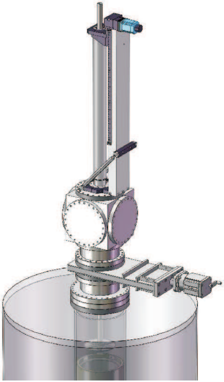






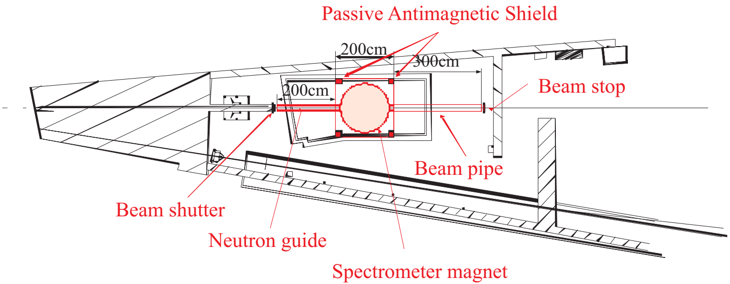
Si detector prototypes (15 cm diameter)

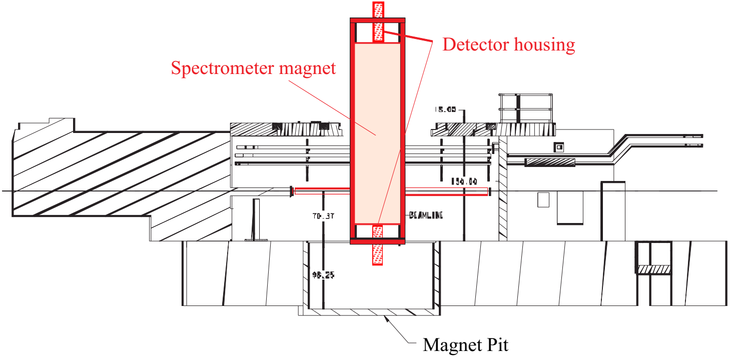




LANL group has full-size prototypes from Micron Corp.
Full thickness $\mathbf{t = 2}$ mm; dead layer thickness $\mathbf{t_d} \leq \mathbf{100}$ nm.
Detailed testing currently under way at LANL.

Spectrometer installation in FnPB:





Statistical uncertainties for **a** and **b**

Statistical uncertainties for **a**

$E_{\mathrm{e,min}}$	0	100 keV	100 keV	300 keV
$t_{\mathrm{p,max}}$	–	–	100 μs	40 μs
$\sigma_{\mathbf{a}}$	$2.4/\sqrt{N}$	$2.5/\sqrt{N}$	$2.5/\sqrt{N}$	$2.5/\sqrt{N}$
$\sigma_{\mathbf{a}}{}^{\dagger}$	$2.5/\sqrt{N}$	$2.6/\sqrt{N}$	$2.6/\sqrt{N}$	$2.7/\sqrt{N}$
$\sigma_{\mathbf{a}}{}^{\S}$	$4.1/\sqrt{N}$	$4.1/\sqrt{N}$	$4.1/\sqrt{N}$	$4.1/\sqrt{N}$

† with $\mathbf{E}_{\mathrm{calib}}$ and $\mathbf{L}_{\mathrm{TOF}}$ variable; § using inner 70% of $\mathbf{p}_{\mathbf{p}}^{\mathbf{2}}$ data.

Statistical uncertainties for **b**

$E_{\mathrm{e,min}}$	0	100 keV	200 keV	300 keV
$\sigma_{\mathbf{b}}$	$7.5/\sqrt{N}$	$10.1/\sqrt{N}$	$15.6/\sqrt{N}$	$26.3/\sqrt{N}$
$\sigma_{\mathbf{b}}{}^{\dagger\dagger}$	$7.7/\sqrt{N}$	$10.3/\sqrt{N}$	$16.3/\sqrt{N}$	$27.7/\sqrt{N}$

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Statistical uncertainties for **a** and **b**

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Nab event rates, statistics and running times

Nab expects data rates of about 300 evts./s.

In a typical ∼10-day run of 7×10^5 s of net beam time we would achieve

$$\frac{\sigma_a}{a} \simeq 2 \times 10^{-3} \qquad \text{and} \qquad \sigma_b \simeq 6 \times 10^{-4}$$

We plan to collect samples of $1 - 2 \times 10^9$ events in several 6–8-week runs.

Overall accuracy will **not be statistics-limited**.

Analysis methods to be used:

A. parametrize edges and width of $\Phi(p_p, 1/t_p)$ by fitting; use central part of Φ ($\sim 70\%$) to extract **a** in a multiparameter fit, and

B. specify all possible parameters of Φ by direct measurement; ⇒ treat **a**, $\mu = \overline{1/t_p^2}(p_p)$, and N_{decays} as free parameters in a two-step fitting procedure,

as well as a hybrid of the two.

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Nab systematic uncertainties

Experimental parameter		$(\Delta a/a)_{\mathrm{SYST}}$
Magnetic field:	curvature at pinch	5×10^{-4}
	ratio $r_B = B_{TOF}/B_0$	2.5×10^{-4}
	ratio $r_{B,DV} = B_{DV}/B_0$	3×10^{-4}
L_{TOF}, length of TOF region		(*)
U inhomogeneity:	in decay / filter region	5×10^{-4}
	in TOF region	1×10^{-4}
Neutron Beam:	position	4×10^{-4}
	width	2.5×10^{-4}
	Doppler effect	small
	unwanted beam polarization	small
Adiabaticity of proton motion		1×10^{-4}
Detector effects:	E_e calibration	(*)
	E_e resolution	5×10^{-4}
	Proton trigger efficiency	2.5×10^{-4}
Accidental coincidences		small
Residual gas		small
Background		small
Sum		1×10^{-3}

abBA/PANDA rates and statistical uncertainties

Additions to Nab apparatus: $\begin{cases} \text{(supermirror) polarizers,} \\ \text{polarization analyzers,} \end{cases}$

yield these rates:

$$\text{decays in DV:} \quad \mathbf{n_d = \frac{dN_d}{dt} \simeq 250\,s^{-1}}\,, \quad \text{and}$$

$$\text{e's in UD:} \quad \mathbf{n_{eU} = \frac{dN_{eU}}{dt} \simeq 30\,s^{-1}}\,.$$

(He-3 polarizers may give higher rates.)

$\mathbf{E_e}$ lower cutoff (keV)	none	100	200	250
$\boldsymbol{\sigma_A}$ (symm., 2 det's)	$\mathbf{2.7/\sqrt{N_d}}$	$\mathbf{2.9/\sqrt{N_d}}$	$\mathbf{4.8/\sqrt{N_d}}$	$\mathbf{7.4/\sqrt{N_d}}$
$\boldsymbol{\sigma_A}$ (asymm., 1 det.)	$\mathbf{4.3/\sqrt{N_d}}$	$\mathbf{4.8/\sqrt{N_d}}$	$\mathbf{7.8/\sqrt{N_d}}$	$\mathbf{11.9/\sqrt{N_d}}$

To reach $\mathbf{\Delta A/A = 1 \times 10^{-3}}$ we need $\mathbf{N_d = 1.7 \times 10^9}$ or **75 live days**.

abBA/PANDA systematic uncertainties

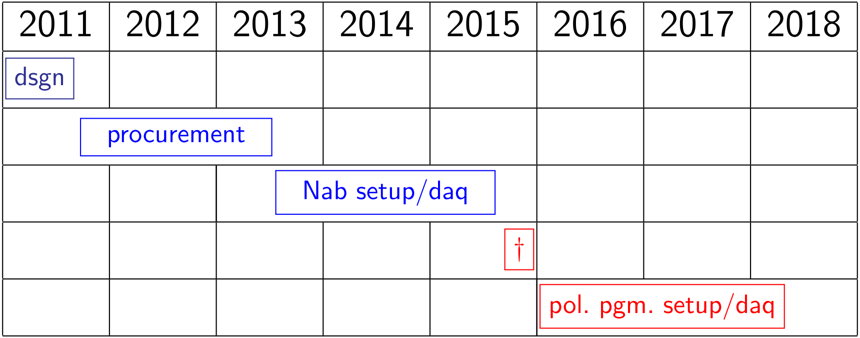
Experimental parameter		$(\Delta A/A)_{\mathrm{SYST}}$
Neutron Beam:	position	not relevant
	profile & edge effect	small
	Doppler effect	small
	polarization	$\leq 1 \times 10^{-3}$
U inhomogeneity:		small
Detector effects:	E_e calibration	2×10^{-4}
	Trigger efficiency	small
Accidental coincidences		small
Residual gas		small
Background		small
Sum		under study

Optimal schedule, excluding major technical, administrative or funding delays:

	Milestone	Completion
0.b	Detector prototype detects protons	Sep. 2011
0.	**Magnet design ready for bidding**	**Sep. 2011**
1.a	Order for magnet placed (design & option to build)	Dec. 2011
1.b	Acceptance of engineering drawings	Dec. 2012
1.c	Delivery of magnet	Sep. 2013
1.	**Spectrometer magnet accepted**	**Dec. 2013**
2.a	Passive Antimagnetic screen: magnetic design finished	Sep. 2012
2.	**Passive Antimagnetic screen built**	**Dec. 2013**
3.a	Detector test chamber available	Mar. 2012
	....	
3.g	Electrode system ready	Mar. 2014
3.	**Main detectors work in spectrometer**	**Jun. 2014**
4.a	Shielding calculation for Nab accepted	Jun. 2013
	....	
4.d	Shielding and utilities ready	Jun. 2014
4.	**Spectrometer ready for data taking**	**Sep. 2014**
5.a	Magnetometer calibrated	Sep. 2012
5.b	Magnetic field mapping system constructed	Dec. 2013
5.	**Magnetic field of spectrometer mapped**	**Mar. 2014**
6.	**Data acquisition**	**Sep. 2015**
7.	**Data analysis**	**Sep. 2016**

Potential shifts in schedule result in a linear translation.

Schedule overview



† Changeover to polarized program.

Last two items (polarized program) may take place at the new NGC beamline at NIST (scientific approval granted).

Tasks and responsibilities

	Subproject	Responsible	
		Instit.	Person(s)
1	Spectrometer magnet	UVa	Baeßler/Počanić
2	Passive antimagnetic screen	ASU	R. Alarcon
3	Beamline	UT	G.L. Greene
4	Shielding and utilities	ORNL	S.I. Penttilä
5	Detectors	LANL UVa U Manitoba U Winnipeg	W.S. Wilburn D. Počanić M.T. Gericke J. Martin
6	DAQ	UKy	C. Crawford
7	Electrode System	ORNL	J.D. Bowman
8	Vacuum system	UVa	S. Baeßler
9	B field measurement	UVa	D. Počanić
10	Beamline modification	ORNL	S.I. Penttilä
11	Polarization & polarimetry	UMich	T. Chupp

Asymptotic manpower commitments

UVa

Faculty:	
D. Počanić	50%
S. Baeßler	40%
Res. Sc./P'doc:	
E. Frlež	50%
A. Salas-B./TBD	67%
Grad. St:	
TBD	100%
TBD	100%
TBD	100%

UMich

Faculty:	
T. Chupp	30%
Grad. St:	
TBD	100%

NCSU

Grad. St:	
TBD	50%†

ASU

Faculty:	
R. Alarcon	35%
Grad. St:	
TBD	100%

UKy

Faculty:	
C. Crawford	50%
Grad. St:	
TBD	100%

UNH

Faculty:	
J. Calarco	50%
Grad. St:	
TBD	100%

ORNL

Sr. Scient:	
S. Penttilä	70%
D. Bowman	70%

LANL

Sr. Scient:	
S. Wilburn	100%[†]
Postdoc:	
N. Fomin/TBD	100%[†]

UTenn

Faculty:	
Geoff Greene	30%
Postdoc:	
S. Kucuker/TBD	10%
Grad. St:	
TBD	100%

UNAM

Faculty:	
L. Barron-Palos	20%
Grad. St:	
TBD	100%

In addition: Karlsruhe, Sussex, Manitoba/Winnipeg, . . .

[†] Shared with UCNx.

Asymptotic manpower commitments in FTE

(Teaching load taken into account for university faculty)

UVa

Faculty:	
D. Počanić	.33
S. Baeßler	.40
Res. Sc./P'doc:	
E. Frlež	.50
A. Salas-B./TBD	.67
Grad. St:	
TBD	1.0
TBD	1.0
TBD	1.0

UMich

Faculty:	
T. Chupp	.20
Grad. St:	
TBD	1.0

NCSU

Grad. St:	
TBD	.50†

ASU

Faculty:	
R. Alarcon	.22
Grad. St:	
TBD	1.0

UKy

Faculty:	
C. Crawford	.33
Grad. St:	
TBD	1.0

UNH

Faculty:	
J. Calarco	.33
Grad. St:	
TBD	1.0

ORNL

Sr. Scient:	
S. Penttilä	.70
D. Bowman	.70

LANL

Sr. Scient:	
S. Wilburn	.05[†]
Postdoc:	
N. Fomin/TBD	1.0[†]

UTenn

Faculty:	
Geoff Greene	.25
Postdoc:	
S. Kucuker/TBD	.10
Grad. St:	
TBD	1.0

UNAM

Faculty:	
L. Barron-Palos	.15
Grad. St:	
TBD	1.0

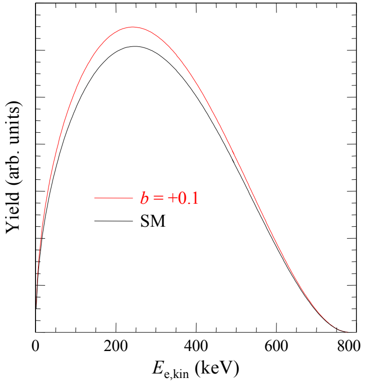
[†] Shared with UCNx.

Additional slides

The determination of the Fierz Interference term

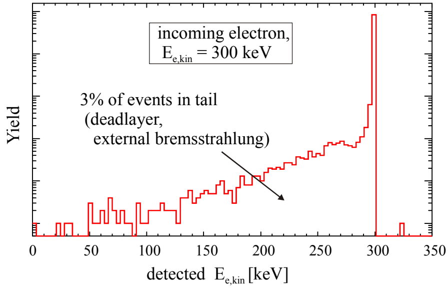
$$dw \propto \rho(E_e)\cdot\left(1+3|\lambda|^2\right)\cdot\left\{1+b\frac{m_e}{E_e}\right\}$$

Electron spectrum:



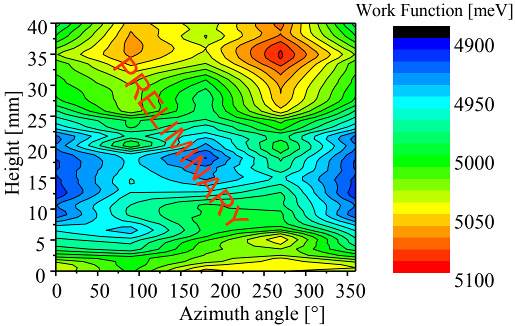
Systematic uncertainties:

1. Electron energy determination



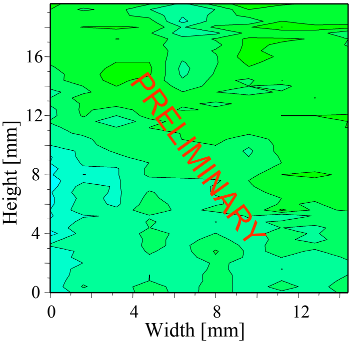
2. Background

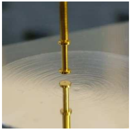
$\Delta b = 3\times10^{-3}$ can be reached (systematically limited)



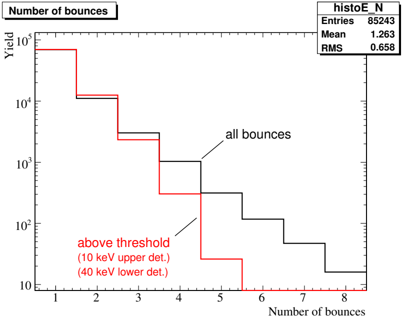
In collaboration with Prof. I. Baikie, KP Technologies

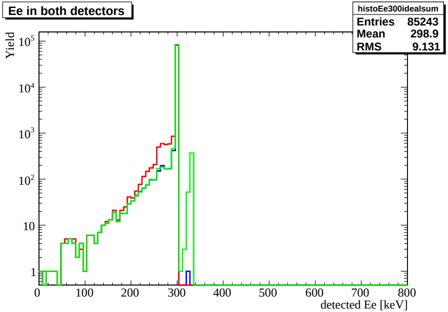
(arbitrary offset added)

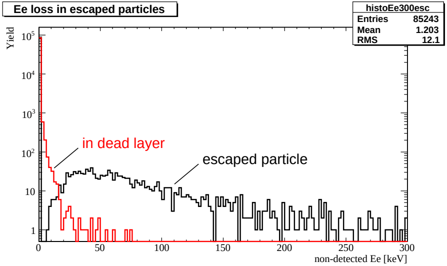




Electron energy response

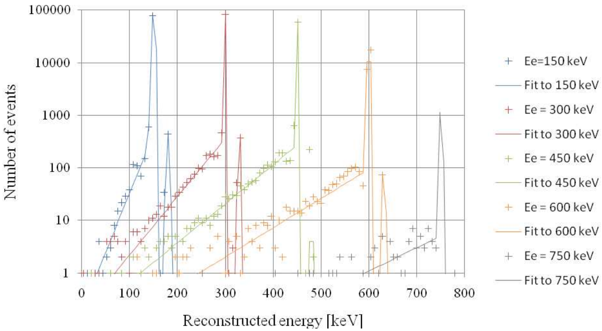




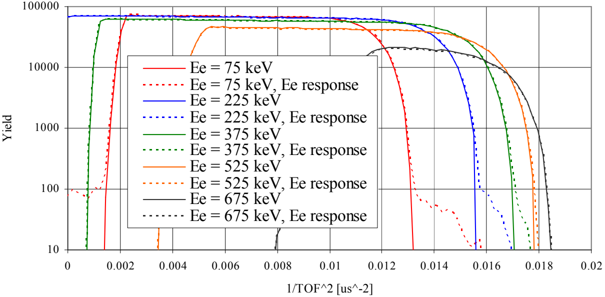


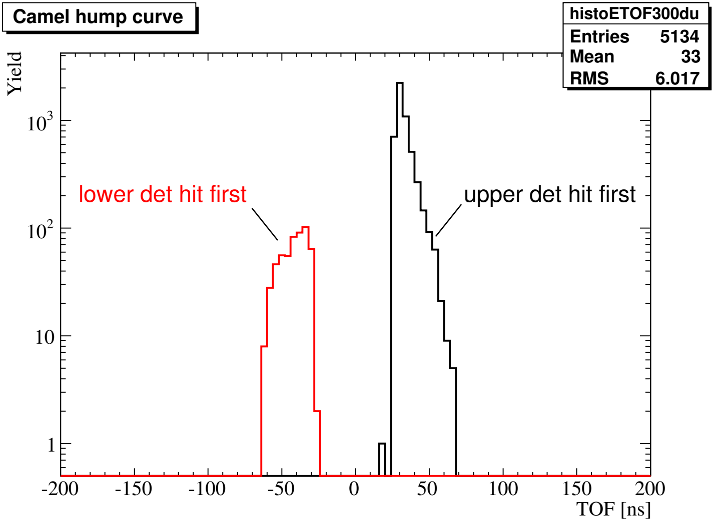
Detector response:

Electron energy



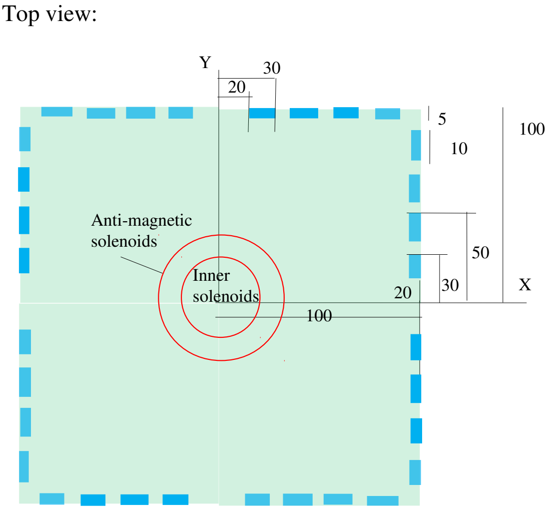
Proton TOF

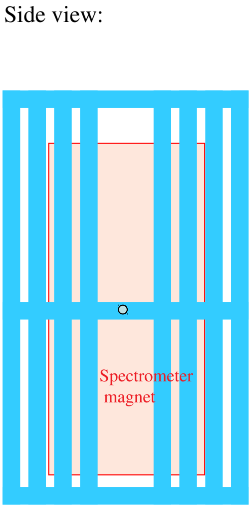




TOF = time of upper det. hit − time of lower det. hit

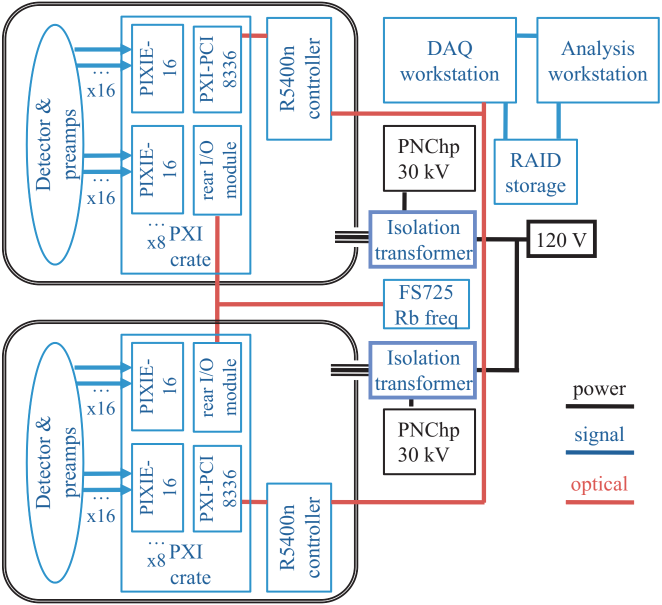
Nab anti-magnetic shield (AMS)





Staging area for Nab would save FnPB beam time during AMS testing.

Nab: DAQ


Detector & preamps
x16
x16
PIXIE-16
PIXIE-16
PXI-PCI 8336
rear I/O module
x8 PXI crate
R5400n controller
Detector & preamps
x16
x16
PIXIE-16
PIXIE-16
rear I/O module
PXI-PCI 8336
x8 PXI crate
R5400n controller
DAQ workstation
Analysis workstation
RAID storage
PNChp 30 kV
Isolation transformer
120 V
FS725 Rb freq
Isolation transformer
PNChp 30 kV
power
signal
optical

R. Alarcon[1], L.P. Alonzi[2§], S. Baeßler[2*], S. Balascuta[1§], J.D. Bowman[3†], M.A. Bychkov[2], J. Byrne[4], J.R. Calarco[5], V. Cianciolo[3], C. Crawford[6], E. Frlež[2], M.T. Gericke[7], F. Glück[8], G.L. Greene[9], R.K. Grzywacz[9], V. Gudkov[10], F.W. Hersman[5], A. Klein[11], M. Lehman[2§], J. Martin[12], S. McGovern[2§], S.A. Page[6], A. Palladino[2§], S.I. Penttilä[3‡], D. Počanić[2†], R. Rodgers[2§], K.P. Rykaczewski[3], W.S. Wilburn[11], A.R. Young[13].

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[5]Univ. of New Hampshire
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[8]Uni. Karlsruhe/RMKI Budapest
[9]University of Tennessee
[10]University of South Carolina
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†Co-spokesmen

*Experiment Manager

‡On-site Manager

§Graduate Students

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