Nab experiment: progress update

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FnPB PRAC Review
15 December 2010

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, never before 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
  - independent measurements of a and b.

Typical goal uncertainties: $\delta v/v \leq 10^{-3}$, and $\delta b \leq 3 \times 10^{-3}$.

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 $$\boxed{\frac{\Delta \mathbf{a}}{\mathbf{a}} \simeq \mathbf{10^{-3}}}$$

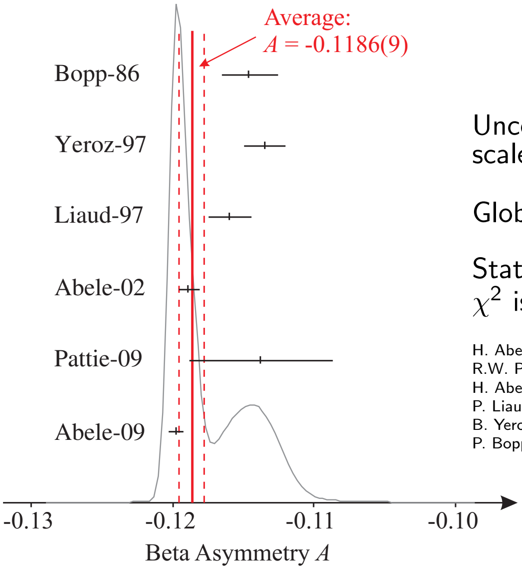
	-0.1054 ± 0.0055	Byrne et al '02
current results:	-0.1017 ± 0.0051	Stratowa et al '78
	-0.091 ± 0.039	Grigorev et al '68

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

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

  current results: **none**

Status of A and λ in n decay



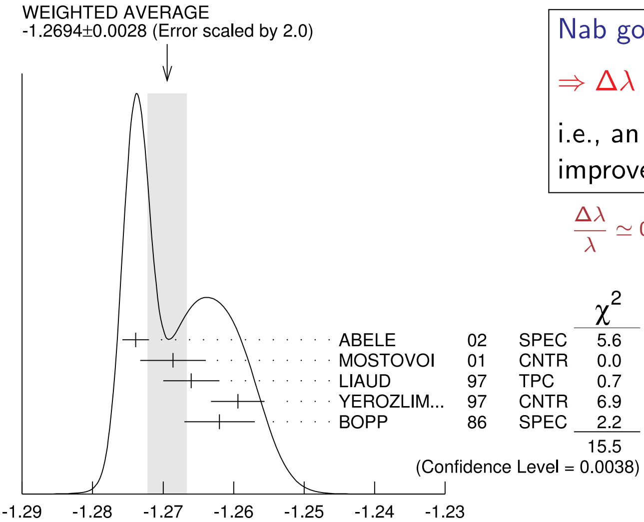
Uncertainty of the average scaled up by factor **2.3×**

Global fit $\chi^2/\mathrm{dof} = 28/5$!

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

H. Abele, private communication (2009).
R.W. Pattie, et al., PRL **102**, 012301 (2009).
H. Abele et al., PRL **88**, 211801 (2002).
P. Liaud et al., NP A 612, 53 (1997).
B. Yerozolimsky et al., PL B **412**, 240 (1997).
P. Bopp et al., PRL **56**, 919 (1986).

Status of A and λ in n decay (cont'd)



$\lambda \equiv g_A \,/\, g_V$

Nab goal value of Δa:

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

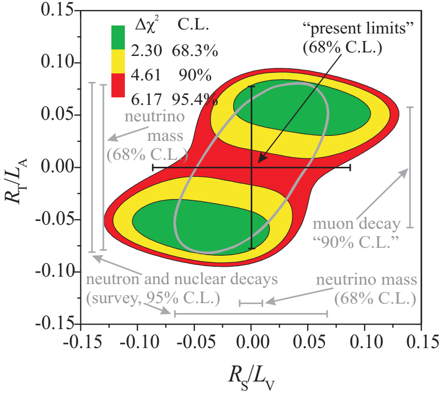
i.e., an order of magn. improvement.

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

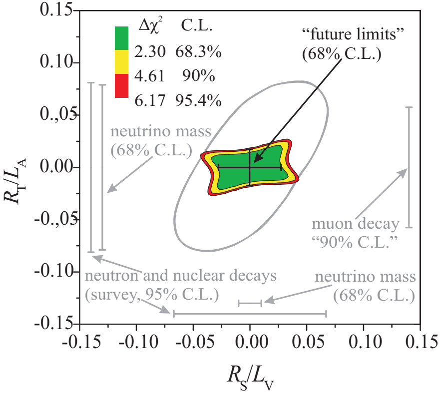
n-decay Correlation Parameters Beyond $\mathbf{V_{ud}}$

- 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.)

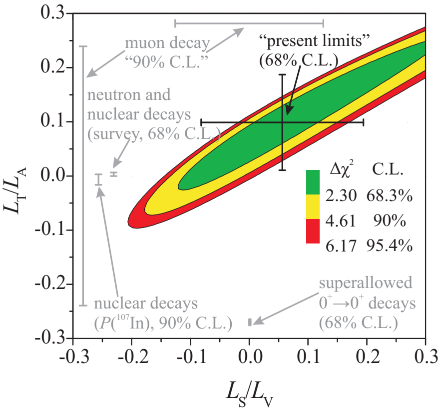


Projected limits; Grey contours: β compilation [Sev-06]

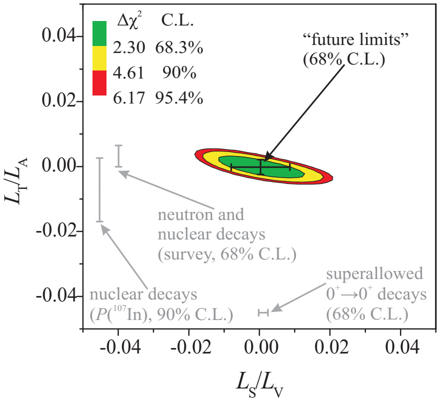
Improvement from more precise $a = -0.1030(1)$; using $b \equiv 0$.

[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.)



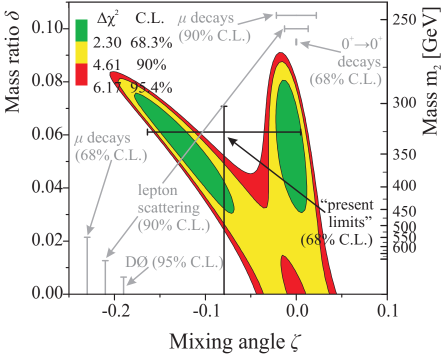
Projected limits assuming
$a = -0.1030(1)$; $b = 0 \pm 0.003$

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

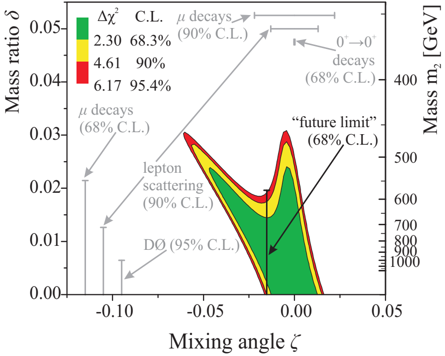
Right-handed W bosons

Adding RH gives non-zero $\delta = m_1^2/m_2^2$, ζ:

$$W_1 = W_L \cos\zeta + W_R \sin\zeta\,, \quad \text{and} \quad W_2 = -W_L \sin\zeta + W_R \cos\zeta\,.$$



Present limits



Projected limits

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

The Fierz interference term b

b can be estimated from nuclear beta decays:

$$b_F = \frac{C_S C_V}{|C_S|^2 + |C_V|^2} \qquad b_{GT} = \frac{C_T C_A}{|C_T|^2 + |C_A|^2}$$

These terms vanish for pure $\nu^{(R)}$ coupling.
$b \neq 0$ only for S, T coupling to $\nu^{(L)}$. (leptoquarks?)
From $0^+ \to 0^+$ decays [Towner + Hardy '98]:

$$|b_F| \simeq \frac{|C_S|}{|C_V|} \leq 0.0077 \; (90\,\% \text{ c.l.})$$

From analysis of GT decays [Deutsch + Quin, '95]:

$$b_{GT} = -0.0056(51) \simeq \frac{C_T}{|C_A|} \qquad \text{(small } F_T \text{ from } \pi_{e2\gamma}\text{!?)}$$

$\Rightarrow$ a $\sim 10^{-3}$ measurement of b_n is very interesting!

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):

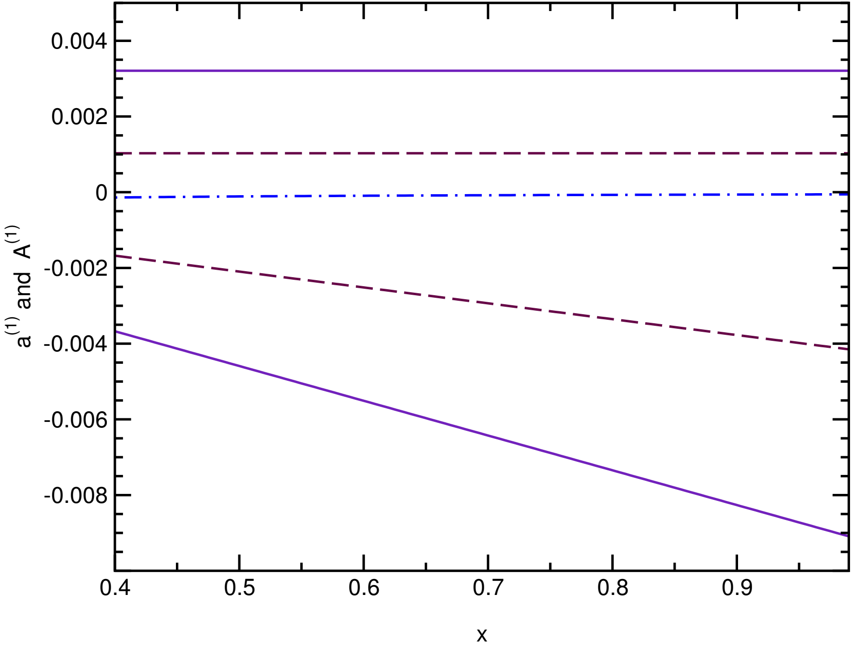
$$\langle \mathbf{p}(\mathbf{p_p})|\mathbf{J}^{\mu}|\mathbf{n}(\mathbf{p_n},\mathbf{P})\rangle =$$

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

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

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:

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


0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
$a^{(1)}$ and $A^{(1)}$
0.4
0.5
0.6
0.7
0.8
0.9
x

Current experiments aiming to measure *a*

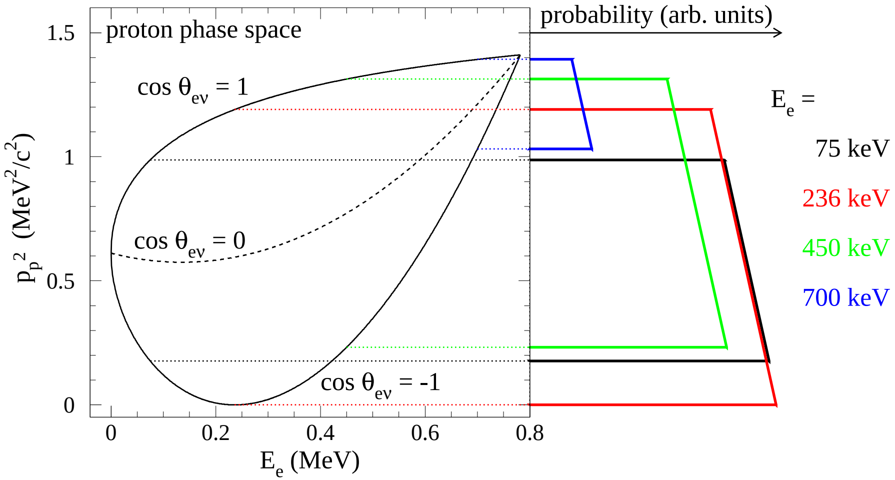
1. **Nab**: goal is to measure $\mathbf{\Delta a/a \sim 10^{-3}}$
   - Best statistical sensitivity,
   - Challenging but manageable systematics, esp. in asymm. design.

2. **abBA**: goal is to measure $\mathbf{\Delta a/a \sim 10^{-3}}$
   - Similar to Nab, but with spectrometer configured for **A**,**B**/**C**,
   - Detection function is very broad, syst. uncert. for **a** very demanding.

3. **aCORN**: goal is to measure $\mathbf{\Delta a/a \sim 0.5 - 2\,\%}$
   - Funded, under construction,
   - Uses only part of neutron decays.

4. **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,
   - Easier determination of detection function than in Nab at the present level of accuracy. Singles measurement!

Nab Measurement principles: Proton phase space

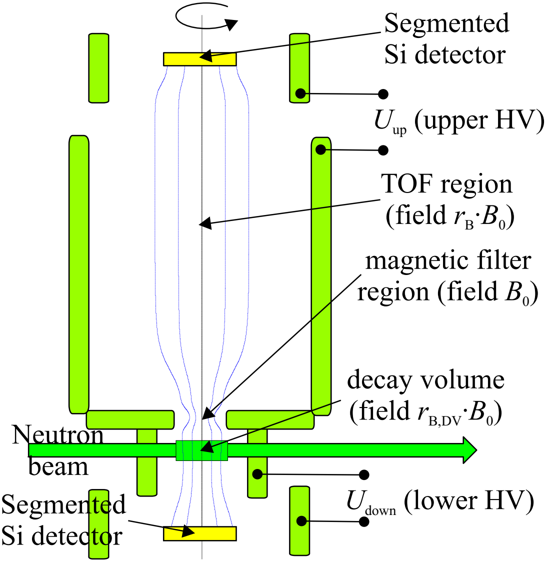


NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

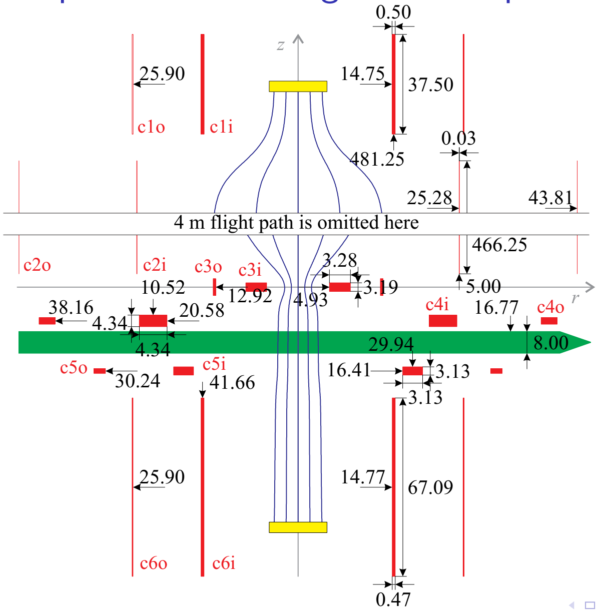
Slope = **a**

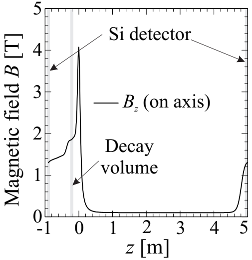
Nab principle of operation

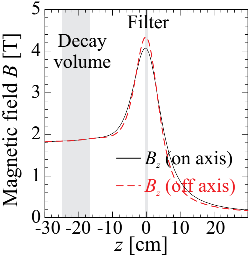
- Collect and detect both electron and proton from neutron beta decay (magnetic field, detectors at both ends)
- Measure electron energy and proton TOF and reconstruct decay kinematics (Magnetic field shape, silicon detectors at both ends).



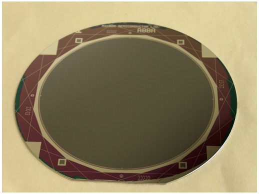
Nab spectrometer: magnetic field profile

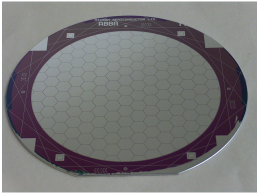


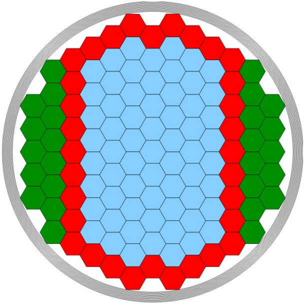


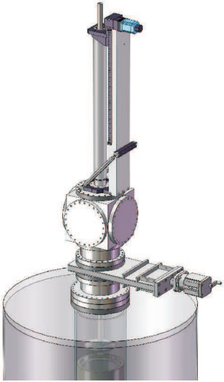


Si detector prototypes (15 cm diameter)





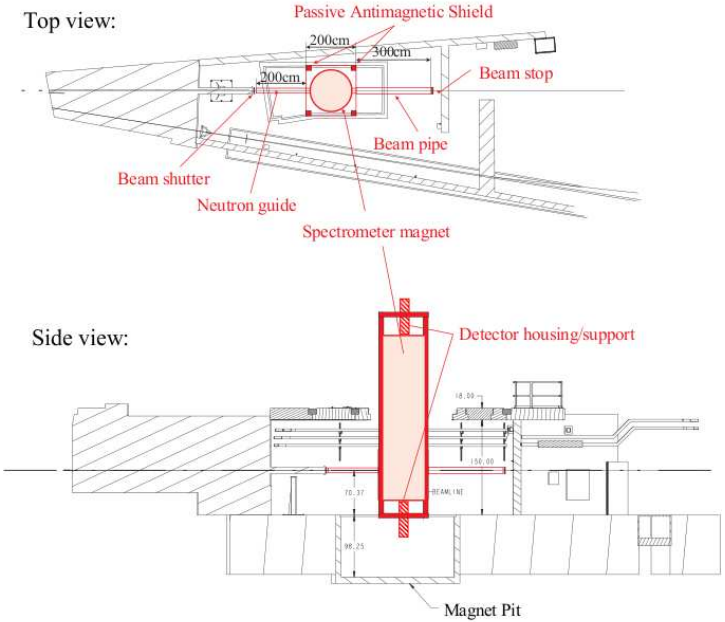




LANL group has full-size prototypes from Micron Corp.
Full thickness $\mathbf{t = 2}$ mm; dead layer thickness $\mathbf{t_d \leq 100}$ nm.
Detailed testing currently under way at LANL.

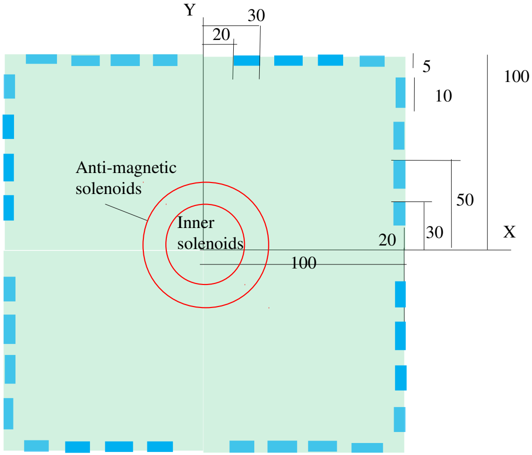
Nab setup (approximately to scale)

Spectrometer installation:

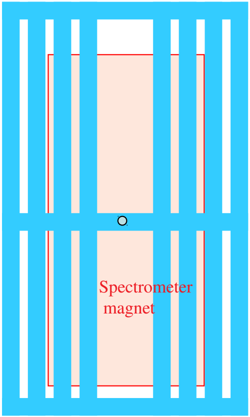


Nab anti-magnetic shield (AMS)

Top view:

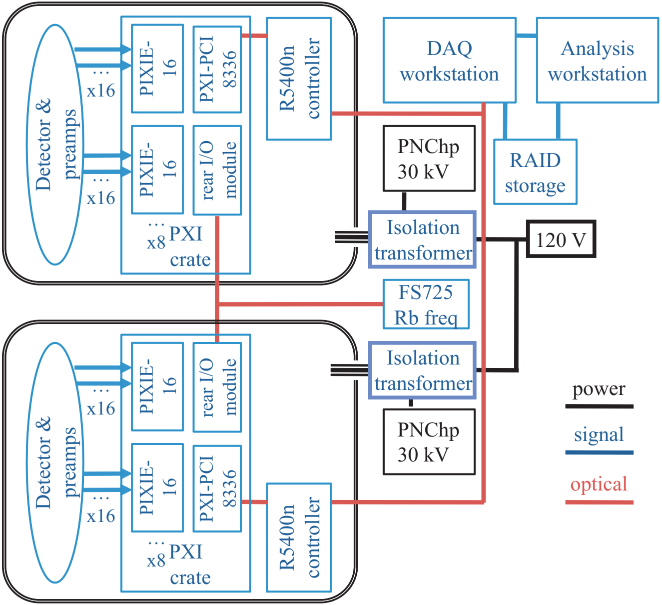


Side view:



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

	Milestone	Completion
0.a	Start of project	Jul 2011
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 Anti-Magnetic screen: magnetic design finished	Sep. 2012
2.	**Passive Anti-Magnetic 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**

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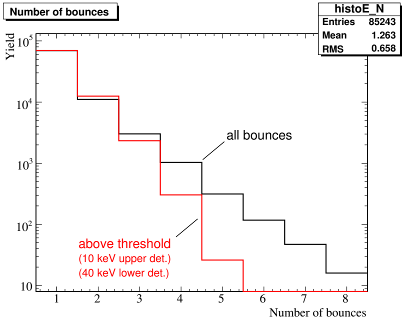
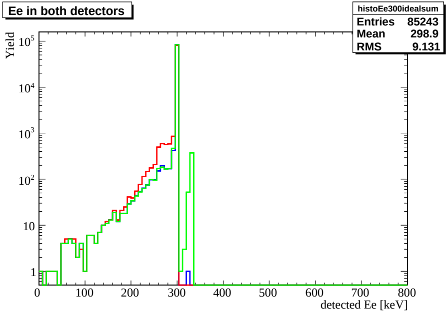
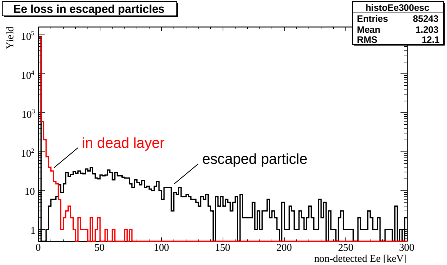
Home page: http://nab.phys.virginia.edu/

Additional slides

Electron energy response

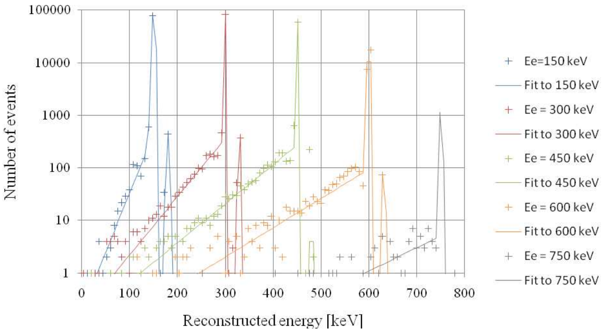




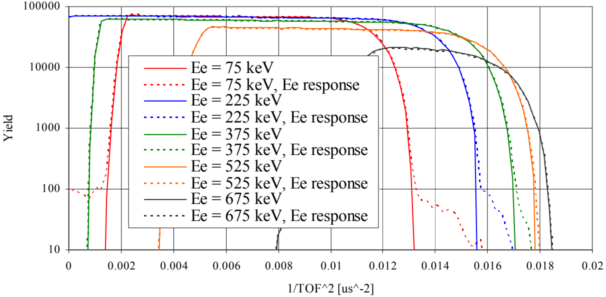


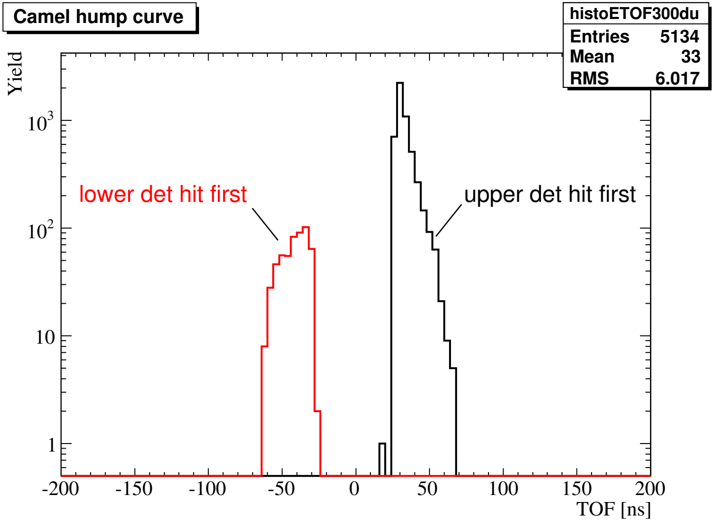
Detector response:

Electron energy



Proton TOF





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