The Nab Neutron Decay Correlation Experiment

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University of Virginia

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Outline

Experiment Basics
- Collaboration
- Motivation and Goals

Nab measurement principles
- Proton TOF and e-ν correlation
- Spectrometer design
- Detection function

Overview of uncertainties
- Event statistics, rates, running time
- Systematic uncertainties

Summary

Nab Collaboration

Arizona State University	R. Alarcon, S. Balascuta,
Los Alamos Nat'l. Lab.	A. Klein, W.S. Wilburn,
University of Manitoba	M.T. Gericke,
Univ. of New Hampshire	J.R. Calarco, F.W. Hersman,
North Carolina State U.	A. Young,
Oak Ridge Nat'l. Lab.	J.D. Bowman, T.V. Cianciolo, S.I. Penttilä, K.P. Rykaczewski, G.R. Young,
Univ. of South Carolina	V. Gudkov,
University of Tennessee	G.L. Greene, R.K. Grzywacz,
University of Virginia	L.P. Alonzi, S. Baeßler, M.A. Bychkov, E. Frlež, A. Palladino, D. Počanić.

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

Goals of the Experiment

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

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

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

  current results: **none**

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Neutron Decay Parameters (SM)

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

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

with:

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

$$B = 2 \frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2} \qquad D = 2 \frac{\mathrm{Im}(\lambda)}{1 + 3|\lambda|^2}$$

$\lambda = \frac{G_A}{G_V}$ (with $\tau_n \Rightarrow$ CKM V_{ud}) ($D \neq 0 \Leftrightarrow T$ inv. violation)

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

- Beta decay parameters constrain L-R symmetric model extensions to the SM. [Review: Herczeg, Prog. Part. Nucl. Phys. **46**, 413 (2001)]
- 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]
- Fierz interference term, never measured for the neutron, offers a sensitive test of non-$(V-A)$ terms in the weak Lagrangian (S, T).
- A general connections 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)]

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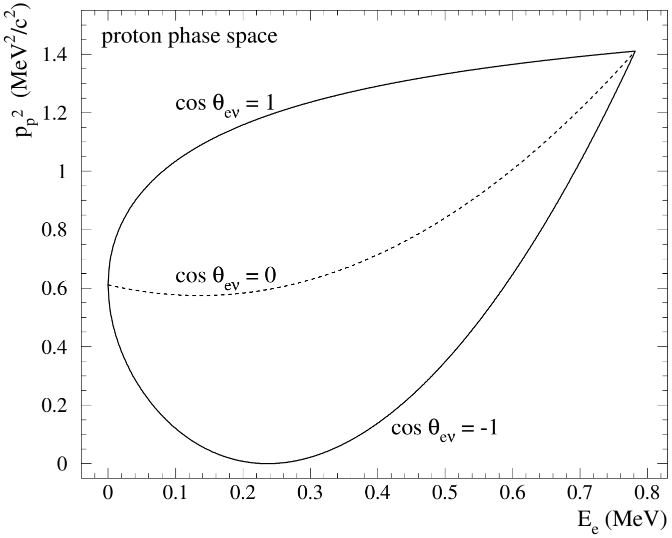
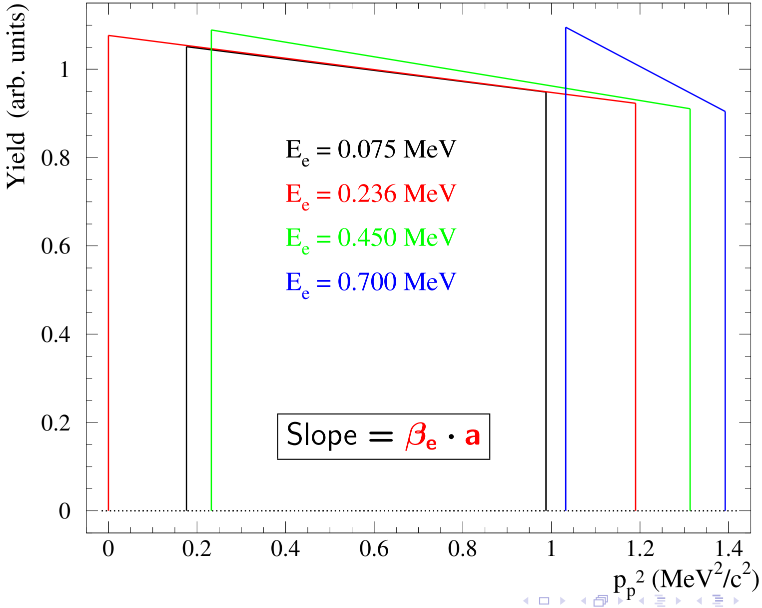
Nab Measurement principles: Proton phase space

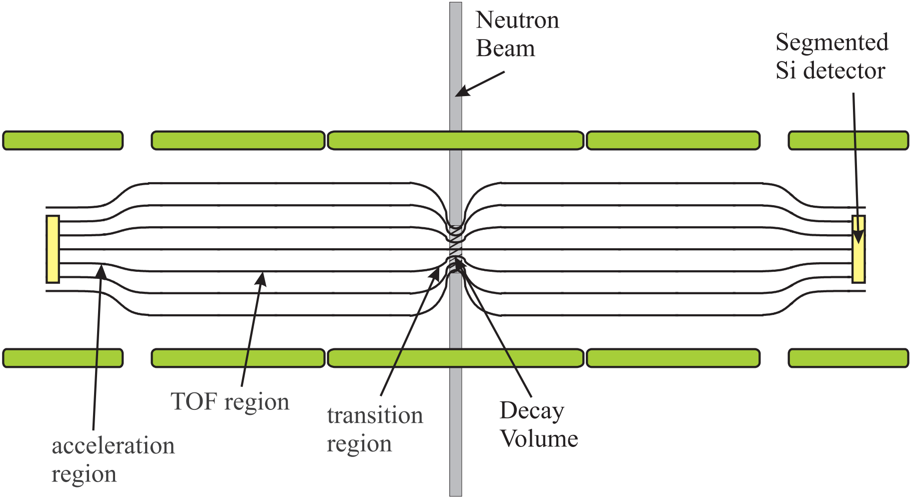


Note: For a given $\mathbf{E_e}$, $\cos\theta_{e\nu}$ is a function of $\mathbf{p_p^2}$ only.

Measurement principles: Proton momentum response

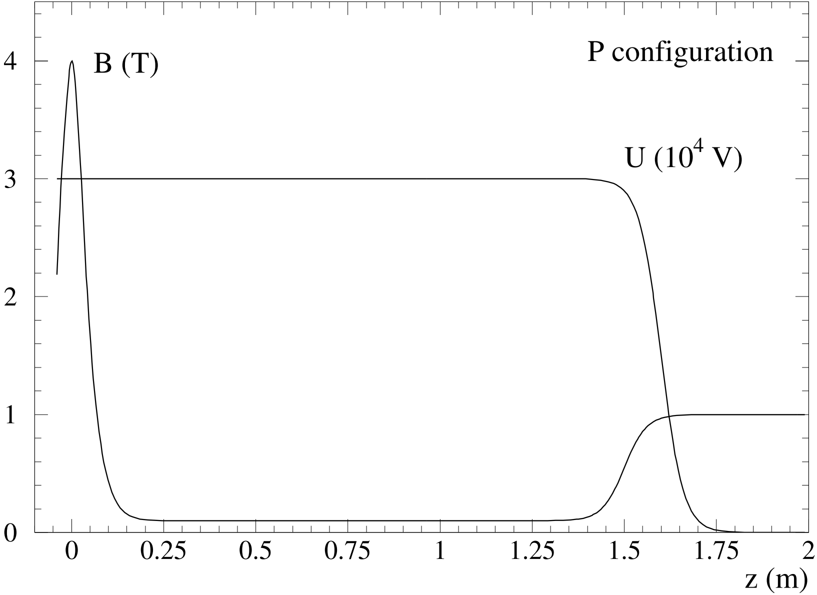


Measurement principles: Spectrometer sketch



Elements of spectrometer to be shared with other n decay experiments, e.g., **abBA**.

Measurement principles: Spectrometer field profiles



Measurement principles: Detection function (I)

Proton time of flight in B field:

$$t_{\rm p} = \frac{f(\cos\theta_{\rm p,0})}{p_{\rm p}} \qquad \text{where} \qquad \cos\theta_{\rm p,0} = \left.\frac{\vec{p}_{\rm p0}\cdot\vec{B}}{p_{\rm p0}B}\right|_{\text{decay pt.}} .$$

For an adiabatically expanding field

$$p_{{\rm p}z}(z) = p_{\rm p}\sqrt{1 - \frac{B(z)}{B_0}\sin^2\theta_{\rm p,0} - \frac{e(U(z)-U_0)}{T_0}}$$

so that, prior to acceleration,

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

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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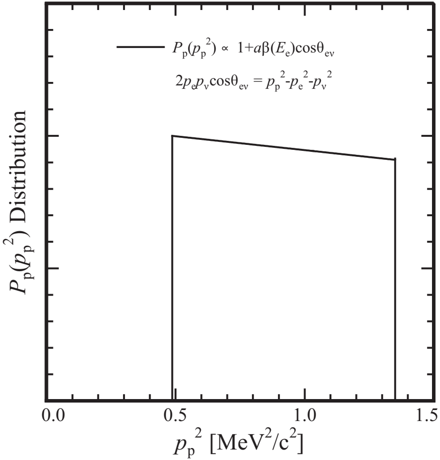
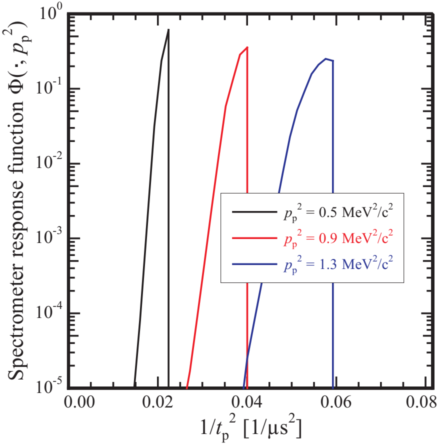
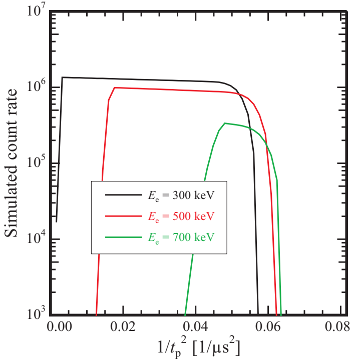
Measurement principles: Detection function (III)



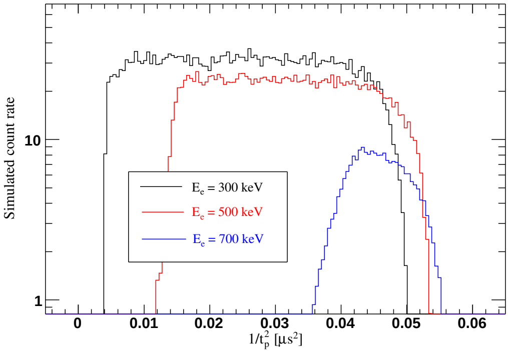


$E_e = 550\,\text{keV}$

Measurement principles: Detection function (IV)



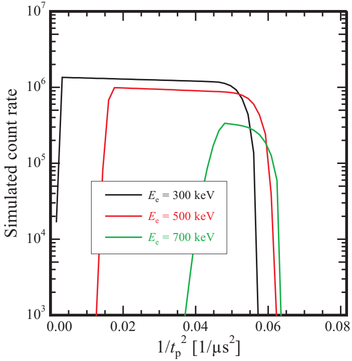
Theoretical calculation (method "B")



Realistic Monte Carlo simulation (1M decays, GEANT4)

Note: 1. central, straight portion sensitive to physics (a),
2. edges sensitive to detection function and calibration.

Measurement principles: Detection function (IV)



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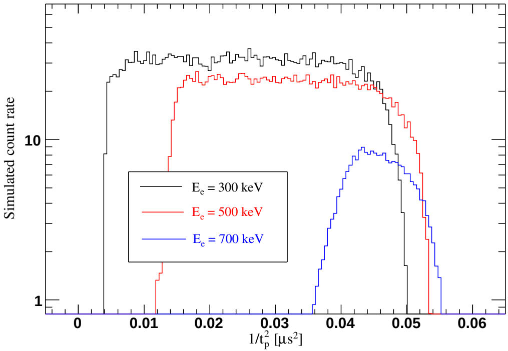

Realistic Monte Carlo simulation (1M decays, GEANT4)

Note:
1. central, straight portion sensitive to physics (**a**),
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Statistical uncertainties for **a** and **b**

Statistical uncertainties for **a**

$E_{\mathrm{e,min}}$	0	100 keV	100 keV	300 keV
$t_{\mathrm{p,max}}$	–	–	10 μs	10 μs
$\sigma_{\mathbf{a}}$	$2.4/\sqrt{N}$	$2.5/\sqrt{N}$	$2.6/\sqrt{N}$	$3.5/\sqrt{N}$
$\sigma_{\mathbf{a}}{}^{\dagger}$	$2.5/\sqrt{N}$	$2.6/\sqrt{N}$	–	–

† with $\mathbf{E_{cal}}$ and **l** variable.

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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σ_a †	$2.5/\sqrt{N}$	$2.6/\sqrt{N}$	–	–

† with $\mathbf{E}_{\mathrm{cal}}$ and **l** variable.

Statistical uncertainties for b

$E_{\mathrm{e,min}}$	0	100 keV	200 keV	300 keV
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Event rates, statistics and running times

FnPB **n** decay rate w/nominal 1.4 MW SNS operation: $r_n \simeq 19.5/(\mathrm{cm}^3\mathrm{s})$.

Nab fiducial volume is: $V_f \simeq 2 \times 2.5 \times 2\mathrm{cm}^3 = 20\,\mathrm{cm}^3$.

This gives a rate of about 400 evts./sec.

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 several samples of 10^9 events in several 6-week runs.

Consequently, overall accuracy will **not be statistics-limited**.

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Systematic uncertainties and checks

- Uncertainties due to spectrometer response
  - Neutron beam profile: 100 μm shift of beam center induces $\Delta a/a \sim 0.2\,\%$; cancels when averaging over detectors; measurement of asymmetry pins it down sufficiently;
  - Magnetic field map:
    field expansion ratio $r_{\mathrm{B}} = B_{\mathrm{TOF}}/B_0$;
    $\Delta a/a \sim 10^{-3} \Rightarrow \Delta r_{\mathrm{B}}/r_{\mathrm{B}} = 10^{-3}$, (use calibrated Hall probe);
    field curvature α, (via proton asymmetry measurement);
    field bumps $\Delta B/B$ must be kept below 2×10^{-3} level;
  - Flight path length: $\Delta l \leq 30\,\mu$m $\Rightarrow$ fitting parameter; ($\exists$ consistency check);
  - Homogeneity of the electric field;
  - Rest gas: requires vacuum of 10^{-9} torr or better;
  - Doppler effect;
  - Adiabaticity;

Systematic uncertainties and checks (II)

- Uncertainties due to the detector
  - Detector alignment;
  - Electron energy calibration: requirement 10^{-4}; we'll use radioactive sources, other strategies, also as fitting parameter;
  - Trigger hermiticity: affected by impact angle, backscattering, TOF cutoff (to reduce accid. bgd.);
  - TOF uncertainties;
  - Edge effects;
- Backgrounds
  - Neutron beam related background;
  - Particle trapping;
- Uncertainties in **b**: fewer than for **a** (no proton detection); dominant are energy calibration and electron backgrounds.

SUMMARY

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- Basic properties of the Nab spectrometer are well understood; details of the fields are under study in extensive analytical and Monte Carlo calculations.
- Elements of spectrometer will be shared with other neutron decay experiments, e.g., abBA.
- Development of abBA/Nab Si detectors is ongoing and remains a technological challenge.
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