

Nab: Measurement Principles, Apparatus and Uncertainties

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University of Virginia

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Outline

Experiment Basics

- Collaboration

- Motivation and Goals

Nab measurement principles

- Proton TOF and $e-\nu$ correlation

- Spectrometer design

- Detection function

Overview of uncertainties

- Event statistics, rates, running time

- Systematic uncertainties

Summary

Nab Collaboration

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

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

current results: -0.1054 ± 0.0055 Byrne et al '02
 -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

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Neutron Decay Parameters (SM)

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

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

with:

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

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

$$\lambda = \frac{G_A}{G_V} \quad (\text{with } \tau_n \Rightarrow \text{CKM } V_{ud})$$

$$(\mathbf{D} \neq 0 \Leftrightarrow \mathbf{T} \text{ inv. violation})$$

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n-decay Correlation Parameters Beyond V_{ud}

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- ▶ 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]
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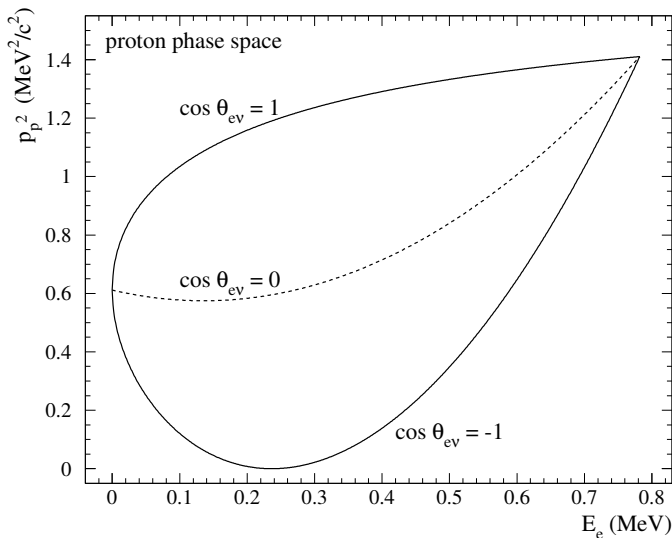
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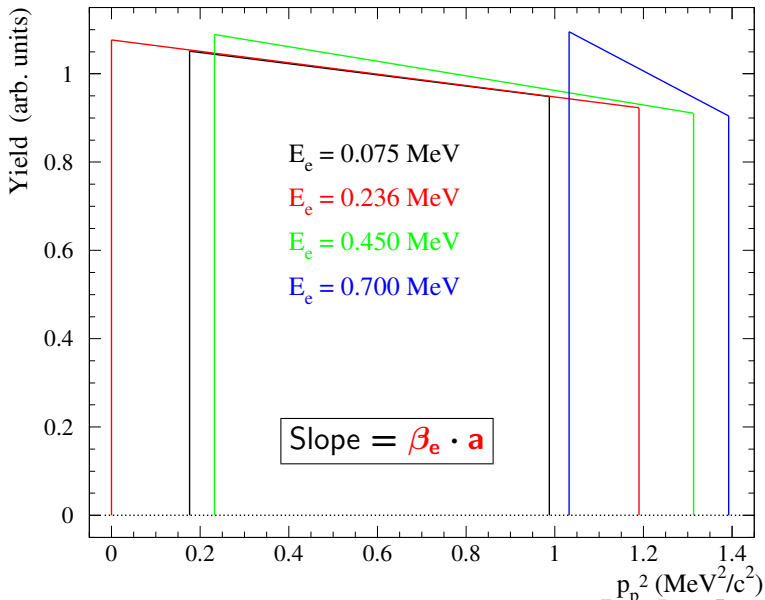
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Nab Measurement principles: Proton phase space

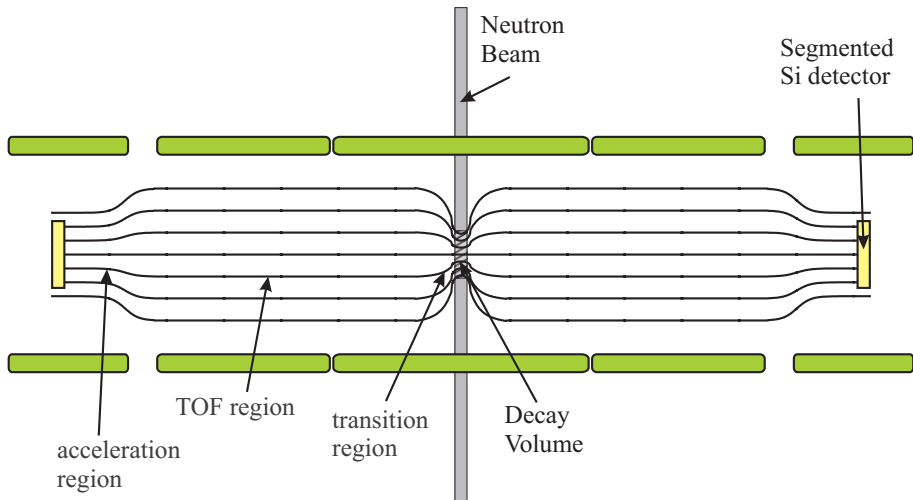


Note: For a given E_e , $\cos \theta_{e\nu}$ is a function of p_p^2 only.

Measurement principles: Proton momentum response

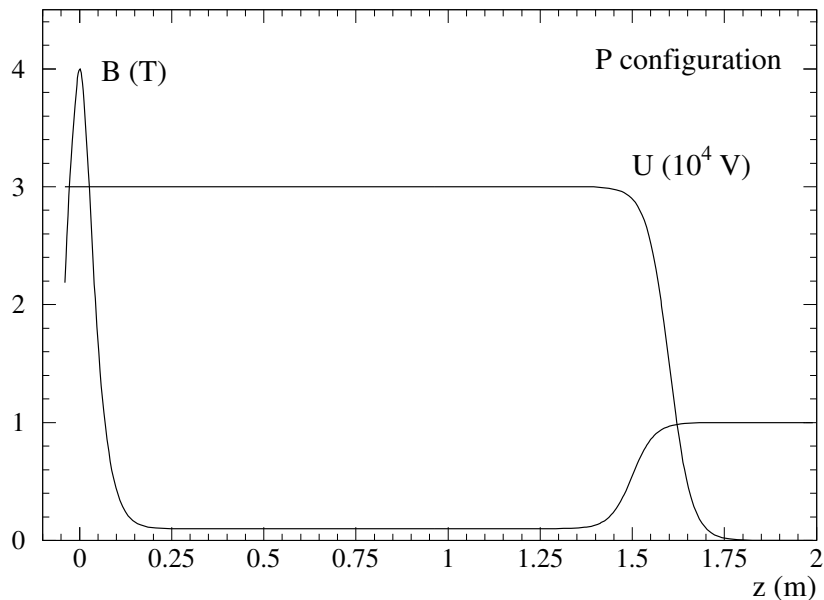


Measurement principles: Spectrometer sketch



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:

$$t_p = \frac{f(\cos \theta_{p,0})}{\rho_p} \quad \text{where} \quad \cos \theta_{p,0} = \frac{\vec{p}_{p0} \cdot \vec{B}}{\rho_{p0} B} \Big|_{\text{decay pt.}}$$

For an adiabatically expanding field

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

so that, prior to acceleration,

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

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

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

while

$$P_t\left(\frac{1}{t_p^2}\right) = \int P_p(p_p^2) \Phi\left(\frac{1}{t_p^2}, p_p^2\right) dp_p^2.$$

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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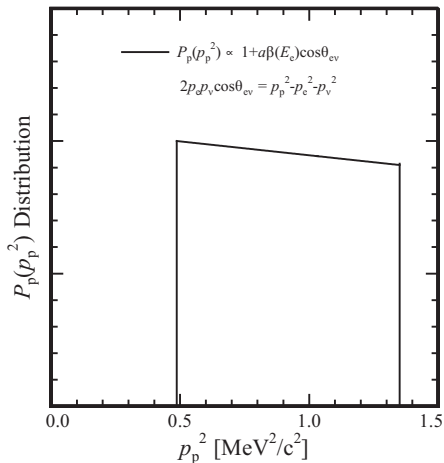
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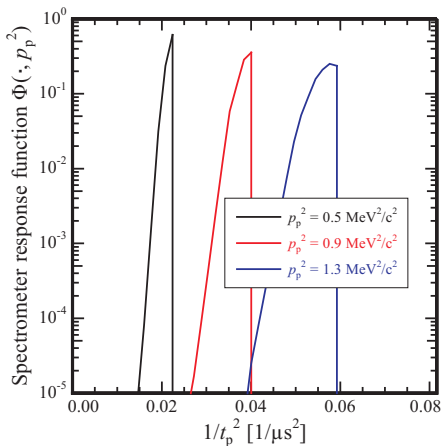
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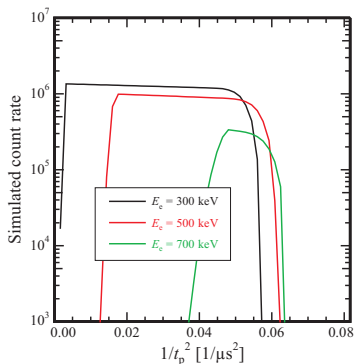
Measurement principles: Detection function (III)



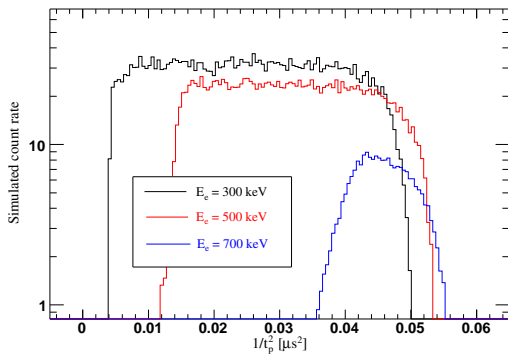
$E_e = 550$ keV



Measurement principles: Detection function (IV)



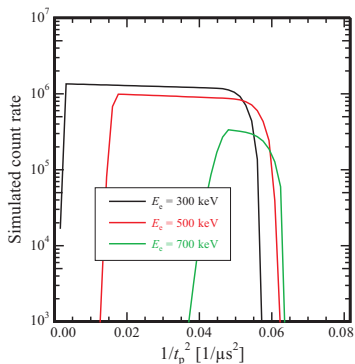
Theoretical calculation
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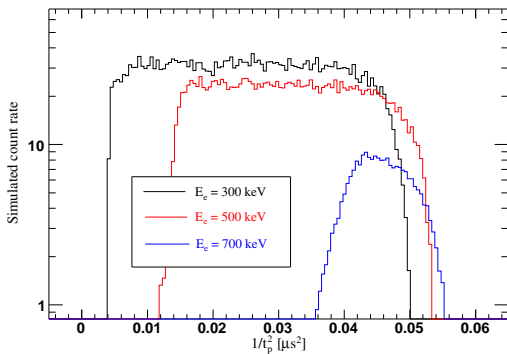
Realistic Monte Carlo simulation
(1M decays, GEANT4)

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

Statistical uncertainties for **a**

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

\dagger with E_{cal} and I variable.

Statistical uncertainties for **b**

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$\sigma_b^{\dagger\dagger}$	$7.7/\sqrt{N}$	$10.3/\sqrt{N}$	$16.3/\sqrt{N}$	$27.7/\sqrt{N}$

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Event rates, statistics and running times

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

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

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

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

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**: $100\ \mu\text{m}$ 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 $r_B = B_{\text{TOF}}/B_0$;
 $\Delta a/a \sim 10^{-3} \Rightarrow \Delta r_B/r_B = 10^{-3}$, (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**: $\Delta l \leq 30\ \mu\text{m} \Rightarrow$ 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.

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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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