Nab: a precise measurement of the *a* and *b* parameters in neutron decay

Dinko Počanić (for the Nab Collaboration)

University of Virginia

7th Workshop on Ultracold and Cold Neutron
Physics and Sources
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Outline

Goals of the Experiment

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

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

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

  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:

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

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

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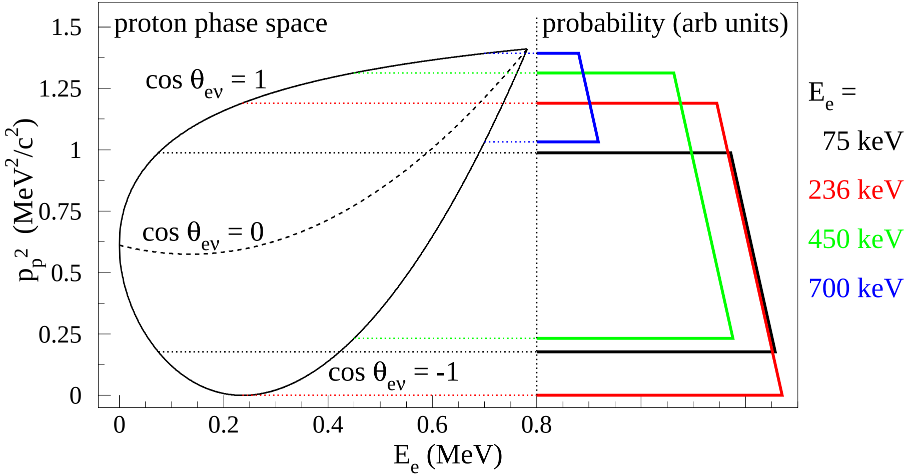
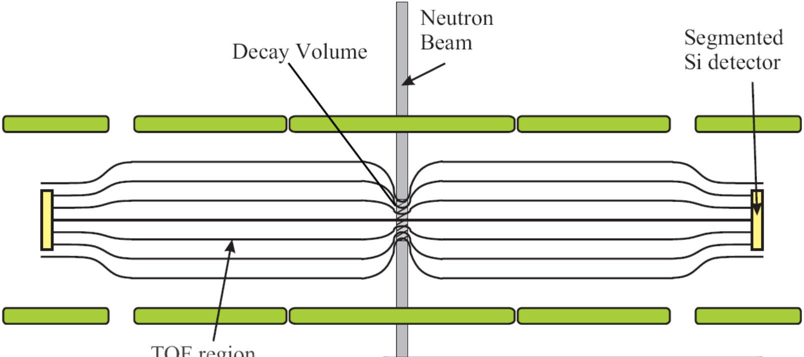
Nab Measurement principles: Proton phase space

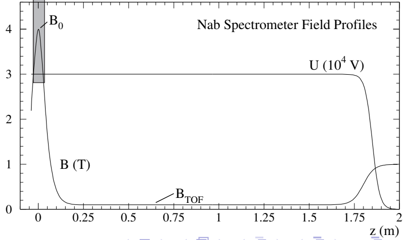


NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

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

Measurement principles: Symmetric pectrometer





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

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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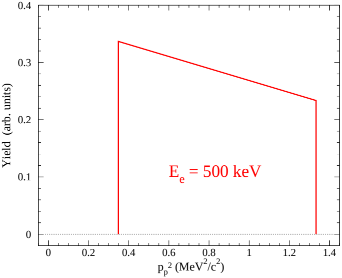

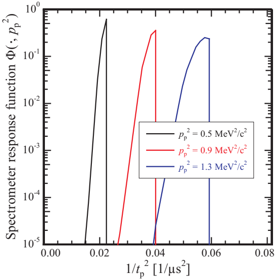

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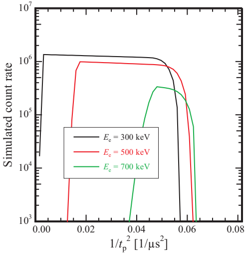

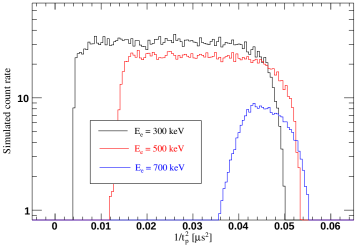

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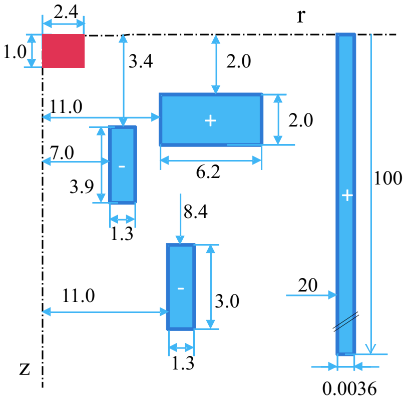
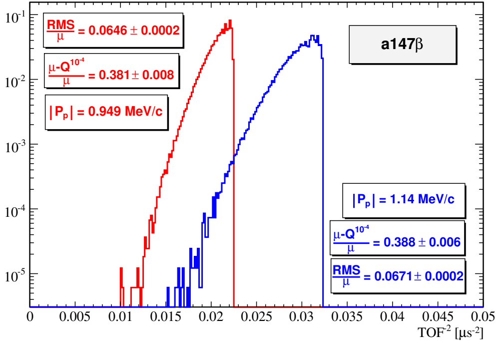
Optimized symmetric spectrometer



dimensions in cm

Current density: 3500 A/cm^2

The “a-147-beta” Configuration



Asymmetric spectrometer

Four serious challenges can be relieved in an asymmetric spectrometer:

- Achieving a long flight path for protons and, hence, high t_p (TOF) resolution,
- Achieving a high degree of proton momentum linearization, and, hence, accuracy of the p_p–t_p relationship (narrow detection function),
- Greatly reducing the sensitivity to particle trapping in small field imperfections in the neutron decay region, and
- Reducing the influence of small nonuniformities in electric potential from $\sim \mu$V level to a more controllable $\sim$mV level.

Key strategy:

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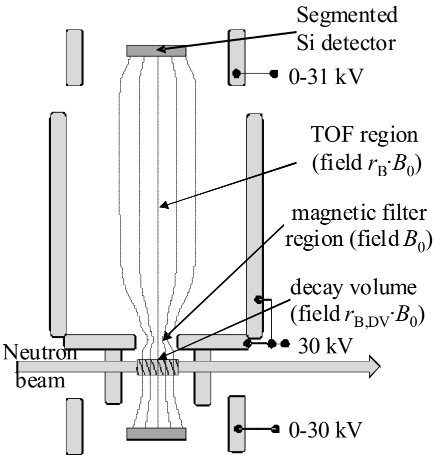
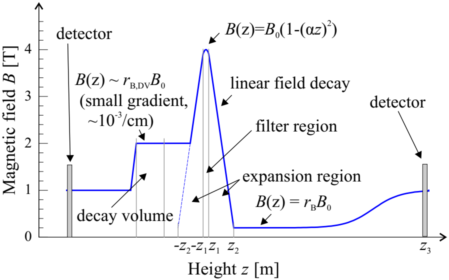
Basic design and features of an asymmetric Nab



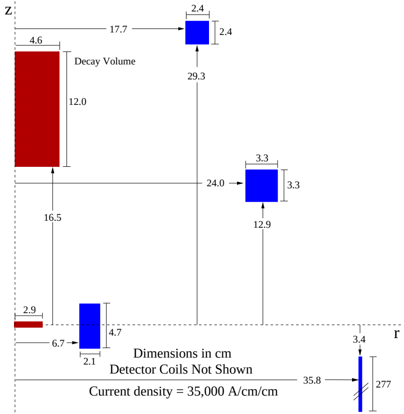
Stefan Baeßler, March 2009

Features:

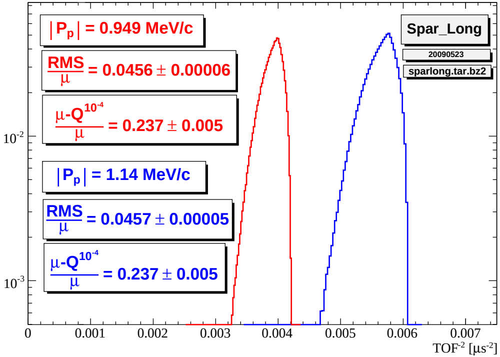
- long TOF above n beam,
- displaced magnetic $\cos\theta$ filter,
- no count rate penalty viz. symmetric Nab.



Asymmetric Nab: expected performance



The “`Simple Long`” Configuration

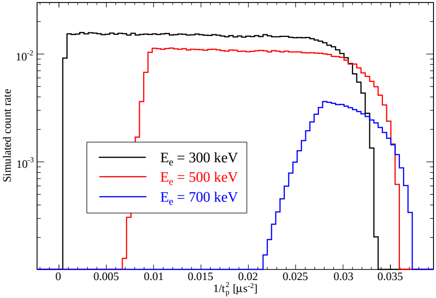


Compare w. symmetric `‘‘a-147b’’`:

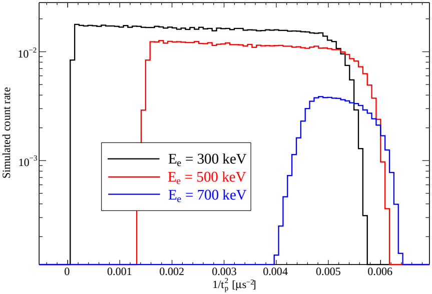
$$\frac{\text{RMS}}{\mu} \sim 0.065 \;/\; \frac{\mu - \text{Q}(10^{-4})}{\mu} \sim 0.38.$$

Asymmetric vs. symmetric Nab performance

The “`a-147-beta`” Symmetric Configuration



The “`Simple Long`” Asymmetric Configuration



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

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$E_{\rm e,min}$	0	100 keV	100 keV	300 keV
$t_{\rm p,max}$	–	–	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 $\mathbf{l}$ variable.

Statistical uncertainties for **b**

$E_{\rm e,min}$	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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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: $V_f \simeq \frac{\pi}{2} 2.4^2 \times 2\mathrm{cm}^3 \simeq 18\,\mathrm{cm}^3$.

This gives a rate of about $\boxed{350\,\text{evts./s}}$.

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 several samples of $\mathbf{10^9}$ events in several 6-week runs.

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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: $V_f \simeq \frac{\pi}{2} 2.4^2 \times 2\mathrm{cm}^3 \simeq 18\,\mathrm{cm}^3$.

This gives a rate of about $\boxed{350\,\text{evts./s}}$.

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 several samples of $\mathbf{10^9}$ events in several 6-week runs.

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

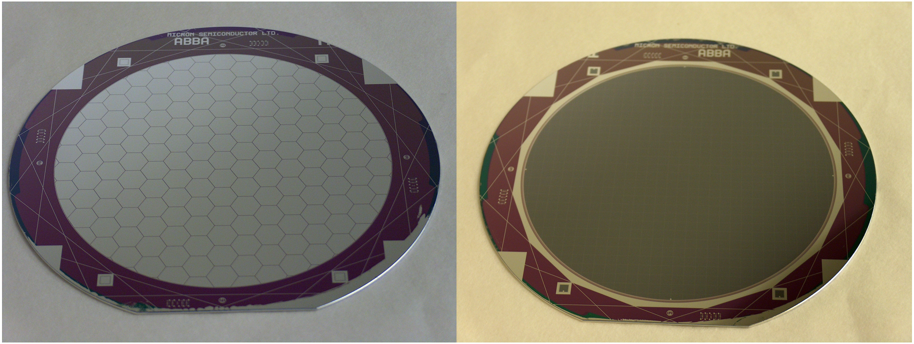
Systematic uncertainties and checks

- 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.

Si detector prototypes (15 cm diameter)



Front face (junction side)

Back face (ohmic side—readout)

(from Scott Wilburn)

SUMMARY

Nab plans a simultaneous high-statistics measurement of neutron decay parameters **a** and **b** with $\boxed{\mathbf{\Delta a/a \simeq 10^{-3}} \text{ and } \mathbf{\Delta b \simeq 3 \times 10^{-3}}}$.

- Basic properties of the symmetric Nab spectrometer are well understood and highly optimized.
- The new asymmetric Nab idea looks very promising; details are under extensive analytical and Monte Carlo study.
- Elements of spectrometer may be shared with other neutron decay experiments, e.g., abBA.
- Development of abBA/Nab Si detectors is ongoing and remains a technological challenge.
- Experiment received approval in Feb. 2008; could be ready for commissioning sometime in 2011/12.

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The Nab collaboration

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