The Nab Neutron Decay Correlation Experiment

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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

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University of Manitoba  M.T. Gericke,
Univ. of New Hampshire  J.R. Calarco, F.W. Hersman,
North Carolina State U.  A. Young,
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                    K.P. Rykaczewski, G.R. Young,
Univ. of South Carolina V. Gudkov,
University of Tennessee  G.L. Greene, R.K. Grzywacz,
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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: $-0.1054 \pm 0.0055$ Byrne et al '02
  $-0.1017 \pm 0.0051$ Stratowa et al '78
  $-0.091 \pm 0.039$ Grigorev et al '68

- Measure the Fierz interference term $b$ in neutron decay with accuracy of $\Delta b \simeq 3 \times 10^{-3}$
  
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Neutron Decay Parameters (SM)

\[
\frac{dw}{dE_e dΩ_e dΩ_ν} \simeq k_e E_e (E_0 - E_e)^2
\]

\[
\times \left[ 1 + a \frac{\vec{k}_e \cdot \vec{k}_ν}{E_e E_ν} + b \frac{m}{E_e} + \langle \vec{σ}_n \rangle \cdot \left( A \frac{\vec{k}_e}{E_e} + B \frac{\vec{k}_ν}{E_ν} + D \frac{\vec{k}_e \times \vec{k}_ν}{E_e E_ν} \right) \right]
\]

with:

\[
a = \frac{1 - |λ|^2}{1 + 3|λ|^2}
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A = -2 \frac{|λ|^2 + \text{Re}(λ)}{1 + 3|λ|^2}
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D = 2 \frac{\text{Im}(λ)}{1 + 3|λ|^2}
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\[
λ = \frac{G_A}{G_V} \quad (\text{with } τ_n \Rightarrow \text{CKM } V_{ud})
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(D \neq 0 \Leftrightarrow T \text{ inv. violation})
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D. Počanić (UVa)
n-decay Correlation Parameters Beyond $V_{ud}$

- 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.  

- 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 $d \rightarrow ue\bar{\nu}$ and limits on $\nu$ masses.  
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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

\[ p^2 (\text{MeV}^2/c^2) \]

\[ \text{Yield (arb. units)} \]

\[ E_e = 0.075 \text{ MeV} \]
\[ E_e = 0.236 \text{ MeV} \]
\[ E_e = 0.450 \text{ MeV} \]
\[ E_e = 0.700 \text{ MeV} \]

Slope = \( \beta_e \cdot a \)
Measurement principles: Spectrometer sketch

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

D. Počanić (UVa)
Measurement principles: Spectrometer field profiles
Measurement principles: Detection function (I)

Proton time of flight in $B$ field:

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

For an adiabatically expanding field

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

so that, prior to acceleration,

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

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

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

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 \( \Phi \) relates the proton momentum and time-of-flight distributions! To extract a reliably:

- \( \Phi \) must be as narrow as possible,
- \( \Phi \) must be understood very precisely.

Two methods ("A" and "B") pursued to specify \( \Phi \).
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Measurement principles: Detection function (III)

\[ P_p(p_p^2) \propto 1 + a \beta(E_e) \cos \theta_{ev} \]
\[ 2p_p p_\nu \cos \theta_{ev} = p_p^2 - p_e^2 - p_\nu^2 \]

\[ E_e = 550 \text{ keV} \]
Measurement principles: Detection function (IV)

Theoretical calculation (method “B”)

Realistic Monte Carlo simulation (1 M 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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Statistical uncertainties for \( a \) and \( b \)

### Statistical uncertainties for \( a \)

<table>
<thead>
<tr>
<th>( E_{e,\text{min}} )</th>
<th>0</th>
<th>100 keV</th>
<th>100 keV</th>
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</tr>
</thead>
<tbody>
<tr>
<td>( t_{p,\text{max}} )</td>
<td>–</td>
<td>–</td>
<td>10 ( \mu \text{s} )</td>
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<tr>
<td>( \sigma_a )</td>
<td>2.4/\sqrt{N}</td>
<td>2.5/\sqrt{N}</td>
<td>2.6/\sqrt{N}</td>
<td>3.5/\sqrt{N}</td>
</tr>
<tr>
<td>( \sigma_a^\dagger )</td>
<td>2.5/\sqrt{N}</td>
<td>2.6/\sqrt{N}</td>
<td>–</td>
<td>–</td>
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</tbody>
</table>

\( \dagger \) with \( E_{\text{cal}} \) and \( l \) variable.

### Statistical uncertainties for \( b \)

<table>
<thead>
<tr>
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<tr>
<td>( \sigma_b )</td>
<td>7.5/\sqrt{N}</td>
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<td>( \sigma_b^{\dagger\dagger} )</td>
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### Statistical uncertainties for a and b

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$\sigma_a$

2.4/$\sqrt{N}$

2.5/$\sqrt{N}$

2.6/$\sqrt{N}$

3.5/$\sqrt{N}$

$\sigma_a^{\dagger}$

2.5/$\sqrt{N}$

2.6/$\sqrt{N}$

–

–

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

#### Statistical uncertainties for b

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\( ^{\dagger\dagger} \) with \( E_{\text{cal}} \) variable.
Event rates, statistics and running times

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

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

This gives a rate of about $400\text{ evts./sec}$.

In a typical $\sim 10$-day run of $7 \times 10^5\text{ s}$ of net beam time we would achieve

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

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 $r_B = B_{TOF}/B_0$;
    - $\Delta a/a \sim 10^{-3} \Rightarrow \Delta r_B/r_B = 10^{-3}$, (use calibrated Hall probe);
    - field curvature $\alpha$, (via proton asymmetry measurement);
    - field bumps $\Delta B/B$ must be kept below $2 \times 10^{-3}$ 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.
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$$\frac{\Delta a}{a} \simeq 10^{-3} \quad \text{and} \quad \Delta b \simeq 3 \times 10^{-3}.$$ 

- 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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