Progress at Los Alamos: the Current Status of UCN and CN Beta-decay Studies

A. R. Young
Outline

• UCNA/UCNB
• Nab
• UCNτ
• One slide on $^{19}\text{Ne}$
UCNA, UCNB
Consistent interpretation of extracted UCN density in LANL production source...

(C. Morris) Predicted: $107 \pm 20$ UCN/$\mu$C/cm$^3$
Internal det: $85 \pm 10$ UCN/$\mu$C/cm$^3$

2010:
V: $52 \pm 9$ UCN/cm$^3$
Mon: $79 \pm 16$ UCN/cm$^3$

Cold flux: Ar activation
UCN flux: V foil activation
Planned LANL UCN source improvements

- Feb. 2014 production tests establish capability to increase proton current 6 → 10 uA. Beam timing also can be optimized to reduce losses (up to another factor 1.8 gain)

- LDRD source upgrade, planned increase of at least a factor of 3 in production (T. Ito)

- Without upgrade, UCNA baseline roughly 50 Hz, UCNτ roughly $10^5$ n/load
$A \propto \frac{\sqrt{R - 1}}{\sqrt{R + 1}}$, where \( R = \frac{N_1^+ N_2^-}{N_2^+ N_1^-} \) is a "super-ratio"
The UCNA and UCNT Experiments at Los Alamos

\[ A_0 = 0.11972(55)_{\text{stat}}(98)_{\text{syst}} \]

<table>
<thead>
<tr>
<th>Systematic</th>
<th>corr. (%)</th>
<th>unc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>+0.67</td>
<td>±0.56</td>
</tr>
<tr>
<td>( \Delta_{\text{backscattering}} )</td>
<td>+1.36</td>
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<td>( \Delta_{\text{angle}} )</td>
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<td>( \epsilon_{\text{MWPC}} )</td>
<td>+0.12</td>
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</tr>
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<td>Muon veto efficiency</td>
<td></td>
<td>±0.03</td>
</tr>
<tr>
<td>UCN-induced background</td>
<td>+0.01</td>
<td>±0.02</td>
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<tr>
<td>( \sigma_{\text{statistics}} )</td>
<td></td>
<td>±0.46</td>
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<tr>
<th>Theory contributions</th>
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Pushing Down the Limits: 2014 and beyond…

### Polarimetry

2010 method calibrated, but required MC corrections:
- add shutter, remove MC corrections

### Scattering corrections

- Backscattering limited by foils:
  - reduce areal density

### Energy Reconstruction

- Add more conversion sources,
  - Xe position-dependent gain maps, LED pulser

#### Table: Systematic Uncertainties

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2011/2012: 57 M decays -- targeting better than 0.6% precision
2014: improving rate for final UCNA in this configuration
## Projected UCNA Error Budget

Preliminary estimates…

<table>
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<tr>
<th>Uncertainty (%)</th>
<th>Mendenhall (2013)</th>
<th>In analysis (TBS 8/14)</th>
<th>Next Step</th>
<th>Source of improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>+/- 0.46</td>
<td>+/- 0.40</td>
<td>+/- 0.28</td>
<td>Decay rate!</td>
</tr>
<tr>
<td>Depolarization</td>
<td>+0.67 +/- 0.56</td>
<td>+0.7 +/- 0.1</td>
<td>+0.7 +/- 0.1</td>
<td>Shutter+ ex situ</td>
</tr>
<tr>
<td>Backscatter</td>
<td>+1.36 +/- 0.34</td>
<td>+0.56 +/- 0.15</td>
<td>+0.56 +/- 0.15</td>
<td>Thin windows</td>
</tr>
<tr>
<td>Angle effect</td>
<td>-1.21 +/- 0.30</td>
<td>-0.8 +/- 0.2</td>
<td>-0.8 +/- 0.1</td>
<td>Windows+APD</td>
</tr>
<tr>
<td>Energy Reconstruction</td>
<td>+/- 0.31</td>
<td>+/- 0.08</td>
<td>+/- 0.08</td>
<td>Xenon + LED</td>
</tr>
<tr>
<td>Total Sys.</td>
<td>+/- 0.82</td>
<td>+/- 0.28</td>
<td>+/- 0.22</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>+/- 0.94</td>
<td>+/- 0.5</td>
<td>+/- 0.35</td>
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Statistics: 0.28% requires 150x10^6 raw decays @100 Hz, 50% duty factor, requires 13 weekends, or ~one full run cycle (But could be split over multiple cycles)
Path Forward for UCNA

Fall 2014:

- Complete analysis of 2011/2013 data (target of end of year for unblinding)
- Install replacement guide
- Investigate impact of switcher to share beam with UCNτ
- **Conduct rate test to confirm gains**

Take first opportunity for “final data run” once statistics are available…
The UCNA Collaboration

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Indiana University
A. T. Holley, C.-Y. Liu, D. Salvat
Institut Laue-Langevin
P. Geltenbort
Los Alamos National Laboratory
Michigan State University
C. Wrede
North Carolina State University/TUNL
A. R. Young (co-spokesperson), B. A. Zeck
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Texas A&M University
D. Melconian
University of California, Los Angeles
K. P. Hickerson
University of Kentucky
M. Brown, S. Hasan, B. Plaster
University of Winnipeg
J. W. Martin
Virginia Polytechnic Institute and State University
X. Ding, M. L. Pitt, R. B. Vogelaar
UCNB: Accessing $b$ and $b_v$

\[
\frac{dW}{d\Omega_e d\Omega_v dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_v}{E_e E_v} + b \frac{m_e}{E_e} + \left\langle \frac{\vec{J}_n}{J_n} \right\rangle \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_v}{E_v} + D \frac{\vec{p}_e \times \vec{p}_v}{E_e E_v} \right) \right]
\]

spectrum

[U.S., Nab exp’t $\sim 0.003$]

[UCNB, $B \sim 10^{-3}$]

“Classic” Method for $B$:

\[
B_{\text{exp}}(E_e) = \frac{Q_{--}(E_e) - Q_{++}(E_e)}{Q_{--}(E_e) + Q_{++}(E_e)}
\]

\[
\propto B_0 + \frac{m_e}{E_e} \left[ \frac{1 + 3\lambda^2}{2\lambda(1+\lambda)} b_v^{\text{BSM}} - b^{\text{BSM}} \right] \approx b_v^{\text{BSM}} - b^{\text{BSM}}
\]

Measure $e$-$p$ coincidences w/ polarized neutrons
Analysis: How to directly measure $b_\nu$

Measure:
- proton asymmetry
- electron asymmetry

Differential Analysis:

\[ 1 \times 10^8 \beta\text{-Decay Events} \]
0–750 keV Fit Window
\[ b_\nu < 0.0031 \text{ at } 68\% \text{ C.L.} \]
\[ \chi^2/\nu = 72.1/74; \text{ Prob} = 0.54 \]

Integral Analysis:

\[ \langle \alpha_p \rangle = \frac{\int dE_e w_s(E_e) \left(Q_+^p \right) - \int dE_e w_s(E_e) \left(Q_-^p \right)}{\int dE_e w_s(E_e) \left(Q_-^p \right) + \int dE_e w_s(E_e) \left(Q_+^p \right)} \]

\[ \langle \alpha_e \rangle = \frac{\int dE_e w_s(E_e) \left(Q_+^e \right) - \int dE_e w_s(E_e) \left(Q_-^e \right)}{\int dE_e w_s(E_e) \left(Q_-^e \right) + \int dE_e w_s(E_e) \left(Q_+^e \right)} \]

\~0.3\sigma \text{ sensitivity to } b_\nu = 10^{-3} \text{ with } N = 1 \times 10^8

Additional advantage: removes leading order dependence on polarization and detector efficiency (Mostovoi et al, Phys. Atomic Nucl. 64, 1955 (2001)).—need to integrate with other e-p coincidence and spectrum measurements for best sensitivity!

B. Plaster, S. Sjue and A.R. Young, in preparation
Experimental strategy is similar to that carried out by PERKEO II, measure same-hemisphere electron-proton coincidences:

\[ B_{\text{exp}} = \frac{N^{--}(E) - N^{++}(E)}{N^{--}(E) + N^{++}(E)} \]  

(use super-ratio)
UCNB Current status

- Detector development integrated into Nab R&D
- Decay trap and electrode development ongoing -- updated error budget under development
- Fall 2014: Configure two full detectors with pixels “ganged” nominally in groups of 6
- Investigate running modes and full error budget for specific goal of high precision beta-spectroscopy as soon as possible (potentially this run cycle)
Nab apparatus in FnPB

Apparatus extends:
- \(~6\) m above beam height,
- \(~2\) m below beam height (existing pit).

Designed to accomplish the goals of Nab:

Measure: \(\frac{\Delta a}{a} \simeq \frac{3 \times 10^{-3}}{10^{-3}}\) and \(\Delta b \simeq 3 \times 10^{-3}\).
Nab principles of operation

- Collect and detect both electron and proton from n decay.
- Measure $E_e$ and $TOF_p$ and reconstruct decay kinematics

\[
P_p(p_p^2) = \begin{cases} 
1 + a \beta \frac{p_e^2 - p_n^2 - p_p^2}{2p_e p_n} & \text{where } \left| \frac{p_e^2 - p_n^2 - p_p^2}{2p_e p_n} \right| < 1 \\
0 & \text{otherwise}
\end{cases}
\]
Analysis strategy

- Use edges to determine and verify shape of detection function $\Phi(1/t_p^2, p_p^2)$;

- Use central part of $P_t(1/t_p^2)$ ($\sim 70\%$) to extract $a$.

Proportional to $p_p^2$
Electron-neutrino asymmetry error budget

>500 Hz expected, necessary statistics (0.07%) available in less than 2 mo.

**Nab systematic uncertainties:** Method B

<table>
<thead>
<tr>
<th>Experimental parameter</th>
<th>((\Delta a/a)_{\text{Syst}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field: curvature at pinch</td>
<td>(5 \times 10^{-4})</td>
</tr>
<tr>
<td>ratio (r_B = B_{\text{TOF}}/B_0)</td>
<td>(2.5 \times 10^{-4})</td>
</tr>
<tr>
<td>ratio (r_{B,\text{DV}} = B_{\text{DV}}/B_0)</td>
<td>(3 \times 10^{-4})</td>
</tr>
<tr>
<td>(L_{\text{TOF}}), length of TOF region</td>
<td>(*)</td>
</tr>
<tr>
<td>(U) inhomogeneity: in decay / filter region</td>
<td>(5 \times 10^{-4})</td>
</tr>
<tr>
<td>in TOF region</td>
<td>(1 \times 10^{-4})</td>
</tr>
<tr>
<td>Neutron beam: position</td>
<td>(4 \times 10^{-5})</td>
</tr>
<tr>
<td>width</td>
<td>(2.5 \times 10^{-4})</td>
</tr>
<tr>
<td>Doppler effect</td>
<td>small</td>
</tr>
<tr>
<td>unwanted beam polarization</td>
<td>small</td>
</tr>
<tr>
<td>Adiabaticity of proton motion</td>
<td>(1 \times 10^{-4})</td>
</tr>
<tr>
<td>Detector effects: (E_e) calibration</td>
<td>(*)</td>
</tr>
<tr>
<td>(E_e) resolution</td>
<td>(5 \times 10^{-4})</td>
</tr>
<tr>
<td>Proton trigger efficiency</td>
<td>(2.5 \times 10^{-4})</td>
</tr>
<tr>
<td>Accidental coinc’s ((\text{will subtract out of time coinc}))</td>
<td>small</td>
</tr>
<tr>
<td>Residual gas</td>
<td>ongoing parametric studies</td>
</tr>
<tr>
<td>Background</td>
<td>ongoing parametric studies</td>
</tr>
<tr>
<td>Overall sum</td>
<td>(1 \times 10^{-3})</td>
</tr>
</tbody>
</table>

(*) Free fit parameter

“b” error budget under development, anticipate less than 0.3% uncertainty
FNPB flux is well understood
# Notional FNPB Experimental Program

(as presented Aug, 2013)

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
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<tbody>
<tr>
<td>R&amp;D / Construct</td>
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<tr>
<td></td>
<td>SNS β-Decay Correlation Magnet</td>
<td>Nab</td>
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<td>Cold Setup</td>
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<td>n³He</td>
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<td>Nab</td>
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<td>Cold Ops</td>
<td>ndγ</td>
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Nab/UCNB Development

- Large area Si detectors the key to high precision $\beta$-spectroscopy and proton detection: 2mm thick, 127 pixels, $\sim$15 cm diam

- Development program underway at LANL

- Used TUNL, low energy proton beam for first evaluation of proton detection sensitivity (A. Salas-Bacci et al., Nuclear Instruments and Methods in Physics Research A 735 (2014) 408–415)

- Si detector response function studies (determine energy-angle response from point sources – S. Sjue et al, submitted)
Research and Development: Detector Mount for Cooling and Acceleration Bias

Acceleration Electrode: -30 kV

Cooling lines (currently 180K)
Research and Development: 2013 Running
(24 channels Instrumented)
Status: 2014

Detectors

Runs in October 2013 and January 2014
• 24 channels instrumented
• Intermittent LN2 cooling used
• Example of thresholds for properly working channel: ~15 keV
• Example of resolution for properly working channel: ~2.5 keV
• Proton-electron coincidences detected (analysis ongoing)
• Pogo-pin tests complete

Nab construction

• Full Nab DAQ ordered, NI PXIe-5171R: 254 chans of 250 Ms/s, 14 bit fADC (with low-level trigger filter capability)
• Magnet ordered
UCN\textsubscript{T}
Analysis: Lifetime consistency check

- Compare measured and predicted n lifetime (using $0^+ \rightarrow 0^+$ vector coupling and $\lambda$ from angular correlations)
- Indep. of (V,A) extensions, do not need to fit for $\lambda$
- Errata required for publication (thanks to K. Vos at RUG)

\[
\frac{1}{\tau_n} - \frac{1}{\tau_{0^+}} = \frac{1}{\tau_n} - K(G_F V_{ud})_m^2 (1+3\lambda m^2) f_n (1+\Delta_r) = \kappa b_n - \alpha b_{0^+}
\]

Measured n decay rate
Predicted n decay rate using $0^+ \rightarrow 0^+$ for $(G_F V_{ud})$

\[
\lambda \text{ extracted from angular corr meas (depends on } b_n)\]

Difference comes only from non-zero Fierz terms!

Use limits for $g_S$, Solve for $g_T$:

\[-4.0 \times 10^{-3} < C_T/C_A < 2.6 \times 10^{-3}\]

(limited at present by unc in $\lambda$)

UCN$\tau$: Magneto-Gravitational Trap

- **Avoid material loss (magnetic trap):** Halbach array of permanent magnets along trap floor repels spin polarized neutrons.

- **Minimize UCN spin-depolarization loss:** EM Coils arranged on the toroidal axis generates holding $B$ field throughout the trap (perpendicular to the Halbach array field).
UCNτ: Unique Features

• Low symmetry construction permits very rapid spectral cleaning

• Populations monitored by conventional analysis through UCN guides and also by V absorber
Asymmetric Trap induces Phase Space Mixing

Low symmetry, together with field ripples, enhance states mixing between (quasi)-periodic orbits through chaotic motion.

→ quick cleaning (~ 10s of seconds) of the ‘quasi-bound’ UCN with large tangential velocities.

PMs in a given row share same M alignment

Rows trace out the surface of a torus patch (circumferentially)

~700 liter volume

Two torus patches of different curvatures join along middle row
UCN Population Monitoring

- V-foil lowered into trap
  - Control for “quasi-bound” trajectories with long emptying time
  - Permits direct study of spectral distributions of UCN in trap

Conventional Fill and empty to UCN detector
UCN Storage Time Measurement: 2013

Conventional load, store and empty to external UCN detector measurement (between 10k and 20k UCN loaded per fill): accepted for PRC
End of 2013, experimented with “mock-up” of replacement trap-door assembly:
- Obtained well over order of magnitude improvement in loaded population
- Observed appropriate impact for spin-flipper
- Concluded depol. losses very large in 2013 geometry—new fill system being installed now
Very short time measured to absorb UCN!

V Activation Scan

\[
\tau = 8 \pm 1 \text{ s}
\]

Load for 150s then trap door/GV closed.
V down at 155s.
V up at 155s + Activation Time
V detector progress

2013:
- Added lead shielding
- Increased number of NaI detectors
- Achieved about 19% counting efficiency (90% from plastic alone)
- More efficiency and background improvements in works

V detector now yielding clean activation decay curves with $S/B > 10$
The Neutron Lifetime Experiment at LANL

Steven Clayton for the UCNτ collaboration

D. Bowman, S. Penttila (ORNL)
B. Vogelaar (V. Tech)
K. Hickerson (UCLA)
A. R. Young, B. VornDick, E. B. Dees, C. Cude (NCSU)

PSI2013
$^{19}\text{Ne}$

- **Lifetime:**
  
  
  Collaboration between KVI/RUG and TUNL

  \[ T_{1/2} = 17.2832 \pm 0.0051 \pm 0.0066 \text{ s} \]

  \[ <T_{1/2}> = 17.2604 \pm 0.0034 \text{ s} \]

  Careful dedicated systematic studies – rate dependence, diffusion and contaminants

- **Asymmetry**

Conclusions!

• UCNA is making good progress towards analysis of 2011-2013 data, and unblinding this year, confirming readiness for high statistics running

• Nab and UCNB achieved major milestones towards fully instrumented detectors, and orders for the Nab DAQ and magnet are placed

• UCNτ should be ready for high statistics running this fall, and detailed assessment of systematic error budget