A New Search for Neutron-Anti-Neutron Oscillations

A. R. Young
NCSU
Thanks to G. Brooijmans for slides

PSI 2016
PSI, October 17, 2016
Outline

• Oscillations in Neutral Systems and B Violation
• Current Limits
• European Spallation Source
• Beamline & Detector Concepts
• Collaboration
Central Questions for the Standard Model

Origin of neutrino mass

The cosmological baryon asymmetry

Pattern of charges and masses for the SM Fermions

Sources of Baryon Number Violation

For example...

All potentially connected by physics at or above EW scale

Observable $N\bar{N}$ oscillations in a next generation experiment!
Gaps in the Standard Model

Many cosmological issues

- Dark matter and dark energy
- Not enough CP violation in the quark sector for baryogenesis
- Baryon number violation required for the baryon asym but where does it come from?
  - Present in the SM through B-L (sphalerons)
  - Baryogenesis through leptogenesis and B-L?

Also find B violation in GUTs

$\Delta B=1$: proton decay $\rightarrow \Lambda > 10^{13}$ TeV

strong exptl limits…

$\Delta B=2$: not constrained by p decay

(wide range of scales for new physics…)

produces oscillations!
The Power of Oscillations

- Neutral particle oscillations have played large role in particle physics
  - $K^0 - \bar{K}^0$ oscillations ($\Delta S = 2$) at the core of our initial understanding of CP-violation
  - B meson oscillations ($\Delta_{\text{Beauty}} = 2$):
    - Sensitive to CKM elements
    - CP-violation "workhorse"
    - Probe $m_t^2/m_W^2$
      → First indication of large top mass! (1987)
- Sensitive probes of high mass
Neutrino Oscillations

Neutrino oscillations unambiguously establish neutrinos are massive

- Since neutral, Majorana mass term allowed
  - If exists, $\Delta L = 2$!
- If both Dirac and Majorana mass terms, mixing induces see-saw effect, explaining small neutrino masses
  - Two scales: Dirac and Majorana mass terms
    - Lead to observed scales $m_\nu \sim m_D^2/M$ and $m_N \sim M$
    - Dirac scale could be close to other fermions
      - Suggests a Majorana ($\Delta L=2$) scale $10^6 - 10^{10}$ GeV
- $\Delta B = 2$ at a similar energy scale?
Experimental Aspects
Process, Critical Parameters

- Potential V (if different for n vs $\bar{n}$)
  - Nuclear potential $\sim 100$ MeV
  - $\mu_n B_{\text{Earth}} \sim 10^{-18}$ MeV
  - Current limit: $\alpha < \sim 10^{-29}$ MeV (same order as nEDM)
- Strongly suppressed unless quasi-free condition holds ($Vt/\hbar << 1$)
  - Free neutron experiment requires substantial cancellation of Earth magnetic field, then:
  - For free neutron experiment, magnetic field can be used to check result if signal is seen
  - A few operators identified that allow oscillation with B, but not present in usual BSM physics

$$P_{n \rightarrow \bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + V^2} \sin^2 \left( \frac{\sqrt{\alpha^2 + V^2}}{\hbar} \cdot t \right)$$

$$P_{n \rightarrow \bar{n}} = \left( \frac{\alpha}{\hbar} \times t \right)^2 = \left( \frac{t}{\tau_{n\bar{n}}} \right)^2$$

FOM: $Nt^2$

arXiv:1504.01176
Current Limits

- $N_t^2 = 1.5 \times 10^9$s, $P < 1.6 \times 10^{-18}$ (run lasted ~1 year) and $\tau > 0.86 \times 10^8$s
  - Many subtle optimizations to minimize losses and backgrounds
  - Experiment was background-free
- Bound neutron limits ~3 times better
  - But model-dependent, and now limited by atmospheric $\nu$ background

New physics could be enhanced or suppressed for bound neutrons.

\[ \tau_{\text{bound}} = R \times \tau_{\text{free}}^2 \]

\[ R_{Ox} = 5 \times 10^{22} \text{ s}^{-1} \]

Recent S-K (2011) limit based on 24 candidates and 24.1 bkgr. from atm. \( v \)

Intranuclear search exp. limits: Super-K, Soudan-2 Frejus

Free neutron search limit (ILL - 1994)

Goal of new n-nbar search with free neutrons

LBNE 35 kt, 10 years, if zero atm. \( v \) background (R&D issue)

Factor of 1,000 sensitivity increase

Post-Sphaleron Baryogenesis

Babu et al

New nuclear theory and uncertainty Friedman and Gal, 2008
Next Generation Free Neutron Experiment

- Increase number of neutrons
  - Flux
    - Moderator brightness and area
  - Angular acceptance
  - Longer run
- Increase time-of-flight
  - Colder neutrons
  - Longer beamline
- Keep (or even increase) detection efficiency (~50%), keep background at ~0
  - Exploit current, established hardware and software technologies
- Better $B_{\text{Earth}}$ suppression
  - Improved passive (+ active?) shield
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European Spallation Source
Large beam port still in baseline!
(details under discussion)

2.0 GeV superconducting linac, 14 Hz, 5 MW
ESS Timeline

• 2014: ESS construction start

• 2019-2022: Initial phase: commissioning, intensity ramp, experiments by friendly users
  • **Experiment construction begins (first source recycle?)**

• 2023-2025: Initial user program operations: reliable operations with public users; establish basis for future cost sharing
  • **Experiment construction completion, commissioning, physics start**

• 2026+: routine operations, completion of final public instruments
  • **Physics run**
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The Experiment
Conceptual Design

- High-m super-mirror
- Residual B field < 5 nT
- Good vacuum < $10^{-5}$ Pa

MC optimization of parameters ongoing!

Supermirror Reflector

- Crucial in acceptance gain
  - 2D, so acceptance scales quadratically
  - Modern multi-layer supermirrors have good reflectivity at increasingly large momentum transfers

Ni reflectivity $\to 0$ defines $m=1$
Detector

- Anti-neutron annihilation target
  - High annihilation probability, low Z, high transparency to neutrons
    - ILL experiment used a carbon foil, 130 μm thick
- Annihilation produces pions, $<n> \sim 5$
- Background suppression:
  - Precise annihilation vertex identification of multitrack events
  - Good mass and position resolution
  - Beam time structure? (Mainly for background control samples)
Detector
Early Simulations: Detector

G4-based

Energy Dep. in Detector Bodies

MC Acc. vs. Active Cal. Energy Cut (signal)

Identify Target
Improvements over ILL

acceptance
~90% (x1.8)

X3 red. in timing
window (50 ns)

Lots of possibilities for detector development!
Expected Sensitivity
# Potential Gains wrt ILL

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<tr>
<td>Brightness</td>
<td></td>
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<tr>
<td>Moderator Area</td>
<td>Needs large aperture</td>
<td>2</td>
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<tr>
<td>Angular Acceptance</td>
<td>2D, so quadratic sensitivity</td>
<td>40</td>
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<tr>
<td>Length</td>
<td>Scale with $t^2$, so $L^2$</td>
<td>5</td>
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<tr>
<td>Run Time</td>
<td>ILL run was 1 year</td>
<td>3</td>
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<td>Total</td>
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$x \times 1000$ in probability, reach $\tau \sim 2-3 \times 10^9$ s
Early Simulations: Sensitivity

- Neutron spectrum files from ESS
- 50% detection efficiency (as for ILL)
Collaboration

- Collaboration growing
- ESS very supportive
  - Agreed to target area modifications needed
  - Revisiting sensitivity studies now that ESS has frozen moderator configuration
- Regular collaboration meetings

<table>
<thead>
<tr>
<th>Name</th>
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<tr>
<td>Gustaaf Brooijmans</td>
<td>Columbia University</td>
</tr>
<tr>
<td>Torsten Axesson</td>
<td>Lund University</td>
</tr>
<tr>
<td>David Baxter</td>
<td>Indiana University</td>
</tr>
<tr>
<td>Hans Calen</td>
<td>Uppsala University</td>
</tr>
<tr>
<td>Lorenzo Calabi</td>
<td>Université Libre de Bruxelles</td>
</tr>
<tr>
<td>Luis Castellanos</td>
<td>University of Tennessee</td>
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<tr>
<td>Joakim Cederwall</td>
<td>Lund University</td>
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<tr>
<td>Peter Christensen</td>
<td>Lund University</td>
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<tr>
<td>Christophe Clément</td>
<td>Stockholm University</td>
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<tr>
<td>Brian Coe</td>
<td>Columbia University</td>
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<tr>
<td>Caterina Doglioni</td>
<td>Lund University</td>
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<tr>
<td>Olef Falkander</td>
<td>Lund University</td>
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<tr>
<td>Gabriele Ferretti</td>
<td>Chalmers University of Technology</td>
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<tr>
<td>Peter Fischinger</td>
<td>TU Munich</td>
</tr>
<tr>
<td>Matthew Frost</td>
<td>University of Tennessee</td>
</tr>
<tr>
<td>Franz Galmeyer</td>
<td>University of Tennessee, Oak Ridge National Laboratory</td>
</tr>
<tr>
<td>Kenneth Ganzer</td>
<td>California State University Dominguez Hills</td>
</tr>
<tr>
<td>Richard Hall-Witton</td>
<td>ESS</td>
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<tr>
<td>Vincent Halberg</td>
<td>Lund University</td>
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<tr>
<td>Lawrence Heilbron</td>
<td>University of Tennessee</td>
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<tr>
<td>Andreas Heinz</td>
<td>Chalmers University of Technology</td>
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<td>Go Ishikawa</td>
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<tr>
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<td>Chalmers University of Technology</td>
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<td>Masahiro Kagawa</td>
<td>Nagoya University</td>
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<tr>
<td>Eskil Klinkby</td>
<td>ESS, Technical University of Denmark</td>
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<tr>
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<td>Lund University</td>
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<tr>
<td>Mats Lindroos</td>
<td>ESS</td>
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<tr>
<td>Else Lykken</td>
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<tr>
<td>Remnant Motsose</td>
<td>University of Texas, Dallas</td>
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<td>Fabindra Naipalpatra</td>
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<td>Anders Ofarsson</td>
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<tr>
<td>Robert Patte</td>
<td>Los Alamos National Laboratory</td>
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<tr>
<td>Christer Peterson</td>
<td>Chalmers University of Technology</td>
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<tr>
<td>David Phillips</td>
<td>North Carolina State University</td>
</tr>
<tr>
<td>Amlan Ray</td>
<td>VECC, Kolkata, India</td>
</tr>
<tr>
<td>Filippo Rosconi</td>
<td>CERN</td>
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<tr>
<td>Arthur Rupeen</td>
<td>University of Tennessee</td>
</tr>
<tr>
<td>Utpal Sarkar</td>
<td>Physical Research Laboratory, Ahmedabad, India</td>
</tr>
<tr>
<td>Alexander Saunders</td>
<td>Los Alamos National Laboratory</td>
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<tr>
<td>Hirohiko M. Shimizu</td>
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<tr>
<td>Robert Shrock</td>
<td>Stony Brook University</td>
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<tr>
<td>David Silvermyr</td>
<td>Lund University</td>
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<tr>
<td>Samuel Silversten</td>
<td>Stockholm University</td>
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<tr>
<td>Oxana Smirnova</td>
<td>Lund University</td>
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<tr>
<td>Per Erik Vargårde</td>
<td>Stockholm University</td>
</tr>
<tr>
<td>ESS coordinator</td>
<td>Camille Therane</td>
</tr>
<tr>
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Expression of Interest for
A New Search for Neutron-Anti-Neutron Oscillations at ESS
Neutron-antineutron oscillations: Theoretical status and experimental prospects


Ongoing work modeling aspects of the oscillation coherence, magnetic field sensitivity, and detailed models of the ESS target and moderator geometry
Conclusion

• Search for n-n oscillation strongly motivated:
  • $\Delta B=2$ baryon number violation appears in many models
  • Probe scales from $10^5$ - $10^{12}$ GeV
  • Connection with baryogenesis, neutrino masses, ...

• Experiment well within current capabilities
  • Very low technical risk – plenty of opportunities to optimize the approach and improve the project!

• Substantial community exists
  • Bridges particle and nuclear physics communities
  • Synergies with ESS neutron scattering community

• Complementary to planned science at LHC (observable particle production...) and the Underground Physics program

• Exploration of test beam program and n-n’ measurements by collaboration is underway

• Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are rare

  Should not be squandered

  http://www.nnbar-at-ess.org