Neutron-Antineutron Oscillations

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Indiana University/CEEM
Neutron summer school 2015

What are neutron-antineutron oscillations?

Why are they interesting to search for?

How do you look for them?

How well can you do?

Recent developments

Students: might be useful to get out pencil and paper
\[ n \leftrightarrow \bar{n} \text{ oscillations} \text{ — can we add them to the list?} \]

Neutral meson \( |q q \rangle \) states oscillate -

\[ K^0, B^0 \rightarrow \left\{ \text{2nd order weak} \right\} \rightarrow \bar{K}^0, \bar{B}^0 \]

And neutral fermions can oscillate too -

\[ \nu_\mu \rightarrow \left\{ \ldots \right\} \rightarrow \nu_e \]

So why not -

\[ n \rightarrow \left\{ \text{New physics} \right\} \rightarrow \bar{n} \]

Neutron is a long-lived neutral particle \( (q_n < 10^{-21}e) \) and can oscillate into an antineutron. No oscillations have been seen yet.

Need interaction beyond the Standard Model that violates Baryon number \( (B) \) by 2 units. No experimental observation of B violation yet. But we expect B violation at some level

Question for students: why do I need zero electric charge to get oscillations?
Neutron-Antineutron Oscillations: Formalism

\[ \Psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix} \text{ n-nbar state vector} \]

\[ H = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix} \text{ Hamiltonian of n-nbar system} \]

\[ E_n = m_n + \frac{p^2}{2m_n} + U_n \; ; \; E_{\bar{n}} = m_{\bar{n}} + \frac{p^2}{2m_{\bar{n}}} + U_{\bar{n}} \]

**Note:**

- \( \alpha \) real (assuming T)
- \( m_n = m_{\bar{n}} \) (assuming CPT)
- \( U_n \neq U_{\bar{n}} \) in matter and in external B \( [\mu(\bar{n}) = -\mu(n) \text{ from CPT}] \)

**Question for students:** calculate the eigenvalues and eigenvectors for \( U=0 \)
B,L are Probably Not Conserved

Baryon Asymmetry of Universe (BAU) is not zero. If $B(t=\text{after inflation}) \ll \text{BAU}$ (otherwise inflation is destroyed, Dolgov/Zeldovich), we need B violation.

Both B and L conservation are “accidental” global symmetries: given $\text{SU}(3) \otimes \text{SU}(2) \otimes \text{U}(1)$ gauge theory and matter content, no dimension-4 term in Standard Model Lagrangian violates B or L in perturbation theory.

Nonperturbative EW gauge field fluctuations (sphealerons) present in SM, VIOLATE B, L, B+L, but conserve B-L. Very important process for trying to understand the physics of the baryon asymmetry in the early universe.

Neutron-antineutron oscillations generically access scales not far above the electroweak scale: physics is completely different from the GUT scales accessed in proton decay.

No evidence that either B or L is a gauge theory like Q: where is the macroscopic B/L force? (not seen in equivalence principle tests).

Question for students: why are tests of the equivalence principle sensitive to a macro B force?
Matter/Antimatter Asymmetry in the Universe in Big Bang, starting from zero

Sakharov Criteria to generate matter/antimatter asymmetry from the laws of physics

- Baryon Number Violation (not yet seen in the lab)
- C and CP Violation (seen, but too small by $\sim 10^{10}$)
- Departure from Thermal Equilibrium (no problem?)

A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Relevant neutron experimental efforts
Neutron-antineutron oscillations (B)
Electric Dipole Moment searches ($T=CP$)
T Violation in Polarized Neutron Optics ($T=CP$)
P, CP, T, and CPT

• Parity violation (1956, or arguably earlier)
  – only in weak interaction

• CP violation (1964)
  – parametrized but not understood
  – seen in $K^0$ & $B^0$ systems
  – Doesn’t seem to be responsible for baryon asymmetry of universe

• T violation (1999)
  – CPT is good symmetry so far: $T \leftrightarrow CP$
Searches for B Violation (Nucleon Decay and Neutron-Antineutron Oscillation) Probe Different Physics

<table>
<thead>
<tr>
<th>Mode</th>
<th>Nucleon decay</th>
<th>N-Nbar oscillations</th>
</tr>
</thead>
<tbody>
<tr>
<td>effect on B and L</td>
<td>$\Delta B=1$, $\Delta L=1$, others</td>
<td>$\Delta B=2$, $\Delta L=0$, $\Delta(B-L)=2$</td>
</tr>
<tr>
<td></td>
<td>$\Delta(B-L)=0,2,...$</td>
<td></td>
</tr>
<tr>
<td>Effective operator</td>
<td>$L = \frac{g}{M^2} QQQL$</td>
<td>$L = \frac{g}{M^5} QQQ\bar{Q}QQ$</td>
</tr>
<tr>
<td>Mass scale probed</td>
<td>Grand Unified (GUT) scale</td>
<td>&gt;electroweak scale (&lt;&lt;GUT)</td>
</tr>
</tbody>
</table>

Question for students: how do I get those powers of M in L?
Nucleon Decay

Question for students: how do you set an experimental limit of 1E33 years if the age of the universe is 1E10 years?
Very Large detectors
Long exposures

From E. Kearns
Neutron-Antineutron Oscillations: Formalism

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Question for students: calculate the eigenvalues for finite \( U \)
Neutron-Antineutron Oscillations with Free Neutrons: The experimental figure-of-merit

For $H = \begin{pmatrix} E + V & \alpha \\ \alpha & E - V \end{pmatrix}$, \[ P_{n \rightarrow \bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + V^2} \times \sin^2 \left[ \frac{\sqrt{\alpha^2 + V^2}}{\hbar} t \right] \]

where $V$ is the potential difference for neutron and anti-neutron.

Present limit on $\alpha \leq 10^{-23}$ eV

Contributions to $V$:
$\langle V_{\text{matter}} \rangle \sim 100$ neV, proportional to matter density
$\langle V_{\text{mag}} \rangle = \mu B$, $\sim 60$ neV/Tesla; $B \sim 10$ nT $\rightarrow V_{\text{mag}} \sim 10^{-15}$ eV
$\langle V_{\text{matter}} \rangle, \langle V_{\text{mag}} \rangle$ both $\gg \alpha$

For $\left[ \frac{\sqrt{\alpha^2 + V^2}}{\hbar} t \right] \ll 1$ ("quasifree condition") \[ P_{n \rightarrow \bar{n}} = \left( \frac{\alpha}{\hbar} \times t \right)^2 = \left( \frac{t}{\tau_{n\bar{n}}} \right)^2 \]

Figure of merit (with no background) $= \sqrt{N T^2}$ $N =$#neutrons, $T$="quasifree" observation time
How to Search for N-Nbar Oscillations

Figure of merit for probability:
\[ N = \text{total # of free neutrons observed} \]
\[ T = \text{observation time per neutron while in “quasifree” condition} \]

When neutrons are in matter or in nucleus, n-nbar potential difference is large->quasifree observation time is short
B field must be suppressed to maintain quasifree condition due to opposite magnetic moments for neutron and antineutron

(1) n-nbar transitions in nuclei in underground detectors
(2) Cold and Ultracold neutrons
### Bound neutron N-Nbar search experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>A</th>
<th>n-year (10^{32})</th>
<th>Det. eff.</th>
<th>Candid.</th>
<th>Bkgr.</th>
<th>(\tau_{\text{nucl}}, \text{ yr (90% CL)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kamiokande</td>
<td>1986</td>
<td>O</td>
<td>3.0</td>
<td>33%</td>
<td>0</td>
<td>0.9/yr</td>
<td>(&gt;0.43 \times 10^{32})</td>
</tr>
<tr>
<td>Frejus</td>
<td>1990</td>
<td>Fe</td>
<td>5.0</td>
<td>30%</td>
<td>0</td>
<td>4</td>
<td>(&gt;0.65 \times 10^{32})</td>
</tr>
<tr>
<td>Soudan-2</td>
<td>2002</td>
<td>Fe</td>
<td>21.9</td>
<td>18%</td>
<td>5</td>
<td>4.5</td>
<td>(&gt;0.72 \times 10^{32})</td>
</tr>
<tr>
<td>SNO *</td>
<td>2010</td>
<td>D</td>
<td>0.54</td>
<td>41%</td>
<td>2</td>
<td>4.75</td>
<td>(&gt;0.301 \times 10^{32})</td>
</tr>
<tr>
<td>Super-K</td>
<td>2011</td>
<td>O</td>
<td>245</td>
<td>12.1%</td>
<td>24</td>
<td>24.1</td>
<td>(&gt;1.89 \times 10^{32})</td>
</tr>
</tbody>
</table>

* Preliminary

- From Kamiokande to Super-K atmospheric \(\nu\) background is about the same \(~ \sim 2.5 /kt/yr.\)
- Large \(D_2O\), Fe, \(H_2O\) detectors are dominated by backgrounds; LAr detectors are unexplored
- Observed improvement is weaker than SQRT due to irreducible background and uncertainties of efficiency and background.
Previous n-nbar search experiment with free neutrons

At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

M. Baldo-Ceolin et al., Z. Phys., C63 (1994) 409

No background observed!

No candidates observed.

Limit set for a year of running:

\[ \tau_{n\bar{n}} > 0.86 \times 10^8 \text{s} \]

with \( L \sim 76 \text{ m} \) and \( \langle t \rangle = 0.109 \text{ sec} \)

measured \( P_{n\bar{n}} < 1.606 \times 10^{-18} \)

sensitivity: \( N \cdot t^2 = 1.5 \times 10^9 \text{ s}^2/\text{s} \)

\( \equiv \) "ILL sensitivity unit"
Better Slow Neutron NNbar Experiment:
What do we want? (HOW DIFFICULT IS IT?)

While still keeping quasifree condition, one wants more with nbar detector watching the annihilation surface $NT^2$

- higher cold neutron brightness from moderator? POSSIBLE
- slower cold neutron energy spectrum? DIFFICULT
- more efficient extraction of cold neutrons with optics to quasifree flight/detector? YES: GREAT PROGRESS SINCE ILL NNBAR
- longer “quasifree” flight time? YES
- longer experiment operation time? YES (ILL only ran 1 year)
How to Improve the Experiment?
Max neutron flux/brightness from production source/target: 
~unchanged for ~4 decades

Neutron flux is increasing only slowly with time

R. Eichler, PSI
Projected ESS Peak Slow Neutron Brilliance (from ESS website)

Upon time-averaging, \(<\text{ESS}\sim\text{ILL}\)
Neutron-Antineutron Oscillations with Free Neutrons: Max. Figure of Merit is for low energy ("cold") neutrons

<table>
<thead>
<tr>
<th>Neutrons</th>
<th>E_kin</th>
<th>T,K</th>
<th>Velocity</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast</td>
<td>~ 1 MeV</td>
<td>~ 10^{10}</td>
<td>~ 0.046 c</td>
<td>~ 0.0003 Å</td>
</tr>
<tr>
<td>Thermal</td>
<td>~ 25 meV</td>
<td>~ 300</td>
<td>~ 2.2 km/s</td>
<td>~ 1.8 Å</td>
</tr>
<tr>
<td>Cold</td>
<td>~ 3 meV</td>
<td>~ 35</td>
<td>~ 760 m/s</td>
<td>~ 5 Å</td>
</tr>
<tr>
<td>Very Cold (VCN)</td>
<td>~ 1 meV</td>
<td>~ 10</td>
<td>~ 430 m/s</td>
<td>~ 9 Å</td>
</tr>
<tr>
<td>Ultra Cold (UCN)</td>
<td>~ 250 neV</td>
<td>~ 0.003</td>
<td>~ 8 m/s</td>
<td>~ 600 Å</td>
</tr>
</tbody>
</table>

[Graph showing number of neutrons as a function of neutron velocity, with peaks for cold, very cold, and thermal neutrons.]
Why is it hard to make colder neutron spectra from neutron moderators?

1. Cryogenic engineering (heat loads, conductivity/heat capacity…)
2. For cold neutrons with $\lambda > d$, $\sigma_{el} >> \sigma_{in}$, most collisions elastic
3. Frozen materials required to lower neutron T also freeze inelastic modes
4. Radiation damage causes cryogenic solids to decompose or explode
5. Phonon phase space decreases as $\omega^3$, need to find other inelastic modes

Research on better slow neutron moderators in progress
µBt<<ℏ: ILL achieved |B|<10 nT over 1m diameter, 80 m beam, one layer 1mm shield in SS vacuum tank, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991). For new experiment need |B|<~1 nT

NEW RESULT: this seems not to be needed anymore (SVG arXiv)

V_{opt}t<<ℏ:
Need vacuum to eliminate neutron-antineutron optical potential difference. P<10^{-5} Pa is good enough, much less stringent than LIGO
Antineutron detector for “zero background” condition

\[ \bar{n} + A \rightarrow \langle 5 \rangle \text{pions} \quad (1.8 \text{ GeV}) \]

Annihilation target: \( \sim 100\mu \) thick Carbon film

\( \sigma_{\text{annihilation}} \sim 4 \text{ Kb} \quad \sigma_{\text{nC capture}} \sim 4 \text{ mb} \)

vertex precisely defined. No background was observed at ILL
Better Free Neutron Experiment (Horizontal geometry)

need slow neutrons from high flux source, illuminate phase space acceptance of neutron focusing reflector, free flight path of ~200m

Improvement on ILL experiment by factor of >~500-1000 in transition probability is possible at ESS with existing n optics technology, sources, and moderators for a reasonable running time.

L ~ 200 m

D ~ 4 m
concept of neutron supermirrors: Swiss Neutronics

neutron reflection at grazing incidence (< ≈2°)

@ smooth surfaces

θc
nc = 1 (vacuum)
n (material)

refractive index n < 1

total external reflection

e.g. Ni θc = 0.1 °/Å

@ multilayer

\[ \lambda = 2d \sin \theta \]

@ supermirror

\[ \theta_{\text{critical}} \rightarrow m\theta_{\text{critical}} \]

m=1

m=2
“Supermirrors”: $\theta_{\text{critical}} \rightarrow m\theta_{\text{critical}}$

Commercial supermirror neutron mirrors are available with $m > 6$

Phase space acceptance for straight guide $\propto m^2$, more with focusing reflector

From P. Boeni, Swiss Neutronics

ILL experiment used $m \sim 1$ optics
Use supermirror elliptical focusing reflector close to the source to increase transverse phase space acceptance for cold neutrons within fixed solid angle $\Delta \Omega$ and direct them to annihilation target.

Supermirror Neutron Optics: Future Possibilities

At a pulsed neutron source like ESS, neutrons of a given speed reach the mirror at a known time. We can therefore imagine an array of mirrors tiling an ellipse and phased to the source to condition the beam through Piezodrivers.

“In the future one may consider varying the shape of the guides actively by means of piezo actuators. If used at pulsed sources, beam size and therefore the divergence for each wavelength during a neutron pulse can be optimized. The combination of fast mechanical actuators with supermirror technology may become useful for active phase space transformation.”


Question for students: does this process obey Liouville’s theorem?
Phenomenology of $n$-$\bar{n}$ oscillations revisited

S. Gardner* and E. Jafari

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University of Kentucky, Lexington, Kentucky 40506-0055 USA

(Dated: August 12, 2014)

Abstract

We revisit the phenomenology of $n$-$\bar{n}$ oscillations in the presence of external magnetic fields, highlighting the role of spin. We show, contrary to long-held belief, that the $n$-$\bar{n}$ transition rate is not suppressed, opening new opportunities for its empirical study.

see that CPT invariance guarantees that a neutron spin state and an antineutron spin state in vacuum are always degenerate irrespective of the size of the magnetic field: the presence of external magnetic fields cannot quench transitions between these states. The study of
Limiting Lorentz Violation from Neutron–Antineutron Oscillation

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(Dated: April 7, 2015)

Abstract

We point out that if neutron–antineutron oscillation is observed in a free neutron oscillation experiment, it will put an upper limit on the strengths of Lorentz invariance violating (LIV) mass operators for neutrons at the level of $10^{-23}$ GeV or so, which would be the most stringent limit for neutrons. We also study constraints on $\Delta B = 2$ LIV operators and find that for one particular operator degaussing is not necessary to obtain a visible signal. We also note that observation of $n - \bar{n}$ oscillation signal in the nucleon decay search experiment involving nuclei does not lead to any limit on LIV operators since the nuclear potential difference between neutron and antineutrinos will mask any Lorentz violating effect.
Neutron–Antineutron Oscillation as a Signal of CP Violation

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\textsuperscript{2}INFN, Laboratori Nazionali Gran Sasso, 67010 Assergi, L’Aquila, Italy
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\textsuperscript{5}Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA

Abstract

Assuming the Lorentz and CPT invariances we show that neutron-antineutron oscillation implies breaking of CP along with baryon number violation. Presence of external magnetic field does not add any new operator to mixing of neutron and antineutron.
Summary

New physics beyond the Standard Model can be discovered by NNbar Experiments with free neutrons can possess very low backgrounds (sharp vertex localization): possibility for a crisp discovery

Sensitivity of free neutron experiment for NNbar transition rate can be improved by factor of >~500-1000 using existing technology [Combination of improvements in neutron optics technology, longer observation time/larger-scale experiment, and source design optimization at green-field facility]. Further improvements in a free neutron experiment can come from further neutron optics technology/moderator/reflecter development