Search for $n - \bar{n}$ Oscillation at the Deep Underground Neutrino Experiment

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Theoretical Overview
Motivations for Experimental Detection of $n-\bar{n}$ Oscillations

- Modern cosmological models propose Baryon Number Violation (BNV) as an explanation for the observed imbalance of matter and antimatter in the universe
  - BNV ($\Delta B \neq 0$) decays can exist while still maintaining $\Delta (B - L) = 0$
    - This is a requirement of the standard model
  - Some proposed BNV mechanisms/models include
    - Proton decay ($\Delta B = 1$ or 2)
    - Leptogenesis
      - Occur at very high energies (GUT scales)
  - Any imbalance arising from these is thought to be erased during the electroweak (EW) phase transition
    - Sphaleron “washes out” effectively all matter-antimatter asymmetry
    - Thus, solely $\Delta (B - L) = 0$ would not be a permissible explanation of baryogenesis
  - Some models DO violate $\Delta (B - L)$ ...
    - They can include $\Delta B = 2$ processes like neutron-antineutron ($n-\bar{n}$) oscillations
    - These probe energies above LHC, but still below the EW phase transition energy
    - A “post-sphaleron” baryogenesis (PSB)
  - Observation of the oscillation would confirm the need to probe higher scales still, or rule out Post-Sphaleron Baryogenesis
Motivations for Experimental Detection of $n-\bar{n}$ Oscillations: The 6-quark $\Delta B = 2$ Operator

Consider the proton decay channel operator

$$H_p \sim \lambda_p \frac{q q q l}{M_{GUT}^2}$$

- Here it should noted that, via operator dimensional analysis, that the $M_{GUT}$ mass scale at one point lead Glashow et al. to propose unification of the forces
- Proposed lifetime due to this $\sim 10^{13} - 10^{14}$ GeV scale lead to low proton decay limit

This differs from the six quark operator pertinent to neutron-antineutron oscillation

$$H_{n\bar{n}} \sim \lambda_{n\bar{n}} \frac{q q q q q q}{M_{\sim EW}^5}$$

- Here, $M_{\sim EW}$ is a rough energy scale near the electroweak phase transition
- This scale of roughly $10^5$ GeV is tantalizingly close to currently and near future testable energy scales
  - DUNE and LArTPCs! ESS!
Motivations for Experimental Detection of $n \rightarrow \bar{n}$ Oscillations: Simplified Model

- Two-level, time-dependent systems can oscillate between two states based on the off-diagonal mixing factor $\delta m$
  - This factor distinguishes the two states from one another
    - Provides insight to their suppression modes
    - In this case, it pertains to the magnetic dipole energy of each particle
      - This assumes that the $n$ and $\bar{n}$ masses are equivalent and that their dipole moments are equal and opposite
      - This can be shown to be a consequence of the CPT Theorem
  - In a short time limit and low-magnetic field configuration, the probability of free transition is:
    \[
    P_{\text{free}}(n \rightarrow \bar{n}) \equiv [(\delta m)t]^2 = \left(\frac{t}{\tau_{\text{free}}}\right)^2 \rightarrow \tau_{\text{free}} = \sqrt{\frac{\tau_{\text{bound}}}{R}}
    \]
  - Here, $R \approx 5 \cdot 10^{22} s^{-1}$ is the nuclear suppression factor, derived given the zero-point motion with a quasi-free condition for neutron motion within the nucleus

\[
\mathcal{M}_B = \begin{pmatrix}
  m_n - \mu_n \cdot \vec{B} - i\lambda/2 & \delta m \\
  \delta m & m_n + \mu_n \cdot \vec{B} - i\lambda/2
\end{pmatrix}
\]
A distribution of proposed PSB models as a function of predicted free oscillation time

- Blue line shows horizontal beamline oscillation time
  - ESS, 3 yr, ~500X ILL
- Red shows DUNE/LBNE
  - 10 years, ~13,500X ILL
  - Assumes no background
- Anti-Neutron
- Neutron
- Proton

Expect: $\sim 2 \text{ GeV}$ Invariant mass

FERMI MOMENTUM/ENERGY?
Previous Simulations and Experimental Results from Super-Kamiokande

We expect DUNE LArTPCs to have much greater background suppression and particle ID capabilities than previous experiments.

- Previous searches for $n-\bar{n}$ occurred at Super-K
  - 24 candidate events were observed
  - Expected atmospheric $\nu$ background of 24.1 events
  - Limitations in the resolution of Cherenkov radiation detector technologies cause large systematic error shifts in expected energy and momentum ranges
    - This is not thought to be a big issue with LArTPCs, given current known results from MicroBOONE, ArgoNeuT, etc.

- Using similar technology proposed for DUNE, ProtoDUNE will continue down MicroBOONE’s path for in-depth LArTPC testing at CERN
  - Scheduled to be commissioned by 2018
  - We hope to complete similar MCs and analysis over the next two years for DUNE

| $\pi^+\pi^0$  | $\pi^+$ | $\pi^+\pi^+$ | 2% |
| $\pi^-\pi^0$  | $\pi^0$ | $\pi^+\pi^0$ | 1.5% |
| $\pi^-3\pi^0$ | $\pi^-\pi^0$ | $\pi^-\pi^+\pi^0$ | 6.5% |
| $2\pi^+\pi^-\pi^0$ | $\pi^+\pi^-\pi^0$ | $\pi^+\pi^-\pi^+\pi^0$ | 11% |
| $2\pi^+\pi^-2\pi^0$ | $\pi^+\pi^-\pi^0$ | $\pi^+\pi^-\pi^+\pi^0$ | 28% |
| $2\pi^+\pi^0$ | $2\pi^0$ | $2\pi^+\pi^-2\pi^0$ | 7% |
| $3\pi^+2\pi^-\pi^0$ | $2\pi^+2\pi^-\pi^+\pi^0$ | $2\pi^+2\pi^-\pi^+\pi^0$ | 24% |
| $\pi^-\pi^0$ | $\pi^-\pi^-\pi^0$ | $\pi^-\pi^-\pi^+\pi^0$ | 10% |
| $2\pi^+2\pi^-2\pi^0$ | 10% |
| Sources | Uncertainty (%) |
| Fermi momentum of nucleons | 6.2 |
| Branching ratio of $\bar{n}+nucleons$ | 4.6 |
| $\pi$ propagation modeling | 6.1 |
| $\pi$-nucleon cross section in the nucleus | 20.0 |
| Energy scale | 1.7 |
| Asymmetry of detector gain | 0.4 |
| Cherenkov ring finding | 2.2 |
| Total | 22.9 |
The Deep Underground Neutrino Experiment and Proposed $n - \bar{n}$ Search

• **DUNE** is an international collaboration of over 800 scientists based at Fermilab
  - DUNE, a partnership between Fermilab and the Long-Baseline Neutrino Facility (LBNF), will construct the most intense neutrino beam in the world along with near and far detectors
  - The far detector will utilize Liquid Argon Time Projection Chambers (LArTPCs)
    - Near detector design still being debated
    - Will have a *fiducial volume* of roughly 40 kilotons
      - Actually nearly 68 kilotons...

• It is hoped that LArTPC’s superior tracking and particle identification abilities will ultimately reduce effects of background in the search for $n - \bar{n}$ oscillation events
  - Will *possibly* permit the chance to observe such a process via free to quasi-free background
FIG. 1. A neutrino interaction in the MicroBooNE detector. This is a charged-current, muon-neutrino event with a long muon track, a charged pion track, and a short proton track coming from the interaction vertex.
The Deep Underground Neutrino Experiment and Proposed \( n \rightarrow \bar{n} \) Search (cont.)

- Using \( n \) bound in Ar, DUNE currently plans to include \( n \rightarrow \bar{n} \) events in their nucleon decay searches

- Using GENIE, modeling is underway on intranuclear interactions mimicking \( n \rightarrow \bar{n} \) annihilation in Ar nuclei
  - Eliminating atmospheric neutrino (\( \nu \)) background from such events will be a challenge for LArTPCs at DUNE
  - Simulation work must be considered for \( \nu \) interactions in Ar nuclei, which may produce similar signals to \( n \rightarrow \bar{n} \) annihilation
  - Key to understanding possible experimental signals will be the integration of these two for a proper robust analysis
    - Will determine the viability of any detection of this process above background levels at truth level \textit{first}
    - Event reconstruction and detector (effects) simulation in LArSoft to come

- One proposed signature of the event is release of roughly 2 GeV of energy (excluding hadronic rest masses) while particles on the whole maintain roughly zero total momentum (excluding Fermi momentum of initial annihilation constituents)
  - Within the nucleus, between 2-6 mesons can be made from the annihilation event, some or all eventually escaping
  - While deeply inelastically scattering \( \nu \)'s can also produce pions, the kinematic signatures of the events differ
Comparison with intranuclear n-nbar search

Hypothetical assumption of big underground backgroundless detectors

Ultimate goal of NNbarX sensitivity. Absence of background is critically important

24 candidate events in Super-K might contain several genuine n-nbar events. Backgroundless PDK detectors are needed to explore nnbar > 10^{33} years. Whether atmospheric neutrinos and n − n̄ signals can be separated in LAr detectors is an R&D issue for LBNE.
References


Monte Carlo Challenge 7 Analysis

Energies are in GeV

Total of 100,000 events for both atmospheric neutrino background and $n - \bar{n}$ annihilation

Argon-40 is the starting nucleus
Introduction

- $n - \bar{n}$ simulation produced by Jeremy Hewes for the DUNE collaboration

- Atmospheric neutrino background event sample generated for the DUNE collaboration (by Aaron Higuera?)
  - Technically: `prodgenie_atmnu_max_dune10kt_1x2x6` and associated .fhcl files
  - Supposedly uses Bartol flux at Soudan site

- Both were part of the MCC7 run in late 2016

- In the proceeding slides, when referring to “all” outgoing particles, these include:
  - Mesons: pions and omegas
  - Baryons: Protons, Neutrons
  - Leptons: Muons, Electrons
    - Evaporation particles, such as large hadron blobs like chlorine, will be considered and labeled separately

- Code is currently developed to consider only primary interactions in the neutrino sample, i.e. only particles that exit the radius of the nucleus

- Most all particles are considered in the $n - \bar{n}$ sample
  - Total energy includes the masses of the particles! Kinetic energy does not include these masses!
d8' `Yb  `888  `8 `888b.  `8 `888  `888'  `8 NEUTRINO MONTE CARLO GENERATOR

Version 2.9.0

http://www.genie-mc.org

Luis Alvarez-Ruso [14], Costas Andreopoulos (*) [6,11], Omar Benhar [10], Flavio Cavanna [5],
Thomas Dealtry [7], Steve Dytman [8], Hugh Gallagher [13], Tomasz Golan [3,9],
Robert Hatcher [3], Yoshinari Hayato [4], Anselmo Meregaglia [12],
Donna Naples [8], Gabriel Perdue [3], Andre Rubbia [2],
Mike Whalley [1]

(The GENIE Collaboration)

(1) Durham University, UK
(2) ETH Zurich, Switzerland
(3) Fermi National Accelerator Laboratory, USA
(4) Kamioka Observatory, ICRR, University of Tokyo, Japan
(5) L'Aquila University and INFN, Italy
(6) University of Liverpool, UK
(7) Oxford University, UK
(8) Pittsburgh University, USA
(9) University of Rochester, USA
(10) Rome Sapienza University and INFN, Italy
(11) STFC Rutherford Appleton Laboratory UK
(12) Strasbourg IPHC, France
(13) Tufts University, USA
(14) Valencia University, Spain
A typical GENIE Event for a $n - \bar{n}$ oscillation and annihilation

**Initial State Particles**

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**Interior Mesons**

**Final State Particles**

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Initial States Within the Argon Nucleus

WHAT IS HAPPENING TO PARTICLES INSIDE THE NUCLEUS?

NO CUTS ARE CONSIDERED IN THIS SECTION
Argon Nuclei Processes
Number of Particles Per Event
(all original particles: $n, p, \omega, \pi^\pm, \pi^0$)

$n - \bar{n}$ OSCILLATION

ATMOSPHERIC NEUTRINO

Data not yet available

- Will re-run 100,000 events to get original (interior) particle 4-vector truths
  - Once current analysis is complete
  - May try to pre-select to 100,000 events which can serve as more definite background candidates?
Argon Nuclei Processes
Total Fermi Momentum Per Event
(only original annihilation constituents: $\bar{n} \rightarrow n$ or $\bar{n} \rightarrow p$)

$n \rightarrow \bar{n}$ OSCILLATION

ATMOSPHERIC NEUTRINO

Data not yet available
- Will re-run 100,000 events to get original (interior) particle 4-vector truths
  - Once current analysis is complete
  - May try to pre-select to 100,000 events which can serve as more definite background candidates?
Argon Nuclei Processes
Component Fermi Momentum Per Event
(only original annihilation constituents: $\bar{n} - n$ or $\bar{n} - p$)

$n - \bar{n}$ OSCILLATION

ATMOSPHERIC NEUTRINO

Data not yet available
- Will re-run 100,000 events to get original (interior) particle 4-vector truths
- Once current analysis is complete
- May try to pre-select to 100,000 events which can serve as more definite background candidates?
Argon Nuclei Processes
Angular Dependence of Fermi Motion
(only original annihilation constituents: $\bar{n} - n$ or $\bar{n} - p$)

$n - \bar{n}$ OSCILLATION

ATMOSPHERIC NEUTRINO

Data not yet available
- Will re-run 100,000 events to get original (interior) particle 4-vector truths
- Once current analysis is complete
- May try to pre-select to 100,000 events which can serve as more definite background candidates?
Argon Nuclei Processes
Total Momentum Per Event
(all original particles: $n, p, \omega, \pi^\pm, \pi^0$, etc.)

$n - \bar{n}$ ANNIHILATION

ATMOSPHERIC NEUTRINO

Data not yet available

- Will re-run 100,000 events to get original (interior) particle 4-vector truths
- Once current analysis is complete
- May try to pre-select to 100,000 events which can serve as more definite background candidates?
Argon Nuclei Processes
Momentum Conservation by Component For Each Event
(Initial particles, $n, p$, with Evaporation Nuclei)

$n - \bar{n}$ ANNIHILATION

ATMOSPHERIC NEUTRINO

Data not yet available
- Will re-run 100,000 events to get original (interior) particle 4-vector truths
  - Once current analysis is complete
  - May try to pre-select to 100,000 events which can serve as more definite background candidates?
Argon Nuclei Processes
Invariant Mass v. Total Momentum
(all original interior mesons: $\omega, \pi^\pm, \pi^0$)

$n - \bar{n}$ ANNIHILATION

ATMOSPHERIC NEUTRINO

Data not yet available
- Will re-run 100,000 events to get original (interior) particle 4-vector truths
- Once current analysis is complete
- May try to pre-select to 100,000 events which can serve as more definite background candidates?
Final States of the Outgoing Products

WHAT ARE THE TRUTH VALUES OF PERTINENT PHYSICAL QUANTITIES WE COULD PLAUSIBLY MEASURE?

NO CUTS ARE CONSIDERED IN THIS SECTION
Argon Nuclei Processes
Total Momentum

\[ n - \bar{n} \text{ ANNIHILATION} \]

ATMOSPHERIC NEUTRINO

![Graph showing the distribution of total momentum for atmospheric neutrino and argon nuclei processes.](image)

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Argon Nuclei Processes
Invariant Mass v. Total Momentum
(all FSI mesons with cuts: $\omega, \pi^\pm, \pi^0$)

$n \rightarrow \bar{n}$ ANNIHILATION

ATMOSPHERIC NEUTRINO
Argon Nuclei Processes
Number of Protons v. Neutrons Per Event
(among all outgoing particles)

$n - \bar{n}$ ANNIHILATION

ATMOSPHERIC NEUTRINO
Argon Nuclei Processes
Total Momentum v. Total Kinetic Energy
All Products, “visible” and not

\[ n - \bar{n} \text{ ANNIHILATION} \]

ATMOSPHERIC NEUTRINO

Neutron-Antineutron Annihilation in Argon Nuclei-All Products

Atmospheric Neutrinos on Argon-All Products