Motivation for a Neutron-Antineutron Oscillation Search in the Sudbury Neutrino Observatory

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Abstract

Grand unified theories generally predict the existence of baryon number nonconservation, manifesting itself in processes like proton decay and neutron-antineutron ($n-\bar{n}$) oscillation. Experimental nonobservation of proton decay has led to the development of several experimental searches for $n-\bar{n}$ oscillations. To date, this phenomenon has never been detected, setting an experimental lower limit on the $n-\bar{n}$ oscillation time ($\tau_{n\bar{n}}$) as $\tau_{n\bar{n}} > 1.3\times10^8 s$ at 90% C.L. (according to Soudan 2). The Sudbury Neutrino Observatory (SNO), a heavy water Čerenkov detector, can be used to increase the lower limit on $\tau_{n\bar{n}}$ if an experimental search is developed. It can be seen that such an experiment in SNO could result in $\tau_{n\bar{n}} > 1.96\times10^8 s$ at 90% C.L., a sizable improvement over the current limit. As more data becomes available from SNO, this limit can be increased.

Outline

- Motivation from Grand Unified Theories
- Sudbury Neutrino Observatory
- Nuclear Suppression
- Annihilation Signature
- Annihilation Detection
- Major Backgrounds
- Expected Results
- Conclusion

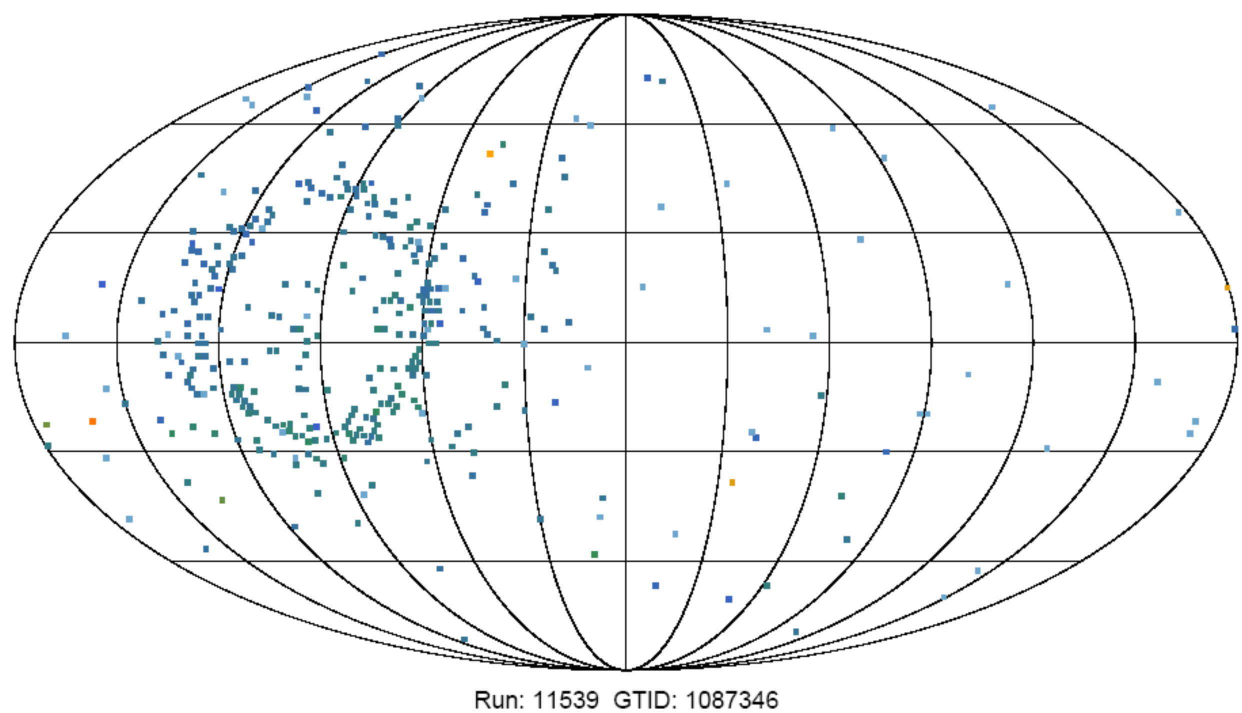
Motivation from Grand Unified Theories

- Grand Unified Theories (GUTs) predict existence of baryon number (B) nonconserving processes
  - Proton decay [$\Delta(B-L)=0$]
  - Neutron-antineutron ($n-\bar{n}$) oscillations [$\Delta(B-L)=2$]
- Standard SU(5) model predicts proton decay
- Nonobservation of proton decay has led to searches for $n-\bar{n}$ oscillations
- Supersymmetric $SU(2)_L$ x $SU(2)_R$ x $SU(4)_c$ model predicts $n-\bar{n}$ oscillations
- If $n-\bar{n}$ oscillations are found and proton decay is not, then it would select GUTs like those based on $SU(2)_L$ x $SU(2)_R$ x $SU(4)_c$ and reject GUTs based on SU(5)
- Sudbury Neutrino Observatory can be used to search for $n-\bar{n}$ oscillations

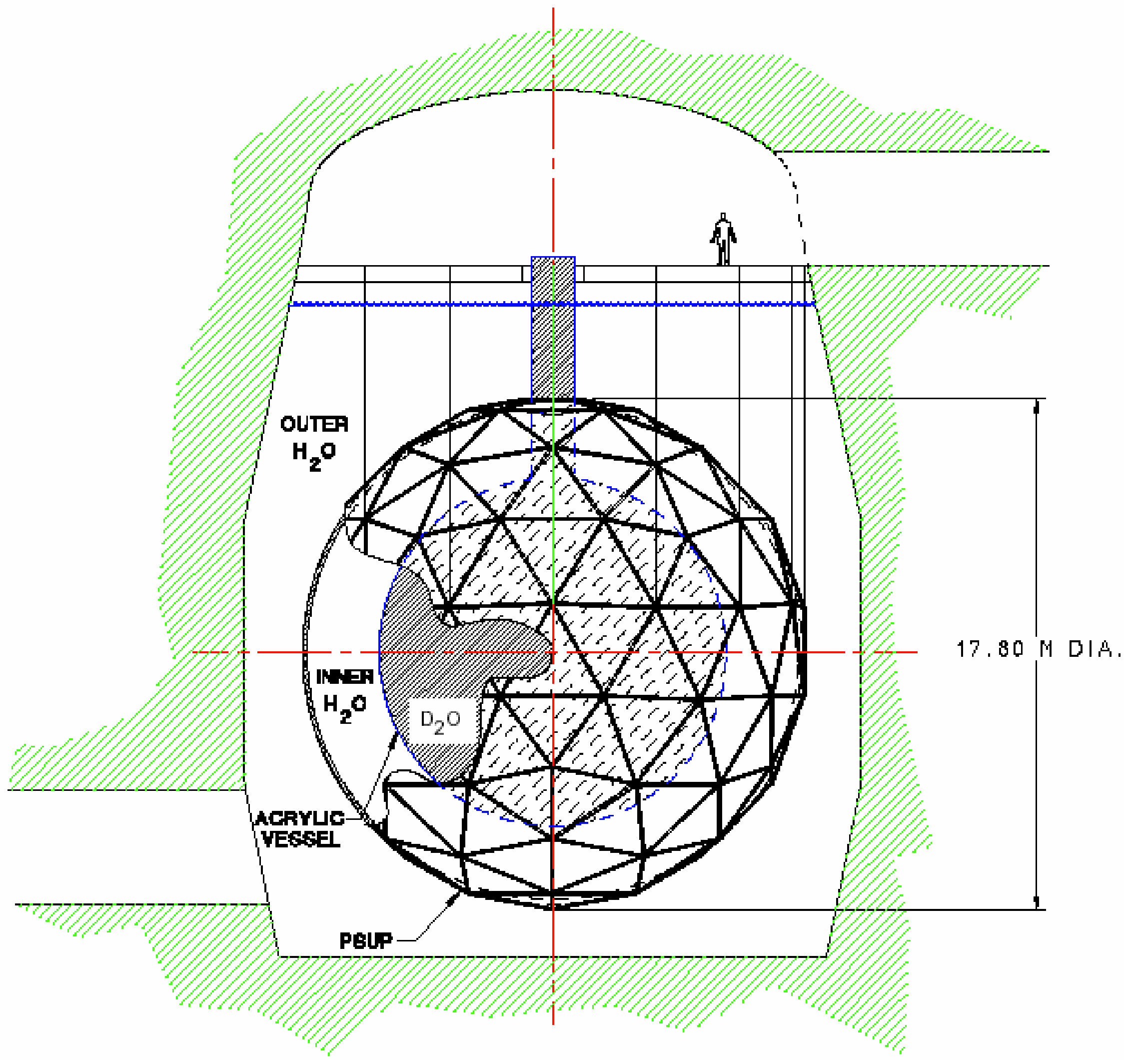
Sudbury Neutrino Observatory

- Located near Sudbury, Ontario
  - 2070 m below ground
- Heavy water Čerenkov radiation detector
  - 12 m diameter acrylic sphere holds heavy water
  - 17.8 m diameter geodesic sphere holds 9456 photomultiplier tubes (PMTs)
  - Acrylic sphere surrounded by light water to shield from radiation
- PMTs detect ring pattern created by intersection of Čerenkov cone with sphere
- SNO is equipped with software designed to fit vertices to events (vertex fitters) and to fit rings to PMT hit patterns (ring fitters)

Sudbury Neutrino Observatory



Sudbury Neutrino Observatory



source: SNO Collaboration, J. Boger *et al.*, Nucl. Instr. and Meth. A 449, 172 (2000).

Nuclear Suppression

- Since antineutrons feel a different nuclear potential than do neutrons, $n-\bar{n}$ oscillations in nuclei are suppressed

$$T = \tau_{n\bar{n}}^2 T_R$$

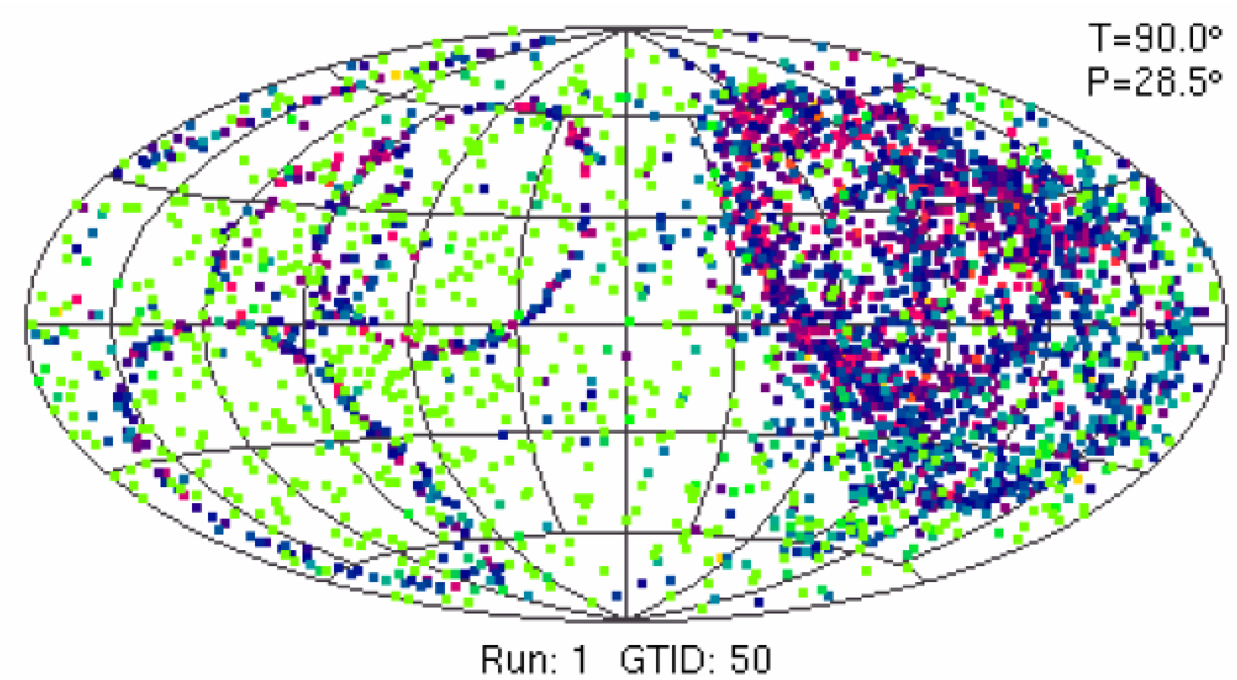
T is nuclear annihilation lifetime
$\tau_{n\bar{n}}$ is free space $n-\bar{n}$ oscillation time
T_R is nuclear suppression factor

- T_R for deuterium is $2.48\times10^{22} s^{-1}$
- T_R for oxygen is $1.0\times10^{23} s^{-1}$
- For $\tau_{n\bar{n}}$ of $10^8 s$, T is of the order $10^{39} s$

Annihilation Signature

- When a neutron oscillates into an antineutron in the nucleus, it quickly annihilates
  - Produces multiple pions
- Charged pions can be seen by Čerenkov radiation
- Neutral pions cannot, but quickly decay into two photons which Compton scatter off of electrons
- Average charged pion multiplicity is 3
- Average neutral pion multiplicity is 2

Annihilation Signature



source: S. Biller, J.A. Formaggio, and C.E. Okada, Nucleon Decay Prospects in the Sudbury Neutrino Observatory, SNO Internal Document, 2002.

Annihilation Signature

Channel	Theory $I=0$	Theory $I=1$	Theory Combined	Experiment CERN	Experiment BNL
$\pi^+\pi^-$	0.02	0.0	0.01	0.37 ± 0.3	0.32 ± 0.04
$\pi^+\pi^-\pi^0$	0.04	0.6	0.32	6.9 ± 0.35	7.3 ± 0.9
$2\pi^+2\pi^-$	9.1	3.0	6.1	6.9 ± 0.6	5.8 ± 0.3
$2\pi^+2\pi^-\pi^0$	26.8	19.8	23.3	19.6 ± 0.7	18.7 ± 0.9
$3\pi^+3\pi^-$	13.8	3.56	8.7	2.1 ± 0.2	1.9 ± 0.2
$3\pi^+3\pi^-\pi^0$	4.38	0.61	2.5	1.9 ± 0.2	1.6 ± 0.2
$\mathrm{n}\pi^0$, $\mathrm{n} > 1$	7.7	15.7	11.7	4.1 ± 0.4	3.3 ± 0.2
$\pi^+\pi^-\mathrm{n}\pi^0$, $\mathrm{n} > 1$	25.1	39.8	32.5	35.8 ± 0.8	34.5 ± 1.2
$2\pi^+2\pi^-\mathrm{n}\pi^0$, $\mathrm{n} > 1$	12.8	17.4	15.2	20.8 ± 0.7	21.3 ± 1.1
$3\pi^+3\pi^-\mathrm{n}\pi^0$, $\mathrm{n} > 1$	0.03	0.014	0.022	0.3 ± 0.1	0.3 ± 0.1
% of secondary πs	29.2	31.3	30.3	33	

source: Y. Lu and R.D. Amado, hep-ph/9504362.

Annihilation Signature

- Total energy of event should be 2 GeV
  - Energy of event can be reconstructed by measuring width of Čerenkov rings
- Total momentum of event should be 0
  - Momentum of event can be reconstructed by knowing the energy of the event and the direction in which the particle propagated
  - Direction is found by using a vertex fitter and comparing the vertex with the ring position

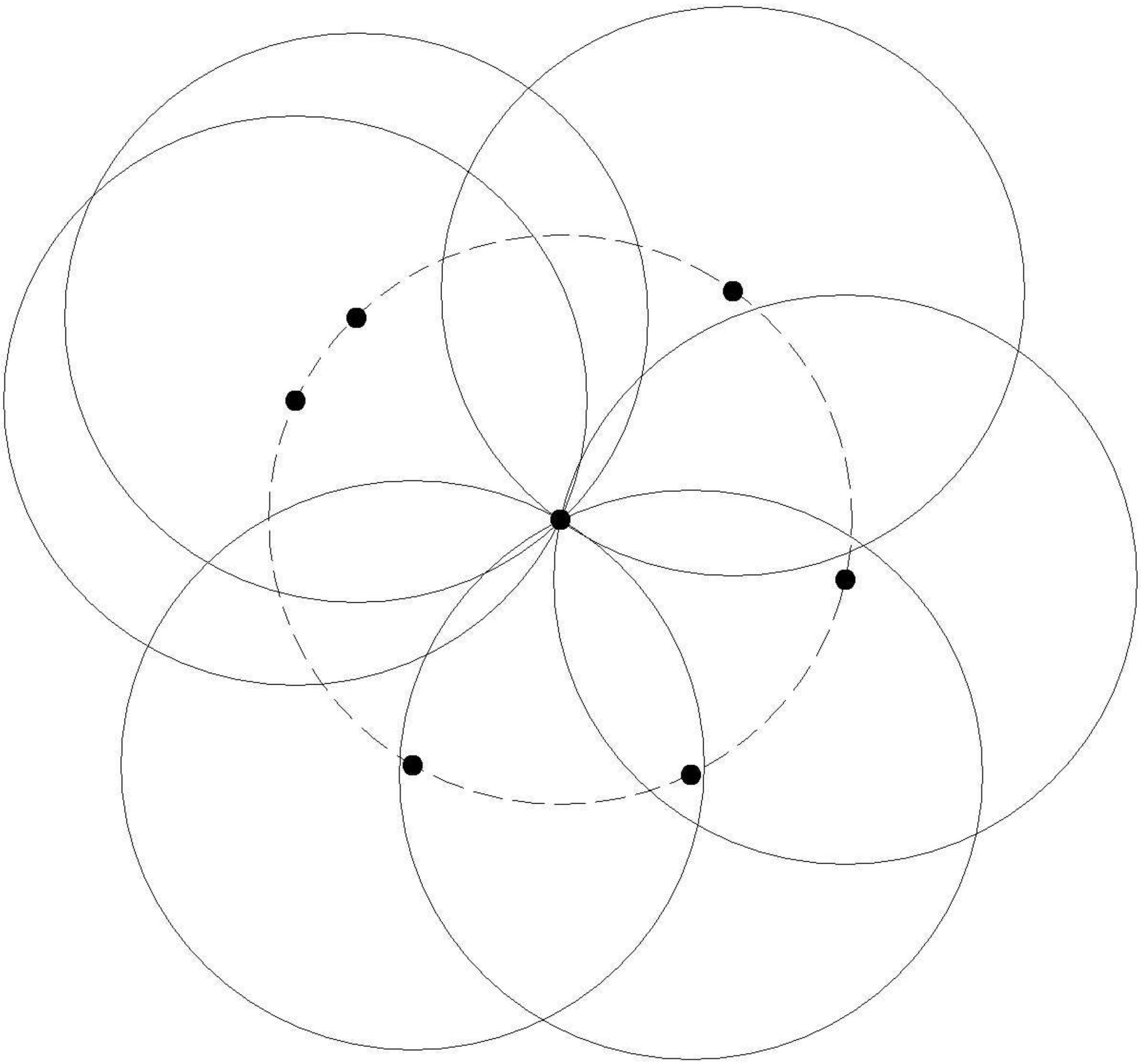
Annihilation Detection

- Need a multi-ring fitter
- All existing ring fitters find only single rings
- Either adjust existing fitter to find multiple rings or make new fitter designed to find multiple rings
- Existing fitters assume single electron produces ring
  - Find most likely vertex and direction for hit PMTs
- Could make a new fitter that uses pattern recognition techniques – e.g. Hough transform

Annihilation Detection

- Hough transform for rings can be used
    - If points on a ring of radius *r* have circles of radius *r* plotted around them, these circles will intersect at the center of the ring
    - Each point in Hough space (congruent to image space) will receive a "vote" for each time a circle passes through it
    - Peak in Hough space (point receiving most votes) corresponds to the center of a possible ring
- If Hough transform is used, parameters must be set to maximize efficiency
    - Number of votes corresponding to positive ring fit
    - Radius step size
    - Angular separation of different peaks

Annihilation Detection



Major Backgrounds

- Backgrounds consist of two events occurring in SNO
    - Deep inelastic scattering of muons off of nuclei
    - Atmospheric neutrinos
- Events occurring after muon events can be removed from the data sample to remove deep inelastic scattering events
- Number of atmospheric neutrino events contributing to background can be reduced by setting ring multiplicity and energy limits

Expected Results

- To determine nuclear annihilation lifetime, the following equation is used

$$T = \frac{\varepsilon N_0 t}{N}$$

ε is the detection efficiency
N_0 is the total number of neutrons in SNO
t is the time over which the experiment is run
N is the number of $n-\bar{n}$ oscillation events

- Assume ε is 100 %, t is 306.4 days (live time of first phase of SNO experiment), N_0 is 3.0133×10^{32}
- Assumed no events and no backgrounds will be seen, resulting in a lower limit on T set by making an upper limit on N of 2.44 using Feldman-Cousins statistics
- Gives $T > 6.534\times10^{38}\,s$

Expected Results

- T_R is found by calculating weighted average of T_R for deuterium and T_R for oxygen
  - $T_R = 8.496 \times 10^{22} s^{-1}$
- This results in $\tau_{n\bar{n}} > 1.96 \times 10^{8} s$

Conclusion

- Using SNO to search for $n-\bar{n}$ oscillations can increase the current lower limit of $\tau_{n\bar{n}} > 1.3\times10^{8}s$ set by Soudan 2
- SNO will be able to increase this limit by an amount comparable to the amount Super-Kamiokande can increase it, even though Super-Kamiokande has a larger number of neutrons
    - This is because of T_R for deuterium is considerably smaller than T_R for oxygen

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