Neutron-Antineutron Oscillation in SNO

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Outline

- Motivation
- Nuclear effects and expected channels
- Oscillation lifetime in Nuclei
- Reconstruction of events
- Estimates of possible limits

Motivation

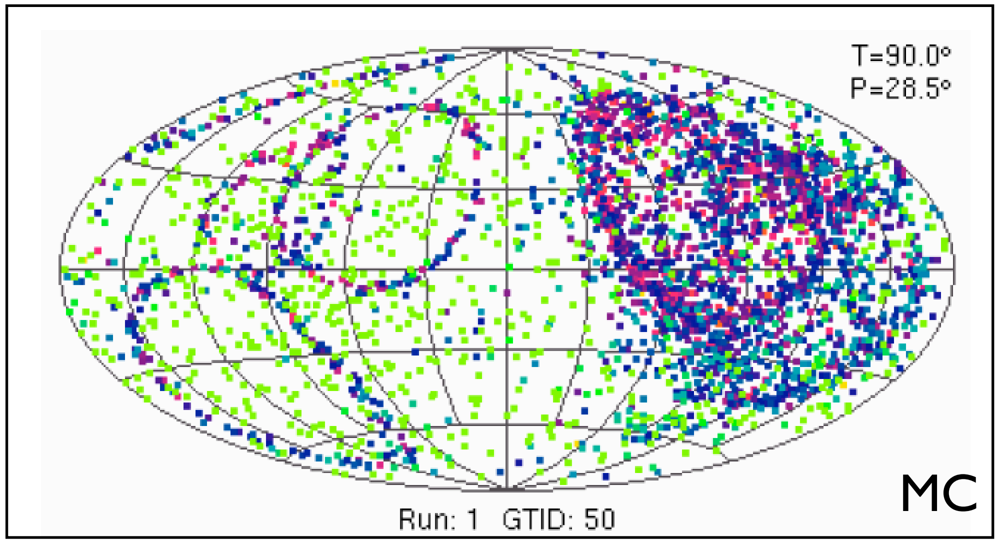
For experiments that are/were in operation, only SNO and SuperK can offer an improvement on the limit set by Soudan-2 on the intra-nuclear nnbar oscillation time.

Because of the large amount of deuterons, SNO is in a unique position to look for a pnbar annihilation through the process of nnbar oscillation in nuclei.

After a preliminary study, we believe the current published limit can be improved.

Annihilation Characteristics

Once the neutron has oscillated to an antineutron (nbar), the Nnbar (N = p or n) annihilation will produce mainly pions. This annihilation is at rest and will be isotropic.



Because of smaller binding energy, the annihilation occurs at the periphery in ^{16}O.

In ^{16}O, pions with energy range of 300 MeV/c can be absorbed and re-emitted by surrounding nuclei via delta resonance. Pions of other energy can also be scattered.

This will affect the isotropy of the annihilation up to a certain point. A treatment of this effect was made by Kamiokande-I.*

**Search for neutron-antineutron oscillation in ^{16}O nuclei,* Takita et al, Phys. Rev D volume 34, number 3, august 1986

Annihilation Characteristics

The average multiplicity of charged pions is (3.24+/-0.16).* The following multiplicity were quoted for Kamiokande, 3.2 for charged pions and 5.1 total pions. (After nuclear effect the mean multiplicity fell to 2.6 for charged pions and 4.1 total pions.)

To obtain possible decay channels an isospin treatment is used.

$p\bar{p}$ channel	BR (10^{-2})	$p\bar{n}$ channel
$\pi^0\rho^0$	1.72 ± 0.27	$\pi^+\rho^0, \pi^0\rho^+$
$\pi^\pm\rho^\mp$	3.44 ± 0.54	$\pi^+\rho^0$
~~$\omega\eta$~~	~~1.6 ± 0.12~~	
~~$\omega\omega$~~	~~3.32 ± 0.34~~	
$\rho^0\omega$	2.26 ± 0.23	$\rho^+\omega$

The nnbar system contains decay isospin channels for both I=0 and I=1, while the pnbar contains only I=1 channels (reducing the possible decay channels available in a pnbar system).

Antineutron Physics, T. Bressani, A. Filippi, Physics Reports 383 (2003) 213-297

Multiple pion Channels

The channels for a pnbar annihilation have been computed from Bubble chamber data.

Channel	BR (%)
$\pi^- + m\pi^0 (m = 1, 2, 3, ...)$	16.4 ± 0.5
$\pi^- + \pi^0$	< 0.7
$2\pi^- + \pi^+ + m\pi^0 (m = 0, 1, 2, ...)$	59.7 ± 1.2
$2\pi^- + \pi^+$	1.57 ± 0.21
$2\pi^- + \pi^+ + \pi^0$	21.8 ± 2.2
$3\pi^- + 2\pi^+ + m\pi^0 (m = 0, 1, 2, ...)$	23.4 ± 0.7
$\omega + 2\pi^- + \pi^+$	12.0 ± 3.0
$4\pi^- + 3\pi^+ + m\pi^0 (m = 0, 1, 2, ...)$	0.39 ± 0.07

Possible channels for a nnbar annihilation have been computed by Lu and Amado.*

	Theory			Experiment	
Channel	$I = 0$	$I = 1$	Combined	CERN	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	

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

Annihilation Characteristics

Since the annihilation is at rest, mainly S-wave are going to be present in the pnbar interaction, reducing the possible decay channels available.

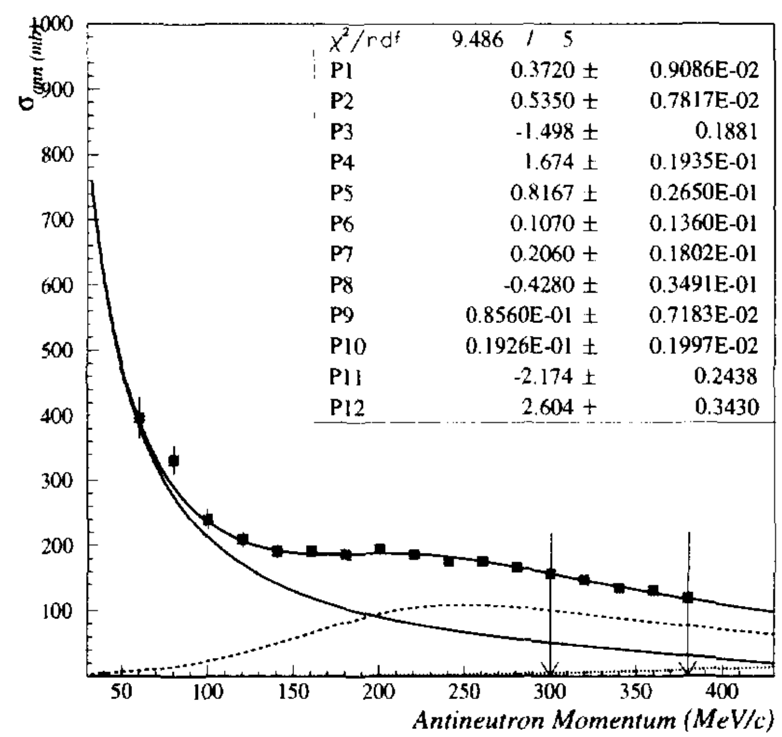


Figure 5. Fit of $\sigma_{ann}^{\bar{n}p}$ measured by Obelix up to 400 MeV/c including S (solid line), P (broken line) and D (point line) wave contributions.

Nuclear Physics B (Proc. Supll.) 56A (1997) 227-233

Channels

Models have been published stating that the dominant mode for npbar (which is similar to pnbar by isospin) annihilation at rest would be a two body system.*

These channels are currently being implemented in our simulations.

TABLE I. Results of fits made to difference spectra for exclusive channels.

Final state	$\pi^- X^0$	M_X (MeV/c^2)	Γ_X (MeV/c^2)	Channel B (%)
$2\pi^-\pi^+$	$\pi^-\rho^0(\rightarrow \pi^+\pi^-)$	806 ± 6	140 ± 12	20 ± 1
	$\pi^- f^0(\rightarrow \pi^+\pi^-)$	1258 ± 3	262 ± 8	75 ± 2
	$\pi^- f_2'(\rightarrow \pi^+\pi^-)$	1522 ± 7	59 ± 12	5 ± 1
				100 ± 3
$2\pi^-\pi^+\pi^0$	$\pi^-\omega(\rightarrow \pi^+\pi^-\pi^0)$	784 ± 3	43 ± 9	5 ± 0.3
	$\pi^- A_2^0(\rightarrow \pi^\pm\rho^\mp)$	1342 ± 4	81 ± 10	18 ± 1
	$\pi^- X^0(\rightarrow \pi^+\pi^-\pi^0)$	1468 ± 6	88 ± 18	25 ± 2
	$\pi^- X^{0\prime}(\rightarrow \pi^+\pi^-\pi^0)$	1594 ± 9	81 ± 12	9 ± 1
	$\pi^0 A_2^-(\rightarrow \rho^0\pi^-)$			9 ± 1
	$\rho^-\rho^0$			34 ± 3
				100 ± 4
$3\pi^-2\pi^+$	$\pi^- X^0(\rightarrow 2\pi^-2\pi^+)$	1477 ± 5	116 ± 9	82 ± 5

**Difference Spectra: Dominance of Two-Body Cascades in Antiproton-Neutron Annihilation at Rest,* D. Bridges, W. Fickinger, Phys. Rev. Lett. volume 56, number 3, January 1986

Backgrounds

The possible backgrounds will come from atmospheric neutrino interactions through delta resonance (multiple pion delta resonance).

$$\nu_\mu p \to \mu^- p \pi^+$$
$$\nu_\mu n \to \mu^- n \pi^+$$
$$\nu_\mu n \to \mu^- p \pi^0$$

$$\nu_\mu p \to \nu_\mu n \pi^+$$
$$\nu_\mu p \to \nu_\mu p \pi^0$$
$$\nu_\mu n \to \nu_\mu n \pi^0$$
$$\nu_\mu n \to \nu_\mu p \pi^-$$

Monte Carlo from Kamiokande have shown that atmospheric neutrino interactions contribute to a background to Nnbar signal when reconstructing the invariant mass.*

Simulations in SNO are being implemented to verify the impact on our analysis.

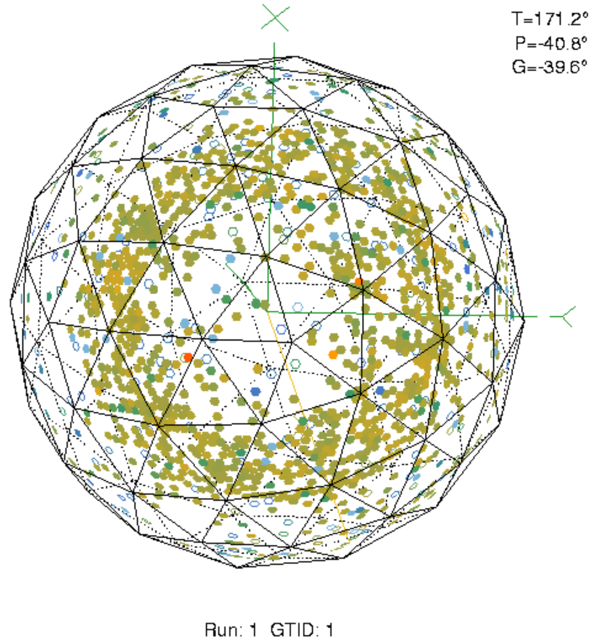
**Search for neutron-antineutron oscillation in ^{16}O nuclei*, Takita et al, Phys. Rev D volume 34, number 3, august 1986

Particle Identification

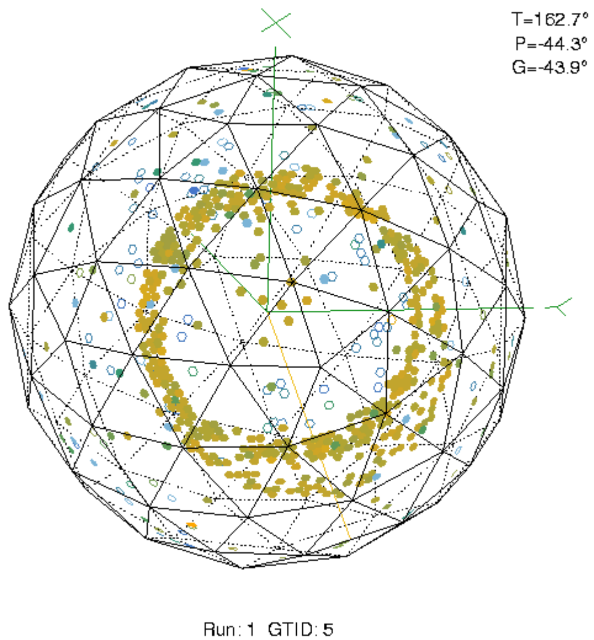
Particle can have two different type of signature inside the detector.

Showering particles such as ($e^{+/-}$,γ). Showering particles will leave "fuzzy" rings inside the detector.

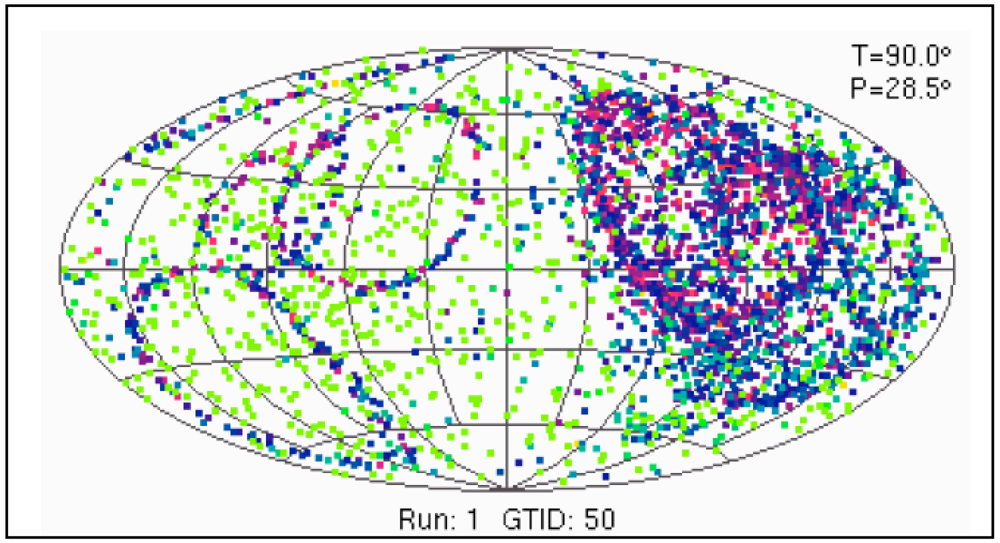
Non-showering particles such as (μ+/-,π+/-) leave "clean" rings inside the detector.



Showering ring



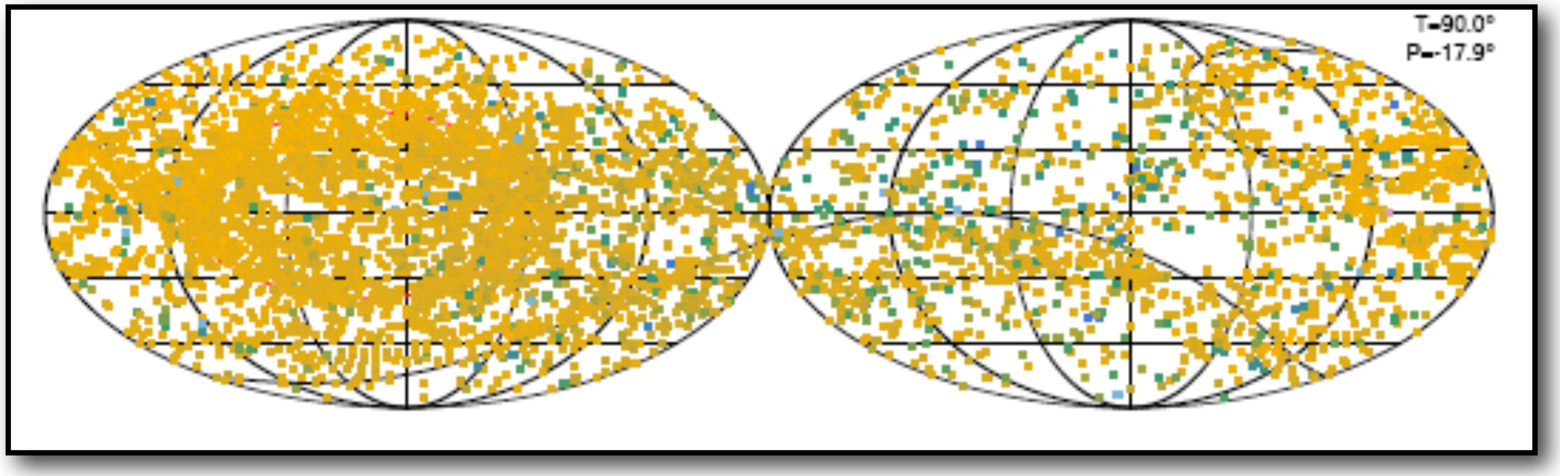
Non-showering ring



Multiple Ring Fitter

A Multiple Ring Fitter has been developed. The fitter combines two separated fitters called the Mid-Point Pair Transform (MPPT) and the Angular Fitter (AF).

While the fitter was created for rings from proton decays, it was applied to different events to test its flexibility. In this event, the fitter was applied and three rings were found (out of five visible rings).



While the fitter needs optimization, tools are available to push a nnbar analysis further.

Oscillation Lifetime in Nuclei

Dover, Gal and Richard (1982) showed that the oscillation time for the neutron-antineutron process is suppressed in the nuclei.

The free oscillation time can be calculated with the use of the reduced "lifetime" T_R (this is in fact a rate):

$$\tau_{nnbar} = (T_{nnbar}/T_R)^{1/2}$$

$T_R = 1.0 \times 10^{23}\ sec^{-1}$ (Oxygen)
$T_R = 0.248 \times 10^{23}\ sec^{-1}$ (Deuteron)
T_{nnbar} = nuclei annihilation lifetime

For an analysis including both D and ^{16}O, an averaged reduced "lifetime" can be calculated:

$$T_R = (2 \times 0.248 + 8 \times 1.00)/10 \times 10^{23}\ sec^{-1} = 0.85 \times 10^{23}\ sec^{-1}$$

Case for a Deuteron only analysis

If we take the lifetime of the first phase of SNO (306.4 days), the lifetime of the Nnbar process can be calculated with a Feldman-Cousins statistic (< 2.3 events at 90% CL).

$$T_{nnbar} = \frac{N_n \times N_{D2O}}{2.3 \text{ candidates}} \times \frac{\text{live days}}{365.25 \text{ days/year}}$$

where N_{D2O} is the number of D_2O molecules while N_n is the number of neutron per molecule.

In an analysis where we look only at Deuteron, the oscillation lifetime limit that could be achieved compared to a full D+O analysis is:

$$(\tau_{nnbar})_D/(\tau_{nnbar})_{D+O} = 82.8\%.$$

Possible Reach

Please note that the following are anticipated sensitivities:

For Deuteron Only Analysis:

$\tau_{nnbar} > 1.67 \times 10^8$ sec (phase 1)
$\tau_{nnbar} > 2.52 \times 10^8$ sec (+phase 2)
$\tau_{nnbar} > 3.13 \times 10^8$ sec (+phase 2 and phase 3)

For Deuteron and Oxygen Analysis:

$\tau_{nnbar} > 2.00 \times 10^8$ sec (phase 1)
$\tau_{nnbar} > 3.04 \times 10^8$ sec (+phase 2)
$\tau_{nnbar} > 3.78 \times 10^8$ sec (+phase 2 and phase 3)

Current published limit:

$\tau_{nnbar} > 1.3 \times 10^8$ sec

Summary

A deuteron analysis can offer improvement on the current free nnbar oscillation limit.

The analysis is simpler than an analysis that includes oxygen since possible scattering on neighboring nuclei and nuclear effect are not present.

Work still needs to be done on the detection efficiency of the antineutron annihilation in D and ^{16}O, but it is expected that the efficiency of detection for ^{16}O will be lower because of scattering effect.