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A Search for $n\bar{n}$ Oscillations at Super-Kamiokande-I

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Abstract: In this paper we summarize a search for neutron-antineutron oscillations using the full 1489.2 day Super-K-I data set. Our results include a 90% confidence level (CL) lower limit on the neutron oscillation lifetime in ^{16}O of $1.77 \times 10^{32} yrs$, a factor of 2.5 improvement over the previous best $n\bar{n}$ oscillation limits for neutrons bound inside nuclei.

The discovery of neutrino oscillations has renewed interest in theories which yield B and L symmetry breaking by allowing $|\Delta(B-L)| = 2$ with $|\Delta L|$=2, as in neutrinoless double beta decay and $|\Delta B|$=2 as in neutron-antineutron oscillations. These models include a large class of supersymmetric and R-L symmetric $SU(2)_L \otimes SU(2)_R \otimes SU(4)_C$ theories[1]. Neutron-antineutron oscillations have also been predicted by recent grand unification theories with large extra space-time dimensions[2] and by R-L symmetric theories that use the see-saw mechanism to generate neutrino masses[3].

The previous best 90% CL neutron oscillation limits are from Kamiokande II, 0.43×10^{32} yrs in water[4]; Frejus[5] followed by Soudan II, with 0.72×10^{32} yrs in iron[6]; and ILL (Grenoble), 0.86×10^{8} s for unbound (free) neutrons[7]. The 2.45×10^{34} neutron-year exposure of the Super-K-I data set is a factor of 50 higher than that of all previous experiments.

The Super-Kamiokande detector is located in Kamioka-town in Gifu prefecture Japan. It contains 50,000 tons of ultra-pure water that serves as a source of nucleons, a target for neutrinos, and a medium for generation of Cherenkov radiation from relativistic charged particles. Super-K was designed to search for spontaneous baryon number violation due to nucleon decay or neutron-antineutron oscillations, and to study cosmic ray neutrinos as well as neutrinos from accelerator beams. Descriptive overviews of Super-Kamiokande and technical details are given in the literature[8]. Super-K consists of an outer detector (OD) that serves as an exterior veto region and an inner detector (ID) which contains the fiducial volume.

Our $n\bar{n}$ simulations involve five stages: 1. spontaneous oscillation of a neutron to an antineutron ($\bar{n}$) in ^{16}O (the oscillation phase), 2. annihilation of the $\bar{n}$ with one of the remaining 15 nucleons (7 neutrons and 8 protons) with presumed equal likelihood resulting in an excited ^{14}O* or ^{14}N* nucleus (the annihilation phase), 3. the production of multiple (2-6 or more) annihilation products including an occasional gamma and or undecayed omega meson and two to six pions (the pionic phase), 4. propagation of the products of the pionic phase through the excited nucleus (the nuclear propagation phase), and 5. fragmentation of the excited nucleus to n, p, H and He isotopes, and to a large residual fragment (the fragmentation phase).

Since the literature on $\bar{n}$ annihilation in nuclei is limited to a small number of studies, $\bar{p}p$ and $\bar{p}d$ data from hydrogen and deuterium bubble chambers are used to determine the branching ratios for the annihilation final states[9]. Produced pions from the $\bar{n}$ annihilation are propagated through the residual nucleus in steps of length 0.1 or 0.2 fm. The pion-residual nucleus interaction cross sections are based upon an interpolation from measured pion-carbon and pion-aluminum cross sections to ^{16}O[10].

Our analysis starts with the atmospheric neutrino and nucleon decay data sample consisting of events of total energy greater than or equal to 30 MeV that are fitted in the fiducial volume and are fully contained within the Super-K ID[8]. Events in this sample are processed through the full reconstruction algorithm, yielding an overall event vertex, the number of Cherenkov rings, and the direction, particle identification, and momentum of each ring.

The $n\bar{n}$ oscillation analysis focuses on extracting candidate events. To isolate $n\bar{n}$ candidates we apply additional criteria to events in the reduced fully contained (FC) sample based on the following reconstructed kinematic variables: (a) number of rings, (b) visible energy, (c) total momentum, and (d) total invariant mass. The total momentum is defined as $P_{tot} = |\sum_i^{allrings} \overrightarrow{p_i}|$ where $\overrightarrow{p_i}$ is the reconstructed momentum vector of the i-th ring and the total invariant mass is defined to be $M_{tot} = \sqrt{E_{tot}^2 - P_{tot}^2}$, where the total energy is given by $E_{tot} = \sum_i^{allrings} |\overrightarrow{p_i}|$.

Fig. 1 compares distributions of our reconstructed kinematic variables for the three relevant event samples, the $n\bar{n}$ MC, the atmospheric neutrino MC, and the full Super-K-I data set, and our selection criteria (cuts) as applied to those distributions. Fig. 2 shows the same samples undergoing our final (total invariant mass, total momentum) criteria after all previous cuts have been made, in our 'signal box'.

For an assumed upper limit on the number of observed signal events, S, the oscillation lifetime is given by

$$T_{n\bar{n}} = \frac{\epsilon \times N \times T}{S}; \tag{1}$$

where ϵ is the signal detection efficiency, N is the number of neutrons inside the fiducial volume, and T is the detector livetime. The cuts in Fig. 1 were chosen to maximize the ratio $\epsilon/\sqrt{b}$, where b is the background rate.

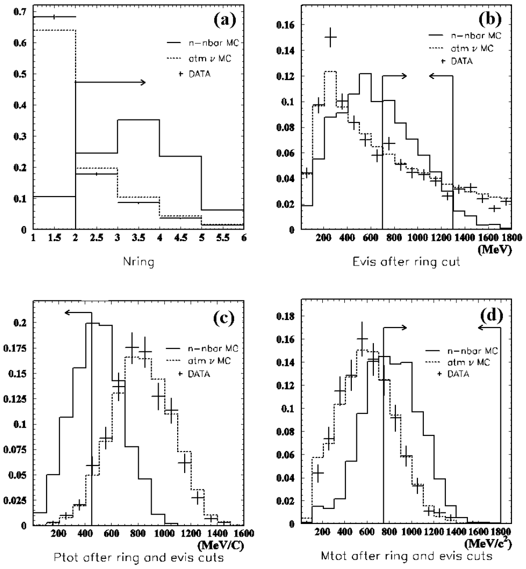

Figure 1: Distributions of the kinematic variables used in our event selection along with the cuts applied to those variables for the $n\bar{n}$ MC, the atmospheric neutrino MC, and the full Super-K-I data set: (a) The number of rings, (b) The visible energy after passing the cuts in (a), (c) The total momentum (Ptot) after passing the cuts in (a) and (b), and (d) The total invariant mass (Mtot) after passing the cuts in (a) and (b).

The overwhelming source of background events for $n\bar{n}$ oscillations in nuclei is atmospheric neutrino interactions. We studied the background for our $n\bar{n}$ search by using a Monte Carlo sample that included as many atmospheric neutrino interactions as one would expect in a 100 year exposure of the Super-K detector. A detailed description of our background simulations is given in [11]. An analysis using our 100 year sample that included the effects of atmospheric muon neutrino oscillations indicated that we would expect 21.3 atmospheric neutrino interactions in the Super-K-I data set. The main contribution to the background sample for our $n\bar{n}$ search came from neutrino interactions that produce single pions via (delta and other nucleon) resonances and through multi-hadron production. Single pion production is an important source of background events because produced hadrons and their secondaries yield multiple Cherenkov rings, that can easily mimic multi-ring events similar to those that we expect from $\bar{n}$

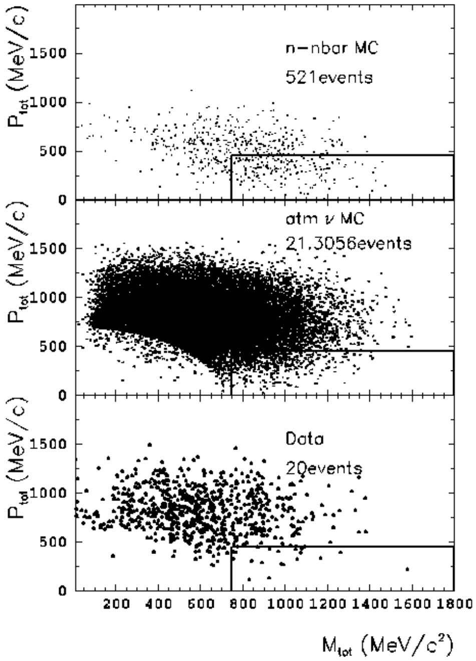

Figure 2: The total momentum vs. total invariant mass for the $n\bar{n}$ MC, the atmospheric neutrino MC, and the full Super-K-I data set.

annihilation. This conclusion is in agreement with Fig. 1(a) which shows that the average $\bar{n}$ annihilation event produces about 3.5 reconstructed rings.

The major sources of systematic uncertainties for ϵ and the exposure and for b are listed in Tables 1 and 2, respectively. For the detection efficiency the most important source of error is the pion-nucleon cross sections in the ^{16}O nucleus, which we estimated to be about 12.5% through an MC study that varied the π-nucleon cross sections. The total uncertainty in the detection efficiency and exposure, due to all of the sources in Table 1, was found to be less than 15.2%. The systematic uncertainty in the background rate is dominated by errors in the neutrino cross sections (18%) and in the energy scale at Super-Kamiokande (12%). Taking into account all sources of error in Table 2, we found that the total uncertainty in the background rate was 32.1%.

	Uncertainty (%)
Detection Efficiency	14.9
Fermi momentum	4.2
annihilation branching ratio	5.2
non-uniformity of detector gain	4.0
energy scale	1.7
ring counting	0.6
nuclear propagation (model dependence)	1.7
nuclear propagation (cross sections)	12.5
Exposure	< 3.2
detector livetime	<0.1
fiducial volume	3.2
Total	<15.2

Table 1: The systematic uncertainties in the efficiency and the exposure.

The signal boxes in Fig. 2 contain 521 out of 5000 $n\bar{n}$ MC, 20 candidate, and 21.3 background events, thus yielding a detection efficiency of 10.4% and demonstrating excellent agreement between the data and the expected background. Using Bayesian statistics with a flat prior for the $n\bar{n}$ lifetime and including all systematic errors, our 90% CL lower limit for the oscillation lifetime was found to be 1.77×10^{32} years.

The lifetime of a neutron bound in a nucleus is much larger than that of a free neutron (τ_{free}) due to the different potentials experienced by n and $\bar{n}$. The relationship between the two lifetimes is

$$T(intranuclear) = R \cdot \tau^2_{n\bar{n}}(free) \qquad (2)$$

where R, the nuclear suppression factor, was estimated to be $1.0 \times 10^{23} s^{-1}$[12].

Using Eqn. (2) we find that our limit for bound neutrons at the 90% CL corresponds to $\tau_{free} = 2.36 \times 10^8$ s, which can be compared with a limit of $\tau_{free} = 0.86 \times 10^8$ seconds, as measured directly at the ILL reactor, and $\tau_{free} = 1.3 \times 10^8$ s, as deduced by Soudan II from their oscillation lifetime lower limit for neutrons bound in iron.

Our $n\bar{n}$ search was the first to include major sources of systematic errors in the computation of its limits. The lower limit that we obtained for the bound neutron oscillation lifetime is 2.5 times higher than the previous best bound neutron limit of 0.72×10^{32} yrs, by Soudan II for ^{56}Fe. Our free neutron oscillation time limit is higher than the previous best limits by ILL of

	Uncert.(%)
Neutrino Flux	21.5
flux absolute normalization	20
flavor ratios	0.1
$\bar{\nu}_e/\nu_e$ ratio	0.9
$\bar{\nu}_\mu/\nu_\mu$ ratio	0.8
up/down ratio	-
horizontal/vertical ratio	-
K/π ratio	5.2
energy spectrum	5.8
Neutrino Cross Sections	18
M_A in quasi-elastic and single-π	4.4
QE scattering	0.4
single-πproduction	2.8
multi-π production	15.9
coherent π production	0.1
NC/CC ratio	6.2
mean free path in ^{16}O	2.7
non-uniformity of Detector Gain	9.0
Energy Scale	12.0
Ring Counting	4.3
Total	32.1

Table 2: The systematic uncertainties in the background rate.

0.86×10^8 s and by Soudan II (deduced from ^{56}Fe) of 1.3×10^8 s, by factors of 2.7 and 1.8, respectively. Even though the inclusion of systematic errors decreases lower limits, the limits we obtained are significantly higher than those of previous experiments. The $n\bar{n}$ results presented here are the first from a large water Cherenkov detector in over 20 years.

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References

[1] S. J. Huber and Q. Shafi, Neutrino oscillations and rare processes in models with a small extra dimension. Phys. Lett. B 512, 365-372, (2001), also hep-ph/0104293.

[2] S. Nussinov and R. Shrock, N-nbar oscillations in models with large extra dimensions, Phys. Rev. Lett. 88, 171601-171603, (2002), also hep-ph/0112337.

[3] K. S. Babu and R. N. Mohapatra, Observable neutron-antineutron oscillations in seesaw models of neutrino mass, Phys. Lett. B, 518, 269-275, (2001).

[4] M. Takita et. al. (Kamiokande), A search for neutron antineutron oscillation in ^{16}O, Phys. Rev. D (Rapid Communications) 34 (3), 902-904 (1986).

[5] Ch. Berger et. al. (The Frejus Collaboration), Search for neutron-anti-neutron oscillations in the Frejus detector, Phys. Lett. B, 240, 237-242, (1990).

[6] J. Chung et. al. (The Soudan Collaboration), Search for neutron anti-neutron oscillations using multiprong events in Soudan 2, Phys. Rev. D 66, 032004,1-11, (2002), also hep-ex/0205093, May (2002).

[7] M. Baldo-Ceolin et al. (ILL, Grenoble France), A new experimental limit on neutron-anti-neutron oscillations, Z. Phys. C 63, 409-416, (1994).

[8] The Super-Kamiokande Collaboration (Y. Fukuda et al.), The Super-Kamiokande detector, Nucl. Instrum. Meth. in Phys. Res. A, 501, 418-462, (2003).

[9] T.W. Jones et. al. (The IMB Collaboration), A search for $n\bar{n}$ oscillations in oxygen, Phys. Rev. Lett. 52 (9), 720-723, (1984).

[10] D. Ashery, Pion nucleus reactions, Nucl. Phys. A 354, 555c-576c, (1981).

[11] The Super-Kamiokande Collaboration (Y. Ashie et al.), A measurement of atmospheric neutrino oscillation parameters by Super-Kamiokande I, Phys. Rev. D 71, 112005, January (2005), also hep-ex/0501064.

[12] C. B. Dover, A. Gal, and J. M. Richard, Neutron anti-neutron oscillations in nuclei, Phys. Rev. D 27, 1090-1100, (1983).