



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

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Abstract: Super-Kamiokande (SK) is a 50 kton ring imaging water cherenkov counter located in Mozumi Japan and designed to study neutrino physics and baryon number violation. Here we summarize a search for neutron-antineutron oscillations using the full 1489.2 day SK-I data set. The results of our search include a 90 % confidence level (CL) lower limit on the lifetime for neutron oscillation in ^{16}O of 1.77×10^{32} yrs, a factor of 4 improvement over the previous best $n - \bar{n}$ oscillation limits for neutrons bound inside nuclei. Using a nuclear suppression factor of $R = 1.0 \times 10^{23}$, our new limit corresponds to a free neutron oscillation limit of 2.36×10^8 seconds, an improvement of a factor of 2.7 over the previous best free neutron limit of 0.87×10^8 seconds, as reported by the ILL reactor experiment (at Grenoble). These new results may constrain some theories involving grand unification and supersymmetry particularly those involving right-left symmetry and the see-saw mechanism such as SO(10)

Introduction

In the twenty-five years that have gone by since the first large (several kton) water cherenkov and fine grained nucleon decay experiments appeared in the early 1980's the impetus for studying $|B - L|$ violating interactions such as neutron oscillation and double beta decay has steadily grown. Improved experimental limits on $p \rightarrow e^+ \pi^0$ and $p \rightarrow \bar{\nu} K^+$ have already ruled out the simplest $|B - L|$ conserving GUT models, minimal SU(5) and MSSM SU(5). Also it has been shown that the triangle anomalies involving electro-weak bosons would wash out any $|B - L|$ conserving baryon asymmetry above the 10 TeV scale. Thus the search for $|B - L|$ violating reactions has become increasingly important as a potential explanation of the observed baryon asymmetry of the universe.

The discovery of neutrino oscillations has renewed interest in theories with Majorana spinors 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[?][0]. Neutron-antineutron oscillations have also been predicted by recent grand unification theories with large extra space-time dimensions [?][?]

It is notable that $n - \bar{n}$ oscillation involves a six quark operator, which scales like m^{-5} instead of m^{-2} in the case of the charged X and Y bosons that mediate nucleon decay in minimal SU(5). Thus, an observable $n - \bar{n}$ oscillation signal in Super-Kamiokande would imply new physics at a scale of about 100 TeV, in a complementary energy range to that which will be probed for new physics at the Large Hadron Collider.

The previous best 90 % CL neutron oscillation limits are from Kamiokande II, 4.3×10^{31} yrs in water; Soudan 2, 4.3×10^{31} yrs in iron; and ILL (Grenoble), 8.6×10^7 seconds for unbound (free) neutrons. limit of The 2.45×10^{34} neutron-year exposure of the SK I data set is a factor of 50 higher than all previous experiments, allowing us to improve neutron oscillation limits in nuclei by a factor of 4.4.

Our $n - \bar{n}$ simulations consist of five stages 1. spontaneous oscillation of an antineutron (\bar{n}) in ^{16}O 2. annihilation of the $n - \bar{n}$ with one of the remaining 15 nucleons (7 neutrons (n) and 8 protons (p)) resulting in an excited ^{15}O or ^{15}N nucleus 3. The production of multiple (2-6 or more) annihilation products including an occasional gamma and 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) 5. and fragmentation of the excited nucleus to n, p, Helium, Hydrogen and to a larger nucleus (the fragmentation phase).

In general $n - \bar{n}$ oscillation events in the SK detector before reconstruction include an average of 4-4.5 pion tracks with one pion track having been absorbed in the ^{16}O nucleus. The pionic and nuclear fragments that make up the event might be expected to have nearly zero total momentum, except for the Fermi momentum of the annihilation \bar{n} and nucleon (n or p) and to have total energy equal to about twice the mass of a nucleon (about 1877 MeV). Since only about 60 % of the pionic rings are reconstructed due to inelastic pion interactions such as scattering and absorption during nuclear propagation and the lack of perfect efficiency in ring reconstruction (due to weak or overlapping rings and imperfections in ring fitting) and the fact that almost all of the nuclear fragments are below Cherenkov threshold, the average total energy is about 60 % of the mass of the annihilating nucleons. Since each of the annihilating nucleons is assumed to have Fermi momentum with a maximum magnitude of about 250 MeV/c the total momentum of a perfectly reconstructed event might be expected to be about 250 MeV/c (1/2 of the maximum Fermi Momentum). Since only a portion of the Cherenkov rings are reconstructed the average momentum of a simulated $n - \bar{n}$ events is expected to be much higher due to the contributions made to the total momentum vector by the 40 % of the tracks that we fail to reconstruct, yielding an expected mean momentum from reconstructed Monte Carlo events of about 550 MeV/c. Therefore an average $\bar{n}n$ event in the SK detector is expected to have a reconstructed total energy and total momentum of about 1100 MeV and 550 MeV/c, respectively. Our simulations show that below cherenkov threshold nuclear fragments carry

about 600 MeV of Kinetic energy (that is invisible in SK).

As stated above, an \bar{n} that is the product of the spontaneous oscillation phase quickly annihilates with one of the remaining (n or p) nucleons in the nucleus with equal likelihood (of 7/15 and 8/15 respectively) and produces multiple (pionic phase) annihilation secondaries with a total energy of about twice the mass of a nucleon.

The Super-Kamiokande (SK) 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 as 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 oscillation, and to study cosmic ray neutrinos as well as neutrinos from accelerator beams. Descriptive overviews of Super-K and technical details are given in the literature [?] Super-Kamiokande-I (SK-I), took data from May 31st, 1996 to July 15th, 2001, using the nominal SK fiducial volume of 22.5 kton. In the $n - \bar{n}$ analysis described in this paper, the complete SK-I data set, having a livetime of 1498.2 days, was used.

The $n - \bar{n}$ Monte Carlo simulations

Since the literature on \bar{n} annihilation in nuclei is meager, $\bar{p}p$ and $\bar{p}d$ data from hydrogen and deuterium bubble chambers are used to determine the branching ratios for the annihilation final states. The kinematics are determined by relativistic phase-space including the Fermi motion of the parent nucleons. The energy of the system is the mass of the original nucleons minus their approximate binding energies.

Produced pions from the $n - \bar{n}$ nucleon annihilations are propagated through the residual nucleus in 0.2 fermi steps. The pion-residual nucleus interaction cross sections are based on an interpolation from measured pion-carbon and pion-aluminum cross sections to ^{16}O . Excitation of the $\Delta(1232)$ resonance is the most important effect in the nuclear propagation phase. As the pions move outward, it is assumed that the cross sections scale linearly with the density which decreases as the pions move

away from the annihilation point.. The Fermi motion of the interacting nucleon and the possibility of Pauli blocking are included in the simulation. We find that 49% of the pions do not interact, while 24% are absorbed and 3% interact with a nucleon to produce an additional pion or occasionally multiple pions; the rest of the pion interactions involve scattering. This gives us total and charged pion multiplicities of 3.5 and 2.2, respectively, and an average charged pion momentum of 310 MeV/c with an RMS deviation of 190 MeV/c. There is also a % probability of an ω^0 escaping the nucleus without decaying for each event.

In events in which a pion interactions occur, the residual nucleus, $^{14}\text{N}^*$ after $\bar{n} - p$ and $^{14}\text{O}^*$ after $\bar{n} - n$ annihilation respectively, fragments to ^2H , ^3H , ^3He , ^4He , n, p and a remaining large nucleus. The final state of the nuclear fragments is simulated using an algorithm that we developed based upon a previous (n) Monte Carlo used briefly in the past at Oak Ridge National Laboratory.. Nuclear fragments containing more than one nucleon are removed before the SK detector simulation since they are below Cherenkov threshold and thus produce no Cherenkov light.

Data reduction and reconstruction

Our analysis starts with the atmospheric neutrino and nucleon decay data sample (collected by the SK atmospheric neutrino and proton decay group, ATMPD) consisting of events of total energy ranging from 50 MeV to 10 GeV that are fitted in the fiducial volume and are fully contained within the SK inner detector. Events are selected from a complete sample of SK high energy triggers and a common data filtering and reduction process used for isolating atmospheric neutrinos and proton decay candidate events[?]. The trigger threshold is based on PMT hit multiplicity and gives about 10 Hz of events above an energy threshold of about 10 MeV. Rejection of events with significant outer detector activity or inner detector hit patterns indicative of radioactivity or PMT afterpulsing reduces the sample to about eight events per day, almost all of which are atmospheric neutrinos.

Events in this sample with energies of 50 MeV or greater are processed through the full recon-

struction program, yielding an overall event vertex, the number of Cherenkov rings, and the direction, particle identification, and momentum for each ring. The vertex resolution is approximately 25 cm for events with only a single muon ring. Each ring is identified as “showering” (e, γ) or “non-showering” (μ, π, p) based on the pattern of hits and the opening angle of its Cherenkov ring. Momentum is subsequently determined using the assigned particle type and the number of collected photo-electrons in the ring after corrections for geometric effects and light attenuation.

Data Analysis

The $n - \bar{n}$ candidate events are extracted using three criteria (‘cuts’) based upon the number of reconstructed Cherenkov rings, the visible energy, and the total momentum and total invariant mass. The visible energy is defined as the energy of a showering electron that would have given the same number of photoelectrons as seen in the event. The total momentum is defined as $P_{tot} = |\sum_{rings} \vec{p}_i|$ and the total invariant mass is defined using $E_{tot} = \sum_{rings} |\vec{P}_i|$.

FIG. 1. compares distributions for our reconstructed kinematical variables for the $n - \bar{n}$ MC, atmospheric neutrino MC and the data. FIG. 2 shows our signal box after all previous cuts have been made. Requiring more than one reconstructed ring eliminate about 64% of the background (atmospheric neutrino) events. The other cuts reduce the atmospheric neutrino background to .16%, while retaining 10.4% of the signal events.

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

$$T_{n-\bar{n}} = \frac{\epsilon \times N \times T}{S}, \quad (1)$$

where ϵ is signal detection efficiency, N is number of neutrons inside of fiducial volume, and T is detector lifetime.

The cuts in FIG. 1 were chosen to maximize ϵ/\sqrt{b} ;

As mentioned in the introduction of this paper, the average total momentum is higher (about 450 MeV/c as opposed to 250 MeV/c) and the total energy lower (about 1000 MeV as opposed to about

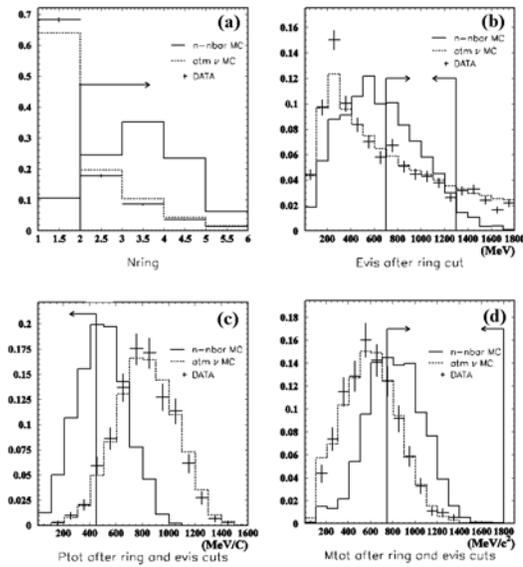


Figure 1: The distributions of variables: (a) Number of rings, (b) Visible energy after passing (a), (c) Total momentum (Ptot) after passing (a) and (b), and (d) Total invariant mass (Mtot) after passing (a) and (b).

twice the mass of the nucleon or about 1877 MeV) for the simulated (Monte Carlo) $n - \bar{n}$ events. These kinematic differences have two causes pion interactions during the nuclear propagation phase which on average results in the conversion of about 600 MeV of pion energy to nuclear fragments that are below Cherenkov threshold and because our analysis is only able to reconstruct about 60 % of the Cherenkov rings in an event.

Background Events

The most significant source of background events for $n - \bar{n}$ oscillations is the interactions of atmospheric neutrinos. We studied backgrounds by using a Monte Carlo simulation that contained as many atmospheric neutrino interactions as one would expect from a 100 year exposure of the SK detector. A detailed description of our background simulations is given in [?]. This 100 yr background sample indicates that we should expect 21.6 atmospheric neutrino interactions in the 1489.2 day SK-I data set (and exposure) and includes the ef-

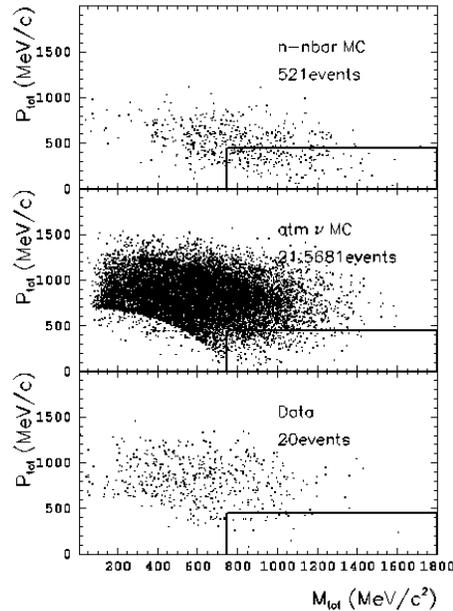


Figure 2: Total momentum vs. invariant mass.

fects of atmospheric muon neutrino oscillations. The main contribution to our background sample comes from neutrino interactions that produce single pions via (Δ and other nucleon) resonances and through multi-hadron production. The reason that these single pion production events are such an important source of background is that produced hadrons and their secondaries yield multiple Cherenkov rings, that can easily mimic the multi-ring events that we expect from \bar{n} annihilation. This conclusion is in agreement with Fig.1 (b) which shows that the average \bar{n} annihilation event produces about 3.5 rings.

Systematic errors

The sources of the systematic uncertainties of detection efficiency and background rate are listed in Table II and III. The main source of the systematic uncertainty of detection efficiency is the pion-nucleon cross section in nucleus. We estimated the uncertainty by changing π -nucleon cross sections, and found the corresponding error to be

about 12.5%. The uncertainty of the detection efficiency is 15.2%, in total. The systematic uncertainty of the background rate largely comes from neutrino cross sections(18%), and energy scale of the Super-Kamiokande (12%). The uncertainty is 32.1% in total.

	Uncertainty (%)
Detection Efficiency	14.9
fermi momentum	4.2
annihilation branching ratio	5.2
un-uniformity of detector gain	4.0
energy scale	1.7
ring counting	0.6
nucl prop (model dependence)	1.7
nucl prop (cross section)	12.5
Exposure	< 3.2
detector livetime	<0.1
fiducial volume	3.2
Total	<15.2

Table 1: Systematic uncertainties in efficiency and exposure.

Results

We find 20 candidate events in the signal box which agrees very well with the expected number of background events of 21.6. Using Bayesian statistics with a flat prior for the $n\bar{n}$ lifetime and including all systematic errors our 90% CL limit for the oscillation lifetime is 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 relation between the two lifetimes is

$$T(intranuclear) = R \cdot \tau_{n\bar{n}}^2(free) \quad (2)$$

where R is estimated to be 1.0×10^{-23} .

Thus our result corresponds to $\tau_{free} = 2.36 \times 10^8$ seconds compared to $\tau_{free} = .87 \times 10^8$ seconds measured at ILL/Grenoble.

	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 Section	18
M_A in quasi-elastic and single- π	4.4
QE scattering	0.4
single- π production	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
Un-uniformity of Detector Gain	9.0
Energy Scale	12.0
Ring Counting	4.3
Total	32.1

Table 2: Systematic uncertainties in background rate.

Conclusions

Previous $n\bar{n}$ experiments using water Cherenkov or iron calorimeter detectors utilized Bayesian or frequentist statistics without including systematic errors in their final limits. Following this procedure would have given us a limit of 4.45×10^{32} years. Thus our measurement improves the previous best limits for bound neutrons by a factor of 4.4. We hope to improve our limits significantly with the inclusion of SK-II and SK-III data. Our results may help to constrain theories of grand unification in particular those that include R-L symmetry and the see-saw mechanism.

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References

- [1] S. Nussinov and R. Shrock, N - \bar{n} Oscillations in Models with Large Extra Dimensions, Phys. Rev. Lett. 88, 171601-171603, (2002), also hep-ph/0112337.
- [2] S. J. Huber and Q. Shafi, Phys. Lett. B 512, 365, (2001), also hep-ph/0104293.
- [3] T.W. Jones et. al. (IMB), Phys Rev Lett. 52 (1984)
- [4] M. Takita et. al. (Kamiokande), Phys Rev D. 34 (1986)
- [5] 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, August 2002, also hep-ex/0205093, May (2002).
- [6] Ch. Berger et. al. (The Frejus Collaboration), Search For Neutron-Anti-Neutron Oscillations In The Frejus Detector, Phys.Lett.B, 240, 237-242, (1990).
- [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, February 2003, (2003).
- [9] 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.