PHYSICAL REVIEW D VOLUME 34, NUMBER 3 1 AUGUST 1986

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

Search for neutron-antineutron oscillation in ^{16}O nuclei

M. Takita,[a] K. Arisaka,[a,*] T. Kajita,[a] T. Kifune,[b] M. Koshiba,[a] K. Miyano,[e] M. Nakahata,[a] Y. Oyama,[a] N. Sato,[c] T. Suda,[b] A. Suzuki,[a] K. Takahashi,[d] and Y. Totsuka[a]

[a]*Department of Physics and International Center for Elementary Particle Physics, University of Tokyo, Tokyo 113, Japan*

[b]*Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan*

[c]*Department of Astronomy, University of Tokyo, Tokyo 113, Japan*

[d]*KEK, National Laboratory for High Energy Physics, Ibaraki 305, Japan*

[e]*Department of Physics, University of Niigata, Niigata 950-21, Japan*

(Received 17 March 1986)

Results are presented on neutron-antineutron oscillations in a ^{16}O nucleus from the Kamioka nucleon-decay experiment KAMIOKANDE. The lower limit on neutron lifetime in ^{16}O is 4.3×10^{31} yr at 90% C.L., corresponding to a lower limit of 1.2×10^{8} sec at 90% C. L. for the neutron-antineutron oscillation time.

Grand unified theories[1] (GUT's) generally predict the existence of baryon-number-nonconserving processes such as nucleon decay. The detection of the signals caused by such phenomena has been of great interest and importance as experimental verification of GUT's. The minimal SU(5) predicts[2] nucleon decay ($\Delta B=1$, $\Delta B-\Delta L=0$) naturally, and neutron-antineutron (n-$\bar{n}$) transitions ($\Delta B=2$) are suppressed. It is predicted by SU(5) that the partial lifetime τ_p/B for a dominant decay mode ($p\rightarrow e^+\pi^0$) should be less than 1.4×10^{32} yr assuming[3] $\Lambda_{\overline{MS}}$ to be less than 400 MeV ($\overline{MS}$ denotes the modified minimal-subtraction scheme). Recent dedicated experiments,[4-6] however, made this prediction incompatible with their results $\tau_p/B(p\rightarrow e^+\pi^0)>3\times10^{32}$ yr (90% C.L.) [a combined result of KAMIOKANDE[4] and Irvine-Michigan-Brookhaven[5] (IMB) experiments]. On the other hand, GUT's incorporating supersymmetry (SUSY GUT's[7]) generally favor decay modes $p\rightarrow\bar{\nu}K^+$, $n\rightarrow\bar{\nu}K^0$ and/or $p\rightarrow\mu^+K^0$, which are now under experimental scrutinization.[5,8] Other models[9] of GUT's exist that predict $\Delta B=2$, $\Delta L=0$ baryon-number-violating processes, such as n-$\bar{n}$ oscillation, rather than ordinary nucleon decay. As the minimal SU(5) is being rejected, it is also important to test $\Delta B=2$ processes. We report on a search for n-$\bar{n}$ oscillation in a ^{16}O nucleus.

The KAMIOKANDE[4] detector, located 1000 m underground [2700 m of water equivalent (mwe)], is a cylindrical water tank, 15.6 m (in diameter)×16 m (in height) weighing 3000 metric tons. It is viewed by 1000 photomultiplier tubes (PMT's) of 20 in. in diameter, covering 20% of the entire inner surface of the tank. The fiducial volume of 880 metric tons is defined to be 2 m inside the PMT planes. The trigger scheme is capable of detecting charged particles with total Cherenkov signals larger than 110 photoelectrons, corresponding to a 30-MeV electron. The 1000 channels of analog-to-digital converters (ADC's) record the pulse height of each PMT, and one of the transient digitizers monitoring total Cherenkov signals C_{tot}, with a time range of 9 μsec after the trigger, enables us to observe μ-e decay signals with a detection efficiency of (71 ± 5)%. Because of the good light collection capability, the vertex position and the direction of a charged particle can be reconstructed from the hit pattern of the Cherenkov ring and the pulse height of each PMT. The rms error of the vertex position is 1.5 m for single muons of momentum 300 MeV/c and 1.2 m for typical multiring events. A Cherenkov ring which is isolated from the others can be classified as nonshower (NS) type ($\mu^\pm,\pi^\pm$) or shower (S) type ($e^\pm,\gamma$) with the probability of 90% by measuring the diffuseness of the hit patterns (NS/S separation). The Cherenkov rings from electromagnetic showers exhibit more diffuse hit patterns than those from $\mu^\pm$ and/or $\pi^\pm$.

In order to estimate detection efficiency of possible n-$\bar{n}$ oscillation and also background from cosmic-ray neutrinos, we have developed a Monte Carlo program. An n from n-$\bar{n}$ oscillations in a ^{16}O nucleus annihilates with a nucleon and produces a burst of pions in the residual nucleus. The pion multiplicity distribution for the Monte Carlo program is determined from the data of hydrogen and deuterium bubble-chamber experiments[10-12] with $\bar{p}$ at rest, because the data of $\bar{n}$-beam experiments in the low-momentum region are meager. The momenta of the pions are generated according to relativistic phase-space distri-

 © 1986 The American Physical Society

butions, with a small contribution (9.3%) from ω^0 mesons. The ω^0 mesons with momentum more than 400 MeV/c (68%) can escape from the residual nucleus and decay outside of it. The pions from this ω^0 decay are therefore free of nuclear effects in the residual nucleus and enhance the detection efficiency. The total- and charged-pion mean multiplicities (5.1 and 3.2, respectively) and the charged-pion momentum spectrum (mean value = 350 MeV/c) calculated from our Monte Carlo program are in good agreement with the experimental results by Horwitz *et al.*[13] The mean C_{tot} of the n-$\bar{n}$ oscillation events without nuclear effects in the fiducial volume is found to be 3300 ± 1000.

Nuclear effects are then taken into considerations. The annihilation of $\bar{n}$ and a nucleon takes place preferentially in the periphery of a ^{16}O nucleus (mean radius = 2.3 fm) because of smaller binding energies.[14] The pions produced by the annihilation then suffer from nuclear effects. The emitted pions with momenta around 300 MeV/c strongly interact with bound nucleons and excite the Δ resonance (1232 MeV/c^2) with a mean cross section as high as 135 mb. The Δ resonance predominantly contributes to inelastic scattering processes. The experimental results of pion-nucleus scattering by Ashery[15] and Ingram,[16] and of pion photoproduction from nuclei by Noguchi[17] are adopted to calculate inelastic, charge-exchange, and absorption processes, in which the nuclear density in a ^{16}O nucles is assumed to have a Woods-Saxon distribution with parameters measured by an electron-scattering experiment.[18] The parameters for the ^{16}O nucleus are then modified for the residual nucleus, considering it has a mass number 14. The program also takes account of the Pauli-blocking effect and Fermi-momentum distributions in a ^{16}O nucleus. The interactions of pions in water after escaping the residual nucleus are similarly simulated. After nuclear effects, total- and charged-pion mean multiplicities become 4.1 and 2.6, respectively, and the mean charged-pion momentum 300 MeV/c. The mean C_{tot} is reduced to 2200 $\pm$ 1100. The details of our Monte Carlo program on nuclear effects will be found in another paper.[19]

The reduction, scanning, and fitting procedures for real data are the same as those for nucleon-decay analysis.[4] The reduction condition of $110 < C_{tot} < 4500$ (1.3 GeV for an electron) does not cause serious losses of detection efficiency (7% loss). During a lifetime of 474 days (1.11 kton yr), 141 fully contained events are observed, which are 97 single-ring events and 44 multiring events. The characteristic signals expected from $\bar{n}$ annihilation in a ^{16}O nucleus are summarized as (1) high ring multiplicities (mean = 3.4), (2) large energy release (ideally as high as 1.9 GeV), (3) comparatively many (0.75/event) μ-e decay signals from π^+, and (4) large invariant mass and rather small residual momentum after complete track reconstruction. Taking these into consideration, the following selection criteria are applied.

(a) Ring multiplicity $\geqq 3$.

(b) Kinematical constraint: By assigning possible combinations of particle species ($\pi^\pm$ or γ) to each ring, the total invariant mass $M_t = [(\sum_i p_i)^2]^{1/2}$ and total residual momentum $\Delta P = |\sum_i \mathbf{p}_i|$ are calculated. $1200 < M_t < 2200$ MeV/c^2 and $\Delta P < 600$ MeV/c are then imposed, with NS/S separations whenever possible.

(c) At least one μ-e decay signal is required, if $C_{tot} < 2500$.

Monte Carlo events simulating n-$\bar{n}$ oscillation (100 events) and cosmic-ray neutrino interaction (10 yr equivalent) are analyzed exactly the same way as real data. The total detection efficiency ε is found to be 33%. Figures 1(a)–1(c) show M_t-ΔP two-dimensional plots for Monte Carlo n-$\bar{n}$ oscillation events, real data, and Monte Carlo cosmic-ray neutrino background, respectively, left

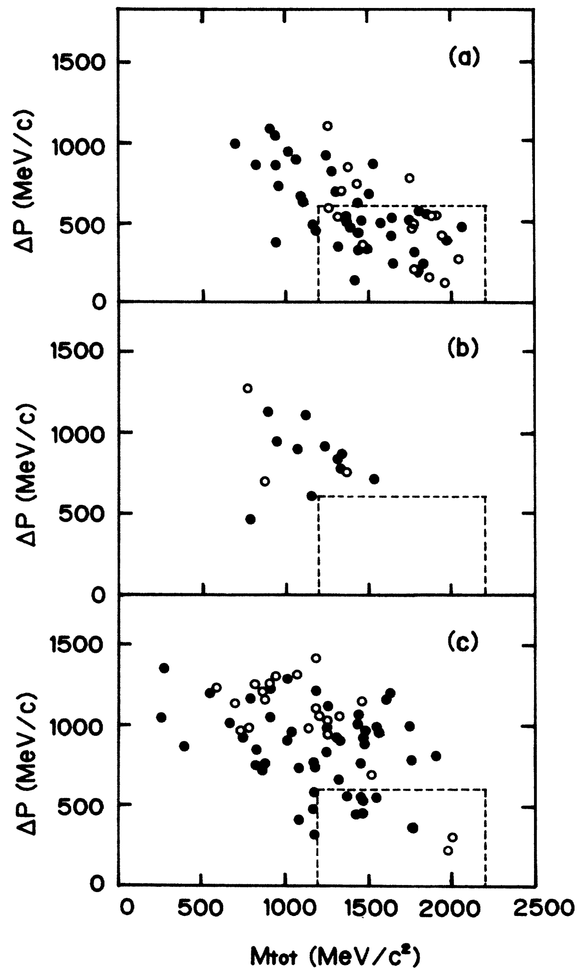

FIG. 1. M_{tot}-ΔP plots for (a) Monte Carlo n-$\bar{n}$ oscillation events (100 events in total generated), (b) real data (1.11 kton yr), and (c) Monte Carlo cosmic-ray neutrino background (8.8 kton yr equivalent) before the kinematical selection, where $M_{tot} = [(\sum_i p_i)^2]^{1/2}$ is the total invariant mass and $\Delta P = |\sum_i \mathbf{p}_i|$, the total residual momentum. Particle assignments of each event, when NS/S separation is not possible, are chosen to minimize

$$|M_{tot} - 1900|^2 + [|\Delta P - 300|\,\theta(\Delta P - 300)]^2 ,$$

where θ is a step function. The region surrounded by dotted lines indicates the criterion (b) described in the text. The filled circles indicate the events with μ-e decay signals and the open circles those without μ-e decay signals. The difference in the number of circles in (b) and (c) is attributed to that in exposure time.

after the selection criteria except for the criterion (b) described above. The distribution of real data is consistent with that of cosmic-ray neutrino background. Cosmic-ray neutrino background is expected to be 0.9 event/yr. No event has survived for real data. The limit on the lifetime $T_{n\text{-}\bar{n}}$ for neutrons in a ^{16}O nucleus is therefore obtained as

$$T_{n\text{-}\bar{n}} > (N_n T)\varepsilon/2.3 = 4.3\times 10^{31}\ \text{yr (90\% C.L.)} ,$$

where $N_n T = 3.0\times 10^{32}$ neutron yr, and $\varepsilon = 33\%$.

The relation between $T_{n\text{-}\bar{n}}$ for bound neutrons and the free-neutron oscillation time $\tau_{n\text{-}\bar{n}}$ has been calculated by many authors[20] with various approximations. Dover et al.[14] recently solved the coupled Schrödinger equations numerically for the n and $\bar{n}$ wave functions in some nuclei, using $\bar{n}$-nucleus optical potentials consistent with the experimental data of $\bar{p}$-atom level shifts and provided a more reliable result than the previous calculations. The relation between $T_{n\text{-}\bar{n}}$ and $\tau_{n\text{-}\bar{n}}$ is expressed as

$$\tau_{n\text{-}\bar{n}} = (T_{n\text{-}\bar{n}}/T_R)^{1/2} .$$

T_R calculated by Dover et al.[14] is

$$T_R = 1\times 10^{23}\ \text{sec}^{-1}\ \text{for a } ^{16}\text{O nucleus} ;$$

therefore our result implies

$$\tau_{n\text{-}\bar{n}} > 1.2\times 10^8\ \text{sec (90\% C.L.)} .$$

Dover et al.[21] estimated the error of $\tau_{n\text{-}\bar{n}}$ extracted from $T_{n\text{-}\bar{n}}$ to be within 30%, which arises mostly from different parametrizations of various optical potential models, consistent with both $\bar{p}$-atom level shifts and low-energy $\bar{p}$-nucleus scattering data available only recently. Kabir,[22] on the other hand, pointed out that $\tau_{n\text{-}\bar{n}}$ obtained from free neutrons might be different from that in a nucleus owing to the existence of spectator nucleons. But Dover et al.[21] provide a rough estimate for this effect of order 25–30% or less, and they also suggested that the existence of $\Delta B = 2$ processes other than $n\text{-}\bar{n}$ oscillation ($\Delta I = 1$, $\Delta S = 0$), such as $n\text{-}\bar{\Delta}$, would shorten observed $T_{n\text{-}\bar{n}}$. Thus, $\tau_{n\text{-}\bar{n}}$ obtained above might be underestimated and conservative.

Our result should be compared with $\tau_{n\text{-}\bar{n}} > 1\times 10^6$ sec from the experiment on the free-nuetron oscillations at the ILL reactor,[23] and with the results of Cherry et al.[24] ($\tau_{n\text{-}\bar{n}} > 2\times 10^7$ sec) and of Jones et al.[25] ($\tau_{n\text{-}\bar{n}} > 8.8\times 10^7$ sec) for $n\text{-}\bar{n}$ oscillation time in a ^{16}O nucleus ($T_R = 1\times 10^{23}$ sec^{-1}) and also with the result of the NUSEX (nucleon-stability) experiment[6] ($\tau_{n\text{-}\bar{n}} > 4\times 10^7$) in a ^{26}Fe nucleus ($T_R = 1.4\times 10^{23}$ sec^{-1}).

We gratefully acknowledge the generous cooperation of Mitsui Mining and Smelting Co. and of Hamamatsu Photomics Co. This work was supported by the Ministry of Education, Science and Culture.

---

*Present address: Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104.

[1]For a review of grand unification, see, P. Langacker, Phys. Rep. **72**, 185 (1981).

[2]H. Georgi and S. L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).

[3]P. Langacker, in *Proceedings of the Twelfth International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, 1985*, edited by M. Konuma and K. Takahashi (Nanissha Printing Co., Kyoto, Japan, 1986), p. 186.

[4]K. Arisaka et al., J. Phys. Soc. Jpn. **54**, 3213 (1985).

[5]H. S. Park et al., Phys. Rev. Lett. **54**, 22 (1985); G. Blewitt et al., ibid. **55**, 2114 (1985).

[6]E. Iarocci, in *Proceedings of the Fifth Workshop on Grand Unification, Providence, Rhode Island, 1984*, edited by K. Kang, H. Fried, and P. Frampton (World Scientific, Singapore, 1984), p. 31.

[7]For references on SUSY GUT's, see H. E. Haber and G. L. Kane, Phys. Rep. **117**, 75 (1985).

[8]T. Kajita et al., J. Phys. Soc. Jpn. **55**, 711 (1986).

[9]R. N. Mohapatra and R. E. Marshak, Phys. Rev. Lett. **44**, 1316 (1980); Phys. Lett. **94B**, 183 (1980).

[10]R. Armenteros and B. French, in *High Energy Physics*, edited by E. H. S. Burshop (Academic, New York, 1969), Vol. 4, p. 237.

[11]P. Pavlopoulous et al., in *Nucleon-Nucleon Interactions, 1977*, proceedings of the Second International Conference, Vancouver, edited by H. Fearing, D. Measday, and A. Strathdee (AIP Conf. Proc. No. 41) (AIP, New York, 1978), p. 340.

[12]A. Backenstoss et al., Nucl. Phys. **B228**, 424 (1983).

[13]N. Horwitz et al., Phys. Rev. **115**, 472 (1959).

[14]C. B. Dover et al., Phys. Rev. D **27**, 1090 (1983).

[15]D. Ashery, Nucl. Phys. **A354**, 555 (1981).

[16]C. H. Q. Ingram, Nucl. Phys. **A374**, 319c (1982).

[17]S. Noguchi, Ph.D thesis, University of Tokyo, 1977.

[18]C. W. de Jager et al., At. Data Nucl. Data Tables **14**, 479 (1974).

[19]M. Nakahata et al. (unpublished).

[20]P. G. Sandars, J. Phys. Lett. **G6**, L161 (1980); Riazuddin, Phys. Rev. D **25**, 885 (1982); W. M. Alberico et al., Phys. Lett. **114B**, 266 (1982); C. Y. Wong et al., Phys. Rev. C **29**, 574 (1984).

[21]C. B. Dover et al., Brookhaven National Laboratory Report No. BNL-35749, 1985 (unpublished).

[22]P. K. Kabir, Phys. Rev. Lett. **51**, 231 (1983).

[23]G. Fidecaro et al., Phys. Lett. **156B**, 122 (1985).

[24]M. L. Cherry et al., Phys. Rev. Lett. **50**, 1354 (1983).

[25]T. W. Jones et al., Phys. Rev. Lett. **52**, 720 (1984).