Search for Nucleon and Dinucleon Decays with an Invisible Particle and a Charged Lepton in the Final State at the Super-Kamiokande Experiment

V. Takhistov,[7] K. Abe,[1,30] Y. Haga,[1] Y. Hayato,[1,30] M. Ikeda,[1] K. Iyogi,[1] J. Kameda,[1,30] Y. Kishimoto,[1,30] M. Miura,[1,30] S. Moriyama,[1,30] M. Nakahata,[1,30] T. Nakajima,[1] Y. Nakano,[1] S. Nakayama,[1,30] A. Orii,[1] H. Sekiya,[1,30] M. Shiozawa,[1,30] A. Takeda,[1,30] H. Tanaka,[1] T. Tomura,[1,30] R. A. Wendell,[1,30] T. Irvine,[2] T. Kajita,[2,30] I. Kametani,[2] K. Kaneyuki,[2,30,*] Y. Nishimura,[2] E. Richard,[2] K. Okumura,[2,30] L. Labarga,[3] P. Fernandez,[3] J. Gustafson,[4] C. Kachulis,[4] E. Kearns,[4,30] J. L. Raaf,[4] J. L. Stone,[4,30] L. R. Sulak,[4] S. Berkman,[5] C. M. Nantais,[5] H. A. Tanaka,[5] S. Tobayama,[5] M. Goldhaber,[6,*] G. Carminati,[7] W. R. Kropp,[7] S. Mine,[7] P. Weatherly,[7] A. Renshaw,[7] M. B. Smy,[7,30] H. W. Sobel,[7,30] K. S. Ganezer,[8] B. L. Hartfiel,[8] J. Hill,[8] N. Hong,[9] J. Y. Kim,[9] I. T. Lim,[9] A. Himmel,[10] Z. Li,[10] K. Scholberg,[10,30] C. W. Walter,[10,30] T. Wongjirad,[10] T. Ishizuka,[11] S. Tasaka,[12] J. S. Jang,[13] J. G. Learned,[14] S. Matsuno,[14] S. N. Smith,[14] M. Friend,[15] T. Hasegawa,[15] T. Ishida,[15] T. Ishii,[15] T. Kobayashi,[15] T. Nakadaira,[15] K. Nakamura,[15,30] Y. Oyama,[15] K. Sakashita,[15] T. Sekiguchi,[15] T. Tsukamoto,[15] A. T. Suzuki,[16] Y. Takeuchi,[16,30] T. Yano,[16] S. Hirota,[17] K. Huang,[17] K. Ieki,[17] T. Kikawa,[17] A. Minamino,[17] T. Nakaya,[17,30] K. Suzuki,[17] S. Takahashi,[17] Y. Fukuda,[18] K. Choi,[19] Y. Itow,[19] T. Suzuki,[19] P. Mijakowski,[20] K. Frankiewicz,[20] J. Hignight,[21] J. Imber,[21] C. K. Jung,[21] X. Li,[21] J. L. Palomino,[21] M. J. Wilking,[21] C. Yanagisawa,[21,†] H. Ishino,[22] T. Kayano,[22] A. Kibayashi,[22] Y. Koshio,[22] T. Mori,[22] M. Sakuda,[22] Y. Kuno,[23] R. Tacik,[24,32] S. B. Kim,[25] H. Okazawa,[26] Y. Choi,[27] K. Nishijima,[28] M. Koshiba,[29] Y. Suda,[29] Y. Totsuka,[29] M. Yokoyama,[29,30,†] C. Bronner,[30] M. Hartz,[30] K. Martens,[30] Ll. Marti,[30] Y. Suzuki,[30] M. R. Vagins,[30,7] J. F. Martin,[31] P. de Perio,[31] A. Konaka,[32] S. Chen,[33] Y. Zhang,[33] and R. J. Wilkes[34]

(The Super-Kamiokande Collaboration)

[1]*Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu 506-1205, Japan*
[2]*Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[3]*Department of Theoretical Physics, University Autonoma Madrid, 28049 Madrid, Spain*
[4]*Department of Physics, Boston University, Boston, Massachusetts 02215, USA*
[5]*Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T1Z4, Canada*
[6]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[7]*Department of Physics and Astronomy, University of California, Irvine, Irvine, California 92697-4575, USA*
[8]*Department of Physics, California State University, Dominguez Hills, Carson, California 90747, USA*
[9]*Department of Physics, Chonnam National University, Kwangju 500-757, Korea*
[10]*Department of Physics, Duke University, Durham, North Carolina 27708, USA*
[11]*Junior College, Fukuoka Institute of Technology, Fukuoka, Fukuoka 811-0295, Japan*
[12]*Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan*
[13]*GIST College, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea*
[14]*Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA*
[15]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan*
[16]*Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan*
[17]*Department of Physics, Kyoto University, Kyoto, Kyoto 606-8502, Japan*
[18]*Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan*
[19]*Solar Terrestrial Environment Laboratory, Nagoya University, Nagoya, Aichi 464-8602, Japan*
[20]*National Centre For Nuclear Research, 00-681 Warsaw, Poland*
[21]*Department of Physics and Astronomy, State University of New York at Stony Brook, New York 11794-3800, USA*
[22]*Department of Physics, Okayama University, Okayama, Okayama 700-8530, Japan*
[23]*Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[24]*Department of Physics, University of Regina, 3737 Wascana Parkway, Regina, Saskatchewan S4SOA2, Canada*
[25]*Department of Physics, Seoul National University, Seoul 151-742, Korea*
[26]*Department of Informatics in Social Welfare, Shizuoka University of Welfare, Yaizu, Shizuoka 425-8611, Japan*
[27]*Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea*
[28]*Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan*
[29]*The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[30]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[31]*Department of Physics, University of Toronto, 60 St., Toronto, Ontario M5S1A7, Canada*
[32]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T2A3, Canada*

[33]Department of Engineering Physics, Tsinghua University, Beijing 100084, China
[34]Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA

Search results for nucleon decays $p \to e^+X$, $p \to \mu^+X$, $n \to \nu\gamma$ (where X is an invisible, massless particle) as well as dinucleon decays $np \to e^+\nu$, $np \to \mu^+\nu$, and $np \to \tau^+\nu$ in the Super-Kamiokande experiment are presented. Using single-ring data from an exposure of 273.4 kton · yr, a search for these decays yields a result consistent with no signal. Accordingly, lower limits on the partial lifetimes of $\tau_{p \to e^+X} > 7.9 \times 10^{32}$ yr, $\tau_{p \to \mu^+X} > 4.1 \times 10^{32}$ yr, $\tau_{n \to \nu\gamma} > 5.5 \times 10^{32}$ yr, $\tau_{np \to e^+\nu} > 2.6 \times 10^{32}$ yr, $\tau_{np \to \mu^+\nu} > 2.2 \times 10^{32}$ yr, and $\tau_{np \to \tau^+\nu} > 2.9 \times 10^{31}$ yr at a 90% confidence level are obtained. Some of these searches are novel.

Many signs indicate that the standard model of particle physics is an incomplete description of nature. Gauge coupling unification, charge quantization, and other features suggest a more unified account, such as a grand unified theory (GUT) [1–4], as an underlying fundamental theory. While the unification scale ($\sim 10^{15}$–10^{16} GeV) is unreachable by accelerators, rare processes predicted by these theories, such as proton decay, can be probed by large underground detectors. Being a signature prediction of GUTs, observation of an unstable proton would constitute robust evidence for physics beyond the standard model, while nonobservation will stringently constrain theoretical models.

The simplest unification scenarios based on minimal SU(5) and supersymmetric (SUSY) SU(5) have been decisively ruled out by bounds on $p \to e^+\pi^0$ [5–7] and $p \to \bar{\nu}K^+$ [8]. Many alternative scenarios as well as potential signatures are possible (see [9] for review).

In this Letter, we analyze a broad class of nucleon and dinucleon decay channels with a showering or nonshowering single Cherenkov ring signature within the Super-Kamiokande (SK) experiment, using the technique of spectral fit [10,11]. First, we have considered two general two-body decays $p \to e^+X$ and $p \to \mu^+X$, where X is a single unknown invisible particle which is assumed to be massless. These searches are distinct from the model-dependent inclusive analyses of [12,13] listed in the Particle Data Group [14]. Similarly, we also consider $n \to \nu\gamma$. Though this radiative process is suppressed, it has a clean signature and has been considered in the context of SU(5) [15], with some models [9] predicting a lifetime of $10^{38\pm1}$ yr.

While single nucleon $\Delta B = 1$ processes have been in general well studied, dinucleon $\Delta B = 2$ channels also pose great interest. These higher-dimensional processes can become significant in models which suppress proton decay and could be connected to baryogenesis [16], accounting for the observed baryon asymmetry of the Universe [17]. Such a connection may already be hinted at from the requirement of baryon number violation as a necessary condition for explaining the asymmetry [18]. The disappearance $\Delta B = 2$

reactions, with invisible final state particles, have been studied and no signal excess was observed [19–21]. The channels $np \to e^+\nu$, $np \to \mu^+\nu$, and $np \to \tau^+\nu$ violate the baryon number by two units and violate the lepton number by either two or zero units. They can become significant in models with an extended Higgs sector [16,22], which could be considered in the context of GUTs [23]. While the τ cannot occur in single nucleon decay, in dinucleon decay the τ channel is allowed [24]. The process $np \to \tau^+\nu$ has not been experimentally studied before and in addition to the electron and muon channel searches we present the first search in the τ channel.

In this work, SK data are analyzed from an exposure of the 22.5 kton fiducial mass for 273.4 kton yr, covering four running periods (SK-I through SK-IV). Details of the detector design and performance in each SK period, can be found in [25,26]. This analysis considers only events in which all observed Cherenkov light was fully contained within the inner detector.

Since final-state neutrinos or X (by definition) are not observed, the only signature of $p \to e^+X$, $p \to \mu^+X$, $n \to \nu\gamma$, $np \to e^+\nu$, and $np \to \mu^+\nu$ is a single charged e^+ or μ^+ lepton, or single γ. Thus, the invariant mass of the initial state cannot be reconstructed and the signal will be superimposed on a substantial atmospheric neutrino background in the e-like and μ-like momentum spectra. For the $np \to \tau^+\nu$ decay, only the $\tau \to e^+\nu\nu$ and $\tau \to \mu^+\nu\nu$ channels are considered, with the respective branching ratios of 17.8% and 17.4%. This allows us to perform all the analyses within a unified framework. The previous searches for $n \to \nu\gamma$, $np \to e^+\nu$, and $np \to \mu^+\nu$, which were performed with a smaller detector using a counting method, resulted in the lifetime limits of 2.8×10^{31} yr [5], 2.8×10^{30} yr [19], and 1.6×10^{30} yr [19], respectively. In contrast, the spectral fit employed within this work allows utilization of the extra information from the energy dependence of signal, background, and the systematic errors. This methodology has been recently employed in the SK nucleon decay [11,27] and dark matter analyses [28].

The nucleon decay signal events are obtained from Monte Carlo (MC) simulations, in which all the nucleons

of the water H_2O molecule are assumed to decay with equal probability. The final state particles are generated with energy and momentum uniformly distributed in phase space. The effects of Fermi motion, nuclear binding energy, as well as nucleon-nucleon correlated decays [29] are taken into account for both nucleon [30–32] and dinucleon searches [33]. The signal Fermi momentum distributions are simulated using a spectral function fit to electron-^{12}C scattering data [34]. The SK detector simulation [26] is based on the GEANT-3[35] package, with the TAUOLA [36] package employed for decaying the τ leptons. For the $np \rightarrow \tau^+\nu$ mode we generated three MC samples, with the τ decaying to $e^+\nu\nu$, $\mu^+\nu\nu$, and all decay channels. The latter allows us to study sample contamination in the two selected leptonic τ channels from the hadronic τ channels and thus identify sample purity after the event selection. We have confirmed that the resulting MC charged lepton spectra from $\tau \rightarrow e^+\nu\nu$ and $\tau \rightarrow \mu^+\nu\nu$ decays agree with the theoretical formula [37]. For $p \rightarrow e^+X$ and $p \rightarrow \mu^+X$ modes, the invisible X particle cannot be a fermion by spin conservation, but in our spin-insensitive MC it was simulated as a neutrino. In total, around 4200 signal events were generated within the fiducial volume for each SK period for single nucleon decays and around 8400 for dinucleon decays.

Atmospheric neutrino background interactions were generated using the flux of Honda *et al.* [38] and the NEUT simulation package [39], which uses a relativistic Fermi gas model. Background MC corresponding to a 500-year exposure of the detector was simulated for each detector phase. We used the same atmospheric neutrino MC simulation as the standard SK oscillation analysis [40].

The event selection applied to the fully contained data is the following: (i) a single Cherenkov ring is present, (ii) the ring is showering (electronlike) for $p \rightarrow e^+X$, $n \rightarrow \nu\gamma$, $np \rightarrow e^+\nu$, and $np \rightarrow \tau^+\nu(\tau \rightarrow e^+\nu\nu)$ and nonshowering (muonlike) for $p \rightarrow \mu^+X$, $np \rightarrow \mu^+\nu$, and $np \rightarrow \tau^+\nu(\tau \rightarrow \mu^+\nu\nu)$, (iii) there are zero decay electrons for modes with an e-like ring and one decay electron for those with a μ-like ring, (iv) the reconstructed momentum lies in the range $100 \text{ MeV}/c \leq p_e \leq 1000 \text{ MeV}/c$ for $p \rightarrow e^+X$, $n \rightarrow \nu\gamma$ and in the range $200 \text{ MeV}/c \leq p_\mu \leq 1000 \text{ MeV}/c$ for $p \rightarrow \mu^+X$, with the range extended to 100–1500 MeV/c for dinucleon decays with an e-like ring and 200–1500 MeV/c for those with a μ-like ring. In total, approximately 37 000 fully contained events were obtained in the SK-I to SK-IV data-taking periods. After the criteria (i)–(iv) have been applied, the final data samples for single nucleon decay searches with an e-like ring contain 8500 events and 6000 events for the case of μ-like ring, with momenta up to one GeV/c. To search for dinucleon decays we consider lepton momenta up to 1500 MeV/c. The final samples for the dinucleon modes contain 9500 events for the e-like channels and 6500 events for the μ-like ones. See Ref. [41] for details regarding reconstruction.

The signal detection efficiency is defined as the fraction of events passing selection criteria compared to the total number of events generated within the true fiducial volume. The average detection efficiency for e-like channels is $(94.0 \pm 0.4)\%$ for all SK data-taking periods. For the μ-like channels, the average detection efficiency is $76.4 \pm 0.6\%$ for SK-I to SK-III and $91.7 \pm 0.4\%$ for SK-IV. The increase in efficiency observed in SK-IV for channels with a μ-like ring, comes from a 20% improvement in the detection of muon decay electrons after an upgrade of the detector electronics [26].

For the e-like momentum spectrum up to 1500 MeV/c, the dominant background contribution, composing 75.8% of the events, comes from the ν_e charged-current (CC) quasielastic (QE) neutrino channel. The ν_e CC single-pion production constitutes 13.0% of the background, while the ν_e CC coherent-pion, CC multipion, and neutral-current (NC) single-pion productions contribute around 1.1%, 1.1%, and 1.6%, respectively. About 3.5% and 1.1% of events come from ν_μ NC single-pion and coherent-pion production. For the μ-like momentum spectrum up to 1500 MeV/c, the dominant contribution of around 78.6% comes from ν_μ CCQE. Similarly, ν_μ CC single-pion, CC coherent-pion, and CC multipion as well as NC single-pion production contribute around 16.2%, 1.4%, 1.6% and 0.8%, respectively.

After event selection, a spectral fit is performed on the reconstructed charged lepton momentum distribution of the events. The χ^2 minimization fit is based on the Poisson distribution, with the systematic uncertainties accounted for by quadratic penalties ("pull terms") [10]. The χ^2 function used in the analysis is

$$\chi^2 = 2 \sum_{i=1}^{n\text{bins}} \left(N_i^{\text{exp}} + N_i^{\text{obs}} \left[\ln \frac{N_i^{\text{obs}}}{N_i^{\text{exp}}} - 1 \right] \right) + \sum_{j=1}^{N_{\text{syserr}}} \left(\frac{\epsilon_j}{\sigma_j} \right)^2,$$

$$N_i^{\text{exp}} = [\alpha N_i^{\text{back}} + \beta N_i^{\text{sig}}] \left(1 + \sum_{j=1}^{N_{\text{syserr}}} f_i^j \frac{\epsilon_j}{\sigma_j} \right), \qquad (1)$$

where i labels the analysis bin. The terms N_i^{obs}, N_i^{sig}, N_i^{back}, N_i^{exp} are the numbers of observed data, signal MC, background MC, and the total (signal and background) MC events in each bin i. The index j labels the systematic errors, while ϵ_j and f_i^j correspond to the fit error parameter and the fractional change in the N_i^{exp} bin due to 1-sigma error uncertainty σ_j, respectively. The fit is performed for two parameters α and β, which denote the background and signal normalizations, respectively. After the event selection, the signal MC distribution is normalized to the background by the integral, which in turn is normalized to the SK live time. This allows us to identify the fit point $(\alpha, \beta) = (1, 0)$ with the no-signal hypothesis. Similarly, $(\alpha, \beta) = (0, 1)$ signifies that the data are described by signal only, with the signal amount equal to background

TABLE I.   Systematic errors of spectrum fits, with 1σ uncertainties and resulting fit pull terms. Errors specific to signal and background are denoted by S and B, while those that are common to both by SB.

Decay mode		$p \to e^+ X$	$p \to \mu^+ X$	
Systematic error	1-σ uncertainty (%)	Fit pull (σ)	Fit pull (σ)	
Final state interactions	10	0.10	−0.60	B
Flux normalization ($E_\nu < 1$ GeV)	25[a]	−0.23	−0.08	B
Flux normalization ($E_\nu > 1$ GeV)	15[b]	−1.44	−0.50	B
M_A in ν interactions	10	0.69	0.23	B
Single meson cross section in ν interactions	10	−0.55	−0.14	B
Energy calibration of SK-I, -II, -III, -IV	1.1, 1.7, 2.7, 2.3	0.58, −0.91, 0.48, 0.38	−0.54, 0.07, −0.14, 0.26	SB
Fermi model comparison	10[c]	−0.08	0.70	S
Nucleon-nucleon correlated decay	100	0.00	0.06	S

[a]Uncertainty linearly decreases with $\log E_\nu$ from 25% (0.1 GeV) to 7% (1 GeV).
[b]Uncertainty is 7% up to 10 GeV, linearly increases with $\log E_\nu$ from 7% (10 GeV) to 12% (100 GeV) and then 20% (1 TeV).
[c]Estimated from comparison of spectral function and Fermi gas model.

MC normalized (prefit) to live time. The χ^2 minimization is carried out over each α and β in the grid according to $\partial\chi^2/\partial\epsilon_j = 0$. The resulting global minimum is defined as the best fit. Further details on the fit and specifics of systematic error treatment can be found in [11,28,42]. For the $np \to \tau^+\nu\nu$ mode, after the appropriate event selection is applied to both MC samples of $\tau \to e^+\nu\nu$ and $\tau \to \mu^+\nu\nu$, the samples are combined for the fit, allowing us to obtain a single value for the permitted number of nucleon decays at 90% C.L.

The systematic errors can be divided into signal-specific (S), background-specific (B) as well as detector and reconstruction errors, which are common to both signal and background (SB). The two signal specific systematics are from Fermi motion and nucleon-nucleon correlated decay. For background, in order to methodically select the dominant systematics, we started from more than 150 errors employed in the SK oscillation analysis [42] and chose those which affect the analyses bins by more than 5% ($|f_i^j| \geq 0.05$). Relaxing this criteria to 1% does not significantly alter the results, but complicates the analysis [11]. As in [11], we have found that the dominant contributions originate from uncertainties related to neutrino flux and energy calibration (common to both

signal and background). Including the signal systematics, the total number of considered errors is 11 and they are the same for all modes. In Table I we display the complete list of systematics, their uncertainties and fitted pull terms for two representative examples $p \to e^+ X$ and $p \to \mu^+ X$.

The spectral fit determines the overall background and signal normalizations α and β, with the fit results displayed in Table II. The outcome shows that no significant signal excess has been observed, with the data $\Delta\chi^2 = \chi^2 - \chi^2_{\min}$ being within 1σ of the background only hypothesis for all search modes except for $p \to \mu^+ X$, which is within 2σ.

The lower lifetime limit on the processes can then be computed from the 90% confidence level value of β ($\beta_{90\,\text{C.L.}}$), which translates into the allowed amount of signal at 90% confidence level according to $N_{90\,\text{C.L.}} = \beta_{90\,\text{C.L.}} \cdot N^{\text{signal}}$, where N^{signal} is the total number of signal events. The partial lifetime limit is then calculated from

$$\tau_{90\,\text{C.L.}}/\mathcal{B} = \frac{\sum_{\text{sk=SK1}}^{\text{SK4}} \lambda_{\text{sk}} \epsilon_{\text{sk}} N^{\text{nucleons}}}{N_{90\,\text{C.L.}}}, \qquad (2)$$

TABLE II.   Best fit (α, β) parameter values, best fit $\chi^2/$d.o.f., no signal $\Delta\chi^2$, 90% C.L. value of β parameter, allowed number of nucleon decay events in the full 273.4 kton yr exposure and a partial lifetime limit for each decay mode at 90% C.L. The sensitivity and lifetime limit for dinucleon decay modes are per ^{16}O nucleus.

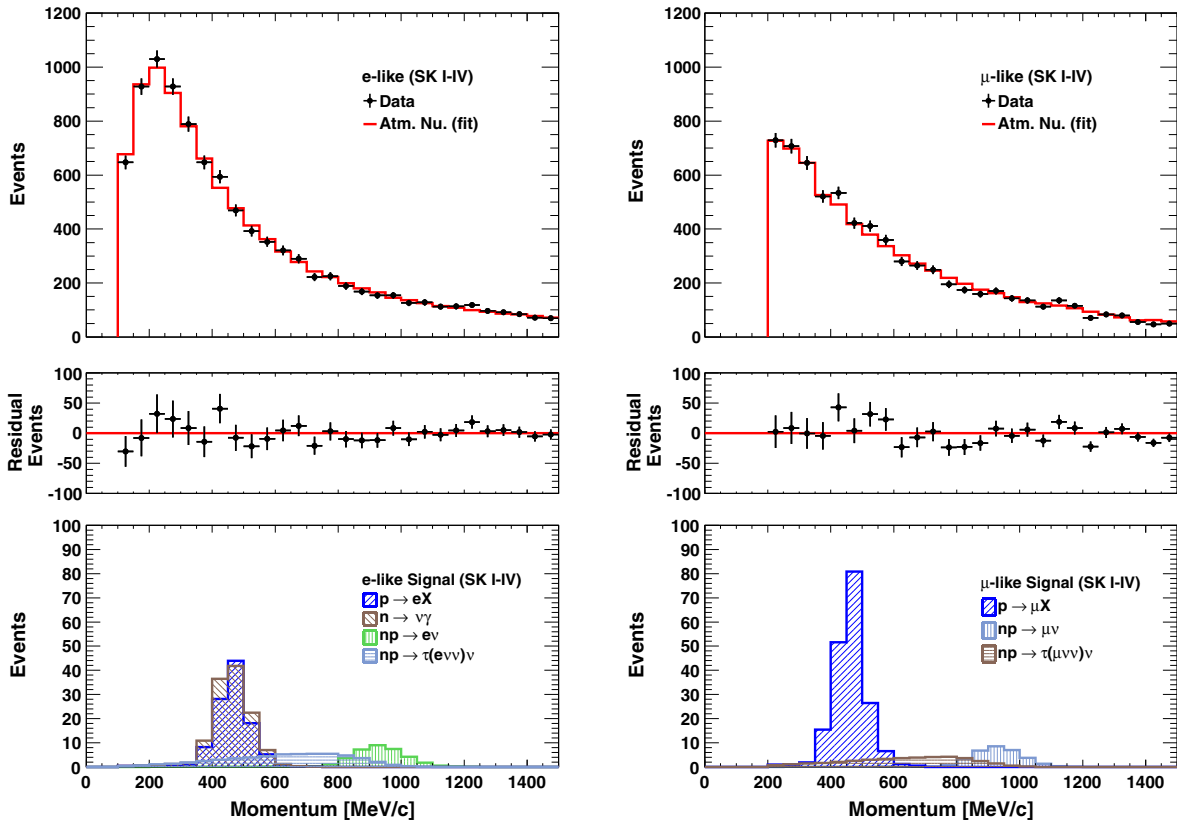| Decay mode	Best fit	Best fit	No signal	Data	Data	Sensitivity	$\tau/\mathcal{B}$
	(α, β)	$\chi^2/$d.o.f.	$\Delta\chi^2$	$\beta_{90\,\text{C.L.}}$	$N_{90\,\text{C.L.}}$	($\times 10^{31}$ yr)	($\times 10^{31}$ yr)
$p \to e^+ X$	(1.050, 0.002)	70.9/70	0.19	0.013	108	79	79
$n \to \nu\gamma$	(1.045, 0.004)	70.5/70	0.43	0.015	125	58	55
$p \to \mu^+ X$	(0.960, 0.016)	63.2/62	3.43	0.032	187	77	41
$np \to e^+\nu$	(0.955, 0.000)	122.5/110	0.00	0.004	33	10	26
$np \to \mu^+\nu$	(0.910, 0.000)	97.0/102	0.00	0.005	36	11	20
$np \to \tau^+\nu$	(0.910, 0.000)	224.6/214	0.00	0.006	96	1	3

FIG. 1 (color online).   (Top) Reconstructed momentum distribution for 273.4 kton yr of combined SK data (black dots) and the best-fit result for the atmospheric neutrino background Monte Carlo simulations (solid line). The corresponding residuals are shown below, after fitted background subtraction from data. (Bottom) The 90% confidence level allowed nucleon decay signal (hatched histograms), from the signal and background MC fit to data. All modes are shown (overlaid), with e-like channels on the left and μ-like channels on the right.

where $\mathcal{B}$ is the branching ratio of a process, ϵ_{sk} and λ_{sk} are the signal efficiency and the exposure in kton yr for each SK phase, $N_{90\,\mathrm{C.L.}}$ is the amount of signal allowed at the 90% confidence level, and N^{nucleons} is the number of nucleons per kiloton of water, corresponding to 3.3×10^{32}, 2.7×10^{32}, and 3.3×10^{31} for proton, neutron, and dinucleon decay searches, respectively.

The resulting fitted spectra for the 273.4 kton · yr of combined SK data can be found in Fig. 1. The upper figures display the best-fit result for atmospheric neutrino background (solid line) without the signal fitted to the data (black dots) and the corresponding residuals after the fitted MC is subtracted from the data. It is seen that the background MC describes the data well. The bottom figures display the 90% C.L. allowed signal (hatched histogram), obtained from the fit of background with signal to data, with all the e-like and μ-like spectra overlaid with all the modes. The $N_{90\,\mathrm{C.L.}}$ as well as resulting sensitivities and calculated lifetime limits for the decays are shown in Table II. The sensitivities were obtained assuming that data are described by background. For the $np \to \tau\nu$ mode we have combined the τ channels $e^{+}\nu\nu$ and $\mu^{+}\nu\nu$, weighted by their respective branching ratios. This limit is then multiplied by 1.15 to account for roughly 85% sample

purity of the tau channels. We set the lower limits on the partial lifetimes of the decay modes at the 90% C.L., with the results shown in Table II.

In conclusion, the single Cherenkov ring momentum spectra in Super-Kamiokande are well described by atmospheric neutrinos, including the effect of neutrino oscillation and systematic uncertainties, up to 1500 MeV/c. We find no evidence for any contribution from the six different nucleon and dinucleon decay modes that would produce a showering or nonshowering Cherenkov ring. The results of this analysis provide a stringent test of new physics. The obtained limits represent more than an order of magnitude improvement over the previous analyses of $n \to \nu\gamma$ [5] and two orders of magnitude for $np \to e^{+}\nu$ and $np \to \mu^{+}\nu$ [19]. The searches for $p \to e^{+}X$, $p \to \mu^{+}X$ (where X is an invisible, massless particle) and $np \to \tau^{+}\nu$, are novel. The dinucleon decay limits restrict $\Delta B = 2$ processes with L violated by either zero or two units.

*Deceased.

†Also at BMCC/CUNY, Science Department, New York, New York, USA.

[1] J. C. Pati and A. Salam, Phys. Rev. D **8**, 1240 (1973).

[2] J. C. Pati and A. Salam, Phys. Rev. Lett. **31**, 661 (1973).

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

[4] H. Fritzsch and P. Minkowski, Ann. Phys. (N.Y.) **93**, 193 (1975).

[5] C. McGrew, R. Becker-Szendy, C. Bratton, J. Breault, D. Cady et al. (IMB-3 Collaboration), Phys. Rev. D **59**, 052004 (1999).

[6] K. Hirata et al. (KAMIOKANDE-II Collaboration), Phys. Lett. B **220**, 308 (1989).

[7] M. Shiozawa et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. **81**, 3319 (1998).

[8] K. Kobayashi et al. (Super-Kamiokande Collaboration), Phys. Rev. D **72**, 052007 (2005).

[9] P. Nath and P. Fileviez Perez, Phys. Rep. **441**, 191 (2007).

[10] G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, and A. Palazzo, Phys. Rev. D **66**, 053010 (2002).

[11] V. Takhistov et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. **113**, 101801 (2014).

[12] J. Learned, F. Reines, and A. Soni, Phys. Rev. Lett. **43**, 907 (1979).

[13] M. L. Cherry, M. Deakyne, K. Lande, C. K. Lee, R. I. Steinberg, and B. Cleveland, Phys. Rev. Lett. **47**, 1507 (1981).

[14] K. Olive et al. (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).

[15] D. Silverman and A. Soni, Phys. Lett. B **100**, 131 (1981).

[16] J. M. Arnold, B. Fornal, and M. B. Wise, Phys. Rev. D **88**, 035009 (2013).

[17] L. Canetti, M. Drewes, and M. Shaposhnikov, New J. Phys. **14**, 095012 (2012).

[18] A. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32 (1967) [Sov. Phys. Usp. **34**, 392 (1991)].

[19] C. Berger et al. (Frejus Collaboration), Phys. Lett. B **269**, 227 (1991).

[20] T. Araki et al. (KamLAND Collaboration), Phys. Rev. Lett. **96**, 101802 (2006).

[21] M. Litos, K. Abe, Y. Hayato, T. Iida, M. Ikeda et al., Phys. Rev. Lett. **112**, 131803 (2014).

[22] R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **49**, 7 (1982).

[23] L. Arnellos and W. J. Marciano, Phys. Rev. Lett. **48**, 1708 (1982).

[24] D. Bryman, Phys. Lett. B **733**, 190 (2014).

[25] Y. Fukuda et al. (Super-Kamiokande Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **501**, 418 (2003).

[26] K. Abe et al., Nucl. Instrum. Methods Phys. Res., Sect. A **737**, 253 (2014).

[27] K. Abe et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. **113**, 121802 (2014).

[28] K. Choi et al. (Super-Kamiokande), Phys. Rev. Lett. **114**, 141301 (2015).

[29] T. Yamazaki and Y. Akaishi, Phys. Lett. B **453**, 1 (1999).

[30] H. Nishino et al. (Super-Kamiokande), Phys. Rev. D **85**, 112001 (2012).

[31] C. Regis et al. (Super-Kamiokande Collaboration), Phys. Rev. D **86**, 012006 (2012).

[32] K. Abe et al. (Super-Kamiokande Collaboration), Phys. Rev. D **90**, 072005 (2014).

[33] J. Gustafson et al. (Super-Kamiokande), Phys. Rev. D **91**, 072009 (2015).

[34] K. Nakamura, S. Hiramatsu, T. Kamae, H. Muramatsu, N. Izutsu, and Y. Watase, Nucl. Phys. **A268**, 381 (1976).

[35] R. Brun, F. Carminati, and S. Giani, Reports No. CERN-W5013, CERN-W-5013, 1994.

[36] S. Jadach, Z. Was, R. Decker, and J. H. Kuhn, Comput. Phys. Commun. **76**, 361 (1993).

[37] M.-C. Chen and V. Takhistov, Phys. Rev. D **89**, 095003 (2014).

[38] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Phys. Rev. D **75**, 043006 (2007).

[39] Y. Hayato, Nucl. Phys. B, Proc. Suppl. **112**, 171 (2002).

[40] K. Abe et al. (Super-Kamiokande), Phys. Rev. D **91**, 052019 (2015).

[41] M. Shiozawa (Super-Kamiokande Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **433**, 240 (1999).

[42] R. Wendell et al. (Super-Kamiokande Collaboration), Phys. Rev. D **81**, 092004 (2010).