Search for Proton Decay via $p \rightarrow e^+ \pi^0$ in a Large Water Cherenkov Detector
(January 9, 2022)

The Super–Kamiokande Collaboration

M. Shiozawa, B. Virei, Y. Fukuda, T. Hayakawa, E. Ichihara, K. Inoue, K. Ishihara, H. Ishitani, Y. Ito, T. Kajita, J. Kameda, S. Kasuga, K. Kobayashi, Y. Kobayashi, Y. Kosho, M. Miura, M. Nakahata, S. Nakayama, A. Okada, M. Oketa, K. Okumura, M. Ota, N. Sakurai, Y. Suzuki, Y. Takeuchi, Y. Totsuka, S. Yamada, M. Earl, A. Habig, E. Kearns, M. D. Messier, K. Scholberg, J. L. Stone, L. R. Suklas, C. W. Walter, M. Goldhaber, T. Barszczak, W. Gajewski, P. G. Halverson, J. Hsui, W. R. Kropp, L. R. Price, F. Reines, H. W. Sobel, M. R. Vagins, K. S. Ganezer, W. E. Keig, R. W. Ellsworth, S. Tatsaka, J. W. Flanagan, A. Kibayashi, J. G. Learned, S. Matsuno, V. Stenger, D. Takemori, T. Ishii, J. Kanazaki, T. Kobayashi, K. Nakamura, K. Nishikawa, Y. Oyama, A. Sakai, M. Sakuda, O. Sasaki, S. Echigo, M. Kohama, A. T. Suzuki, T. J. Haines, E. Blaufuss, R. Sanford, R. Svoboda, M. L. Chen, Z. Conner, J. A. Goodman, G. W. Sullivan, M. Mori, J. H. Ill, C. K. Jung, K. Martens, C. Maguire, C. McGrew, E. Sharkey, C. Yanagisawa, W. Doki, T. Ishizuka, Y. Itaguchi, H. Koga, M. Miyano, H. Okazawa, C. Saji, M. Takahata, A. Kusano, Y. Nagashima, T. Takekuma, T. Yamaguchi, M. Yoshida, S. B. Kim, K. Fujita, A. Hasegawa, T. Hasegawa, S. Hatakeyama, T. Iwamoto, T. Kinebuchi, M. Koga, T. Maruyama, H. Ogawa, A. Suzuki, F. Tsushima, M. Koshiba, M. Nemoto, K. Nishijima, T. Futagami, Y. Hayato, Y. Kamay, K. Kaneyuki, Y. Watanabe, D. Kieclczewska, R. Doyle, J. George, A. Stachyra, L. Wai, J. Wilkes, K. Young.

We have searched for proton decay via $p \rightarrow e^+ \pi^0$ using data from a 25.5 kton-year exposure of the Super–Kamiokande detector. We find no candidate events with an expected background induced by atmospheric neutrinos of 0.1 events. From these data, we set a lower limit on the partial lifetime of the proton $\tau / B_{p\rightarrow e^+\pi^0}$ to be 1.6 × 10^{34} years at a 90% confidence level.

14.20.Dh,13.30.E,11.30.Fs,29.40.Ka

In the Standard Model, which is the modern paradigm of elementary particle physics, protons are assumed to be stable. In Grand Unified Theories (GUTs), however, the decay of the proton is one of the most dramatic predictions of various models. In the past two decades, several large mass underground detector experiments have looked for proton decay but no clear evidence has been reported. In general, GUTs predict many modes of proton decay. In many models, the $p \rightarrow e^+\pi^0$ mode is dominant and there are several GUTs which predict a decay rate within the observable range of Super–Kamiokande (see, for example, (11) (13)). This decay mode has a characteristic event signature, in which the electromagnetic shower caused by the positron is balanced against the two showers caused by the gamma rays from the decay of the $\pi^0$. This signature enables us to discriminate the signal events clearly from atmospheric neutrino background. In this letter, we report the results of our search for proton decay via $p \rightarrow e^+\pi^0$ in 414 live-days of data between May 1996 and October 1997, corresponding to an exposure of 25.5 kton-year in Super–Kamiokande.
Super-Kamiokande is a large water Cherenkov detector located in the Mozumi mine at 2700 meters-water-equivalent below the peak of Mt. Ikenoyama in Kamioka, Gifu prefecture, Japan. The detector holds 50 ktons of ultra-pure water contained in a cylindrical stainless steel tank measuring 41.4 m in height and 39.3 m in diameter. The water is optically separated into three concentric cylindrical regions.

The 36.2 m high and 33.8 m in diameter inner detector, is viewed by 11146, inward-facing, 50 cm diameter photomultiplier tubes (PMTs). These PMTs uniformly surround the region giving a photocathode coverage of 40%. They were specially developed to have good single photoelectron (p.e.) response and have a time resolution of 2.5 ns RMS for 1 p.e. equivalent signals \[1\]. The PMT signals are digitized asynchronously by a custom built data acquisition system \[2\] which can process two successive signals, enabling us to detect the electron from the decay of a muon. The system records the number and arrival times of the photons collected in each PMT. From these values, along with the positions of the PMTs, the events are reconstructed.

The 2.0–2.2 m thick outer detector completely surrounds the inner detector. This region is viewed by 1885 outward pointing 20 cm diameter PMTs with 60 cm by 60 cm wavelength shifter plates \[3\]. The walls of the outer detector are lined with DuPont Tyvek, a white reflective material, to increase the number of Cherenkov photons detected. The primary function of the outer detector is to veto cosmic ray muons and to help identify contained events.

The 0.5 m thick middle region (dead space) between the inner and outer detectors is uninstrumented and is occupied by the stainless steel support structure as well as water. The border with the inner detector is lined with opaque black plastic and the border with the outer detector, by opaque black low density polyethylene bonded to the reflective Tyvek.

The trigger we use in this analysis is issued when 29 or more inner PMTs produce signals greater than 1/4 p.e. in a 200 ns coincidence window. This trigger threshold corresponds to the mean number of PMTs hit by the Cherenkov photons from 5.7 MeV electrons. The trigger rate ranges between 10 Hz and 12 Hz, of which 2.2 Hz is due to cosmic ray muons entering the inner detector.

The data sample we use for this analysis consists of events which are fully contained within the inner detector and is identical to that used for the atmospheric neutrino analysis. (For details, see \[15\,\] \[16\].) The essential criteria of this selection are as follows: (1) no significant outer detector activity, (2) the total number of p.e.’s in the inner detector is greater than 200, (3) the ratio of the maximum number of p.e.’s in a single PMT to the total number of p.e.’s in the event is less than 0.5, (4) the time interval from the preceding event is greater than 100 \(\mu\)sec.

Essentially 100% of the cosmic ray muons are eliminated by criterion (1). Criterion (2) corresponds to a lower momentum cut of 22 MeV/c for electrons and 190 MeV/c for muons. Criterion (3) removes spurious electrical noise events. Criterion (4) removes electrons from the decay of stopping cosmic ray muons as well as the noise events caused by unwanted PMT signals following highly energetic events (“after pulsing”). By applying these criteria, the number of events is reduced from about 400 million to about 12,000. In addition all events which follow a previous event within 30 \(\mu\)sec are tagged as an electron from the decay of a muon.

After criteria (1)–(4) are applied, further reduction is done by scanners using an interactive graphic event display to eliminate most of the few remaining cosmic ray muons or other noise events. About 6,000 events are classified as fully contained events. In this analysis, only events with a fitted vertex inside of the fiducial volume are used. This fiducial volume is defined as all points which are more than 2 m from the inner detector wall. This volume cut removes any remaining entering cosmic ray muon events and assures that the performance of the reconstruction algorithms is uniform throughout the fiducial volume. We observe 3468 fully contained events in the fiducial volume. The inefficiency to recover \(p \rightarrow e^\pm\pi^0\) candidates due to the criteria (1)–(4) and scanning is estimated to be less than 0.1%.

All measurement of physical quantities of an event such as vertex position, the number of Cherenkov rings, momentum, particle type and the number of decay electrons, is automatically performed \[18\] by reconstruction algorithms. The vertex position is estimated by finding the position at which the timing residual ((photon arrival time)-(time of flight)) distribution is most peaked. Using a Monte Carlo (MC) simulated data sample, the vertex resolution for \(p \rightarrow e^\pm\pi^0\) events is estimated to be 18 cm. To find the rings in an event, the charge, viewed from the vertex as a function of \(\{\theta, \phi\}\), is Hough transformed \[19\]. The resulting space is searched for peaks, giving the ring centers. With \(p \rightarrow e^\pm\pi^0\) MC, 44% of the simulated events passing proton decay selection criteria (described below) are classified as 3–ring events and 56% are classified as 2–ring events. The 2–ring classification is primarily for events with one of the two \(\gamma\) rings taking only a small fraction of the \(\pi^0\)’s energy or overlapping too much with other rings.

The particle identification (PID) classifies a particle as a showering particle \((e^\pm, \gamma)\) or a nonshowering particle \((\mu^\pm, \pi^\pm)\), using the photon distribution of its Cherenkov ring. For single ring events, the particle misidentification probability is estimated to be less than 1.0% using the atmospheric neutrino MC. This is confirmed with stopping cosmic ray muons and their associated decay electrons. The PID performance was also checked using a 1 kton water Cherenkov detector with \(e\) and \(\mu\) beams from the 12 GeV proton synchrotron at KEK \[20\]. However, the
The momentum reconstruction is important because an appropriate momentum cut will reject atmospheric neutrino background but accept proton decay events. The momentum is estimated from the total sum of p.e.'s detected within a 70° half opening angle from the reconstructed ring direction. The number of p.e.'s collected in each PMT is corrected for light attenuation in water, PMT angular acceptance and PMT coverage. In the momentum reconstruction, we assume that the particle is an electron for showering particles and a muon for nonshowering particles. For single ring events, the reconstructed momentum resolution is estimated to be ±(2.5/√E(GeV) + 0.5)% for electrons and ±3% for muons, respectively. For multi-ring events, the fraction of p.e.'s in each PMT due to each ring is determined using the expected p.e. distribution. Then, the momentum for each ring is determined by the same method used for single ring events. The reconstructed momentum resolution is ±10% for each ring in the \( p \rightarrow e^\pm \pi^0 \) events.

The energy scale stability is checked by the reconstructed mean energy of decay electrons from stopping cosmic ray muons. It varies within ±0.5% over the exposure period. The absolute energy scale was checked with many calibration sources such as electrons from a linear accelerator [21], decay electrons from stopping cosmic ray muons, stopping cosmic ray muons themselves, and the reconstructed mass of \( \pi^0 \) events observed in atmospheric neutrino interactions. From comparisons of these sources and MC simulation, the absolute calibration error is estimated to be smaller than ±2.5%.

Finally, the efficiency for detection of decay electrons is estimated to be 80% for \( \mu^+ \) and 63% for \( \mu^- \) by a Monte Carlo study. The difference in these efficiencies is due to \( \mu^- \) capture on \(^{16}\text{O}\). This efficiency was confirmed to an accuracy of 1.5% using stopping cosmic ray muons.

The main sources of background for this analysis are atmospheric neutrino interactions which could mimic a \( p \rightarrow e^\pm \pi^0 \) event. To estimate the number of background events, we have developed a detailed MC simulation of atmospheric neutrino interactions, meson propagation in the \(^{16}\text{O}\) nucleus, and propagation of secondary particles, as well as Cherenkov photons, in the detector water [13]. We use the atmospheric neutrino flux of Honda et al. [22]. For neutrino interactions in the detector, the following types of interaction are simulated: quasi elastic scattering, single–π production, multi–π production, and coherent single–π production for both charged current (CC) and neutral current (NC). For the \( p \rightarrow e^\pm \pi^0 \) mode, CC π production is the most important background because it could produce an \( e^\pm \) accompanied by a \( \pi^0 \). We use Rein-Sehgal’s model to simulate single–π production [23]. The pion cross-sections in \(^{16}\text{O}\) are calculated with the model by Oset et al. [24]. Propagation of produced particles and Cherenkov light in water is simulated with a GEANT [25] based custom detector simulator. Propagation of charged pions in the detector water is simulated by a custom simulator [26] for less than 500 MeV/c pions and by the CALOR [27] simulator for more than 500 MeV/c pions. For the \( p \rightarrow e^\pm \pi^0 \) MC, the same simulator is used. In this, as well as the atmospheric neutrino MC, the Fermi motion of protons, the nucleon binding energy, and pion interactions in \(^{16}\text{O}\) are considered.

The observed atmospheric neutrino flavor ratio (\( \nu_\mu/\nu_e \)) in Super–Kamiokande is significantly smaller than the expected value [13]. For comparison of data and atmospheric neutrino MC, the neutrino MC sample is normalized to the number of observed atmospheric neutrino events at Super–Kamiokande in the following manner. The number of \( \nu_e \) (\( \nu_\mu \)) CC events is normalized by the ratio of the number of single ring events with a showering (nonshowering) PID in the data to the number of single ring events with a showering (nonshowering) PID in the atmospheric neutrino MC. For NC events, the same normalization factor as that of the \( \nu_e \) CC events is used.

To extract the \( p \rightarrow e^\pm \pi^0 \) signal from the event sample, these selection criteria are defined: (A) 6800 p.e. < total p.e. < 9500 p.e., (B) the number of rings is 2 or 3, (C) all rings have a showering PID, (D) 85 MeV/c^2 < \( \pi^0 \) invariant mass < 185 MeV/c^2, (E) no decay electron, (F) 800 MeV/c^2 < total invariant mass < 1050 MeV/c^2 and total momentum < 250 MeV/c. Criterion (A) roughly corresponds to a total energy of 800 MeV to 1100 MeV. Criterion (C) selects \( e^\pm \) and \( \gamma \). Criterion (D) only applies to 3-ring events. Here, at least one pair of rings must give a reconstructed invariant mass which is consistent with the estimated \( \pi^0 \) mass resolution of 135 ± 35 MeV/c^2. Criterion (E) is required since the desired \( e^\pm \) and \( \pi^0 \) particles produce no decay electrons. In criterion (F), the total momentum is defined as \( P_{\text{tot}} = |\sum_i^{\text{all rings}} \vec{p}_i| \) where \( \vec{p}_i \) is reconstructed momentum vector of i-th ring. The total invariant mass is defined as \( M_{\text{tot}} = \sqrt{E_{\text{tot}}^2 - P_{\text{tot}}^2} \) where total energy \( E_{\text{tot}} = \sum_i^{\text{all rings}} |\vec{p}_i| \). Criterion (F) checks that the total invariant mass and total momentum correspond to the mass and momentum of the source proton, respectively.
FIG. 1. The total invariant mass and total momentum distributions after criteria (A)–(E) (see text) for 3 samples: (a) $p \to e^+\pi^0$ Monte Carlo, (b) atmospheric neutrino Monte Carlo corresponding to 900 kton-year, (c) data corresponding to 25.5 kton-year. The boxed region in each figure shows the criterion (F) for the $p \to e^+\pi^0$ signal.

Figure (a) shows total invariant mass and total momentum distributions for the $p \to e^+\pi^0$ MC sample after criteria (A)–(E). The boxed region in the figure shows the criterion (F). From this sample, the detection efficiency of $p \to e^+\pi^0$ events is estimated to be 44%. The absorption, charge exchange and scattering of $\pi^0$’s in the $^{16}\text{O}$ nucleus are the dominant contribution to the detection inefficiency. To estimate the background from atmospheric neutrino interactions, we generate a MC sample of 900 kton-year. By applying the proton decay selection criteria to this sample, we estimate the number of background events in the signal region to be 0.1 event in 25.5 kton-year. Figure (b) shows the total invariant mass and total momentum distributions of the neutrino MC sample.
FIG. 2. The total invariant mass distributions of data (circles), normalized atmospheric neutrino Monte Carlo corresponding to 10 years (unshaded histogram), and $p \to e^+\pi^0$ Monte Carlo normalized to one event (shaded histogram) which satisfy the criteria (B)–(E) (see text) and have a total reconstructed momentum $< 250 \text{ MeV}/c$.

Finally we apply the same criteria to the data to search for the $p \to e^+\pi^0$ signal. No events survive all criteria as shown in Figure 2(c). Figure 2 compares the reconstructed total mass for atmospheric neutrino MC, the $p \to e^+\pi^0$ MC, and the data events which satisfy the criteria (B)–(E) and have a total reconstructed momentum $< 250 \text{ MeV}/c$. For this comparison criterion (A) is omitted to provide enough statistics. The mass distribution of data is well reproduced by the neutrino MC. Figure 3 shows the event rate after applying each of criteria (A) through (F) for the data and atmospheric neutrino MC events. The data are well represented by the neutrino MC.

As an overall consistency check, a simpler analysis is done. This analysis, while free of the systematic errors associated with tight, ring–fitting–based momentum and invariant mass cuts, allows a non-negligible background to pass its cuts. The selection criteria are as follows: (1) Visible energy is within 200 MeV of the proton rest mass energy. (2) The light anisotropy is less than 30%. (3) No electrons from muon decays follow the primary products. The visible energy of an event is the total energy assuming all Cherenkov light is from electromagnetic showers. The light anisotropy of an event is a rough measure of the total momentum imbalance and is defined as the magnitude of the normalized vector sum of the unit directions from the vertex to each PMT, weighted by the charge and corrected for water attenuation and PMT acceptance. For a typical single ring event the light anisotropy is $\sim 75\%$. This simple analysis finds 4 events with a background of 3.5, which is consistent with the 0 candidates and 0.1 background of the primary analysis.

From these results, we conclude we do not find any evidence for proton decay via the mode $p \to e^+\pi^0$. Therefore we set a lower limit on the partial decay lifetime. The quantities of this calculation are a detection efficiency of 44%, 0 candidate events out of 25.5 kton-year data, and 3 background candidates out of 900 kton-year of simulated background MC. In addition, the uncertainties associated with these quantities are included in the limit calculation by employing a Bayesian method [28], (for details, see [29]). In this method, the prior probability density functions
(priors) for the exposure and detection efficiency are taken as Gaussian distributions, truncated to disallow unphysical regions. The background prior is taken to be a convolution of Poisson and Gaussian distributions in order to account for both the statistical uncertainty of a finite background MC sample size and the systematic uncertainty in the atmospheric neutrino fluxes and cross sections used in the background MC sample. Finally, the prior for the decay rate is taken to be uniform. This corresponds to the uniform prior implicitly used in simple Poisson limits [30]. The resulting limit on the partial lifetime for $p \to e^+ \pi^0$ is found to be, $\tau/B_{p \to e^+ \pi^0} > 1.6 \times 10^{34}$ years at a 90% CL.

In calculating the limit, the parameter with the dominant uncertainty is the detection efficiency. This uncertainty is primarily due to imperfectly known pion–nucleon cross sections in $^{16}$O nuclei and is estimated by comparing with another detailed model (based on [31]). This uncertainty is estimated to be 15%. In addition, systematic differences in the energy scale for data and MC contribute 1%, lack of uniformity in the detector gain contributes 2% and fitting resolution contributes 5% to the uncertainty in the detection efficiency. The total uncertainty in the detection efficiency is then 16%. The statistical uncertainty in the background is 60% due to the small number of MC background events passing the cuts. Finally, the uncertainty in the exposure is negligible.

In this letter, we have reported the results of a proton decay search in Super–Kamiokande. We have no evidence of the proton decaying via the mode $p \to e^+ \pi^0$ in the 25.5 kton-year data. We set the most stringent limit on the partial lifetime of the proton to be $1.6 \times 10^{33}$ years at a 90% CL, which should be compared with the previous experimental results, $2.6 \times 10^{32}$ years [7] and $5.5 \times 10^{32}$ years [8].

We gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. The Super–Kamiokande experiment was built from, and has been operated with, funding by the Japanese Ministry of Education, Science, Sports and Culture, and the United States Department of Energy.

---

[1] Due to the chiral anomaly in the Standard Model the proton could have a finite but unobservably long lifetime. G. ’t Hooft, Phys. Rev. Lett. 37, 8 (1976).
[2] Jogesh C. Pati and Abdus Salam, Phys. Rev. Lett. 31, 661 (1973).
[3] H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 438 (1974).
[4] P. Langacker, Phys. Rep. 72, 185 (1981).
[5] G. G. Ross, *Grand Unified Theories* (ADDISON WESLEY, California, 1985).
[6] T. J. Haines et al., Phys. Rev. Lett. 57, 1986 (1986).
[7] K. S. Hirata et al., Phys. Lett. B220, 308 (1989).
[8] R. Becker-Szendy et al., Phys. Rev. D42, 2974 (1990).
[9] C. Berger et al., Z. Phys. C50, 385 (1991).
[10] C. Berger et al., Nucl. Phys. B313, 509 (1989).
[11] J. Ellis et al., Phys. Lett. B252, 53 (1990); J. Ellis et al., Phys. Lett. B371, 65 (1996).
[12] N. T. Shaban and W. J. Stirling, Phys. Lett. B291, 281 (1992).
[13] D. Lee, R. N. Mohapatra, M. K. Parida and M. Rani, Phys. Rev. D51, 229, (1995)
[14] A. Suzuki et al., Nucl. Inst. and Meth. A329, 299 (1993).
[15] H. Ikeda et al., Nucl. Inst. Meth. A320, 310 (1992).
[16] T. Tanimori et al., IEEE Trans. Nucl. Sci. 36, 497 (1989).
[17] R. Claus et al., Nucl. Inst. and Meth. A261, 540 (1987).
[18] Super-Kamiokande collaboration, Y. Fukuda et al., *Measurement of a small atmospheric $\nu_\mu/\nu_e$ ratio*, Phys. Lett. B (to be published).
[19] Davies and E. Roy, *Machine vision: theory, algorithms, practicalities* (Academic Press, San Diego, 1997).
[20] S. Kasuga et al., Phys. Lett. B374, 238 (1996).
[21] Super-Kamiokande collaboration, Y. Fukuda et al., *Calibration of Super–Kamiokande using an electron linac*, to be submitted to NIM.
[22] M. Honda et al., Phys. Rev. D52, 4985 (1995); M. Honda et al., Phys. Lett. B248, 193 (1990).
[23] D. Rein and L. M. Sehgal, Ann. of Phys. 133, 79 (1981); D. Rein, Z. Phys. C35, 43 (1987).
[24] E. Oset et al., Nucl. Phys. A468, 631 (1987).
[25] CERN Program Library W5013 (1994).
[26] M. Nakahata et al., J. Phys. Soc. Jpn. 55, 3786 (1986).
[27] T. A. Gabriel et al., IEEE Trans. Nucl. Sci. 36, 14 (1989).
[28] T. J. Loredo, in Maximum Entropy and Bayesian Methods, edited by P. F.ougère (Kluwer Academic, Dordrecht, The Netherlands, 1990).
[29] B. Viren, Super-Kamiokande Report No. 98-3, 1998, (unpublished but available from http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/pub).
[30] R. M. Barnett et al. Phys. Rev. D54, 1 (1996).
[31] H. W. Bertini, Phys. Rev. C6, 631 (1972).