

## Search for Proton Decay via $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$ in a Large Water Cherenkov Detector

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We have searched for proton decays via  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  using data from a 91.7 kt · yr exposure of Super-Kamiokande-I and a 49.2 kt · yr exposure of Super-Kamiokande-II. No candidate events were observed with expected backgrounds induced by atmospheric neutrinos of 0.3 events for each

decay mode. From these results, we set lower limits on the partial lifetime of  $8.2 \times 10^{33}$  and  $6.6 \times 10^{33}$  years at 90% confidence level for  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  modes, respectively.

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One of the unique predictions of grand unified theories (GUTs) is baryon number violation. Via the exchange of a very heavy gauge boson, two quarks in a proton can transform into a lepton and an antiquark resulting in a lepton plus meson final state. Because the mass of the gauge boson is predicted to be very heavy, such processes are expected to be very rare. The prototypical GUT, minimal SU(5) [1–3], predicts the lifetime of the proton when it decays to  $e^+ \pi^0$  to be less than  $10^{32}$  years. A number of other GUT models favor proton decay into this final state [4,5], or with comparable branching into the similar final state  $\mu^+ \pi^0$  [6,7]. Contemporary theories must take steps to evade the stringent limits set by Super-Kamiokande [8] and prior experiments [9,10] that decisively ruled out minimal SU(5). One means is by introducing supersymmetry, which raises the mass of the heavy gauge boson, but which introduces other decay channels which are also constrained by experiment [11].

In this Letter, we describe our search for proton decay by the reactions  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$ . The result of the search was negative, no proton decay was found. We update our lifetime limit on the  $e^+ \pi^0$  channel based on 6 times greater exposure than our previous publication [8]; we report for the first time our limit on the  $\mu^+ \pi^0$  channel. Approximately 1/3 of the exposure was with photocollecion coverage reduced by a factor of 2, so we also describe the effect of reduced photocoverage on these studies.

Super-Kamiokande is a 50-kiloton water Cherenkov detector located in the Kamioka Observatory in Japan [12]. The 22.5-kiloton fiducial volume of the detector was viewed by 11 146 20-inch diameter photomultiplier tubes (PMTs). Super-Kamiokande started observation in April 1996 and stopped in September 2001 (SK-I) for a detector upgrade. On November 12, 2001, during water filling after the upgrade, a shock wave was initiated by an imploding bottom PMT. About half of the PMTs were lost in this accident. In the first recovery stage (SK-II), 5182 PMTs were enclosed in a fiber reinforced plastic case with an acrylic cover for protection against another chain reaction. SK-II restarted observation in October 2002 and stopped in October 2005 for full detector reconstruction. The transparency and the reflection of the acrylic cover were 97% and 1%, respectively. The photo-sensor coverage was 40% and 19% in SK-I and SK-II, respectively.

A Monte Carlo simulation was used to estimate the efficiency of detecting proton decay occurring in water ( $H_2O$ ). The two free protons and eight bound protons in an  $H_2O$  molecule are assumed to decay with equal probability. For the case of a free proton in hydrogen, the momenta of the decay particles are uniquely determined

by two-body kinematics. For the case of a bound proton in oxygen, the decay particle momenta are no longer determined by simple two-body decay; this is due to Fermi motion of the protons and the nuclear binding energy, as well as meson-nuclear interactions in oxygen.

The Fermi momentum distribution of the nucleons was taken to be the same as that measured by electron scattering on  $^{12}C$  for  $S$  states and  $P$  states [13]. Nuclear binding energy was taken into account by using a modified proton mass given by  $M'_p = M_p - E_B$ , where  $M_p$  is the proton rest mass, and  $E_B$  is the nuclear binding energy. The value of  $E_B$  for each simulated event was randomly selected from a Gaussian probability density function with  $(\mu, \sigma) = (39.0, 10.2)$  MeV for the  $S$  state and  $(\mu, \sigma) = (15.5, 3.82)$  MeV for the  $P$  state. Pions interact strongly in the nucleus and may undergo scattering, charge exchange, or absorption as they travel through the nucleus. These interactions affect our ability to reconstruct the  $p \rightarrow e^+ \pi^0$  event, and were carefully simulated to give our best estimate of the detection efficiency of our expected signal. The cross sections used in the simulation of each type of pion-nucleon interaction were calculated by the model of Oset *et al.* [14]. Another effect in the nuclear medium which we take to occur for approximately 10% of proton decay events is that of correlated decay:  $pN \rightarrow e^+ \pi^0 N$  [15]. The value of the invariant mass calculated in the case of correlated decays is lower than that of standard (uncorrelated) proton decays, leading to a reduction in the proton decay detection efficiency when an invariant mass selection criterion is applied.

Backgrounds to the proton decay search arise from atmospheric neutrino interactions which may mimic the  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  signals by charged current interactions such as  $\nu N \rightarrow \ell N' \pi^0$  and neutral current interactions such as  $\nu N \rightarrow \nu N' \pi(\pi')$ s. Backgrounds were estimated using the NEUT [16] neutrino interaction Monte Carlo simulation with an input atmospheric neutrino flux [17].

Particles produced in the simulation of proton decay events and atmospheric neutrino interactions were passed through a GEANT-3 [18] based custom detector simulation to model Cherenkov light emission from charged particles, particle and light propagation through matter, detector geometry, and the response of the PMTs and data acquisition electronics. Hadronic interactions were treated by CALOR [19] for nucleons and charged pions of  $p_\pi > 500$  MeV/ $c$ , and by a custom simulation program [20] for charged pions of  $p_\pi \leq 500$  MeV/ $c$ .

We used data from a 91.7 kt · yr exposure of 1489 live days during SK-I and a 49.2 kt · yr exposure of 798 live

days during SK-II. There were about  $10^6$  event triggers/day above a threshold of a few MeV. We applied several stages of data reduction in order to remove background from cosmic rays, flashing PMTs and radioactivities. In SK-I and SK-II, 12 232 and 6584 events were obtained, respectively. The background contamination of non-neutrino interactions in the final fiducial volume sample was negligible, less than 1%. The efficiency for proton decay events to appear in this sample was estimated to be greater than 99%.

For events after the chain of reduction processes, physical quantities were reconstructed using timing and charge information from each PMT. Software reconstruction algorithms are shared between SK-I and SK-II analyses, taking into account the different PMT densities. The directions and opening angles of visible Cherenkov rings were reconstructed with a likelihood method, using the fitted vertex position where the time-of-flight subtracted timing distribution was most sharply peaked. Each identified Cherenkov ring was categorized as a showering electron-like ( $e$ -like) or a nonshowering muonlike ( $\mu$ -like) ring. Momentum was determined by the sum of photoelectrons corrected for light attenuation in water, PMT angular acceptance, and PMT coverage. Finally, the number of electrons from muon decay was determined by searching for delayed electron signals. The delayed signals were found as delayed timing peaks within the primary event (up to 800 ns from the trigger time), or as subsequent event triggers within 20  $\mu$ s after the primary event. In multiring events such as proton decay signals, each PMT observes an integrated sum of Cherenkov light coming from all rings. In order to determine the momentum for each ring, the fraction of the photoelectrons from each ring was estimated for each PMT using an expected Cherenkov light distribution for each ring. Those photoelectrons were corrected by the amount of scattered Cherenkov light in water, reflected light on PMT surfaces, and the vertex position shift due to the  $\gamma$ 's conversion length.

For SK-I (SK-II) free proton decays of  $p \rightarrow e^+ \pi^0$ , the estimated vertex resolution was 18.1 (20.1) cm, the fraction of two-ring and three-ring events was  $39 \pm 2\%$  and  $60 \pm 2\%$  ( $38 \pm 2\%$  and  $60 \pm 2\%$ ), and the  $\mu/e$  particle misidentification probability was estimated to be 3.3% (3.4%). We define the total momentum in an event as  $P_{\text{tot}} =$

$|\sum_i^{\text{all rings}} \vec{p}_i|$ , where  $\vec{p}_i$  is the reconstructed momentum vector of the  $i$ th ring. The total invariant mass is also defined as  $M_{\text{tot}} = \sqrt{E_{\text{tot}}^2 - P_{\text{tot}}^2}$ , where total energy  $E_{\text{tot}} = \sum_i^{\text{all rings}} \sqrt{|\vec{p}_i|^2 + m_i^2}$ , and  $m_i$  is assumed to be the electron (muon) rest mass for the  $e$ -like ( $\mu$ -like) ring. The total invariant mass for simulated free proton decays was well reconstructed both in SK-I and SK-II. The mean of reconstructed masses agreed within 1% between SK-I and SK-II. The resolution of the total momentum and total invariant mass was 30.5 MeV/ $c$  and 28.7 MeV/ $c^2$  for SK-I, and 36.6 MeV/ $c$  and 38.4 MeV/ $c^2$  for SK-II, respectively.

The energy scale stability of the detector was tested by the mean reconstructed energy of stopping cosmic ray muons and their decay electrons. It varied within  $\pm 0.88\%$  ( $\pm 0.55\%$ ) over the SK-I (SK-II) period. The absolute energy scales for SK-I and SK-II were separately adjusted by using observed photo electrons of penetrating cosmic ray muons in each data taking period. The scale was checked by many calibration data such as stopping cosmic ray muons, electrons from their decays, and the invariant mass of  $\pi^0$ 's produced in atmospheric neutrino interactions. From comparisons of these sources and MC simulation, the absolute calibration error was estimated to be less than  $\pm 0.74\%$  ( $\pm 1.6\%$ ) for the SK-I (SK-II) period.

In order to select proton decay signals from the data samples, the following selection criteria were applied: (A) The number of rings is two or three. (B) One of the rings is  $e$ -like ( $\mu$ -like) for  $p \rightarrow e^+ \pi^0$  ( $p \rightarrow \mu^+ \pi^0$ ) and all the other rings are  $e$ -like. (C) For three-ring events,  $\pi^0$  invariant mass is reconstructed between 85 and 185 MeV/ $c^2$ . (D) The number of electrons from muon decay is 0 (1) for  $p \rightarrow e^+ \pi^0$  ( $p \rightarrow \mu^+ \pi^0$ ). (E) The reconstructed total momentum is less than 250 MeV/ $c$ , and the reconstructed total invariant mass is between 800 and 1050 MeV/ $c^2$ .

The detection efficiencies at each selection criterion for the  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  search are shown in Table I. The efficiencies were estimated to be 44.6% (43.5%) and 35.5% (34.7%) for SK-I (SK-II), respectively. The difference between the detection efficiencies of SK-I and SK-II was only 1%, which implies that SK-II has a similar performance with SK-I for these types of proton decay

TABLE I. Number of surviving events in the data and the atmospheric neutrino MC at each selection criterion in 91.7(SK-I) + 49.2(SK-II) kt  $\cdot$  yr exposure. Detection efficiencies using the proton decay MCs are also listed.

Criteria	$p \rightarrow e^+ \pi^0$ data (atm. MC)	$p \rightarrow \mu^+ \pi^0$ data (atm. MC)	Efficiency (%) ( $e^+ \pi^0$ ) ( $\mu^+ \pi^0$ )
in fiducial	18 816 (19 269)	18 816 (19 269)	98.6 98.8
(A)	4889 (5124)	4889 (5124)	73.1 73.6
(B)	3036 (3141)	1536 (1604)	64.7 61.4
(C)	2541 (2613)	1281 (1284)	62.6 59.7
(D)	1859 (1941)	642 (580)	61.8 46.3
(E)	0 (0.3)	0 (0.3)	44.2 35.3

events. The inefficiency for proton decay detection is mainly due to nuclear interaction effects of pions in  $^{16}\text{O}$ . In the simulated proton decay samples, about 37% of  $\pi^0$ 's from proton decay in  $^{16}\text{O}$  were absorbed or charge-exchanged by interactions with nucleons. Those events rarely survive the selection criteria. The efficiency for  $p \rightarrow \mu^+ \pi^0$  was lower than that for  $p \rightarrow e^+ \pi^0$  because in criterion (D) one electron from muon decay was required for the  $p \rightarrow \mu^+ \pi^0$  search and the detection efficiency for electrons from muon decay was approximately 80%.

The number of remaining events of the atmospheric neutrino MC calculation and the data at each selection criterion are also shown in Table I. The atmospheric neutrino MC calculation, in which neutrino oscillation was accounted for with  $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 2\theta = 1.0$ , was normalized with the observed data using the number of single-ring  $e$ -like events, which are assumed to have negligible neutrino oscillation. Comparison of the number of events in Table I demonstrates that the atmospheric neutrino MC calculation reproduces the observed data well. The number of background events from atmospheric neutrinos in the  $91.7 + 49.2 \text{ kt} \cdot \text{yr}$  exposure for the  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  selection criteria were estimated to be  $0.30 \pm 0.04(\text{MC stat.}) \pm 0.11(\text{sys.})$  events ( $= 2.1 \pm 0.3 \pm 0.8 \text{ events/megaton} \cdot \text{year}$ ) and  $0.34 \pm 0.05(\text{MC stat.}) \pm 0.12(\text{sys.})$  events ( $= 2.4 \pm 0.4 \pm 0.9 \text{ events/megaton} \cdot \text{year}$ ), respectively. Approximately 81% (96%) of background events for  $p \rightarrow e^+ \pi^0$  ( $p \rightarrow \mu^+ \pi^0$ ) were due to charged current neutrino interactions, which consisted of 32% (47%) single-pion production, 19% (21%) multipion production, and 28% (15%) quasi-elastic scattering (CCQE). In most background events from CCQE, a highly energetic proton ( $>1 \text{ GeV}/c$ ) produced by the neutrino interaction scatters in water and produces a secondary  $\pi^0$  which makes a similar event signature to proton decay. For the systematic error of the background rate, uncertainties of event reconstruction, hadron propagation in water, pion-nuclear effects, cross sections of neutrino interactions and neutrino fluxes were considered.

The background event rates were also estimated by another neutrino interaction model, NUANCE [21], and the experimental data of the K2K  $\nu$  beam and the 1-kiloton water Cherenkov detector [22]. The expected background rates were  $1.9 \pm 0.7(\text{MC stat.}) \text{ events/megaton} \cdot \text{year}$  by NUANCE for both decay modes and  $1.63_{-0.33}^{+0.42}(\text{stat.})_{-0.51}^{+0.45} \times (\text{sys.}) \text{ events/megaton} \cdot \text{year}$  by the K2K data for  $p \rightarrow e^+ \pi^0$ . These estimates are consistent with those from our atmospheric neutrino MC.

We have searched for proton decay signals in fully contained event samples in SK-I and SK-II. Figures 1(a3) and 1(b3) and Fig. 2 show distributions of total invariant mass and total momentum for the samples satisfying the selection criteria except for (E) compared with proton decay MC [Figs. 1(a1) and 1(b1)] and atmospheric neutrino MC [Figs. 1(a2) and 1(b2)]. After applying all the

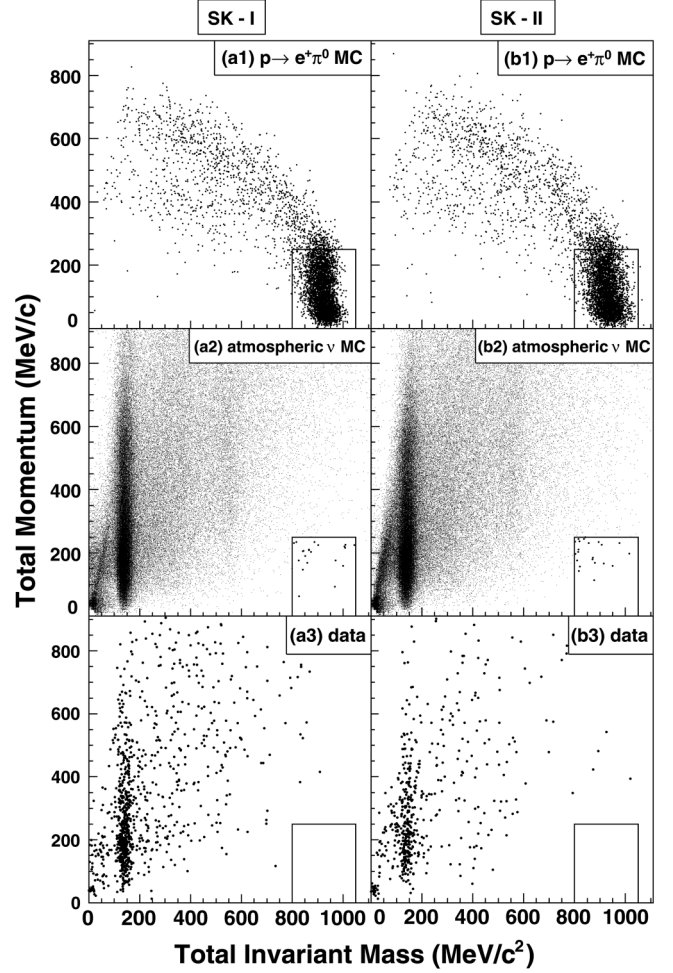


FIG. 1. Total momentum versus total invariant mass distributions for events of proton decay MC (a1),(b1), 500 yr-equivalent atmospheric neutrino MC (a2),(b2) and data (a3),(b3) which satisfy the selection criteria of  $p \rightarrow e^+ \pi^0$  except for (E) in SK-I (left figures) and SK-II (right figures). The boxes in figures indicate the criterion (E). Points in signal boxes of the atmospheric neutrino MC (a2),(b2) are shown in a larger size.

proton decay event selection criteria, no candidate events for  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  were found in the data.

Because there were no candidates, we calculated lower limits on the partial lifetime. In the limit calculation, uncertainties on the exposure were negligible. The total systematic uncertainty on the detection efficiency was estimated to be 19% for both  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  and for both SK-I and SK-II. The largest contribution to the detection efficiency uncertainty came from uncertainties in the cross sections for pion-nuclear effects in  $^{16}\text{O}$ ; these were estimated to be 15% for the  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  detection efficiencies by comparing the pion escape probability from a nucleus with another model [23]. The systematic error from the uncertainty of the Fermi motion was estimated by comparing its momentum distribution with the Fermi gas model; this changes the detection

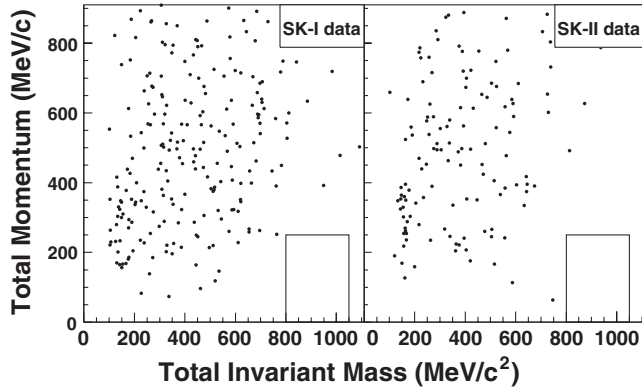


FIG. 2. Total momentum versus total invariant mass distributions for events in SK-I (left) and SK-II (right) data, which satisfy the selection criteria of  $p \rightarrow \mu^+ \pi^0$  except for (E). The box in figures show the criterion (E).

efficiencies by 9%. The fraction of proton decays correlated with other nucleons in  $^{16}\text{O}$  also contributes an uncertainty that we conservatively set to 100% uncertainty for a fraction of events; this changes the detection efficiencies by 7%. There were no significant differences between  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  in these uncertainties. Other sources of uncertainties from energy scale stability, particle identification and decay electron finding efficiency were estimated to be negligible.

The lifetime limits were calculated by a method based on Bayes theorem that incorporates the systematic uncertainty. These calculations give limits on the partial lifetime for  $p \rightarrow e^+ \pi^0$  of  $\tau/B_{p \rightarrow e^+ \pi^0} > 8.2 \times 10^{33}$  years and  $p \rightarrow \mu^+ \pi^0$  of  $\tau/B_{p \rightarrow \mu^+ \pi^0} > 6.6 \times 10^{33}$  years at 90% confidence level.

We have reported the results of proton decay searches in a  $140.9 \text{ kt} \cdot \text{yr}$  exposure of the Super-Kamiokande detector. The proton decay search performance of SK-II is comparable with that of SK-I. No evidence for proton decays via the mode  $p \rightarrow e^+ \pi^0$  and  $p \rightarrow \mu^+ \pi^0$  were found and we set limits on the partial lifetime of a proton. These limits are more stringent compared with the previous results of  $1.6 \times 10^{33}$  years [8] and  $4.7 \times 10^{32}$  years [9], respectively.

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