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The Super-Kamiokande Collaboration

(February 23, 1999)

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We present results of a search for proton decays, $p \to \bar{\nu}K^+$, using data from a 33 kton·year exposure of the Super–Kamiokande detector. Two decay modes of the kaon, $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^0$, were studied. The data were consistent with the background expected from atmospheric neutrinos; therefore a lower limit on the partial lifetime of the proton $\tau/B(p \to \bar{\nu}K^+)$ was found to be 6.7×10^{32} years at 90% confidence level.

11.30.Fs,11.30.Pb,13.30.Ce,14.20.Dh,29.40.Ka

One of the most unique predictions of Grand Unified Theories (GUTs) is baryon number violation. The minimal SU(5) GUT [1] predicts the dominant decay mode to be $p \to e^+\pi^0$ with a predicted lifetime shorter than $\sim 10^{31}$ years. The current experimental lower limit is about 100 times longer than this [2]. Furthermore, the weak mixing angle predicted by this model does not agree with the experimental value and the three running coupling constants of the strong and electroweak forces do not meet exactly at a single point [3]. Alternatively, the minimal supersymmetric (SUSY) SU(5) GUT makes a prediction for the weak mixing angle which is much closer to experimental results and predicts the lifetime of the proton decay into $e^+\pi^0$ to be more than four orders of magnitude longer than that in non-SUSY minimal SU(5) GUT [4]. The minimal SUSY SU(5) model predicts the proton decay mode $p \to \bar{\nu}K^+$ to be dominant with the partial lifetime prediction varying from $\mathcal{O}(10^{29})$ to $\mathcal{O}(10^{35})$ yr [4].

In this letter, we report the result of the search for proton decay through the channel $p \to \bar{\nu}K^+$ in 535 live-days of data in Super–Kamiokande, corresponding to a 33 kt·year exposure.

The Super–Kamiokande detector is a ring imaging water Cherenkov detector located in Kamioka Observatory, ICRR, Univ. of Tokyo, 1000 m (2700 m water equivalent) below the peak of Mt. Ikenoyama near Kamioka, Japan. 50 kilotons of ultra pure water are held within a stainless steel tank of height 41.4 m and diameter 39.3 m. The tank is optically separated into two regions, the inner and outer detectors, by a photomultiplier tube (PMT) support structure and a pair of opaque plastic sheets. The inner detector has a height of 36.2 m and a diameter of 33.8 m. The outer detector completely surrounds the inner detector and is used to identify incoming and outgoing particles. On the wall of the inner detector, there are 11146 50 cm inward facing PMTs which cover 40% of the surface. The outer detector is lined with 1885 20 cm outward facing PMTs equipped with 60 cm × 60 cm wavelength-shifter plates to increase the collection efficiency of Cherenkov photons.

In the search for rare proton decays, neutrinos produced by cosmic ray interactions in the upper atmosphere (atmospheric neutrinos) typically represent the limiting background. Super-Kamiokande detects about 8 fully-contained atmospheric neutrino events per day [5]. These events have vertices which were reconstructed inside the 22.5 kiloton fiducial volume of the detector, defined to be 2 m from the PMT support structure. All the events were required to have no coincident light in the outer detector.

After the event selection, events were reconstructed using PMT pulse height and timing information to determine the vertex position, number of Cherenkov rings, particle type, momentum, and number of decay electrons. A particle is classified as a showering(e-like) or a non-showering(μ-like) type [5]. Details of the detector, event selection, and event reconstruction are described in [2] and [5].

The absolute scale of the momentum reconstruction was checked with several calibration sources such as the electrons from a LINAC [6], decay electrons from cosmic-ray muons which stopped in the detector volume (stopping muons), dE/dx of stopping muons, and the reconstructed mass of π^0s produced by atmospheric neutrino interactions. The error in the absolute energy scale was estimated to be less than $\pm 2.5\%$. The time variation of the energy scale was checked with muon decay electrons and was found to vary by $\pm 1\%$ over the exposure period.

The momentum of the K^+ from $p \to \bar{\nu}K^+$ is 340 MeV/c and is below the threshold momentum for producing Cherenkov light in water. Candidate events for this decay mode are therefore identified through the decay products of the K^+. Due to the smallness of the hadronic cross-section of low-momentum K^+, we calculated that 97% of the K^+ exit from the ^{16}O nucleus without interaction, and that 90% of these decay at rest. In this paper, we therefore searched for K^+ decays at rest through two dominant modes: $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^0$. Two separate methods were used to search for $K^+ \to \mu^+\nu_\mu$.

We now describe the first method to search for $p \to \bar{\nu}K^+$; $K^+ \to \mu^+\nu_\mu$. The momentum of the μ^+ from the decay of the stopped K^+ is 236 MeV/c. If a proton in the $p_{3/2}$ state of ^{16}O decays, the remaining ^{15}N nucleus is left in an excited state. This state quickly decays, emitting a prompt 6.3 MeV γ-ray. The signal from the decay particles of the K^+ should be delayed relative to that of the γ-ray due to the lifetime of the K^+ ($\tau = 12$ ns). The probability of a 6.3 MeV γ-ray emission in a proton decay in oxygen is estimated to be 41% [7]. By requiring this prompt γ-ray, almost all of the background events are eliminated.

To determine the signal region and to estimate the detection efficiency, a total of 2000 $p \to \bar{\nu}K^+$; $K^+ \to \mu^+\nu_\mu$ Monte Carlo (MC) events were generated. The same reduction and reconstruction as for the data were applied to these events. For these proton decay MC events, 96% were identified as having one ring. The resolution of the vertex fitting was 52 cm and the probability of misidentification of the particle type was 2.9%. Based on this simulation, a signal region of the reconstructed momentum of the μ^+ was defined to be between 215 MeV/c and 260 MeV/c. Candidate events for this analysis were then selected by the following criteria: A1) one ring A2) μ-like A3) with one decay electron, A4) 215 MeV/c < momentum(μ) < 260 MeV/c, A5) Goodness of fit requirement, and A6) detection of a prompt γ-ray. The A5 criterion required a successful vertex fitting for the correct identification of the prompt γ-ray. The prompt γ-ray signal was selected using the number of hit PMTs within a 12ns timing window which slides between 12ns and 120ns before the μ signal. Criterion A6 required the number of hit PMTs to be more than 7. The total detection efficiency, including the selection criteria A1-A6, the branching ratio of $K^+ \to \mu^+\nu_\mu$ (63.5%), the ratio of bound protons in oxygen to all of the protons in H_2O (80%), and the emission probability of the 6.3 MeV γ-ray (41%), was estimated to be 4.4%. The reason for the relatively low efficiency was due to the inefficiency of the detection of the prompt γ-rays. The number of background events was estimated using a 225 kt·year equivalent sample of atmospheric neutrino MC events. When estimating this background, the flux was normalized based on the observed deficit of ν_μ's. The normalization factors were 0.74 for ν_μ charged current events and 1.17 for any other neutrino induced events [5]. The background contamination was estimated to be 0.4 events/33 kt·yr. When the same criteria were applied to the real data, no events were observed. Figure 1 shows the number of hit PMTs within the timing region of the prompt γ-ray for proton decay MC events, simulated atmospheric neutrino events, and real data.

The partial lifetime (τ/B) was calculated:

$$\tau/\beta \geq (\Lambda \times \epsilon B_m)/N_{cand}, \tag{1}$$

where Λ is the exposure in proton·years, ϵB_m is the detection efficiency (4.4%) and N_{cand} is the 90% Poisson upper limit on the number of candidate events (2.3). The lower limit of the partial lifetime obtained for this mode was found to be 2.1×10^{32} yr at 90% C.L.

The overall detection efficiency of the prompt γ-ray tagging method is rather small. Therefore, as a second method we searched for an excess of events of mono-energetic 236 MeV/c μ^+'s produced by the stopped K^+ decay for events with no observed prompt γ-ray. For this analysis, the selection criteria were: A1 to A4 described above and A7 no prompt gamma-ray signal. The detection efficiency of this mode (including the branching ratio of $K^+ \rightarrow \mu^+\nu_\mu$) was estimated to be 40%.

To estimate the excess of proton-decay signal, the number of events in three momentum regions, 200 MeV/c to 215 MeV/c, 215 MeV/c to 260 MeV/c, and 260 MeV/c to 300 MeV/c, were summed separately for $p \rightarrow \bar{\nu}K^+$;$K^+ \rightarrow \mu^+\nu_\mu$ MC, atmospheric ν MC, and data. The χ^2 method was applied to fit parameters. The χ^2 function was defined as follows:

$$\chi^2(a,b) = \sum_{i=1}^{3} \frac{[N_i^{data} - (a \cdot N_i^{atm\nu} + b \cdot N_i^{pdcy})]^2}{N_i^{data}} \tag{2}$$

where a and b are the fit parameters, $N_i^{data}, N_i^{pdcy}, N_i^{atm\nu}$ are the numbers of events of real data, proton decay MC, and atmospheric ν MC, respectively, in each momentum region i.

The minimum χ^2, $\chi^2_{min} = 0.3$, was in the unphysical region ($b \cdot N_2^{pdcy} = -16.3$). The χ^2_{min} in the physical region ($b \cdot N_2^{pdcy} = 0$), $\chi^2_{min}(phys)$ was 2.0. The data were therefore consistent with no excess of $p \rightarrow \bar{\nu}K^+$ events. The 90% C.L. upper limit on the number of proton decay events(N_{cand}) was obtained by requiring $\chi^2 - \chi^2_{min}(phys) = 3.7$ based on the prescription described in Ref. [8]. The 90% upper limit on the number of candidates was estimated to be 13.3. The momentum distribution of the events which satisfy criteria A1 to A3 is shown in Figure 2. Also shown is the expected signal of proton decay at the 90% C.L. The lower limit of the partial lifetime of $p \rightarrow \bar{\nu}K^+; K^+ \rightarrow \mu^+\nu_\mu$ using the above method was found to be 3.3×10^{32} years at 90% C.L.

Finally, we describe the search for $p \rightarrow \bar{\nu}K^+$; $K^+ \rightarrow \pi^+\pi^0$. The π^0 and π^+ from the K^+ decay at rest have equal and opposite momenta of approximately 205 MeV/c. The decay γ's from the π^0 reconstruct this momentum. The π^+, barely over Cherenkov threshold with $\beta \approx .86$, emits very little Cherenkov radiation. However it does decay into a muon ($\pi^+ \rightarrow \mu^+\nu_\mu$) which decays into a positron ($\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$). Detection of this positron is possible. Furthermore, a small amount of Cherenkov radiation from the π^+, sometimes visible as a collapsed Cherenkov ring, can be detected in the direction opposite that of the π^0. To quantify this, we defined "backwards charge" (Q_b) as the sum of the photoelectrons detected by the PMTs which lay within a 40° cone whose axis was the opposite direction of the reconstructed direction of the π^0. This charge was corrected for light attenuation in the water, angular dependence of photon acceptance, and photocathode coverage.

To determine the signal region and estimate the detection efficiency, a total of 1000 $p \rightarrow \bar{\nu}K^+$; $K^+ \rightarrow \pi^+\pi^0$ MC events were generated, 771 of which had vertices which reconstructed inside the fiducial volume of the detector. For these 205 MeV/c π^0 events, the resolution of vertex fitting was 29 cm and 66% of the events were identified as 2-ring events.

The selection criteria for this type of event were defined: B1) 2 e-like rings, B2) with 1 decay electron, B3) 85 MeV/c^2 < mass$_{\gamma\gamma}$ < 185 MeV/c^2, B4) 175 MeV/c^2 < momentum$_{\gamma\gamma}$ < 250 MeV/c^2 and B5) 40 p.e. < Q_b < 100 p.e. Criteria B1,B3, and B4 required the π^0 with the monochromatic momentum expected. Criterion B2 required the decay of the π^+ into muon into positron. Criterion B5 required the Cherenkov light from the π^+. The π^0 mass resolution was determined to be 135±21 MeV/c^2. By passing the proton decay MC events through these selection criteria, the detection efficiency was determined to be 31%. The largest contribution to the inefficiency was the inefficiency of detection of two γ-rays from the decay of the π^0. Including the kaon branching ratio of 21.2% into $\pi^+\pi^0$, the total detection efficiency for this mode was estimated to be 6.5%.

Charged current interactions such as $\nu_\mu N \rightarrow \mu N' \pi^0$ from atmospheric neutrinos can imitate a kaon decay mode of this type. The selection criteria were applied to the sample of atmospheric neutrino MC. The flux was normalized in the same manner as in the prompt γ-ray search. The number of background events expected was estimated to be 0.7 events/33kt·yr. Figures 3a and b show $|\vec{p}_{\pi^0}|$ vs. backwards charge (Q_b) for proton decay MC and atmospheric neutrino MC, respectively.

The selection criteria for this decay mode were applied to the data. Figure 3c shows the results of the final two cuts. No events passed. The single event which lay close to the cuts was examined visually with an event display.

We found no additional evidence that it could be a signal event that fell outside of the cuts. The backwards charge appeared to be a fragment of one of the rings and not from a small collapsed ring. Based on these numbers, the lower limit of the partial lifetime of $K^+ \to \pi^+\pi^0$ was estimated to be 3.1×10^{32} yr at the 90% C.L. based on Eqn. 1.

The combined 90% C.L. upper limit for the number of proton decay candidates (x_{limit}) was calculated by integrating the likelihood function to the 90% probability level:

$$\frac{\int_0^{x_{limit}}[\prod_{i=1}^3 P(N_i^{obs}, N_i(x))]dx}{\int_0^{\infty}[\prod_{i=1}^3 P(N_i^{obs}, N_i(x))]dx} = 0.90, \tag{3}$$

$$N_i(x) = X_i^{BG} + \frac{\epsilon B_m^i}{\sum_{j=1}^n[\epsilon_i B_m^j]}x, \tag{4}$$

where $P(N,x)$ is the probability function of Poisson statistics, N_i^{obs} is the number of observed candidates, X_i^{BG} is the number of estimated background events, ϵ_i is the detection efficiency, and B_m^i is the meson branching ratio. The index i stands for the i-th method. The lower limit of partial lifetime was calculated with

$$\tau/B = \frac{1}{x_{limit}}(\sum_{i=1}^3 \epsilon_i B_m^i)\Lambda, \tag{5}$$

where Λ is the exposure in proton·years. The combined lower limit of the partial lifetime for $\tau/B(p \to \bar{\nu}K^+)$ using the three independent methods was 7.3×10^{32} yr at the 90% C.L.

The main sources of systematic errors in the calculation of the lifetime limits were: 1) uncertainty in the energy calibration, 2) uncertainty in the detection efficiency of the decay electron from the stopped muon, 3) uncertainty in the atmospheric neutrino fluxes and interaction cross sections used in the Monte Carlo simulation, 4) uncertainty in the emission probability of prompt γ-ray from ^{16}O.

For the $K^+ \to \pi^+\pi^0$ mode search, the detection efficiency changed by less than $\pm1\%$ if the reconstructed momentum criterion was shifted by $\pm2.5\%$. For the $K^+ \to \mu^+\nu_\mu$ mode, if the reconstructed momentum was shifted by $\pm2.5\%$, the lifetime limit obtained from this analysis was changed by $\pm10\%$ at most. The systematic error of the detection efficiency of decay electrons from muons was estimated to be 1.5% [5] by comparing the fraction of cosmic-ray muon events with decay electrons between MC simulation and real data. The uncertainty of the estimation of number of background events came from the uncertainty of the neutrino flux and the interaction cross sections. This uncertainty was estimated by comparing the number of events of the normalized atmospheric neutrino background with the real data at each reduction step. For the prompt γ-ray tagging method and $K^+ \to \pi^+\pi^0$ mode search, the data and atmospheric ν Monte Carlo agreed within statistical errors at each step. In searching for the excess of 236 MeV/c μ^+s, the shape of the momentum distribution and the absolute normalization was left as a free parameter in the fitting. Therefore, the uncertainties of neutrino flux and the interaction cross-sections did not significantly affect the lower limit of the partial lifetime. The systematic error in the 6.3 MeV γ-ray emission probability was estimated to be $\pm15\%$ [9]. This error directly affected the detection efficiency of the prompt γ-ray tagging method. Also it is expected that there are some other promt γ-rays, whose energies are 9.93 MeV, 7.03 MeV, 7.01 MeV [7]. Including these deexcitation modes, the detection efficiency of the prompt γ-ray tagging method should be higher. However, these emission probabilities are more than 10 times smaller than the probability of that of 6.3 MeV γ-ray and they have much larger uncertainties in the emission probability, which are estimated to be larger than 30% [9]. Therefore, we neglected these modes in the analysis. However, these modes were taken into account in the systematic uncertainty of the lifetime limit, which was estimated to be $^{+7}_{-3}\%$.

Considering all of these effects, the systematic error of the lower limit of the partial lifetime was estimated to be $^{+10}_{-8}\%$. As a result, the lower limit of the partial lifetime for $p \to \bar{\nu}K^+$ was estimated to be 6.7×10^{32}yr(90%C.L.).

In this paper, we have reported the result of a search for proton decay into $\bar{\nu}K^+$ in a 33 kt·year exposure of the Super–Kamiokande detector. The data are consistent with the background expected from atmospheric neutrinos and no evidence for proton decay was observed. We set the lower limit of partial lifetime for $p \to \bar{\nu}K^+$ to be 6.7×10^{32} yr at 90% C.L. This limit is more than six times longer than the previously published best limit (1.0×10^{32} yr.(90% C.L.)) [10] and will help to constrain SUSY GUT models.

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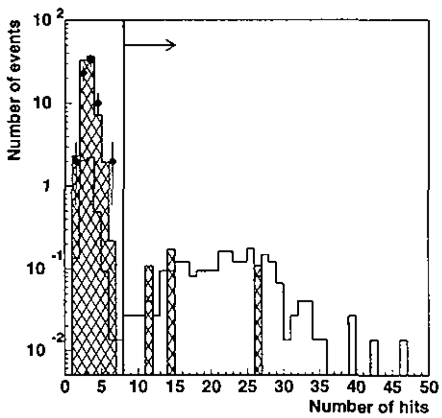

FIG. 1. Number of hit PMTs within the timing region of the prompt γ-ray search in $p \to \bar{\nu}K^+, K^+ \to \mu^+\nu_\mu$. Histogram shows the proton decay Monte Carlo with 6.3MeV γ-ray, shaded histogram shows 33kt·yr equivalent atmospheric neutrino Monte Carlo events, and data points with error bars show 33kt·yr data of Super–Kamiokande. For the proton decay Monte Carlo, $\tau/B(p \to \bar{\nu}K^+)$ of 2.1×10^{32} yr is assumed.

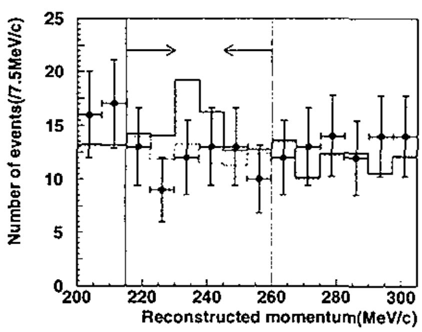

FIG. 2. Reconstructed momentum distribution. Solid (dotted) line shows the estimated 90% C.L. number of proton decay ($\tau/B(p \to \bar{\nu}K^+) = 3.3 \times 10^{32}$ yr) + atmospheric ν (atmospheric ν) events; the black points with error bars show the data with the statistical errors.

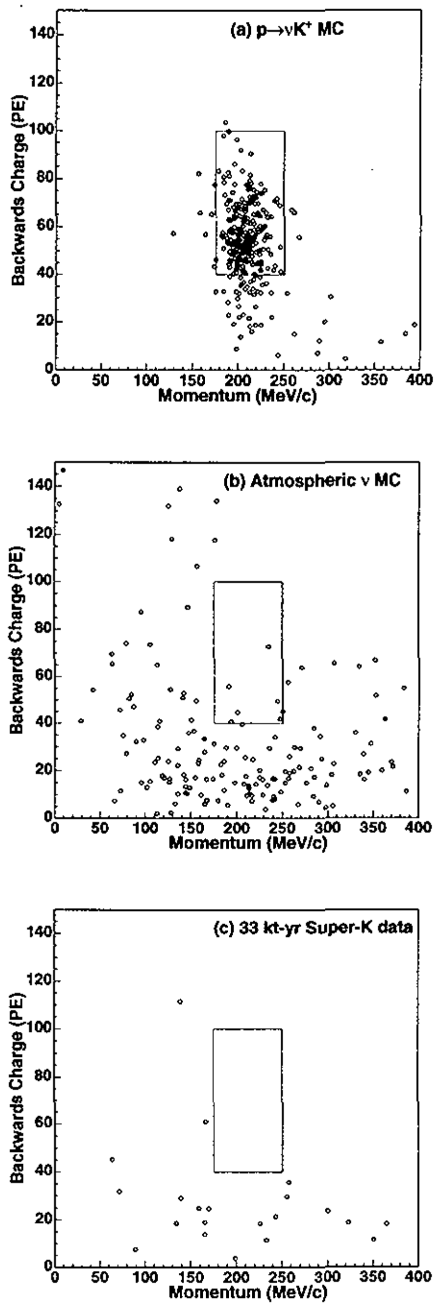

FIG. 3. Backwards charge versus π^0 momentum for (a) $p \to \bar{\nu}K^+;K^+ \to \pi^+\pi^0$ Monte Carlo, (b) 225 kt·yr equivalent atmospheric ν Monte Carlo, and (c) 33 kt·yr data from Super–Kamiokande.