Search for Nucleon Decay in Super-Kamiokande

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Searches for nucleon decays are performed by Super-Kamiokande, a large water cherenkov detecor. The total exposure is 141 kton·year which includes 1489 days data of Super-Kamiokande-I (SK-1) and 799 days of Super-Kamiokande-II (SK-2). We have not observed any evidence of nucleon decay yet. The lower limit of proton life time decay into $e^+\pi^0$, which is dominant mode predicted by non-SUSY model, is 8.2×10^{33} years with 90 % confidence level. The lower limit of proton life time decay into $\overline{\nu}K^+$, which is dominant mode predicted by SUSY model, is 2.8×10^{33} years with 90 % confidence level.

1 Introduction

1.1 GUTs and Nucleon decays

The standard model based on the gauge group has been successful in accounting for many experimental results. However, the standard model has a lot of unanswered questions, such as why there are so many parameters. Various attempts have been made to resolve the shortcoming by unifying the electroweak and the strong interactions in the context of Grand Unified Theory (GUTs). GUTs is motivated by the apparent merging of the coupling constants of the strong, weak, and electromagnetic forces at a large energy scale ($\sim 10^{16} GeV$), which is out of the reach of accelerators, when low energy measurements extrapolated. One of the other general features of GUTs is that they allow lepton and baryon number violations and they predict instability of nucleons. Then nucleon decay experiments are the direct probe for GUTs.

In GUTs, nucleon decay can proceed via an exchange of a massive boson between two quarks in a nucleon, and one quark transforms into a lepton and another into an anti-quark which binds a spectator quark creating a meson. The favored decay mode in GUTs based on SU(5) symmetry is $p \rightarrow e^+\pi^0$. On the other hand, GUTs model incorporating supersymmetry (SUSY-GUTs) suppress the decay mode $p \rightarrow e^+\pi^0$ but favor the other mode $p \rightarrow \overline{\nu}K^+$ via dimension five operator interactions with the exchange of a heavy supersymmetric color triplet

Table 1: Proton life times predicted by GUTs and SUSY-GUTs models .

Model	Mode	Prediction (years)
Minimal SU(5)	$p \to e^+\pi^0$	$10^{28.5} \sim 10^{31.5}$ [1]
Minimal SO(10)	$p \to e^+\pi^0$	$10^{30} \sim 10^{40}$ [2]
Minimal SUSY SU(5)	$p \to \overline{\nu}K^+$	$\leq 10^{30}$ [3]
SUGRA SU(5)	$p \to \overline{\nu}K^+$	$10^{32} \sim 10^{34}$ [4]
SUSY SO(10)	$p \to \overline{\nu}K^+$	$10^{32} \sim 10^{34}$ [5]

Higgsino. Proton life times predicted by some GUTs and SUSY-GUTs models are listed in Table 1.

1.2 Super-Kamiokande detector

The Super-Kamiokande is a large water cherenkov detector. It is cylindrical shape, 39 m in diameter and 40 m in height, and it contains 50 kton pure water. It lies about 1,000 m underneath the top of Mt. Ikenoyama (2,700m water equivalent underground) to reduce cosmic ray background. The detector is optically separated into two regions; inner detector (ID) and outer detector (OD). 20 inch PMTs facing inward and 8 inch PMTs facing outward are used as photo device to observe cherenkov light from charged particles. The fiducial volume is defined as a cylindrical volume with surface 2 m away from the ID PMT plane and it corresponds to 22.5 kton, 7×10^{33} protons. The detector can separate cherenkov rings into electromagnetic shower type (e-like) and muon type (μ-like) by opening angle and hit pattern of the cherenkov ring. A detailed description of the Super-Kamiokande detector can be found else where [6].

The Super-Kamiokande started observation from April 1996 with 11,146 ID PMTs which covered 40 % of ID surface. The observation was continued until July 2001, corresponding to 1489.2 days, 91.7 kton·year, and this period is called Super-Kamiokande-I (SK-1). After an accident in 2001, about half of ID PMTs were lost and the detector was reconstructed with 5,182 ID PMTs, decreasing photo coverage to 19 %. The period from December 2002 until October 2005, corresponding to 798.6 days, 49.2 kton·year, is called Super-Kamiokande-II (SK-2).

The results of $p \to e^+\pi^0$ and $p \to \overline{\nu}K^+$ for SK-1 data were already published [7] [8] and they excluded minimal SU(5) and minimal SUSY SU(5). In this paper, the results of combined analysis of SK-1 and SK-2 are reported.

2 MC simulations

A Monte Carlo simulation is used to estimate detection efficiencies of proton decay occurring in water (H_2O). For the case of a free proton decay in hydrogen, the momentum of the decay particles are uniquely determined by two-body kinematics. For the case of a bound proton in oxygen, Fermi motion of the protons, the nuclear binding energy, and meson-nuclear interactions are taken into account.

Backgrounds to the proton decay search arise from atmospheric neutrino interactions. The neutrino interactions in water are simulated by **neut** [9] with an input atmospheric neutrino flux calculated by Honda, *et al.* [10] , which are used for neutrino oscillation analysis.

Particles produced in the simulations of proton decay and atmospheric neutrino are passed through a detector simulation which is based on GEANT-3 to model Cherenkov light emission from charged particles, propagation of particles and lights through the matter, detector geometry response of the PMTs and electronics.

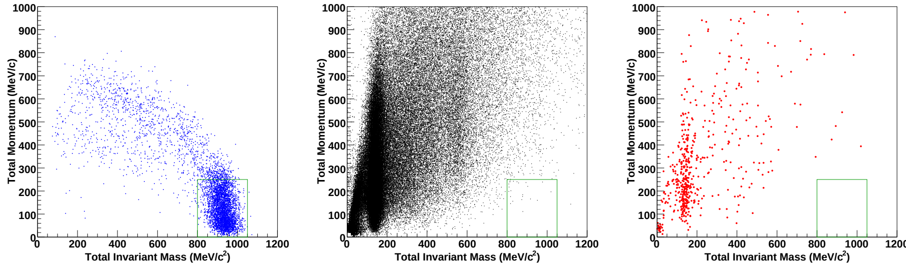

Figure 1: Total momentum versus total invariant mass distributions for SK-2, left:proton decay MC, middle: atmospheric neutrino MC, right: data. The box areas are signal region.

3 $p \to e^+\pi^0$

If a proton decays into e^+ and π^0, they are emitted back-to-back in the proton rest frame. The π^0 immediately decays into two gamma rays. Then we may observe 2 or 3 e-like cherenkov rings, and we can reconstruct π^0 mass from two gamma rays and also proton mass from all rings if we succeed to reconstruct all of the rings. In $p \to e^+\pi^0$ mode, the following selection criteria are applied: (A1) the vertex is in the fiducial volume described in Sec 1.2, and the event is fully contained in the detector (FC event), (A2) the number of rings is two or three and all rings are e-like, (A3) there is no Michel electron. (A4) for three ring events, π^0 invariant mass is reconstructed in between 85 to 185 MeV/c^2, (A5) the reconstructed total momentum is less than 250 MeV/c and the reconstructed total invariant mass is in between 800 to 1050 MeV/c^2. Figures 1 show total momentum versus total invariant mass of SK-2 after (A1)-(A4) cuts, for the proton decay MC, the atmospheric neutrino MC, and the data.

The detection efficiencies are estimated to be 44.6 and 43.5 % for SK-1 and SK-2, respectively. The difference of efficiency is 1 % and it implies SK-2 has a similar performance with SK-1 even though the photo coverage of SK-2 is almost a half of SK-1. The inefficiency is mainly due to nuclear interaction effects of pions in oxygen. The total systematic uncertainties are estimated to be 19 % both for SK-1 and SK-2, and the largest contribution is the uncertainty of the cross section for pion-nuclear effects (15 %).

The remaining backgrounds are estimated to be 0.2 and 0.1 events for SK-1 and SK-2, respectively. The dominant sources of neutrino interaction are charged current (CC) single-pion production (32 %), CC multi-pion production (19 %), and CC quasi-elastic scattering (28 %). The systematic uncertainty comes from reconstruction performance, hadron propagation in water, pion-nuclear effect, cross sections and flux of neutrinos are taken into account and the uncertainty of the background is estimated to be 37 %.

Figures 2 show the reconstructed π^0 mass, the total momentum, and the total invariant mass distributions of SK-2 data and the atmospheric neutrino MC. The data agrees with the atmospheric neutrino MC. The number of observed data in the signal box in Figure 1 are 0 both for SK-1 and SK-2. The life time limit calculated by a method based on Bayes theorem [11] is $\tau/B_{p\to e^+\pi^0} > 8.2 \times 10^{33}$ years at 90 % confidence level.

4 $p \to \overline{\nu}K^+$

If a proton decays into K^+ and $\overline{\nu}$, the momentum of K^+ is below cherenkov threshold and it cannot emit cherenkov light. Most of K^+ are stopped in water and decay into other particles. For $p \to \overline{\nu}K^+$ mode, three methods are employed to analyze and merged results are shown later section.

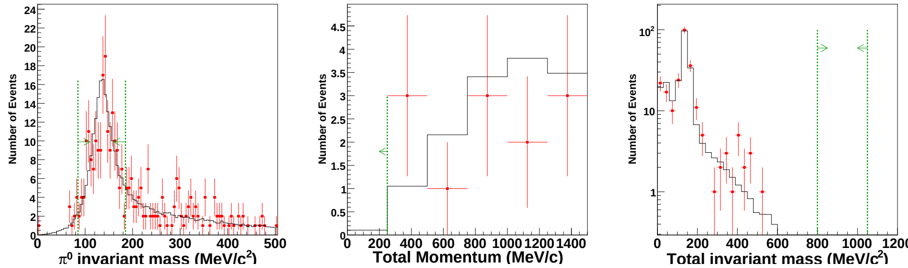

Figure 2: π^0 mass, total momentum, total invariant mass distributions for SK-2. Histograms are atmospheric neutrino MC and plots are data in the figures.

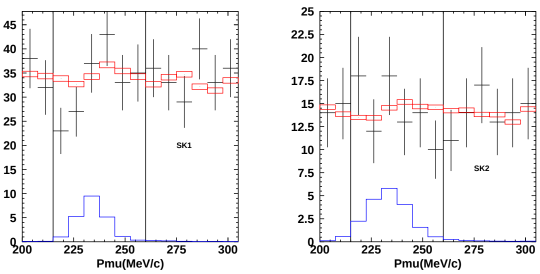

Figure 3: Momentum distribution of FC1R μ-like sample of SK-1 (left) and SK-2(right). Cross dots are data, boxes are atmospheric neutrino MC, and histograms are proton decay MC.

4.1 $K^+ \to \mu^+\nu_\mu$

A K^+ decays into $\mu^+\nu_\mu$ with 63.5 % fraction and they have monochromatic momentum (236 MeV/c) and back-to-back because most of K^+ are stopped and decay. So we may see event excess around this momentum region if the protons decay in this mode. Selection criteria requires; (B1) FC event in the fiducial volume, (B2) single μ-like ring, (B3) there is one Michel electron. Then the momentum distribution of μ in data are divided into 3 regions; 200 - 215 MeV/c, 215 - 260 MeV/c, and 260 - 300 MeV/c and compared by atmospheric neutrino MC and proton decay MC. Figures 3 show muon momentum distributions of data, atmospheric neutrino MC, and proton decay MC. The data and atmospheric neutrino MC agree well and there is no indication of the proton decay. If the data is fitted by the atmospheric neutrino MC and the proton decay MC, the upper limit of contamination of the proton decay can be obtained and the lifetime limit can be calculated.

4.2 $K^+ \to \mu^+\nu_\mu$ *with prompt* γ

There are much background events in single ring μ sample as shown in the previous section. To eliminate the background, further cuts are applied. If a proton decays in the oxygen, the remaining nitrogen nucleus left in excited states emit γ rays immediately. The most significant branch is the 6.32 MeV γ ray from $p_{3/2}$ hole state with 41 % probability [12]. Thus the signal of γ ray may be observed before μ and it is very powerful tool to eliminate the backgrounds.

To select $K^+ \to \mu^+\nu_\mu$ with prompt γ, the following selection criteria are applied after (B1)-(B3) in section 4.1; (B4) the distance between μ and decay electron is less than 200 cm, (B5) the goodness of vertex fit is grater than 0.6. The cuts (B4) and (B5) are helpful to reject proton ring which mainly comes from charged current quasi-elastic interaction ($n + \nu \to p + \mu$) and the case μ is below cherenkov threshold. To determine initial vertex, time information of each PMT is used (TDC fit). Then a precise vertex fitter which uses opening angle and hit pattern

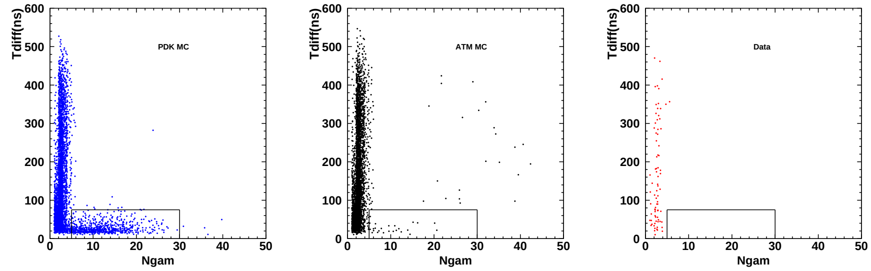

Figure 4: N_γ versus $T_\mu - T_\gamma$ distribution of SK-2. Right is proton decay MC, middle is atmospheric neutrino MC, and left is data. Boxes show signal region.

of a cherenkov ring is applied assuming particle type (e-like/μ-like) in the analysis. If a proton ring is taken as a μ-like ring, the precise fitter may fail to fit the vertex because the actual opening angle is smaller than expectation as μ. Further proton rejection cut is applied; (B6) the difference of goodness between precise fit and TDC fit is less than 0.1. Then number of hit versus time distribution is made for an event and a time window with 12 nsec is opened before muon peak and is slid to earlier time to find a maximum hit cluster which may be produced by γ ray. N_γ and T_γ are defined as the maximum number of hit in the time window and the time of middle of the time window. (B7) $8 < N_\gamma < 60$ for SK-1 and $4 < N_\gamma < 30$ for SK-2, (B8) $T_\mu - T_\gamma < 75$ nsec.

Figures 4 show N_γ versus $T_\mu - T_\gamma$ distributions for the proton decay MC, the atmospheric neutrino MC, and the data. The detection efficiencies are estimated to be 7.2 % and 5.8 % for SK-1 and SK-2, respectively. Event though the photo coverage of SK-2 is almost a half of SK-1, the detection efficiency keeps about 80 % of SK-1. That is useful information to design a large water cherenkov detector of the next generation. The systematic uncertainties are estimated to be 22 % both for SK-1 and SK-2, which are dominated by the uncertainty of the γ ray emission probability (20 %). The background events for each livetime are estimated to be 0.16 and 0.08 events for SK-1 (1489 days) and SK-2 (799 days), respectively. The most dominant neutrino interaction in the background is that the neutrino interacts with nuclei and makes resonance N(1650) and it decays into $K^+\Lambda$. On the other hand, there are no candidates in both SK-1 and SK-2.

4.3 $K^+ \to \pi^0\pi^+$

A K^+ decays into $\pi^0\pi^+$ with 21.5 % fraction, and most of them have monochromatic momentum. The momentum of π^+ is just above cherenkov threshold and its cherenkov ring cannot be observed clearly. The π^+ decays into μ with momentum below cherenkov threshold. As a result, two γs from a π^0 and PMT activities in the backward of π^0 direction, and a decay electron can be observed if a proton decays in this mode. The selection criteria is required; (C1) FC 2 rings and both are e-like, (C2) one decay electron, (C3) reconstructed π^0 mass is grater than 85 MeV/c^2 and less than 185 MeV/c^2, (C4) reconstructed π^0 momentum is grater than 175 MeV/c and less than 250 MeV/c. Then a backward charge, Q_{bk} and a residual charge, Q_{res} are defined as sum of the charges in $140^\circ \sim 180^\circ$ and $90^\circ \sim 140^\circ$ from the π^0 direction. (C5) $40(20) < Q_{bk} < 100(50)$ pe for SK-1 (SK-2), (C6) $70(35)pe < Q_{res}$ for SK-1 (SK-2).

Figures 5 shows Q_{bk} versus Q_{res} plots for the proton decay MC, the atmospheric neutrino MC, and the SK-2 data. The detection efficiencies are estimated to be 6.2 % and 4.8 % for SK-1 and SK-2, respectively. The detection efficiency of SK-2 also keeps about 80 % of SK-1. The systematic uncertainties are 8.6 % both for SK-1 and SK-2 and the most dominant error comes from uncertainty of N-π cross section in water (5.0 %). The numbers of backgrounds

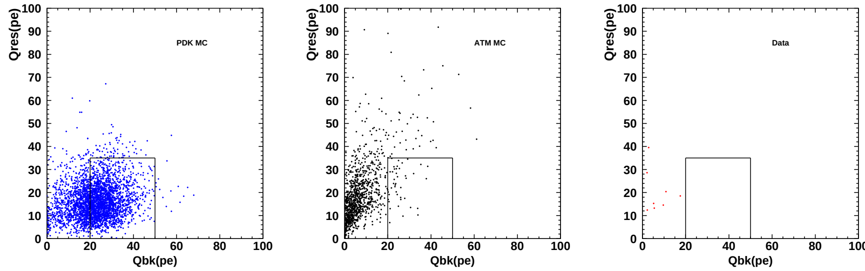

Figure 5: Backward charge versus residual charge distribution of SK-2. Right is proton decay MC, middle is atmospheric neutrino MC, and left is data. Boxes show signal region.

are estimated to be 0.43 and 0.31 for SK-1 and SK-2, respectively. The large contributions are single π production in charged and neutral current interactions. There are no candidates in the data.

4.4 Combined limit for $p \rightarrow \overline{\nu} K^+$

The three methods are used to calculate lifetime limit for the proton decay mode $p \rightarrow \overline{\nu} K^+$ based on the Bayes theorem. Detail descriptions can be found in reference [8]. The obtained lower limit of the proton lifetime via $p \rightarrow \overline{\nu} K^+$ is 2.8×10^{33} years at 90 % confidence level.

5 Summary

We have searched for nucleon decay via $p \rightarrow e^+ \pi^0$, which is dominant mode in the non-SUSY GUTs, and $p \rightarrow \overline{\nu} K^+$, which is dominant mode in the SUSY-GUTs mode, from an exposure of 141 kton year. No significant excess above background of the atmospheric neutrino interactions is observed. The lower limits of the partial nucleon lifetime at 90 % confidence level are 8.2×10^{33} years and 2.8×10^{33} years, respectively.

Acknowledgments

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References

1. P. Langacker, *Phys. Reports* **72**, 185 (1981).
2. D.G. Lee, M.K. Parida, and M. Rani, *Phys. Rev.* D **51**, 229 (1995).
3. H. Murayama and A. Pierce, *Phys. Rev.* D **65**, 55009 (2002).
4. T. Goto and T. Nihei, *Phys. Rev.* D **59**, 115009 (1999).
5. V. Lucas and S. Ruby, *Phys. Rev.* D **55**, 6986 (1997).
6. Y. Fukuda *et al. Nucl. Instrum. Methods* A **501**, 418 (2003).
7. M. Shiozawa *et al. Phys. Rev. Lett.* **81**, 3319 (1998).
8. K. Kobayashi *et al. Phys. Rev.* D **72**, 052007 (2005).
9. Y. Hayato *Nucl. Phys. Proc. Suppl.* **112**, 171 (2002).
10. M. Honda *et al. Phys. Rev.* D **75**, 043006 (2007).
11. R.M. Barnett *et al. Phys. Rev.* D **54**, 375 (1996).
12. H. Ejiri *Phys. Rev.* C **48**, 1442 (1993).