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Search for Nucleon Decay in Super-Kamiokande

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Abstract

Nucleon decay search is one of key for opening a door to Grand Unified Theories (GUTs). A favored proton decay mode by GUTs based on SU(5) symmetry is $p \to e^+\pi^0$. On the other hand, SUSY moderated GUTs prefer $p \to \nu K^+$. The Super-Kamiokande, a large water cherenkov detector, has been running more than 10 years and it is suitable for the nucleon decay search. In this paper, the latest results of nucleon decay searches in Super-Kamiokande are summarized.

Keywords:
Grand Unified theories, Nucleon Decay

1. INTRODUCTION

The standard model of elementary particle physics, based on $SU(3)$ for the strong interaction and the unification of $SU(2) \times U(1)$ for the electroweak interaction, has been successful in accounting for many experimental results. However, the standard model offers no guidance on the unification of the strong and electroweak forces, and has several other open questions. Various attempts have been made to resolve the shortcomings by unifying the strong and electroweak interactions in a single larger gauge group, i.e. a Grand Unified Theory (GUT) [1]. GUTs are motivated by the apparent convergence of the running couplings of the strong, weak, and electromagnetic forces at a high energy scale (10^{15} – 10^{16} GeV). Energy scales this large are out of the reach of accelerators but may be probed by virtual processes such as those that govern particle decay. A general feature of GUTs is the instability of nucleons by baryon number violating decay. Therefore nucleon decay experiments are direct experimental tests of the general idea of grand unification.

In GUTs, nucleon decay can proceed via exchange of a massive gauge boson between two quarks. The favored gauge-mediated decay mode in many GUTs is $p \to e^+\pi^0$. GUT models incorporating supersymmetry [2] (SUSY-GUTs) raise the GUT scale [3], suppressing the decay rate of $p \to e^+\pi^0$, thereby allowing compatibility with the experimental limit. However, SUSY-GUTs introduce dimension five operators that enable the mode $p \to \bar{\nu}K^+$ to have a high branching fraction and short partial lifetime [4].

This report describes results of search for two major proton decay modes, $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$, by using 260 kiloton · year data of Super-Kamiokande. In addition, new decay modes which changes $|\Delta(B-L)|$ by two have been studied recently. They are described in the later part of this report.

2. SUPER-KAMIOKANDE

Super-Kamiokande [5] is a large water Cherenkov detector. It is an upright cylinder in shape, 39 m in diameter and 40 m in height, and it contains 50 kton of pure water. It lies about 1,000 m underneath the top of Mt. Ikenoyama (2,700 m water equivalent underground) to reduce cosmic ray background. The detector is optically separated into two regions: inner detector (ID) and outer detector (OD). Cherenkov light in the ID is detected by 20-inch PMTs [6] facing inward, evenly covering the cylindrical inner surface. Cherenkov light from penetrating particles, usually cosmic ray muons

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	Live days	kton·yr	Coverage
SK-I	1489.2	91.7	40%
SK-II	798.6	49.2	19%
SK-III	518.1	31.9	40%
SK-IV	1417.4	87.3	40%

Table 1: Summary of data sets that are used in this paper. Note that the photo coverage in SK-II was almost a half of the other periods. In SK-IV (current run), new electronics read out have been installed and it contributes for improving Michel electron tagging.

or exiting muons, is detected by 8-inch PMTs facing outward. The fiducial volume is defined as a cylindrical volume with surfaces 2 meters inwards from the ID PMT plane. The fiducial mass is 22.5 ktons, corresponding to 7.5×10^{33} protons.

Super-Kamiokande started observation in April 1996 with 11,146 PMTs which covered 40% of the ID surface. The observation was continued until July 2001, with 1489.2 live days, or equivalently, 91.7 kton·years. This period is called Super-Kamiokande-I (SK-I). After an accident in 2001, about half of the ID PMTs were lost and the detector was reconstructed with 5,182 ID PMTs uniformly distributed over the cylindrical surface decreasing photo coverage to 19%. The PMTs were thereafter enclosed in acrylic and FRP cases. The period from December 2002 until October 2005, corresponding to 798.6 live days (49.2 kton·years), is called SK-II. After production and installation of replacement 20-inch PMTs, the photo coverage was recovered to 40% in 2006. The period between July 2006 and September 2008, corresponding to 518.1 live days (31.9 kton·years), is defined as SK-III. In the summer of 2008, we upgraded our electronics with improved performance including a data acquisition that records all PMT hit information without dead time [7]. This has been the configuration of the detector since September 2008; it is called SK-IV. In this paper, we use data until February 2013, corresponding to 1417.4 live days (87.3 kton·years). Table 1 summarizes the data sets used for the proton decay search in this paper.

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

The proton decay mode in which a proton decays into a positron and a neutral pion is regarded as a dominant mode in several GUT models. The neutral pion decays into two gammas immediately thus all particles can be detectable by a water Cherenkov detector such as SK, that means, the proton mass and momentum can be reconstructed from detected Cherenkov rings. The following cuts are applied to data and MC; (A-1) the events are fully contained in the fiducial volume which is defined as inward from 2 meter from the detector wall (FCFV), (A-2) 2 or 3 rings and all rings shoule be electron like, (A-3) there are no Michel electrons, (A-4) reconstructed π^0 mass should be $85 < M_{\pi^0} < 185$ MeV/c^2 for 3 ring events, (A-5) reconstructed total mass should be $800 < M_{total} < 1050$ MeV/c^2 and reconstructed total momentum should be less than 250 MeV/c. In cut (A-2), events include two Cherenkov rings are allowed because if two γ rays from π^0 decay are emitted to similar direction, or one of them has small momentum, one γ may be failed to detect. Figure 1 shows reconstructed total invariant mass distribution merging from SK-I to SK-IV after cuts from (A-1) to(A-4) and total momentum cut. The data and atmospheric ν MC are in good agreement and no data observed in 260 kiloton·year data. Table 2 shows selection efficiencies estimated by signal MC, expected number of atmospheric ν backgrounds, and observed events for each periods. If proton decay happens but neutral pion interacts in nucleus (absorption, scattering, or charge exchange), proton mass and momentum can not be reconstructed correctly. That causes dominant inefficiency and also systematic uncertainty (15% among 19% in total systematic error). However, a water molecule has two free protons and they are free from such pion interactions. This is one of reason that a water cherenkov detector has high efficiency for this mode. 0.7 events of atmospheric ν background are expected in 260 kiloton·year exposure, on the other hand, there are no observed events. From those results, a lower limit of lifetime for $p \to e^+\pi^0$ is set as 1.4×10^{34} years.

	Eff(%)	BKG(events)	Obs(events)
SK-I	39.2	0.27	0
SK-II	38.5	0.15	0
SK-III	40.1	0.07	0
SK-IV	39.5	0.22	0

Table 2: Summary of efficiencies, expected numbers of background, and observed events in data.

4. $p \to \nu K^+$

If a proton decays into ν and K^+, momentum of K^+ is below Cherenkov threshold, and stops in water and decays into $\mu^+ + \nu_\mu$ or $\pi^+ + \pi^0$ with monochromatic mo-

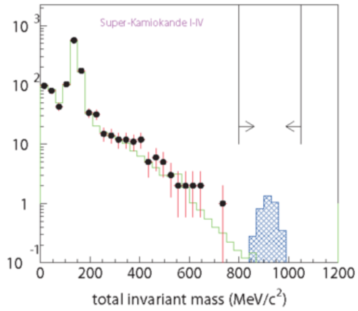

Figure 1: Reconstructed total invariant mass distributions after all other cuts. Black dots show data, green histogram is atmospheric ν MC, and blue hatched histogram corresponds to signal MC, respectively. Peak below 200 MeV/c^2 is made by π^0 events with two rings which are survived after cut (A-2).

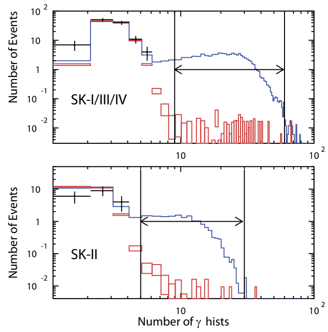

Figure 2: Number of γ ray hit distributions. The upper figure shows sum of SK-I, III, and IV which have 40% photo coverage, the lower figure corresponds to SK-II with 19% photo coverage. Bars, squares, and histogram correspond to data, atmospheric ν MC normalized to livetime of data, and proton decay MC with arbitrary normalization, respectively. The signal regions are indicated by arrows. The peaks at small numbers of hits are due to dark hits of the PMTs.

mentum in most of case. Thus, decay products from K^+ with 12 nsec lifetime are used for tagging this proton decay mode. In addition, after proton decay, gamma rays could be emitted due to deexcitation of the remaining nucleus, in which dominant energy is 6 MeV. This gamma ray acts as a prompt signal and the atmospheric ν background can be largely reduced if it is tagged. To detect $p \to \nu K^+$, three methods are applied; (a) tag muon with 236 MeV/c with prompt gamma ray, (b) fit μ momentum distribution of data with signal and background MC, (3) tag π^0 with 206 MeV/c. For method (a) and (b), FCFV events with single ring μ-like with one Michel electron are selected. To tag prompt gamma ray, a sliding time window with 12 nsec width is used to find hit cluster before μ signal. Figure 2 show number of PMT hits in the window after all cuts except itself. Ther are no candidate observed.

In method (c), stopped K^+ which decays into $\pi^+ + \pi^0$ is the target, but momentum of π^+ is close to Cherenkov threshold and it doesn't make clear ring. Thus we search for π^0 with 206 MeV/c in momentum, and PMT hit cluster in the backward of π^0 direction. Detailed selection for $p \to \nu K^+$ can be found in Ref. [8]. Table 3 summarizes efficiencies, expected backgrounds, and observed events for method (a) and (c). No candidates have been observed for method (a) and (c) in 260 kton·years data. Selection efficiencies in SK-IV are higher than the other periods because the new electronics introduced in SK-IV contributes to increase Michel electron finding efficiency which is used in the selection in (a) and (c). Figure 3 shows momentum distribution for FCFV single ring sample in data, atmospheric ν MC, and signal MC. There are no excess in the signal region. Combining these three methods, the lifetime limit for $p \to \nu K^+$ is obtained as 5.9×10^{33} years.

5. $|\Delta(B-L)|$=2 mode

In the previous section, search for $p \to e^+\pi^0$ and $p \to \nu K^+$, which are regarded as dominant mode in non-SUSY and SUSY SU(5), are described and those events have not been observed yet. There is reinvigorated interest in other approaches and possible signatures. A popular scenario may be found in a left-right symmetric partial unification of Pati and Salam[9] and its embedding into SO(10), providing natural right-handed neutrino candidate and unifying quarks and leptons. In the scheme of Ref. [10], trilepton modes such as $p \to e^+\nu\nu$ and $p \to \mu^+\nu\nu$ could become significant. Violating

		SK-I	SK-II	SK-III	SK-IV
Exp.(kt·yrs)		91.7	49.2	31.9	87.3
Prompt γ	Eff.(%)	7.9	6.3	7.7	9.1
	BKG	0.08	0.14	0.03	0.13
	OBS	0	0	0	0
$\pi^+\pi^0$	Eff.(%)	7.8	6.7	7.9	10.0
	BKG	0.18	0.17	0.09	0.18
	OBS	0	0	0	0

Table 3: Summary of the proton decay search with selection efficiencies and expected backgrounds for each detector period.

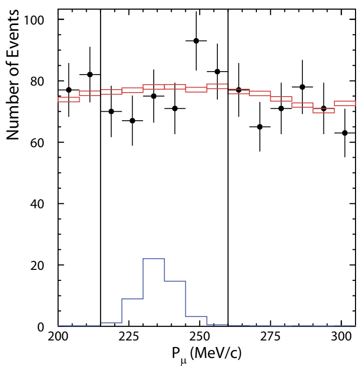

Figure 3: Muon momentum distribution for 260 kton·year. Dots, boxes, and histogram correspond to data, atmospheric ν MC, and proton decay MC, respectively. The data are fit by the background plus signal by free normalization. No excess above the expected background is observed. The normalization of the proton decay MC histogram shown is at the upper limit allowed by the fit.

baryon and lepton number by two units $|\Delta(B-L)|$=2, unusual for standard decay channels, may lead to favorable implications for baryogenesis[11]. Because of three body decays, charged leptons have broad momentum distributions with 313 MeV/c in mean value. If $p \to e^+\nu\nu$ and $p \to \mu^+\nu\nu$ happen, we may see excess in momentum distribution of single ring e-like and mu-like events which are produced by atmospheric neutrino interactions, mostly (~80%) come from charged current quasi-elastic interactions. Thus momentum distributions of data are fitted by distributions made by signal MC and background MC with systematic errors. Details of analysis can be found in Ref. [12]. Figure 4 and Figure 5 show momentum distributions of data, signal MC, and atmospheric neutrino background MC. In both figures, data agree with atmospheric neutrino MC and no excess due to proton decay have not been observed in 273.4 kton·year exposure. Lower limits of proton lifetime are obtained from the fitting, $1.7{\times}10^{32}$ years for $p \to e^+\nu\nu$, and $2.2{\times}10^{32}$ years for $p \to \mu^+\nu\nu$. These limits are one order longer than the previous limits.

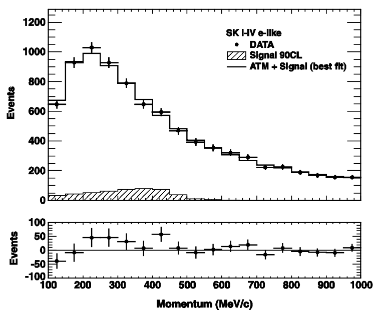

Figure 4: Upper figure shows momentum distribution of FC single ring e-like events in data (dots), atmospheric ν MC (solid line), and proton decay MC (hatched histogram). Lower figure is residuals from data after background subtraction.

If two nucleons decays simultaneously, it also changes $|\Delta(B-L)|$ by two. Recently $pp \to \pi^+\pi^+$, $pn \to \pi^+\pi^0$, and $nn \to \pi^0\pi^0$ are investigating. Charged πs are included in the final state particles of $pp \to \pi^+\pi^+$ and $pn \to \pi^+\pi^0$ and their momentum are difficult to reconstruct in water cherenkov detector due to hadron interactions. Several kinematic variables are input to boosted decision tree method to separate signal and background. In $nn \to \pi^0\pi^0$ mode, signal can be tagged by total invariant mass and total momentum. As preliminary results, lower limits for $pp \to \pi^+\pi^+$, $pn \to \pi^+\pi^0$, and $nn \to \pi^0\pi^0$ are obtained as 7.3×10^{31}, 1.8×10^{32}, and 4.1×10^{32} years, respectively.

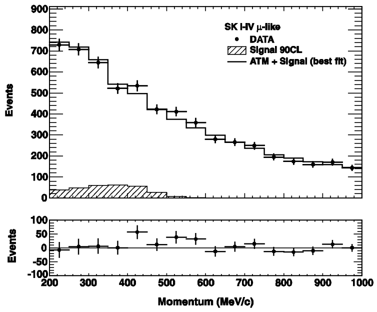

Figure 5: Upper figure shows momentum distribution of FC single ring mu-like events in data (dots), atmospheric ν MC (solid line), and proton decay MC (hatched histogram). Lower figure is residuals from data after background subtraction.

6. SUMMARY

Super-Kamiokande has been search for nucleon decay but no evidences has been observed so far. Figure 6 shows nucleon lifetime limits of modes which have been investigated by Super-Kamiokande detector. The lower lifetime of $p \to e^+\pi^0$ and $p \to \nu K^+$ are obtained as 1.4×10^{34} and 5.9×10^{33} years, respectively, and simple GUTs models have been rejected. Some of exotic modes which changes $|\Delta(B-L)|$ by two are studied recently, and lifetime limits for those modes are improved by one order longer than the previous limits.

7. Acknowledgments

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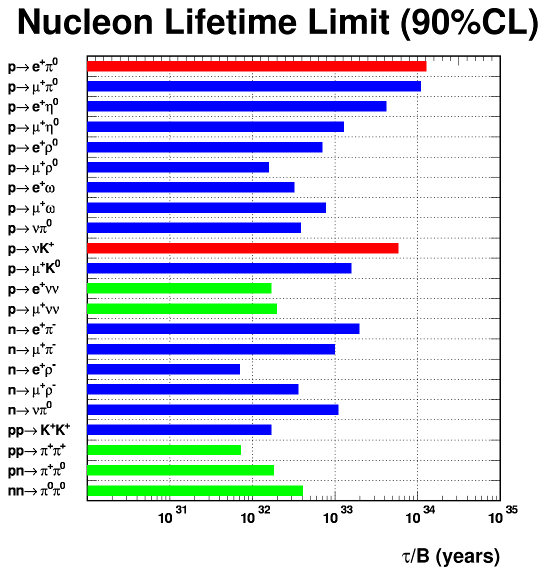

Figure 6: Summary of lifetime limits obtained by Super-Kamiokande.

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