Search for Nucleon Decay into Charged Antilepton plus Meson in Super-Kamiokande

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Abstract. **Nucleon decays into a charged anti-lepton (e or μ) plus a light meson (π^0, π^-, η, ρ^0, ρ^-, ω) were searched for using the Super-Kamiokande I and II data. Twelve nucleon decay modes were analyzed in this search. The total exposure is 140.9 kiloton·year, which is the largest exposure for a nucleon decay search experiment. We did not observe statistically significant evidence for the nucleon decay. The lower limits of nucleon partial lifetime at 90% confidence level were obtained. The lower limit of the lifetime for the $p \to e^+\pi^0$ mode is set to be 8.2×10^{33} years, which is 5 times longer than the current best limit. For the other modes, their lifetime limits range from 3.6×10^{31} to 6.6×10^{33} years depending on the decay modes. The more stringent limits than the current best limits are set for ten modes in the twelve searched modes.**

Keywords**: GUT, Nucleon Decay, Super-Kamiokande**

I. INTRODUCTION

The standard model in particle physics has been successful in accounting for many experimental results. However, the standard model has a lot of unanswered questions. There are a lot of free empirical parameters, such as coupling constants, mixing angles and so on. Various attempts have been made to resolve the short-comings by unifying the electroweak and the strong interactions in the context of Grand Unified Theory (GUT).

The simplest GUT is the minimal SU(5) model proposed by Gerogi and Glashow [1] in 1974. As a consequence of the SU(5) GUT model, there will be new interactions in which leptons and quarks can transform one into the other. This interaction can lead to the baryon number violation, such as nucleon decay. Two quarks in a proton can transform into a lepton and an anti-quark resulting in a lepton plus meson final state. Thus, a nucleon decay signal detection can be a direct evidence for the GUT.

Although the minimal SU(5) GUT is ruled out by past nucleon decay experiments, such as the KAMIOKANDE [2] and IMB [3] experiments, there are still many surviving models, such as SO(10) GUT, supersymmetric GUT and so on.

The Super-Kamiokande experiment published the result for nucleon decays via an anti-lepton plus a meson mode only in the most dominant mode, $p \to e^+\pi^0$ [4]. However, the other nucleon modes can have considerable branching ratios depending on GUT models. Thus, first systematical studies for nucleon decays are performed. Table I shows the summary of searched nucleon decay modes. The nucleon decay search results in 12 nucleon decay modes are presented.

$N \to$	lepton	meson	meson decay mode	(Br.)
$p \to$	e^+ (μ^+)	π^0	$\pi^0 \to 2\gamma$	(98.8%)
$p \to$	e^+ (μ^+)	η	$\eta \to 2\gamma$	(39.3%)
			$\eta \to 3\pi^0$	(32.6%)
$p \to$	e^+ (μ^+)	ρ^0	$\rho^0 \to \pi^+\pi^-$	(∼100%)
$p \to$	e^+ (μ^+)	ω	$\omega \to \pi^0\gamma$	(8.9%)
			$\omega \to \pi^+\pi^-\pi^0$	(89.2%)
$n \to$	e^+ (μ^+)	π^-		
$n \to$	e^+ (μ^+)	ρ^-	$\rho^- \to \pi^-\pi^0$	(∼100%)

TABLE I
SEARCHED NUCLEON DECAY MODES IN THIS PRESENTATION. BRANCHING RATIOS FOR MESON DECAYS ARE ALSO SHOWN.

II. SUPER-KAMIOKANDE EXPERIMENT

The Super-Kamiokande experiment (SK) is a large water Cherenkov detector located in the Kamioka mine, under $\sim$ 1000m rock overburden. The Super-Kamiokande experiment started data taking in April, 1996 and had continued observation for five years until the detector maintenance in July 2001. This period is referred to SK-I. On November 2001, an accident which destroyed more than half of photomultiplier tubes (PMTs) occurred. After the partial reconstruction, Observation began again in October 2002 and stopped in October 2005 for a full detector reconstruction. This latter period is referred to as SK-II. The nucleon decay search results in these tow periods of SK-I and SK-II are shown here.

The Super-Kamiokande detector is made of a cylindrical stainless steel tank, of which the size is 39.3m in diameter and 41.4m in height. The detector is optically separated into two regions, which are called the inner detector (ID) and the outer detector (OD). On the surface of the ID, 11,146 inward-facing 20-inch PMTs were uniformly attached and covered 40% of the surface. The OD is used to reject cosmic ray muon events and to tag outgoing charged particles.

We used data from a 91.7 kton·year exposure of 1489 live days during SK-I and a 49.2 kton·year exposure of 798 live days during SK-II. About 10^6 event were accumulated every day. Most of those events are cosmic ray muon events or low energy background events from radioactivities from materials around the detector wall.

Several stages of data reduction were applied in order to remove them. In SK-I and SK-II, 12232 and 6584 events were obtained after the reduction. The efficiency for proton decay $p \rightarrow e^+\pi^0$ events was estimated to be greater than 99% for this reduction.

III. NUCLEON DECAY SEARCH IN SUPER-KAMIOKANDE

A. Selection Criteria

After the event reduction described in the previous section, atmospheric neutrino events and nucleon decay events survive in the data. Thus, we have to eliminate atmospheric neutrino backgrounds and extract only nucleon decay signals by the event selection criteria described below.

In order to study many nucleon decay modes systematically, the criteria were chosen to be as simple and common as possible. The primary policy for the criteria was not to optimize it for the best sensitivity lifetime limits, but to obtain a low enough background level. Basically, the following reconstructed informations were used in the criteria,

A) the number of Cherenkov rings,
B) particle type of each ring,
C) the meson invariant mass (if it is possible to be reconstructed),
D) the number of Michel electrons,
E) the total invariant mass and the total momentum (if it is possible to be reconstructed).

The total momentum P_{tot}, the total energy E_{tot} and the total invariant mass M_{tot} are defined as ;

$$P_{\text{tot}} = \left| \sum_i^{\text{all}} \vec{p_i} \right|, \quad (1)$$

$$E_{\text{tot}} = \sum_i^{\text{all}} \sqrt{|\vec{p_i}|^2 + m_i^2}, \quad (2)$$

$$M_{\text{tot}} = \sqrt{E_{\text{tot}}^2 - P_{\text{tot}}^2}, \quad (3)$$

where $\vec{p_i}$ is the momentum of each ring, m_i is the mass of a particle (γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$).

Figure 1 shows the total invariant mass distributions in SK-I and SK-II. The invariant mass is well reconstructed both in SK-I and SK-II. Although our particle identification algorithm can only classify a Cherenkov ring into a shower type ring ($e^{\pm}$ or γ) or a non-shower type ring ($\mu^{\pm}$ or $\pm^{\pm}$), the invariant mass reconstruction required to distinguish $e^{\pm}$ from γ or $\mu^{\pm}$ from $\pi^{\pm}$ in several modes. In those cases, the invariant mass was calculated for all the possible combinations of particle type assignment. Then, the best combination in which a reconstructed mass is closest to a true mass is selected.

All the searched nucleon decay modes are two body decays with back-to-back kinematics, and have isotropic event signatures, which is the most significant difference from the typical atmospheric neutrino events. Therefore, the selection by the total momentum and the total invariant mass is a powerful tool to eliminate the atmospheric neutrino background. The threshold of the total momentum is normally set to be 250 MeV/c considering the Fermi motion of bound nucleons. In order to keep background rates low enough, the tighter total momentum cut with the threshold of 150 (200) MeV/c is applied in several relatively high background mode searches.

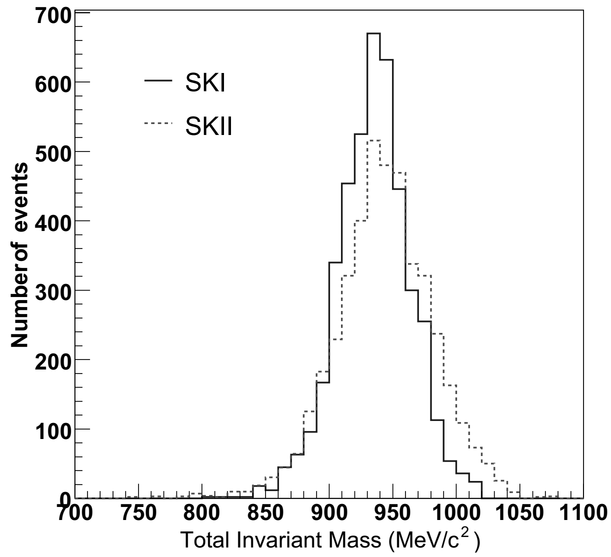

Fig. 1. Total invariant mass distributions of the $p \rightarrow e^+\pi^0$ mode MC in SK-I and SK-II. Only the free proton decay events are filled.

The details of the event selection criteria are described in another document [5].

B. Estimated Signal Detection Efficiency and Background Rate

Detection efficiencies for nucleon decay signals and background rates for atmospheric neutrino signals were estimated using their MC simulations. Figure 2 shows the total momentum and total invariant mass distributions for the proton decay $p \rightarrow e^+\pi^0$ MC and the atmospheric neutrino MC. Characteristics of each signals can be seen by comparing these two distributions.

Table II summarizes signal detection efficiencies and background rates for each mode in SK-I and SK-II.

The detection efficiency for the dominant mode $p \rightarrow e^+\pi^0$ were estimated to be 44.6% and 43.5% in SK-I and SK-II, respectivelly. The detection efficiency in SK-II is comparable to that in SK-I for this mode. The background events for the mode was estimated to be 0.31 events in SK-I+SK-II. Pure $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation was considered in these estimations. For free proton decay events, high detection efficiency was achieved and estimated to be 87%.

The dominant reason for inefficiency for the $p \rightarrow e^+\pi^0$ search is the interactions of π^0 in a nucleus in the case of a nucleon decay in a Oxygen nucleus (nuclear effect). In our nuclear effect simulation, 37% of π^0s produced by a proton decay were abosorbed

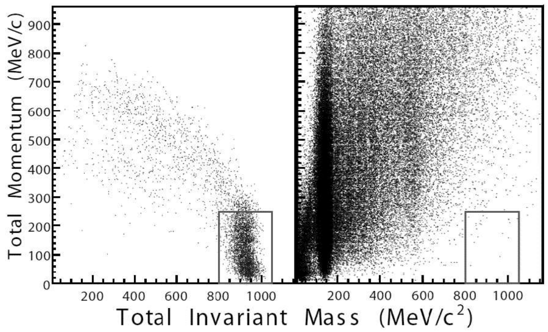

Fig. 2. Total momentum and total invariant mass distributions for the proton decay $p \rightarrow e^+\pi^0$ MC (left) and the atmospheric neutrino MC (right) in SK-I. The boxes in the figures indicate the signal region for $p \rightarrow e^+\pi^0$.

or charge-exchanged. Those events hardly survived the event selection criteria.

The detection efficiencies of the other modes estimated to be lower than that of $p \rightarrow e^+\pi^0$. Especially for the modes in which Cherenkov rings from charged pions are required to be found, the detection efficiencies were estimated to be very low. Since charged pions strongly interact with nucleon, and are scattered or absorbed in water, it is more difficult to find their Cherenkov rings than to find rings from electrons or muons.

	Eff.($\times$Br.)(%)		BG events	
	SK-I	SK-II	SK-I	SK-II
$p \rightarrow e^+\pi^0$	44.6	43.5	0.20	0.11
$p \rightarrow \mu^+\pi^0$	35.5	34.7	0.23	0.11
$p \rightarrow e^+\eta$				
$(\eta \rightarrow 2\gamma)$	18.8	18.2	0.19	0.09
$(\eta \rightarrow 3\pi^0)$	8.1	7.6	0.08	0.08
$p \rightarrow \mu^+\eta$				
$(\eta \rightarrow 2\gamma)$	12.4	11.7	0.03	0.01
$(\eta \rightarrow 3\pi^0)$	6.1	5.4	0.30	0.15
$p \rightarrow e^+\rho^0$	4.9	4.2	0.23	0.12
$p \rightarrow \mu^+\rho^0$	1.8	1.5	0.30	0.12
$p \rightarrow e^+\omega$				
$(\omega \rightarrow \pi^0\gamma)$	2.4	2.2	0.10	0.04
$(\omega \rightarrow \pi^+\pi^-\pi^0)$	2.5	2.3	0.26	0.13
$p \rightarrow \mu^+\omega$				
$(\omega \rightarrow \pi^0\gamma)$	2.8	2.8	0.24	0.07
$(\omega \rightarrow \pi^+\pi^-\pi^0)$	2.7	2.4	0.10	0.07
$n \rightarrow e^+\pi^-$	19.4	19.3	0.16	0.11
$n \rightarrow \mu^+\pi^-$	16.7	15.6	0.30	0.13
$n \rightarrow e^+\rho^-$	1.8	1.6	0.25	0.13
$n \rightarrow \mu^+\rho^-$	1.1	0.94	0.19	0.10

TABLE II
SUMMARY OF THE DETECTION EFFICIENCIES AND THE BACKGROUND RATES FOR NUCLEON DECAY SEARCHES.

C. Systematic Errors

The largest systematic error source is the uncertainty of meson interaction in a nucleus for many modes. For the $p \rightarrow e^+\pi^0$ mode, the systematic error from the meson interaction is estimated to be 15% for the detection efficiency. The uncertainty of the π^0 interaction in a nucleus was estimated by comparing the two different interaction models. The uncertainties of the η and ω interactions were estimated using the meson photoproduction cross section in a nucleus. They contribute approximately 20% for the detection efficiencies.

Total systematic uncertainties were estimated to be about 20$\sim$30% considering all the systematic error sources. For $N \rightarrow lepton^+\rho^-$, the uncertainties were estimated to be much larger and about 40$\sim$70%.

On the other hand, the systematic uncertainties on the background estimations were estimated to be relatively larger than those on the detection efficiencies and about 40$\sim$70%. The dominant error source for them is the uncertainty of hadron interactions in water.

D. Nucleon Decay Signal Search in SK-I and SK-II data

Nucleon decay signals were searched using the selection criteria described above. Figure 3 shows the total momentum and total invariant mass distributions of the observed data in SK-I and SK-II. Unfortunately, no candidate events were found in the data for $p \rightarrow e^+\pi^0$.

No significant nucleon decay signals were found in the other modes. In total, six candidates were found in the SK-I and SK-II data. The candidates were found in the five largest background modes. For example, two candidates were found for $p \rightarrow \mu^+\eta(\eta \rightarrow 3\pi^0)$ mode. Probability to observe these candidates from the backgrounds were calculated by Poisson statistics to be 7.5%. This probability is not so small that we cannot take these candidates as serious evidences for a nucleon decay. Moreover, the number of background events in total was 4.7 events. Therefore, the number of candidates is consistent with the estimation by the atmospheric neutrino MC. Figure 4 shows the total invariant mass distributions of the observed data and the atmospheric neutrino MC. The atmospheric neutrino MC reproduces the data well.

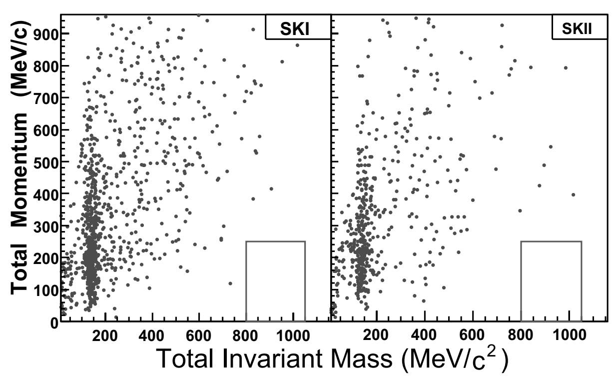

Fig. 3. Total invariant mass distributions of the observed data in SK-I(left) and SK-II(right). Events satisfying the selection criteria except for the total momentum and total invariant mass are filled in these figures. The boxes indicate the signal region for $p \rightarrow e^+\pi^0$.

IV. Lifetime Limits

As described in the previous section, the observed data in SK-I and SK-II are consistent with the atmospheric neutrino MC. Consequently, the lower limits of

	BG	Candidates
$p \to \mu^+\eta(\eta \to 3\pi^0)$	0.45	2
$p \to \mu^+\rho^0$	0.42	1
$p \to e^+\omega(\omega \to \pi^+\pi^-\pi^0)$	0.39	1
$n \to \mu^+\pi^-$	0.43	1
$n \to e^+\rho^-$	0.38	1
other 11 modes	2.6	0
Total	4.7	6

TABLE III
CANDIDATE EVENTS AND EXPECTED BACKGROUND EVENTS.

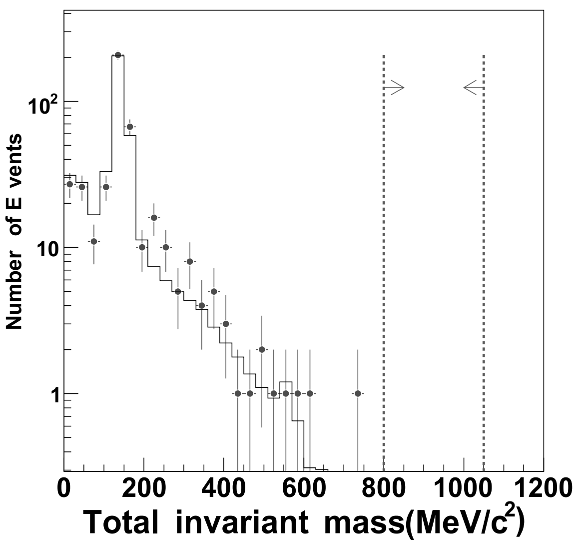

Fig. 4. The total invariant mass distribution in SK-I. The atmospheric neutrino MC and the observed data are shown in in the solid line and points with error bars, respectively. Events satisfying the event selection criteria except for the criteria for the total momentum and total invariant mass are filled in this figure.

the nucleon partial lifetime were calculated. They are derived from a method based on Bayes' theorem which incorporates systematic errors.

The nucleon partial lifetime limits at 90% confidence level were obtained as shown in Table IV. They are also shown in Figure 5 with the results of the past experiments. The lifetime limit for $p \to e^+\pi^0$ is $\tau/B_{p\to e^+\pi^0} > 8.2 \times 10^{33}$ years, which is the most stringent limit for this mode.

	τ/Br		τ/Br
$p \to e^+\pi^0$	8.2	$p \to \mu^+\pi^0$	6.6
$p \to e^+\eta$	4.2	$p \to \mu^+\eta$	1.3
$p \to e^+\rho^0$	0.71	$p \to \mu^+\rho^0$	0.16
$p \to e^+\omega$	0.32	$p \to \mu^+\omega$	0.78
$n \to e^+\pi^-$	2.0	$n \to \mu^+\pi^-$	1.0
$n \to e^+\rho^-$	0.070	$n \to \mu^+\rho^-$	0.036

TABLE IV
PARTIAL LIFETIME LIMIT FOR EACH NUCLEON DECAY MODE AT 90% C.L. LIFETIME LIMITS ARE SHOWN IN A UNIT OF 10^{33} YEARS.

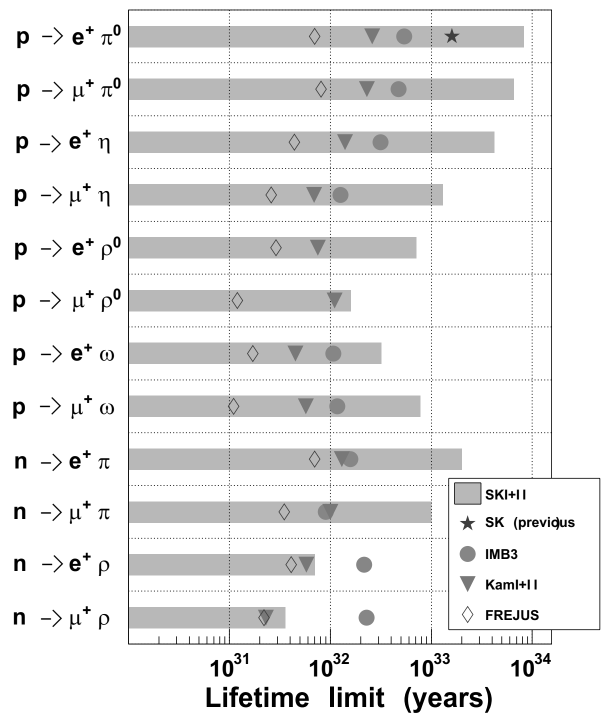

Fig. 5. Comparison of lifetime limits with the past experiments.

V. SUMMARY

Nucleon decays into a charged anti-lepton plus a light meson were searched in 91.7 and 49.2 kton·year exposures of the SK-I and SK-II data, respectively.

This is the first nucleon decay search results using the SK-II data. The observation in the SK-II period had the similar performance to that in the SK-I period even though the photo coverage is half of SK-I.

No evidence for a nucleon decay was found. Six candidate events were found in the SK-I and SK-II data, while the total expected background from the atmospheric neutrino was 4.7 events. The number and the feature of candidate events are consistent with the background estimation.

The nucleon partial lifetime limits were obtained for 12 decay modes. The lower limit on the partial lifetime via $p \to e^+\pi^0$ was set to be 8.2×10^{33} years at 90% confidence level. This limit is more stringent than than the past results. The obtained lower lifetime limits via the other modes except for $n \to lepton^+\rho^-$ are also more stringent than the previous limits by the IMB or KAMIOKANDE experiments. They range from 1.6×10^{32} to 6.6×10^{33} years.

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