Updated Results on Nucleon Decay Searches in Super–Kamiokande–I

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Abstract

Baryon number violated proton decays (or nucleon decays in general) have been extensively looked for in the Super–Kamiokande–I detector. Thanks to its huge detector size and excellent particle identification capability, we obtained the most stringent lower limit on nucleon partial lifetime for various decay modes. From the full Super–Kamiokande–I data (1489 days livetime or 91.6 kton·year exposure), the obtained experimental limit is 5.4×10^{33} years for $p \rightarrow e^+\pi^0$ mode and 2.2×10^{33} years for $p \rightarrow \bar{\nu}K^+$ mode at 90% confidence level.

1. Introduction

Most of Grand Unified Theories (GUTs) allow baryon number violated transitions between leptons and quarks and proton decay channels into lighter leptons and mesons become open. Therefore, the decay of the proton is one of the most dramatic predictions of various GUT models [4,6].

It has been noted that there are several indirect evidence of GUT such as the observed family-structure of elementary particles and the meeting of the three gauge couplings. Moreover, recent discovery of finite, small neutrino mass [2] also suggests the physics at the energy scale far beyond the standard model [7]. Proton decays would provide the window for viewing the new physics and it is important to push up the experimental sensitivity for this processes.

2. The Super–Kamiokande detector

Super–Kamiokande (SK) is a large water Cherenkov detector holding 50 ktons of ultra-pure water. Details of the detector can be found elsewhere [3]. The fiducial volume is 22.5 kiloton and total detector livetime for physics analysis is finally 1489 days corresponding to 91.6 kt·year exposure.

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3. Nucleon Decay searches

3.1. $p \to e^+\pi^0$ *mode*

This decay mode has a characteristic event signature, in which the electromagnetic shower caused by the positron is balanced against the two showers caused by the gamma rays from the decay of the π^0. This signature enables us to discriminate the signal events clearly from atmospheric neutrino background. To extract the $p \to e^+\pi^0$ signal from the event sample, these selection criteria are defined [9,10]: (A1) the number of rings is 2 or 3, (A2) all rings have a showering particle identification (PID), (A3) 85 MeV/c^2 $<$ π^0 invariant mass $<$ 185 MeV/c^2, (A4) no decay electron, (A5) 800 MeV/c^2 $<$ total invariant mass $<$ 1050 MeV/c^2 and total momentum $<$ 250 MeV/c. Criterion (A2) selects $e^\pm$ and γ. Criterion (A3) only applies to 3-ring events. Criterion (A5) checks that the total invariant mass and total momentum correspond to the mass and momentum of the source proton, respectively.

From $p \to e^+\pi^0$ Monte Carlo sample, detection efficiency is estimated as 40%. Expected number of backgrounds from atmospheric neutrino interactions is estimated from atmospheric neutrino Monte Carlo sample as 0.3 events. Finally, there is no candidate events found in data sample. From these results, the lower limit on partial lifetime of proton is obtained as 5.4×10^{33} years at 90% confidence level (CL).

3.2. $p \to \bar{\nu}K^+$ *mode*

The $p \to \bar{\nu}K^+$ mode is generally favored by GUT models implemented with supersymmetry [1,8,11]. Because produced K^+ is expected to have momentum below Cherenkov threshold, the K^+ is generally invisible in a water Cherenkov detector. Therefore, experimental searches are performed by looking for decay products of the K^+. There are two prominent decay channels of K^+; $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^0$ and three search methods for $p \to \bar{\nu}K^+$ have been developed [5].

In the first method, K^+ decays into μ^+ are looked for. The μ^+ is expected to have monochromatic momentum of 236 MeV/c. Selection criteria for this decay mode are defined as: (B1) the number of rings is one, (B2) the ring has a nonshowering PID, (B3) one decay electron, (B4) 215 MeV/c $<$ muon momentum $<$ 260 MeV/c, (B5) the ring is not proton Because we found no significant excess in the signal region, we applied spectrum fitting to obtain upper limit of signal events. From this analysis, we obtained the partial lifetime limit for $p \to \bar{\nu}K^+$ decay mode as 4.2×10^{32} years at 90% CL.

In the second method, additional criterion is required to eliminate the remaining backgrounds. This criterion requires nuclear deexcitation γ from the residual ^{15}N nucleus. We expect the γ to be observed proceeding to the K^+ decay with the time difference corresponding to the K^+ lifetime ($\tau_{K^+} = 12$ nsec). By this criterion along with criteria (B1–B5), expected number of backgrounds is reduced to 0.7 events while detection efficiency including the kaon decay branching ratio is 8.6%. Candidate events are looked for in the data sample but no candidate is found. Obtained partial lifetime from this method is 11.4×10^{32} years at 90% CL.

In the third method, K^+ decays into two pions are used. Selection criteria for this method are: (C1) the number of rings is 2, (C2) all rings have a showering PID, (C3) 85 MeV/c^2 < π^0 invariant mass < 185 MeV/c^2, (C4) 175 MeV/c < π^0 momentum < 250 MeV/c, (C5) 40 p.e.s < photo electrons emitted by π^+ < 100 p.e.s, (C6) residual charge < 70 p.e.s (C7) one decay electron. The criteria (C1–C4) select desired π^0 and the criteria (C5–C7) are defined for produced π^+. Detection efficiency including the kaon branching ratio is 6.0% and expected number of backgrounds is 0.6. Again, there is no candidate remaining after these criteria and partial lifetime limit is 7.9×10^{32} years at 90% CL. In summary, we cannot find any candidate events for $p \to \bar{\nu} K^+$ decay mode in three methods. Combined lifetime limit from the three methods is obtained as 2.2×10^{33} years at 90% CL.

3.3. Other Decay modes

We have also performed searches for nucleon decays to other combinations of a lepton and a meson: $\mu^+ + \pi^0$, $e^+ + \eta$, $\mu^+ + \eta$, $\nu + \eta$, $e^+ + \rho$, $e^+ + \omega$, and $e^+ + \eta$. Other kaon modes have been also looked for: proton decays to $e^+ + K^0$ and $\mu^+ + K^0$, and neutron decays to $\nu + K^0$. In all searches, we have found no significant excess of signals. Obtained nucleon lifetime limits are summarized in Fugure 1.

4. Summary

In this article, proton decay searches via various decay modes are presented. The obtained experimental limit from full SK–I data is 5.4×10^{33} years for $p \to e^+\pi^0$ mode and 2.2×10^{33} years for $p \to \bar{\nu} K^+$ mode at 90% CL. Figure 1 shows obtained lifetime limits for these decay modes from SK, IMB3, Kamiokande, and Soudan2. In conclusion, there is no evidence for nucleon decays so far. However it should be noticed that the background level in SK is still low in many decay modes and we can expect further improvements beyond the current experimental limits by increasing statistics. We need to keep watching nucleons to open new physics beyond the standard model.

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mode	exposure (ktï yr)	εB_m (%)	observed event	B.G.	
$p \to e^+ + \pi^0$	92	40	0	0.2	54
$p \to \mu^+ + \pi^0$	92	32	0	0.2	43
$p \to e^+ + \eta$	92	17	0	0.2	23
$p \to \mu^+ + \eta$	92	9	0	0.2	13
$n \to \bar{\nu} + \eta$	45	21	5	9	5.6
$p \to e^+ + \rho$	92	4.2	0	0.4	5.6
$p \to e^+ + \omega$	92	2.9	0	0.5	3.8
$p \to e^+ + \gamma$	92	73	0	0.1	98
$p \to \mu^+ + \gamma$	92	61	0	0.2	82
$p \to \bar{\nu} + K^+$	92				22
$K^+ \to \nu\mu^+$ (spectrum)		34	--	--	4.2
prompt $\gamma + \mu^+$		8.6	0	0.7	11
$K^+ \to \pi^+\pi^0$		6.0	0	0.6	7.9
$n \to \bar{\nu} + K^0$	92				2.0
$K^0 \to \pi^0\pi^0$		6.9	14	19.2	3.0
$K^0 \to \pi^+\pi^-$		5.5	20	11.2	0.8
$p \to e^+ + K^0$	92				10.7
$K^0 \to \pi^0\pi^0$		9.2	1	1.1	8.7
$K^0 \to \pi^+\pi^-$					
2-ring		7.9	5	3.6	4.0
3-ring		1.3	0	0.1	1.7
$p \to \mu^+ + K^0$	92				13.9
$K^0 \to \pi^0\pi^0$		5.4	0	0.4	7.1
$K^0 \to \pi^+\pi^-$					
2-ring		7.0	3	3.2	4.9
3-ring		2.8	0	0.3	3.7

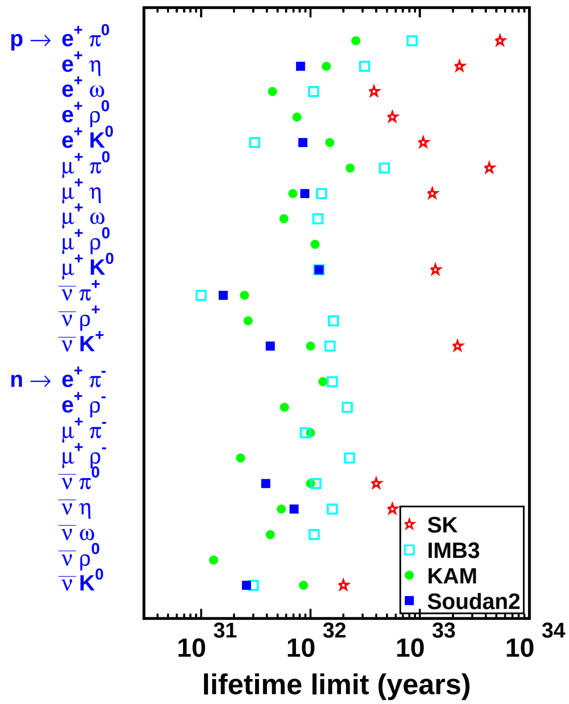

Fig. 1. The obtained lifetime limit of nucleons from SK–I (left figure) and their comparisons with other experiments (right figure).

6. References

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