Proton Decay Search Sensitivity with the Enlarged Fiducial Mass of Super-Kamiokande

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Abstract. We have studied enlarging the fiducial mass of the Super-Kamiokande detector from 22.5 kton to 27.2 kton to improve the proton decay search sensitivity. For the \( p \rightarrow e^+\pi^0 \) \((\mu^+\pi^0)\) decay mode, the estimated efficiency and the expected number of atmospheric neutrino background events in the enlarged region (78 kton-years) are 25.8% (25.2%) and 0.10 (0.20), respectively while in the conventional region (372 kton-years) they are 39.8% (36.3%) and 0.49 (0.74). As a result, enlarging the fiducial mass increases the proton decay search sensitivity by 12%.

1. Introduction - Proton Decay

The standard model of particle physics has succeeded in predicting almost all experimental results, however it still leaves important questions about the universe and it is believed that a new physics paradigm beyond the standard model exists.

Electric charge quantization and the convergence of the running coupling constants of electronic, weak and strong interactions in the super high energy scale motivate the Grand Unified Theory [1]. In the Grand Unified Theory, quarks and leptons are incorporated into the same multiplet and proton decay, which is a direct transition between quarks and leptons, is predicted. In particular, the \( p \rightarrow e^+\pi^0 \) and \( \mu^+\pi^0 \) decay modes have great potential because they are commonly predicted in many theories and because of their unique event topologies, signal and atmospheric neutrino background events can be clearly discriminated experimentally. Super-Kamiokande has not yet observed any evidence of proton decay and set the world’s most stringent limits on the proton lifetime [2].

2. Super-Kamiokande Detector

Super-Kamiokande (SK) is the world largest underground water Cherenkov detector [3]. It is an upright cylinder in shape, about 40 m in diameter and height and contains a total of 50 kton of water. It is optically separated into two regions, an inner detector (ID) and an outer detector (OD). Water Cherenkov light emitted from charged particles in the ID is detected by 20-inch photomultiplier tubes mounted on the ID wall facing inwards. The OD is used for external background rejection, composed of 8-inch photomultiplier tubes facing outwards and reflective Tyvek to collect light more efficiently. For the proton decay search analysis, fully contained (FC) events are used. FC events have a reconstructed vertex in the ID without a cluster of hits.
in the OD. In the conventional analysis [2], the defined fiducial mass region is located more than 2 m from the ID wall (called “dwall 2 m cut”) and corresponds to 22.5 kton of water.

3. Enlarging the Fiducial Mass
Since detector exposure is crucial to improving the proton decay search sensitivity, following studies on enlarging the fiducial mass from 22.5 kton to 27.2 kton (dwall 1 m cut) have been conducted. Since more external background events were found in the enlarged region than in the conventional region, new event selection algorithms have been developed to keep the non-neutrino external background contamination rate within a tolerable (~1% w.r.t neutrino and proton decay candidate) level in the enlarged region.

For events occurring in the enlarged region, event reconstruction performance is worse because the number of PMT hits is fewer and secondary particles are more likely to reach the ID wall with non-negligible momentum. To improve this, reconstruction algorithms also have been re-tuned especially in particle identification performance.

4. Proton Decay Search Selection Criteria and Performance

The proton decay $p \rightarrow e^+\pi^0$ and $\mu^+\pi^0$ modes search event selection criteria are as follows:

**Cut-1** Events must be identified as FC events with the vertex position within fiducial mass region.

**Cut-2** Events must have 2 or 3 reconstructed Cherenkov rings.

**Cut-3** All rings must be reconstructed as a shower-like ring for $p \rightarrow e^+\pi^0$ and one ring must be a non shower-like ring for $p \rightarrow \mu^+\pi^0$.

**Cut-4** There must be no tagged Michel electrons for $p \rightarrow e^+\pi^0$ and one for $p \rightarrow \mu^+\pi^0$.

**Cut-5** Reconstructed $\pi^0$ mass must be $85 < M_{\pi^0} < 185$ MeV/c$^2$.

**Cut-6** Reconstructed total mass must be $800 < M_{\text{tot}} < 1050$ MeV/c$^2$.

**Cut-7** Reconstructed total momentum must be $P_{\text{tot}} < 250$ MeV/c.

**Cut-8** There must be no tagged neutrons for SK-IV (2008 ~ 2018) data.

The signal efficiencies and the expected number of atmospheric neutrino background events for both the conventional region and the enlarged region are estimated by applying the same selection cuts to the signal and atmospheric neutrino MC samples. Their values at each event selection step are shown in Figure 1. The expected number of atmospheric neutrino background events is normalized by the SK livetime and the latest oscillation fit result [4]. The signal efficiencies in the enlarged region have been improved by ~20% by improving event reconstruction algorithms but because of fewer PMT hits and escaping particles from the ID, efficiencies are still lower than in the conventional region especially in the cut steps 3 and 6 for $p \rightarrow e^+\pi^0$ and in the cut steps 3 and 4 for $p \rightarrow \mu^+\pi^0$.

To further improve the search sensitivity, the signal region is further divided into the lower total momentum region ($P_{\text{tot}} < 100$ MeV/c) and the higher total momentum momentum region ($100 \leq P_{\text{tot}} < 250$ MeV/c). The final signal efficiencies and the expected number of atmospheric neutrino background events in each region are summarized in Table 1 with this technique.

Finally, we have estimated the discovery potential (the expected lower lifetime limit) and confirmed that enlarging the fiducial mass from 22.5 kton to 27.2 kton increases it from $1.7 \times 10^{34}$ to $1.9 \times 10^{34}$ years for $p \rightarrow e^+\pi^0$ and from $1.4 \times 10^{34}$ to $1.6 \times 10^{34}$ years for $p \rightarrow \mu^+\pi^0$.

5. Conclusion and Prospect
We have studied the feasibility and physics potential of enlarging the fiducial mass of the SK detector. We confirmed that enlarging the fiducial mass enhances the sensitivity of proton
Figure 1. The signal efficiencies (upper) and the expected number of atmospheric neutrino background events (lower) for $p \rightarrow e^+ \pi^0$ in left and $p \rightarrow \mu^+ \pi^0$ in right. For signal efficiencies, the blue circles show the conventional and the magenta triangles show the enlarged region. For atmospheric neutrino background, the red solid line shows the conventional and the green broken line shows the enlarged region.

| Signal Efficiency | Signal Region | Conventional (22.5 kton) | Enlarged (4.7 kton) | Inclusive (27.2 kton) |
|-------------------|---------------|--------------------------|---------------------|----------------------|
| Lower $P_{tot}$   | 19.5%         | 10.3%                    | 18.1%               |
| Higher $P_{tot}$  | 20.3%         | 15.5%                    | 19.5%               |

The expected number of atmospheric $\nu$ backgrounds

| Signal Efficiency | Lower $P_{tot}$ | Higher $P_{tot}$ |
|-------------------|-----------------|------------------|
| $p \rightarrow e^+ \pi^0$ | 0.01            | 0.01             |
| $p \rightarrow \mu^+ \pi^0$ | 0.48            | 0.09             |

Table 1. $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$ search performance summary
decay via $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$ by $\sim 12\%$. We are finalizing the systematic uncertainties in the enlarged region and will search for both decay modes with all the SK data, which is $\sim 450$ kton · years and 1.5 times larger exposure than the last paper [2].

References

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