論文の内容の要旨

Search for Proton Decay via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ with an Enlarged Fiducial Mass of the Super-Kamiokande Detector

(スーパーカミオカンデ検出器の拡張有効質量を用いた陽子崩壊 $p \to e^+\pi^0$ と $p \to \mu^+\pi^0$ の探索)

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The standard model of elementary particle physics, which is based on the $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry, has succeeded in predicting almost all experimental results. However, it is hard to believe that the standard model is an ultimate theory to describe elementary particle physics. Grand Unified Theories (GUTs) are extensions of the standard model and provide answers to some of the unresolved problems, such as the quantization of electric charge between quarks and leptons. One of the unique predictions in GUTs is proton decay, which is a direct transition between quarks and leptons without conserving the baryon number. The $p \to e^+\pi^0$ mode is predicted to be a dominat decay mode in many GUT models, and some models favor the $p \to \mu^+\pi^0$ mode. Both decay modes are prospective in water Cherenkov detectors because all final state particles, a positron or anti-muon and two gamma rays from the π^0 decay, are visible, and their back-to-back event topologies make it possible to clearly discriminate between a proton decay signal and atmospheric neutrino backgrounds. In this thesis, the results of the proton decay search via $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ are presented.

We have conducted these searches with the Super-Kamiokande detector. It is the world's largest underground water Cherenkov detector, containing a total of 50 kton of ultrapure water in the upright cylindrical water tank and viewed by about 11,000 50 cm diameter photomultiplier tubes (PMT). The detector is separated into two regions, an inner detector (ID) and an outer detector (OD), and the ID is 33.8 m in diameter and 36.2 m in height. The detector has been operated since 1996 and accumulated more than 6000 days of livetime. More detailed descriptions of the detector and its calibration are presented in Chapter 3 and reference materials therein.

The detector fiducial mass region was defined as the region more than 200 cm from the closest ID wall, giving a 22.5 kton water fiducial mass. In this analysis, we have extended the fiducial mass boundary from 200 cm to 100 cm from the closest ID wall and enlarged the fiducial mass from 22.5 kton to 27.2 kton, by about 20%. In order to achieve this expansion, we have conducted the following studies:

- Development of tighter background rejection criteria and estimation of external background events outside the conventional fiducial mass region.
- Improvements of the event reconstruction algorithm including that for particle identification which has a sizable impact on proton decay events in the region closer to the ID wall.
- Estimation of systematic uncertainties in the additional fiducial mass region.

Since the detector fiducial mass region added in this analysis is closer to the outside of the detector, more external backgrounds, such as cosmic-ray muons and dummy events induced by

PMT flashing, were anticipated to exist, but it has not been estimated quantitatively. Therefore, we have developed tighter event selection criteria and scanned all events reconstructed in the additional fiducial mass region with a graphical event display tool and demonstrated that the external background contamination rate is kept within 1%, a tolerable level for nucleon decay and atmospheric neutrino analyses in Super-Kamiokande. On the other hand, introducing tighter selection criteria does not significantly reduce the proton decay and atmospheric neutrino selection efficiencies, and they are kept more than 96%. The data selection algorithm and more detailed discussion are given in Chapter 5.

Since one of the particles in the final state from $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ decays in the additional fiducial mass region generically has a small distance to the ID wall along its direction, the number of hit PMTs associated with that particle tends to be small. Lower numbers of hit PMTs make it difficult to separate between a showering particle and a non-showering particle from the Cherenkov hit profile. In this work, we have updated the expected charge tables using events in both the conventional and additional fiducial mass regions, and they mitigate the deterioration of the particle identification performance. An overview of the event reconstruction algorithm, performance on proton decay events as well as the update described above are explained in Section 6.1.

In this analysis, systematic uncertainties in the additional fiducial mass region have been estimated separately. One of the most important uncertainties is the energy scale uncertainty because the reconstructed invariant mass and momentum are used to distinguish proton decay events and atmospheric neutrino backgrounds. The energy scale uncertainty has been evaluated using various control samples, such as cosmic-ray muons, Michel electrons, and neutral pions from atmospheric neutrino interactions, and we have demonstrated that momentum and mass spectra in data and simulation agree within a few percent in both fiducial mass regions. The evaluation of the energy scale uncertainty is described in Section 6.2.

Besides the evaluation of the systematic uncertainties using Super-Kamiokande data, we have tested our detector simulation if it is tolerable for enlarging the fiducial mass. Because incident positions of Cherenkov photons on the PMT photocathode depend on the charged particle's position and direction inside the detector, in events outside the conventional fiducial mass region, effects from the photon incident position dependence of the PMT response might be critical. However, such position dependence is not implemented in the detector simulation. Therefore, we have measured the photon incident position dependence as well as its ambient magnetic field dependence in an independent setup. We also measured all the PMTs' dynode directions and residual magnetic field in the detector, and we implemented the detailed PMT response into the detector simulation. As a result, average impacts to the event reconstruction performance have been estimated to be limited using "implemented simulation", and we confirmed that our current modeling of the PMT response is tolerable for enlarging the fiducial mass. More detailed descriptions can be found in Appendix A.

An analysis of the proton decay search is presented in Chapter 7. The signal selection efficiencies and the expected number of atmospheric neutrino background events for both fiducial mass region have been estimated using proton decay simulation events and atmospheric neutrino simulation events. The physics modeling used in the simulation is described in Chapter 4. Although the evaluated signal selection efficiency for both $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ modes in the additional fiducial mass region is lower than that in the conventional fiducial mass region due to the deterioration of the event reconstruction performance, we have confirmed that enlarging the fiducial mass increases the search sensitivity by about 12% for both search modes. Compared to the last published results, we have added 25% more livetime and enlarged the fiducial mass by about 20%, resulting in 1.5 times larger statistics. The proton decay search has been performed using the updated data set. No candidates have been observed for the $p \to e^+\pi^0$ mode, while a single candidate, which is the same event reported in the previous publication, has been found for the $p \to \mu^+\pi^0$ mode. These results are consistent with the atmospheric neutrino background predictions, 0.59 events for $p \to e^+\pi^0$, and 0.94 events for $p \to \mu^+\pi^0$. Therefore, we set lower limits on the proton partial lifetime for each of these modes at 90% confidence level:

$$\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34} \text{ years},$$
$$\tau/B(p \to \mu^+\pi^0) > 1.6 \times 10^{34} \text{ years}.$$

Although no major GUT models are completely ruled out by these limits, they are more than 1.5 times longer than the previous results and are the world's most stringent constraints and should be referred to in building GUT models.