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Sensitivity study for proton decay via $p \rightarrow e^+\pi^0\pi^0$ and $p \rightarrow \mu^+\pi^0\pi^0$ in the Super-Kamiokande Detector

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Super-Kamiokande is a 50 *ktons* water Cherenkov detector in Japan and has been operating from April 1996 thus accumulating 0.37 megaton-years exposure of data. One of the main physics topics of the Super-Kamiokande(SK) experiment is searching for proton decays to test a Grand Unified Theory. One of the three-body proton decay modes, a charged lepton and two pion decay mode can be considered in a model-independent manner and its expected decay rate is 24% ~ 140% in comparison with $p \rightarrow e^+\pi^0$. The Super-Kamiokande detector can detect all final particles above Cherenkov thresholds and the proton mass and momentum could be reconstructed. Most of atmospheric neutrino backgrounds could be rejected in fiducial volume as 2 m inside the wall of the inner detector. The aim of this analysis is to search for nucleons decaying directly to a lepton and multiple neutral pions in Super-Kamiokande. In this poster, results on sensitivity studies of the three-body proton decay using Monte Carlo, especially via $p \rightarrow e^+\pi^0\pi^0$ and $p \rightarrow \mu^+\pi^0\pi^0$ decay modes will be presented.

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1. Introduction

The nucleon decay is an important physics topic to test a Grand Unified Theory (GUT) experimentally. One of the three-body decay modes of proton, a charged lepton and two pion decay mode can be considered in a model-independent manner. For searches of proton decays, we study $p \rightarrow e^+\pi^0\pi^0$ and $p \rightarrow \mu^+\pi^0\pi^0$, expected decay rates of these modes are 24% ∼ 140% in comparison with $p \rightarrow e^+\pi^0$ theoretically[1]. In this work, we present sensitivities of searches for $p \rightarrow e^+\pi^0\pi^0$ and $p \rightarrow \mu^+\pi^0\pi^0$. This analysis is the first search for nucleon decaying directly to a charged lepton and multiple pions in SK.

1.1 The Super-Kamiokande experiment

The Super-Kamiokande detector is the worlds largest underground water Cherenkov detector about 1,000 m deep. The detector has a cylinderical shape, 39.3 m diameter and 41.4 m height filled with 50kton of ultrapure water. It is divided into concentric two volumes, an inner detector (ID) and an outer detector (OD). There are more than 11,000 20-inch PMTs installed on the ID wall facing inwards to detect the Cherenkov lights from charged particles. The SK experiment has been collecting data since 1996 and the data taken till 2018 is divided into four phases, SK-I, SK-II, SK-III and SK-IV. We analyze all the available data from SK-I to SK-IV. The considered exposure is $372.6 kton \cdot year$ in total by summing up 91.7, 49.2, 31.9 and $199.8 kton \cdot year$ respectively.

1.2 Proton decay

A proton from hydrogen atom and eight protons from oxygen atom in water within the ID are the source of proton decays. Protons in hydrogen are called free protons which have an initial mass and momentum 938.27 MeV/c^2 and 0 MeV/c. Hydrogen nuclei (free proton) is stationary and do not interact with other nucleons, whereas protons in oxygen nuclei (bound proton) interact with other nucleons. In this analysis, we took into account the Fermi motion and the correlated decay of bound protons.

2. Event selection

In this analysis, all the detected particles must be fully contained in the ID with the reconstructed vertex inside the fiducial volume (FV). The FV is defined as the volume 2 m inside the top, barrel and bottom ID walls. The following selection criteria are applied to separate proton decay signals from atmospheric neutrino background events. The event selection was optimized for each $p \rightarrow e^+\pi^0\pi^0$ and $p \rightarrow \mu^+\pi^0\pi^0$ mode to maximize the sensitivity and to minimize the background rate.

(A) There must be 3,4 or 5 reconstructed Cherenkov rings.

(B) Particle identification (PID) of Cherenkov rings must be consistent with each decay mode. There must be all electron like rings for the $p \rightarrow e^+\pi^0\pi^0$ and only one muon like ring and other electron like rings for the $p \rightarrow \mu^+\pi^0\pi^0$.

(C) The number of Michel electron should be 0 for the $p \rightarrow e^+\pi^0\pi^0$ and $p \rightarrow \mu^+\pi^0\pi^0$.

(D) The total invariant mass should satisfy $800 < M < 1050 MeV/c^2$.

(E) The total momentum should satisfy $P < 200 MeV/c$.

(F) There should be no tagged neutron for both $p \to e^+\pi^0\pi^0$ and $p \to \mu^+\pi^0\pi^0$.

Although 5 ring case is an ideal one, most of reconstructed events have 3 or 4 Cherenkov rings because some rings are fully not reconstructed due to scattering, absorption, and geometric acceptances. About 90% of atmospheric neutrino background events are rejected by the cut (a). Gammas from a π^0 decay could generate electron like rings by electro-magnetic showers in the SK detector and the cut (b) requires all of electron like rings for electron mode and 1 muon ring and electron rings for muon mode. In the cut (c), the number of Michel electrons is required to be 1 for muon mode only. Total invariant mass cut (d) and momentum cut (e), are required so that the kinematics of one charged lepton and two neutral pions is consistent with proton decay signal. The cut (f) could reject ~ 70% of atmosphetic neutrino background events and keep signal events.

3. Sensitivity

The systematic error estimation is still in progress and in this presentation we studied expected upper limits of proton lifetime by assuming the systematic errors from previous $p \to e^+\pi^0\pi^0$ and $p \to \mu^+\pi^0\pi^0$ analysis [2]. We considered five scenarios of systematic errors; no systematic errors, systematic errors of previous analysis, two times larger signal systematic errors, two times larger background systematic errors and two times larger total systematic errors.

In Figure 1, the effects of systematic uncertainties are clearly identified and the systematics from signal events affects upper limits on the proton lifetime most significantly. On the other hand, the effect of background systematic errors is much smaller. Considering various systematic error cases, we expect upper limits on the proton lifetime to be about $4 \sim 8 \times 10^{33}$ years for electron mode and $2 \sim 6 \times 10^{33}$ years for muon mode which are larger than the IMB-3 result by an order of magnitude [3].

4. Summary

Proton decays into one charged lepton and two neutral pions have been studied using 372.6 $kton \cdot year$ of SK exposure. We optimized the event selections to reject the atmospheric neutrino background events effectively. The expected upper limit at 90 % CL were calculated for each electron and muon mode using assumed systematic errors of published analysis. Compared with the previous limit by IMB-3 experiment, it is shown that the expected limit can be improved by an order of magnitude.

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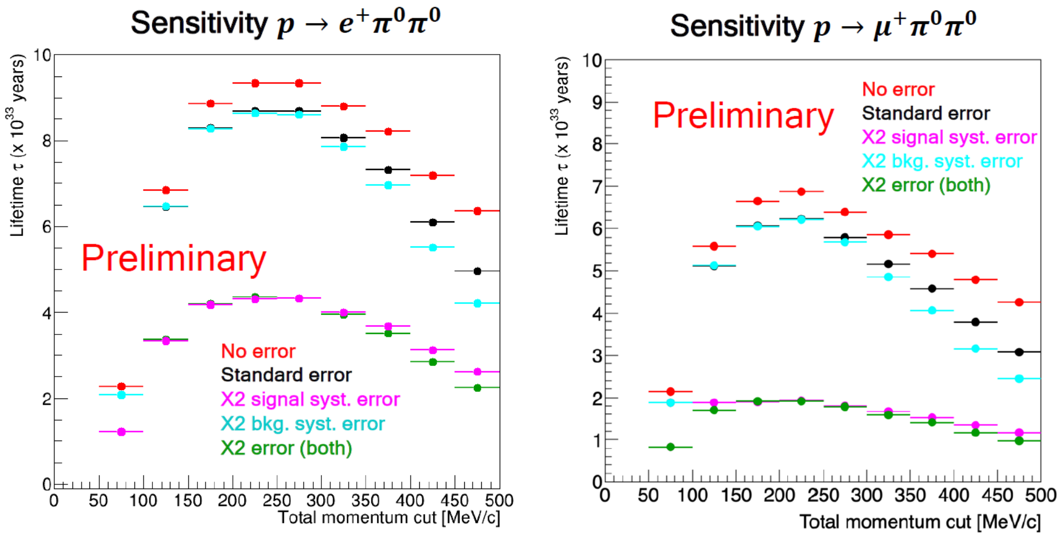

Figure 1: Sensitivity of $p \to e^+\pi^0\pi^0$(left) and $p \to \mu^+\pi^0\pi^0$(right). Horizontal axis represents total momentum cut and vertical axis represents the expected lifetime limit. Five colors of data points represent no systematic error by red, published systematic errors by black, 2 times larger signal related systematic errors by magenta, 2 times larger background related systematic errors by cyan and 2 times larger total systematic errors by green.

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