RECENT RESULTS FROM SUPER-KAMIOKANDE

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I will summarize the most recent nucleon decay and sterile neutrino results from Super-Kamiokande (SK) experiment.

1 Introduction

SK is the world's largest water Cerenkov detector, located in the Kamioka mine, under $\sim$1 km mountain in Japan. There are four experimental periods SK-I (1996-2001), SK-II (2002-2005), SK-III (2006-2008), and SK-IV (2008-present). The inner detector photo coverage is $\sim$40% in SK-I, SK-III, and SK-IV and $\sim$20% in SK-II. A new front-end electronics module QBEE was implemented from SK-IV. The SK experiment has been running for $\sim$17 years in total. More details about the SK detector as well as its calibration are found in the references[1].

SK has been publishing important physics results in many subjects. For example, in 2014 and 2015 (until Moriond 2015 in March), papers were published on nucleon decay searches[2,3,4,5], atmospheric neutrino oscillation analyses[6,7], solar neutrino oscillation analysis[8], and supernova relic neutrino searches[9]. Among them, I focus on the nucleon decay searches and the sterile neutrino analysis.

2 Nucleon Decay Searches

Grand Unified Theories (GUTs) are very attractive and a strong motivation for experimental nucleon decay searches. If there would be a single symmetry group which involves $SU(3)_{color}\times SU(2)_L\times U(1)_Y$, the number of coupling constants could be unified, the quantization of electric charge could be explained, and so on. Among various GUTs, SO(10) GUTs and Super-Symmetry (SUSY) GUTs are recently popular and related to the recent nucleon decay searches in SK. In the SO(10) GUT, fifteen fermions and a ν_R would fit in a single representation, and very tiny mass of the ν_L could be explained by using the ν_R as a partner in the seesaw mechanism. In SUSY GUT, three coupling constants could meet at $\sim 10^{16}$ GeV and gravity could be included. In all of these cases, GUTs predict nucleon decay.

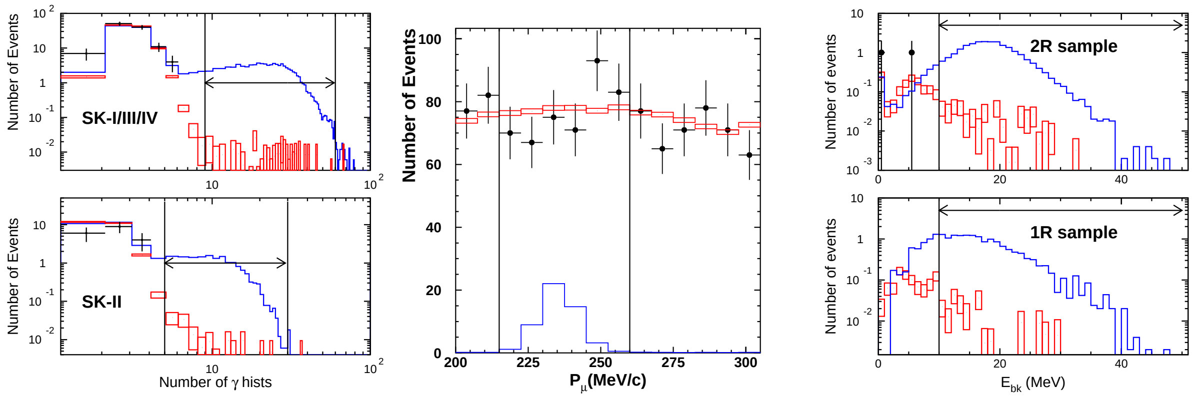

Figure 1 – p→ νK$^+$ search. The number of PMT hits for prompt γ candidate, muon momentum, and visible energy for π^+ candidate are shown from left to right, respectively. p→ νK$^+$ MC, atmospheric neutrino MC, and data are shown in blue, red, and black, respectively.

SK has the world's best sensitivities on the nucleon lifetime thanks to large fiducial volume (22.5 kt corresponding to $\sim$7.5 $\times 10^{33}$ protons), excellent event reconstruction performances, and long stable detector operation. The lifetime limit is proportional to exposure for the background free case but it's not anymore true for non-zero background case. It is important to increase signal efficiency and background rejection and decrease their systematic errors. Many analysis improvements have been done recently especially in the p→ νK$^+$ search and several new searches have been undertaken.

2.1 p→ νK^+

p→ νK$^+$ is one of the dominant decay modes in SUSY GUTs and some models predict a lifetime $<\sim 10^{34}$ years which could be probed by SK. In a new data analysis[2], data from SK-II to SK-IV are added, event reconstructions and selections are improved, and Michel electron tagging efficiency is higher in SK-IV thanks to the QBEEs with respect to the previous SK published result[10].

There are three analysis methods. In the first method ("Prompt γ"), the prompt nuclear γ as well as mono-energetic muon from K$^+$ decay and Michel electron are tagged. Figure 1 (left) shows the number of PMT hits for the prompt γ candidate. The data and atmospheric neutrino (background) MC agree well with each other and no data candidate is seen in the signal region. The same event selections are applied in the second method ("P_μ spec.") except for a relaxed momentum cut and no prompt γ hits. Figure 1 (center) shows the muon momentum distributions and no data excess is seen in the signal region. In the third method ("$\pi^+\pi^0$), both π^+ and π^0 from K$^+$ decays are used. Figure 1 (right) shows visible energy distributions for the π^+ candidate and no data candidate is seen in the signal region.

Table 1 summarizes the results from all the methods. The numbers in parentheses in SK-I are from the previous SK paper, and the expected background rates are significantly reduced in new analysis. The number of total expected background events (sum of the expected background events from SK-I to SK-IV) are less than 1 in both Prompt γ and $\pi^+\pi^0$ methods.

There is no data excess above the background expectation and the lower limit on the lifetime is set to be $>5.9\times 10^{33}$ years (90% CL). This result is the world's best limit, 2.5 times more

Table 1: Summary of p→ νK^+ search.

		SK-I	SK-II	SK-III	SK-IV
Exposure (kt·yrs)		91.7	49.2	31.9	87.3
Prompt γ	Signal Efficiency (%)	7.9±0.1(8.6)	6.3±0.1	7.7±0.1	9.1±0.1
	Exp. Background	0.08(0.7)	0.14	0.03	0.13
	Data Candidate	0	0	0	0
P_μ spec.	Signal Efficiency (%)	33.9±0.3	30.6±0.3	32.6±0.3	37.6±0.3
	Exp. Background	193	94.3	69.0	223.1
	Data Candidate	177	78	85	226
$\pi^+\pi^0$	Signal Efficiency (%)	7.8±0.1(6.0)	6.7±0.1	7.9±0.1	10.0±0.1
	Exp. Background	0.18(0.6)	0.17	0.09	0.18
	Data Candidate	0	0	0	0

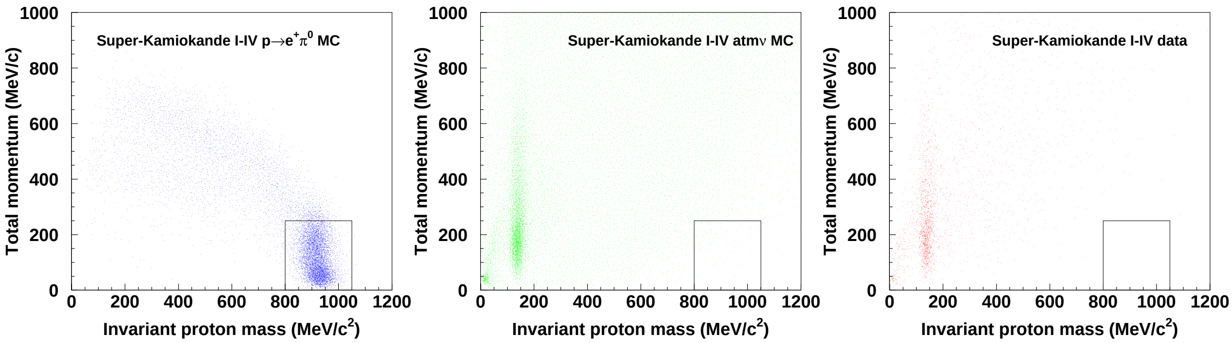

Figure 2 – p→eπ^0 search. Total invariant mass and total momentum are shown for p→eπ^0 MC, atmospheric neutrino MC, and data from left to right, respectively. The signal box is also shown.

stringent than the previous published SK result, and constrains recent SUSY GUT models.

2.2 p→eπ^0

p→eπ^0 is one of the dominant decay modes in non-SUSY GUTs and the most recent result is shown in this report. Detail of the data analysis can be found in the previous published paper[11].

Figure 2 shows total invariant mass and total momentum for p→eπ^0 MC, atmospheric neutrino (background) MC, and real data. The signal efficiency and the number of total expected background events as estimated with the MC are ∼40% and ∼0.7, respectively. The number of expected background events as well as various kinematics of the final particles used in the background MC was validated with the K2K neutrino beam data[12].

There is no data candidate in the signal box, and the data distribution agrees with that of background. The agreement was also confirmed in various basic distributions such as the total mass and the total momentum, respectively, as well as all the parameters used in the event selections. The lifetime lower limit is set to be $>1.4\times10^{34}$ years (90% CL). This is the world's best limit for this mode.

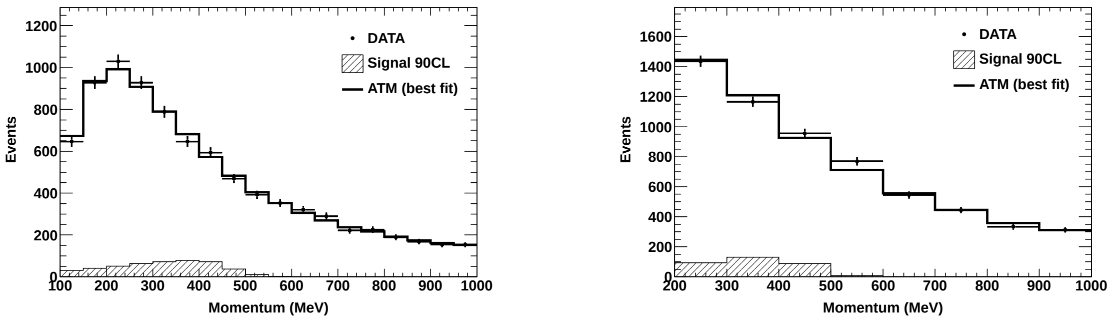

Figure 3 – p→e$\nu\nu$ and p→ $\mu\nu\nu$ searches. Electron momentum (left) and muon momentum (right) are shown for p→e$\nu\nu$ and p→ $\mu\nu\nu$ searches, respectively.

Major on-going improvements being worked on now include neutron tagging in SK-IV, sophisticated event reconstruction algorithm, and reduction of the systematic errors.

2.3 p→e$\nu\nu$ and p→ $\mu\nu\nu$

As an example of recent nucleon decay searches which had never been done before in SK, p→e$\nu\nu$ and p→ $\mu\nu\nu$ search results[4] are shown in this report. Some SO(10) models embedded in Pati-Salam's left-right symmetric model predict lifetimes around 10^{30-33} years. Unlike standard nucleon decay channels with $|\Delta(B-L)|=0$, these decay modes have $|\Delta(B-L)|=2$.

Figure 3 shows electron and muon momentum distributions in the p→e$\nu\nu$ and p→ $\mu\nu\nu$ searches, respectively. There is no significant excess in the signal regions in both searches and the lifetime limits are set to be >1.7×10^{32} years (90% CL) and >2.2×10^{32} years (90% CL) for p→e$\nu\nu$ and p→ $\mu\nu\nu$ searches, respectively. They are the world's best limits, an order of magnitude improvement over previous results by other experiments, and provide strong constraints to these models.

3 Sterile Neutrino Analysis

Primary cosmic rays strike air nuclei and decay of the resulting hadrons gives atmospheric neutrinos. The number of atmospheric neutrinos collected so far in SK is more than 40,000. The travel length (~10-10,000km) and energy (~0.1-10^4GeV) have wide ranges and both neutrino and anti-neutrino exist (~30% for anti-neutrino in the final samples). The atmospheric neutrino is, therefore, an excellent tool for broad studies of neutrino oscillations in SK. In this report, I focus on the sterile neutrino oscillation analysis [6].

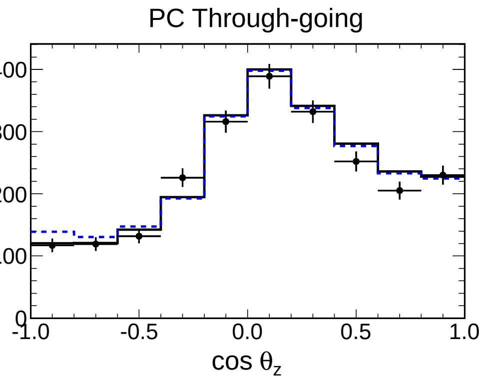

Figure 4 – Sterile neutrino analysis. Zenith angle of partially contained through-going sample for atmospheric neutrino MC without sterile neutrino (black solid), with $|U_{\tau 4}|^2 = 0.31$ (blue dashed), and data (black cross).

The unitary matrix with sterile neutrino is given by:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ . & . & . & . & . \\ . & . & . & . & . \end{pmatrix} \tag{1}$$

where $|U_{\mu 4}|^2$ induces a decrease in event rate of μ-like data of all energies and zenith angles but is not sensitive to $\delta\mathrm{m}^2$ due to fast oscillations, and $|U_{\tau 4}|^2$ causes shape distortion of angular distribution of higher energy μ-like data.

Figure 4 shows zenith angle distribution of the partially contained through-going sample (average energy $\sim$10GeV) for the atmospheric neutrino MC with and without sterile neutrino oscillation overlaid with the data. No evidence of sterile neutrino oscillations is observed and the upper limit on $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ are set to be <0.054 (90% CL) and <0.23 (90% CL), respectively. Our results as well as other experimental results are summarized in Figure 5.

4 Summary and Future

No evidence of nucleon decay has been observed so far in SK and we set the most stringent lifetime limits in the world. We are continuing to improve our analyses and increase the data statistics. No indication of non-standard models has been found in the atmospheric neutrino oscillation analyses and we set stringent limits on the relevant parameters.

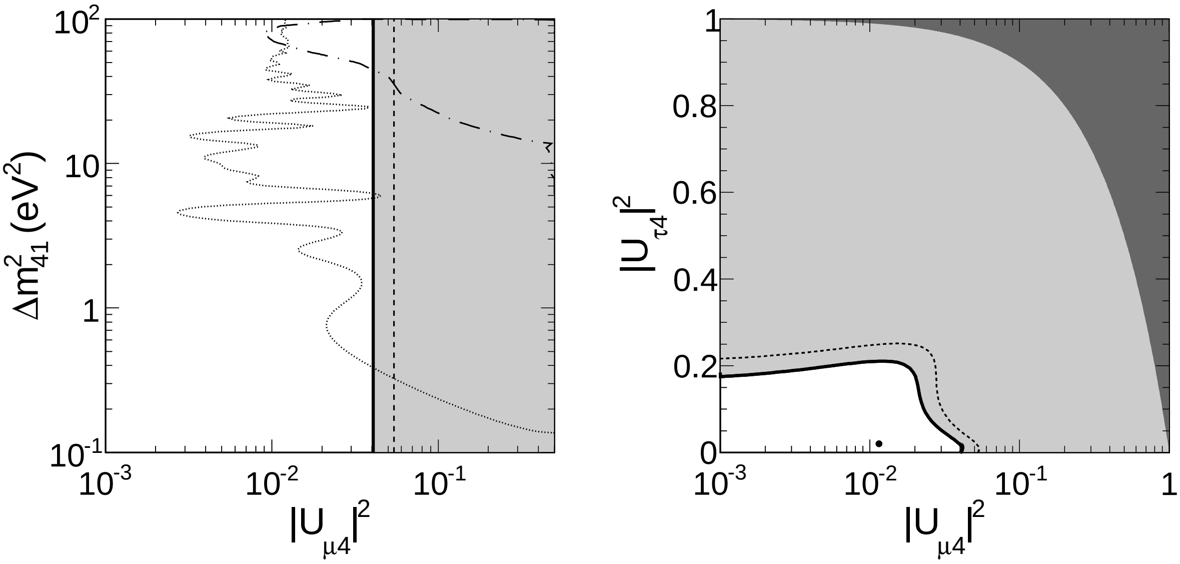

Figure 5 – Sterile neutrino oscillation analysis. The SK 90% CL (99% CL) upper limits are shown as black solid (dashed) lines for $|U_{\mu4}|^2$ and $|U_{\tau4}|^2$. Light gray regions are excluded by SK (90% CL). Thin dotted and dot-dashed curves in left are from other experiments. Dark gray region in right is disallowed by unitarity.

In all of these analyses, we hope to improve our sensitivity by increasing the sophistication of our reconstruction algorithm, reducing systematic errors, and so on. In the future, the sensitivities would be increased dramatically by building Hyper-Kaimiokande[13,14] (a next generation water Cerenkov detector with a 25 times larger fiducial volume than SK).

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