Journal of Physics: Conference Series **718** (2016) 062044 doi:10.1088/1742-6596/718/6/062044

Recent nucleon decay results from Super Kamiokande

S Mine for Super Kamiokande collaboration

Department of Physics and Astronomy, University of California, Irvine, USA

E-mail: smine@uci.edu

Abstract. I will summarize the most recent nucleon decay results from Super Kamiokande experiment.

1. Introduction

Super Kamiokande (SK) [1] is the world's largest water Cherenkov detector, a vertical cylinder measuring 40 m×40 m, located in the Kamioka mine under about 1 km deep in a mountain in Japan. The SK experiment has been running since 1996. There are four experimental periods from SK-I to SK-IV. The inner detector photo coverage is about 40% in SK-I, SK-III, and SK-IV and is about 20% in SK-II. A new front-end electronics module QBEE was implemented for SK-IV.

Grand Unification Theories (GUTs) are very attractive and a strong motivation for experimental nucleon decay searches. If there would be a single symmetry group which involves the standard model $SU(3)_{color} \times SU(2)_L \times U(1)_Y$, the number of coupling constants could be unified, the quantization of electric charge could be explained, and so on. They also predict nucleon decay. Among various GUTs, SO(10) GUTs and Super Symmetry (SUSY) GUTs are recently popular and related to the recent nucleon decay searches in SK. There are two benchmark decay modes, $p \rightarrow e\pi^0$ and $p \rightarrow \nu K^+$, favored by non-SUSY and SUSY GUTs, respectively. Some GUTs predict the lifetimes are shorter than 10^{34} years and could be probed by SK. Nucleon decay is one of necessary conditions to explain baryon asymmetry of the universe.

Since grand unification occurs at around 10^{16} GeV which can not be achieved by any accelerator experiments, nucleon decay search in SK is a unique way to directly probe GUTs. SK has the world's best sensitivities on the nucleon lifetime thanks to its large fiducial volume (22.5 kilo-ton corresponds to about 7.5×10^{33} protons and about 6×10^{33} neutrons), excellent event reconstruction performances [2], and long stable detector operation. The lifetime sensitivity is proportional to exposure for the background free case but is proportional to square root of exposure for non-zero background case. It is important to increase signal efficiency and background rejection. Several analysis improvements have been done recently especially in the benchmark modes [3] and several new searches have been undertaken [4, 5, 6, 7, 8, 9]. The former results will be described in this report.

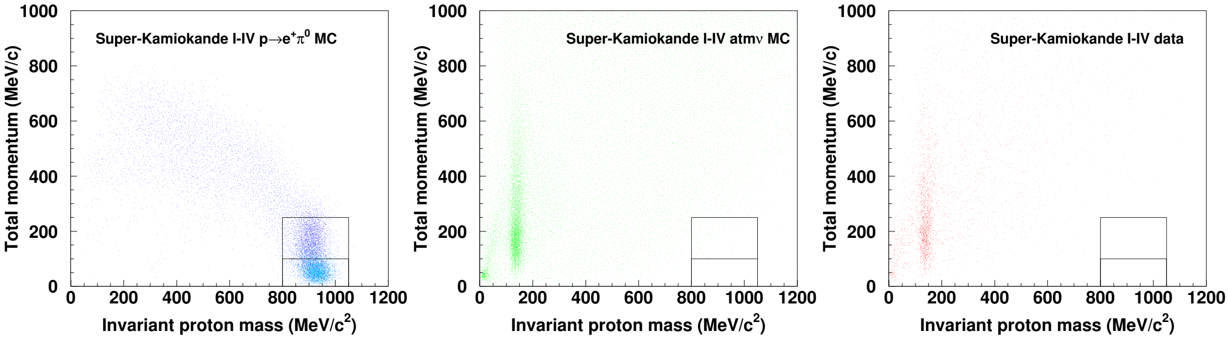

Figure 1. p→eπ^0 search. Total invariant mass and total momentum are shown for p→eπ^0 MC, atmospheric neutrino MC, and data from left to right, respectively. The cyan dots in the left plot are from free proton decays. The signal box is also shown.

2. p→eπ^0 and p→ $\mu\pi^0$ searches

The data analyses on the p→eπ^0 search as well as the p→ $\mu\pi^0$ search are described in [10] in detail. In this report, I focus on the recent analysis improvements.

The left and middle plots in Figure 1 show the total mass and momentum for p→eπ^0 MC and atmospheric neutrino background MC events, respectively. We introduced the total momentum separation at 100 MeV/c. As shown in the left plot, most events in the lower signal box come from free proton decays and therefore suffer smaller systematic uncertainties. Because the dominant systematic errors on the signal efficiency come from uncertainties on bound proton decays in the oxygen nucleus. The total expected background events are about 0.05, almost background free, and 0.5 in the lower and upper signal boxes, respectively, enhancing the discovery potential The atmospheric neutrino background events are frequently accompanied with neutron production, n+p→d+γ(2.2 MeV). In SK-IV, hit cluster search for the 2.2 MeV γ is enabled thanks to dead time less DAQ and software trigger with QBEE. The detection efficiency is about 21%. By requiring that there is no reconstructed neutron associated with the 2.2 MeV γ, about half the background events are rejected while loss of the signal efficiency is only a few %. For more exposure, more benefit on the lifetime sensitivities would be achieved. For example, the sensitivities would be better by more than 10% at 1 Mega-ton year exposure with both the total momentum separation and the neutron tagging for both p→eπ^0 and p→ $\mu\pi^0$ searches. The total mass and momentum for data is shown in the right plot in Figure 1. There is no data candidate in the signal box for 306.3 kilo-ton years and the lifetime lower limit is set to be 1.67×10^{34} years at 90% C.L. Table 1 summarizes the signal efficiencies, expected backgrounds, and data candidates. The event rate at each cut and the cut parameter distributions are compared between the atmospheric neutrino MC events and data, and they agree well with each other.

Flipped SU(5) predicts high branching ratio of p→ $\mu\pi^0$ comparable to that of p→eπ^0. The analysis proceeds as with the eπ^0 with additional requirement of one Michel electron. Figure 2 shows the total mass and momentum for p→ $\mu\pi^0$ search. There are two data candidates in the upper signal box near upper edge of the total momentum cut for 306.3 kilo-ton years exposure. The signal efficiencies, expected backgrounds, and data candidates are summarized in Table 2. The better Michel electron tagging with QBEE results in the higher signal efficiency in SK-IV. The total expected backgrounds are about 0.05 and 0.82 in the lower and upper signal boxes, respectively. The Poisson probability to observe two events in the upper signal box is

Table 1. Summary of p→eπ^0 search.

		SK-I	SK-II	SK-III	SK-IV
Exposure (kt·yrs)		91.7	49.2	31.9	133.5
P_{tot} ≥100MeV/c	Signal Efficiency (%)	20.4±3.1	20.2±3.1	20.5±3.2	19.4±2.9
	Exp. Background	0.22±0.06	0.12±0.01	0.06±0.02	0.15±0.05
	Data Candidate	0	0	0	0
P_{tot} <100MeV/c	Signal Efficiency (%)	18.8±0.9	18.3±1.0	19.6±1.3	18.7±1.2
	Exp. Background	0.03±0.01	<0.01	<0.01	0.02±0.01
	Data Candidate	0	0	0	0

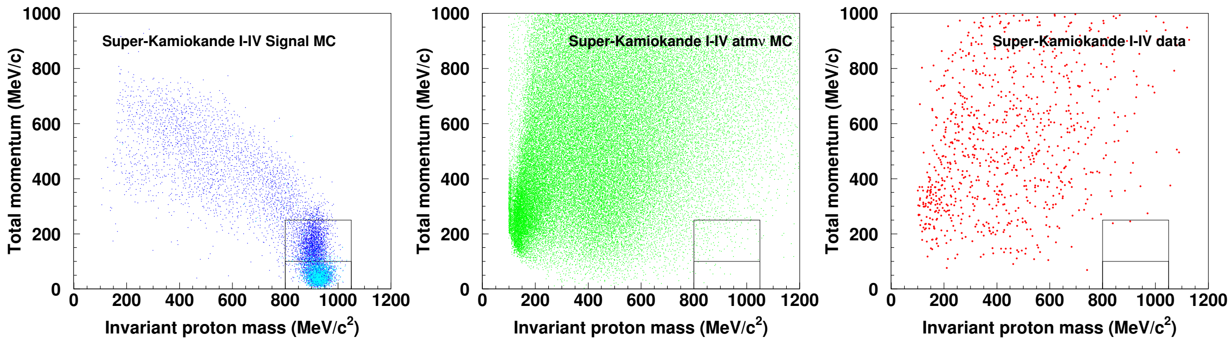

Figure 2. p→ $\mu\pi^0$ search. Total invariant mass and total momentum are shown for p→ $\mu\pi^0$ MC, atmospheric neutrino MC, and data from left to right, respectively. The cyan dots in the left plot are from free proton decays. The signal box is also shown.

Table 2. Summary of p→ $\mu\pi^0$ search.

		SK-I	SK-II	SK-III	SK-IV
Exposure (kt·yrs)		91.7	49.2	31.9	133.5
P_{tot} ≥100MeV/c	Signal Efficiency (%)	15.3±2.5	15.3±2.6	16.5±0.8	18.2±1.1
	Exp. Background	0.33±0.09	0.14±0.04	0.12±0.03	0.23±0.07
	Data Candidate	0	0	0	2
P_{tot} <100MeV/c	Signal Efficiency (%)	16.4±0.8	16.0±0.8	16.4±1.0	20.1±1.0
	Exp. Background	0.04±0.01	<0.01	<0.01	0.01±0.01
	Data Candidate	0	0	0	0

about 20%. The time interval between two events is about 20 kilo-ton years and the KS test probability is about 5%. The event rates and the cut parameter distributions between the atmospheric neutrino MC events and data show good agreement. Therefore, we performed the lifetime lower limit calculation and obtained 7.78×10^{33} years at 90% C.L.

Journal of Physics: Conference Series **718** (2016) 062044 doi:10.1088/1742-6596/718/6/062044

Table 3. Summary of p→ νK$^+$ search.

		SK-I	SK-II	SK-III	SK-IV
Exposure (kt·yrs)		91.7	49.2	31.9	133.5
Prompt γ	Signal Efficiency (%)	7.9	6.3	7.7	8.5
	Exp. Background	0.08	0.14	0.03	0.14
	Data Candidate	0	0	0	0
$\pi^+\pi^0$	Signal Efficiency (%)	7.8	6.7	7.9	9.0
	Exp. Background	0.18	0.17	0.09	0.12
	Data Candidate	0	0	0	0

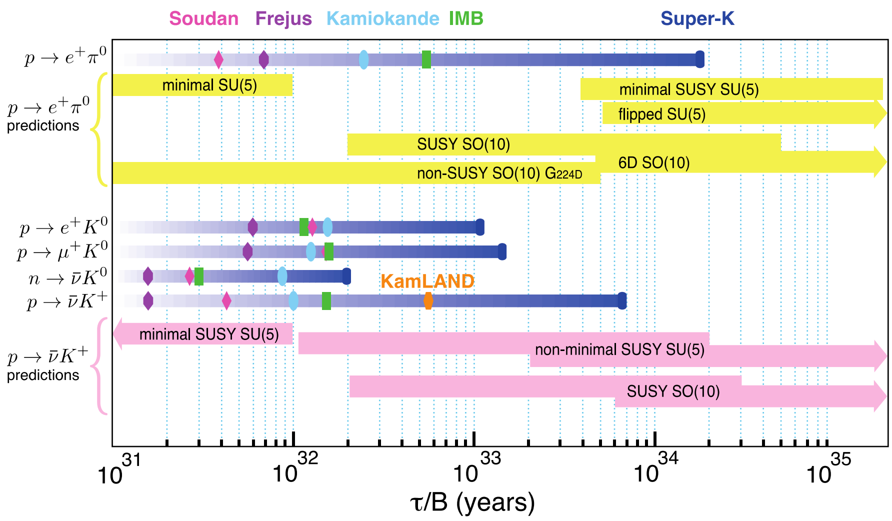

Figure 3. The dark blue bands are the latest SK (Super-K) results. The yellow and pink bands are the theoretical predictions.

3. p→ νK$^+$ search

Since the last published results [3], more data has been added. Table 3 summarizes the signal efficiencies, expected backgrounds, and data candidate for the prompt γ and the $\pi^+\pi^0$ methods. There is no data excess above the background expectation for 306.3 kilo-ton years and the lifetime lower limit is set to be 6.61×10^{33} years at 90% C.L.

4. Summary of nucleon decay searches in SK

Figure 3 summarizes the benchmark decay mode searches in SK and theoretical predictions. There are huge theoretical uncertainties in the predictions, more than one order of magnitude, and the current experimental searches in SK are in the interesting ranges.

In summary, testing baryon number violation is an essential and high priority objective of particle physics. No evidence of nucleon decay has been observed so far in SK and we set the most stringent lifetime limits in the world. We keep discovery potential, are continuing to improve our analyses, and increase the data statistics. In all analyses, we hope to improve our sensitivity by increasing the sophistication of our event reconstruction algorithm, reducing systematic errors, and so on. We also search for new modes which have not been previously studied in SK.

5. Hyper Kamiokande

Hyper Kamiokande (HK) is a next generation large water Cherenkov detector [11]. The fiducial volume would be about 20 times larger than SK and the lifetime sensitivities for $p \rightarrow e\pi^0$ and $p \rightarrow \nu K^+$ searches would be about 1×10^{35} years and 3×10^{34} years for 10 years exposure, respectively.

References

[1] K Abe *et al* (Super Kamiokande Collaboration) 2014 *Nucl. Instr. and Methods A* **737** *253*
[2] M Shiozawa *et al* (Super Kamiokande Collaboration) 1999 *Nucl. Instr. and Methods A* **433** *240*
[3] K Abe *et al* (Super Kamiokande Collaboration) 2014 *Phys. Rev. D* **90** *072005*
[4] K Abe *et al* (Super Kamiokande Collaboration) 2014 *Phys. Rev. Lett.* **113** *121802*
[5] V Takhistov *et al* (Super Kamiokande Collaboration) 2014 *Phys. Rev. Lett.* **113** *101801*
[6] V Takhistov *et al* (Super Kamiokande Collaboration) 2015 *Phys. Rev. Lett.* **115** *121803*
[7] M Litos *et al* (Super Kamiokande Collaboration) 2014 *Phys. Rev. Lett.* **112** *131803*
[8] J Gustafson *et al* (Super Kamiokande Collaboration) 2015 *Phys. Rev. D* **91** *072009*
[9] K Abe *et al* (Super Kamiokande Collaboration) 2015 *Phys. Rev. D* **91** *072006*
[10] H Nishino *et al* (Super Kamiokande Collaboration) 2012 *Phys. Rev. D* **85** *112001*
[11] K Abe *et al* (Hyper Kamiokande Proto-Collaboration) 2015 *Prog. Theor. Exp. Phys.* 053C02