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C. Regis *et al.* (The Super-Kamiokande Collaboration)

Phys. Rev. D **86**, 012006 — Published 23 July 2012

DOI: [10.1103/PhysRevD.86.012006](https://doi.org/10.1103/PhysRevD.86.012006)

Search for Proton Decay via $p \rightarrow \mu^+ K^0$ in Super-Kamiokande I, II, and III

C. Regis,⁶ K. Abe,¹ Y. Hayato,^{1,28} K. Iyogi,¹ J. Kameda,¹ Y. Koshio,¹ L. Marti,¹ M. Miura,¹ S. Moriyama,^{1,28} M. Nakahata,^{1,28} S. Nakayama,¹ Y. Obayashi,¹ H. Sekiya,¹ M. Shiozawa,^{1,28} Y. Suzuki,^{1,28} A. Takeda,¹ Y. Takenaga,¹ K. Ueno,¹ T. Yokozawa,¹ H. Kaji,² T. Kajita,^{2,28} K. Kaneyuki,^{2,28,*} K. P. Lee,² K. Okumura,² T. McLachlan,² L. Labarga,³ E. Kearns,^{4,28} J. L. Raaf,⁴ J. L. Stone,^{4,28} L. R. Sulak,⁴ M. Goldhaber,^{5,*} K. Bays,⁶ G. Carminati,⁶ W. R. Kropp,⁶ S. Mine,⁶ A. Renshaw,⁶ M. B. Smy,^{6,28} H. W. Sobel,^{6,28} K. S. Ganezer,⁷ J. Hill,⁷ W. E. Keig,⁷ J. S. Jang,^{8,†} J. Y. Kim,⁸ I. T. Lim,⁸ J. B. Albert,⁹ K. Scholberg,^{9,28} C. W. Walter,^{9,28} R. A. Wendell,⁹ T. Wongjirad,⁹ T. Ishizuka,¹⁰ S. Tasaka,¹¹ J. G. Learned,¹² S. Matsuno,¹² S. N. Smith,¹² T. Hasegawa,¹³ T. Ishida,¹³ T. Ishii,¹³ T. Kobayashi,¹³ T. Nakadaira,¹³ K. Nakamura,^{13,28} K. Nishikawa,¹³ Y. Oyama,¹³ K. Sakashita,¹³ T. Sekiguchi,¹³ T. Tsukamoto,¹³ A. T. Suzuki,¹⁴ Y. Takeuchi,^{14,28} K. Ieki,¹⁵ M. Ikeda,¹⁵ H. Kubo,¹⁵ A. Minamino,¹⁵ A. Murakami,¹⁵ T. Nakaya,^{15,28} Y. Fukuda,¹⁶ K. Choi,¹⁷ Y. Itow,^{17,18} G. Mitsuka,¹⁷ M. Miyake,¹⁷ P. Mijakowski,¹⁹ J. Hignight,²⁰ J. Imber,²⁰ C. K. Jung,²⁰ I. Taylor,²⁰ C. Yanagisawa,²⁰ H. Ishino,²¹ A. Kibayashi,²¹ T. Mori,²¹ M. Sakuda,²¹ J. Takeuchi,²¹ Y. Kuno,²² S. B. Kim,²³ H. Okazawa,²⁴ Y. Choi,²⁵ K. Nishijima,²⁶ M. Koshihara,²⁷ Y. Totsuka,^{27,*} M. Yokoyama,^{27,28} K. Martens,²⁸ M. R. Vagins,^{28,6} S. Chen,²⁹ H. Sui,²⁹ Z. Yang,²⁹ H. Zhang,²⁹ K. Connolly,³⁰ M. Dziomba,³⁰ and R. J. Wilkes³⁰

(The Super-Kamiokande Collaboration)

¹Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu 506-1205, Japan

²Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan

³Department of Theoretical Physics, University Autonoma Madrid, 28049 Madrid, Spain

⁴Department of Physics, Boston University, Boston, MA 02215, USA

⁵Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

⁶Department of Physics and Astronomy, University of California, Irvine, Irvine, CA 92697-4575, USA

⁷Department of Physics, California State University, Dominguez Hills, Carson, CA 90747, USA

⁸Department of Physics, Chonnam National University, Kwangju 500-757, Korea

⁹Department of Physics, Duke University, Durham NC 27708, USA

¹⁰Junior College, Fukuoka Institute of Technology, Fukuoka, Fukuoka 811-0295, Japan

¹¹Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan

¹²Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA

¹³High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

¹⁴Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan

¹⁵Department of Physics, Kyoto University, Kyoto, Kyoto 606-8502, Japan

¹⁶Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan

¹⁷Solar Terrestrial Environment Laboratory, Nagoya University, Nagoya, Aichi 464-8602, Japan

¹⁸Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Aichi 464-8602, Japan

¹⁹National Centre For Nuclear Research, 00-681 Warsaw, Poland

²⁰Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800, USA

²¹Department of Physics, Okayama University, Okayama, Okayama 700-8530, Japan

²²Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

²³Department of Physics, Seoul National University, Seoul 151-742, Korea

²⁴Department of Informatics in Social Welfare, Shizuoka University of Welfare, Yaizu, Shizuoka, 425-8611, Japan

²⁵Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea

²⁶Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan

²⁷The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan

²⁸Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba 277-8583, Japan

²⁹Department of Engineering Physics, Tsinghua University, Beijing, 100084, China

³⁰Department of Physics, University of Washington, Seattle, WA 98195-1560, USA

(Dated: May 30, 2012)

We have searched for proton decay via $p \rightarrow \mu^+ K^0$ using data from a 91.7 kiloton-year exposure of Super-Kamiokande-I, a 49.2 kiloton-year exposure of Super-Kamiokande-II, and a 31.9 kiloton-year exposure of Super-Kamiokande-III. The number of candidate events in the data was consistent with the atmospheric neutrino background expectation and no evidence for proton decay in this mode was found. We set a partial lifetime lower limit of 1.6×10^{33} years at the 90% confidence level.

PACS numbers:

*Deceased.

†Present address: GIST College, Gwangju Institute of Science and Technol-

I. INTRODUCTION

The experimental observation of proton decay would provide strong evidence for Grand Unified Theories (GUTs) [1] which unify the strong, electromagnetic, and weak forces. Supersymmetry (SUSY) GUTs predict the unification of coupling constants consistent with the non-observation of $p \rightarrow e^+\pi^0$ [2] via gauge boson exchange. In some SUSY GUT models [3] $p \rightarrow \bar{\nu}K^+$ is then favored by dimension five operators. However, in other models [4] $p \rightarrow \mu^+K^0$ may dominate. So far there has been no experimental observation of either of these decays and in this paper we focus on the later, whose most stringent partial lifetime lower limit comes from Super-Kamiokande (SK), $\tau/B_{p \rightarrow \mu^+K^0} > 1.3 \times 10^{33}$ years (90% C.L.) [5]. The partial lifetime of $p \rightarrow \mu^+K^0$ is predicted to be just above this limit [4].

The K^0 is a composite state of the K_S^0 (50%) and K_L^0 (50%). The analysis presented in [5] searched only for proton decay into $\mu^+K_S^0$ using data from the first run period of SK (91.7 kton-years). In this paper we present a combined search for proton decay into both K_S^0 and K_L^0 with an updated data set (172.8 kton-years).

A $p \rightarrow \mu^+K^0$ signal would appear in SK as one muon-like (μ -like) ring with monochromatic momentum of about 327 MeV/c and secondary ring(s) from the decay of the K^0 . The total momenta of all such rings should be consistent with the decay of a proton, as well as an invariant mass close to the proton mass. The dominant decay modes of the K_S^0 are $\pi^+\pi^-$ (69.2%), and $\pi^0\pi^0$ (30.7%). The K_L^0 decays predominantly into $\pi^\pm e^\mp \nu_e$ (40.6%), $\pi^\pm \mu^\mp \nu_\mu$ (27.0%), $3\pi^0$ (19.5%), and $\pi^+\pi^-\pi^0$ (12.5%). Since the K_L^0 has a relatively long decay length ($c\beta\tau \sim 8.4$ m, where τ is the mean life), proton decay events into this channel are characterized by two vertices separated in time and space: a primary vertex from which the μ^+ emerges and a secondary vertex for the decay products of the K_L^0 . We developed new event reconstruction for events with two vertices.

The outline of this paper is as follows. A review of the SK detector is presented in Section II. In section III the $p \rightarrow \mu^+K^0$ Monte Carlo (MC) simulation as well as the atmospheric neutrino MC simulation used to calculate the signal efficiency and expected background rate are presented. Section IV and V describe the data reduction and the event reconstruction, respectively. The results of the data analysis are summarized in Section VI and a comparison with the previous result [5] is described in subsection VI-C. Finally, Section VII concludes this study.

II. SUPER-KAMIOKANDE DETECTOR

The Super-Kamiokande detector [6] is located in Gifu Prefecture, Japan, at a depth of 2,700 m water equivalent within the Kamioka mine at Mt. Ikenoyama. The detector is a 50 kton right cylinder that is optically separated into two concentric regions, an inner (ID) and an outer detector (OD). Inward-facing 20 inch diameter Hamamatsu photomultiplier tubes (PMTs) [7] are mounted uniformly on the walls of the ID. During the SK-I (SK-III) run period from April 1996 (October 2006) to July 2001 (September 2008) approximately 11,100 PMTs lined the ID walls. There were about 5,200 PMTs in the ID during the SK-II run period from October 2002 to October 2005. The photocathode coverage during the run was about 40% (20%) in SK-I and -III (SK-II). A black sheet spans the region between PMTs to absorb light and optically separate ID and OD. Starting with SK-II, each ID PMT is encased in an acrylic cover to reduce the effect of implosion on neighboring PMTs. The transparency of this cover is more than 96% for >350 nm photons with normal incidence. A 22.5 kton fiducial volume used in the data analysis presented below is defined by the cylindrical volume taken 2 m from the ID walls.

The OD is a 2 m thick cylindrical shell enclosing the ID that is instrumented with 1,885 outward-facing 8 inch diameter Hamamatsu PMTs. To improve the light collection efficiency, a 60 cm \times 60 cm wavelength shifting plate is attached to each PMT and the OD walls are covered with reflective material called ‘‘Tyvek sheet’’. The main purpose of the OD is to tag incoming cosmic ray muons and muons induced by atmospheric neutrinos that escape the ID. The OD region also serves as a passive shield against radioactivity from outside the detector wall. The SK-I detector and its calibration are described in detail elsewhere [6].

III. SIMULATION

The $p \rightarrow \mu^+K^0$ MC and the SK atmospheric neutrino MC are used to estimate signal efficiencies and the expected background rates. Using these MCs the event selections described in Sec. VI-A are optimized to maximize the analysis’ sensitivity prior to examining the data.

A. Proton Decay

The $p \rightarrow \mu^+K^0$ MC used here is the same as that used in [5] with the exception that $p \rightarrow \mu^+K_L^0$ events are additionally simulated in this analysis. In this analysis the decays of both free proton and protons bound on the oxygen nucleus are considered. For the decay of free protons the directions of the μ^+ and K^0 are exactly back-to-back, and each has a momentum of 326.5 MeV/c. In the case of proton decay within the oxygen nucleus, the effects of Fermi momentum, correlation with other nucleons, the nuclear binding energy, kaon-nucleon interactions, and $K_L^0 \rightarrow K_S^0$ regeneration are all taken into account. The Fermi momentum distribution measured by

electron- ^{12}C scattering [8] is used in the simulation. The nuclear binding energy effect is taken into account by modification of the proton's mass. The modified proton mass, m'_p , is calculated by $m'_p = m_p - E_b$ where m_p is the proton rest mass and E_b is the nuclear binding energy. The value of E_b for each simulated event was randomly selected from a Gaussian probability density function with $(\mu, \sigma) = (39.0, 10.2)$ MeV for the S-state and $(\mu, \sigma) = (15.5, 3.82)$ MeV for the P-state. The correlation of the decaying proton's wave function with other nucleons reduces the invariant mass of the decay products since some of the system's momentum is carried by these nucleons. This effect is present in about 10% of proton decays [9] and produces a broad invariant mass spectrum down to about $600 \text{ MeV}/c^2$. The location of protons within the ^{16}O nucleus is calculated according to the Woods-Saxon nuclear density model [10]. The kaon nucleon interactions within the ^{16}O nucleus that are considered include elastic scattering and inelastic scattering via charge exchange. The K^+N scattering amplitudes were fitted by a partial wave analysis using many data samples by Hyslop *et al.* [11]. The $K^+n \rightarrow K^0p$ charge exchange cross section was measured by Glasser *et al.* [12]. The detail of the K^+N interaction is described in [5]. From isospin symmetry, the K^0N reactions have essentially the same magnitude as the K^+N reactions. If an interaction occurs, the effect of Pauli blocking is introduced by requiring the nucleon momentum after interaction be larger than the Fermi surface momentum, given by $p_F(r) = (\frac{3}{2}\pi^2\rho(r))^{\frac{1}{3}}$, where $\rho(r)$ is the nuclear density distribution and r is the distance from the center of the nucleus. The $K_L^0 \rightarrow K_S^0$ regeneration effect is implemented as a decay mode of the K_L^0 in this analysis. The regeneration probability in water is based on the results of a kaon scattering experiment using a carbon target [13]. Regeneration within the ^{16}O nucleus is also considered and is assumed to be proportional to its density relative to water. The fraction with regeneration is about 0.1% of the total generated $p \rightarrow \mu^+ K_L^0$ MC events.

We simulate propagation of particles and Cherenkov light production in water by custom software based on GEANT [14]. The propagation of charged pions in water is simulated using custom code based on [15] for pion momenta less than $500 \text{ MeV}/c$ and using CALOR [16] otherwise.

B. Atmospheric Neutrinos

The interactions of atmospheric neutrinos within SK pose the dominant source of background to searches for nucleon decay. For the $p \rightarrow \mu^+ K^0$ mode, the decay products of the K_L^0 and K_S^0 often include pions which can be created in atmospheric neutrino interactions. Notably, charged current multiple pion production and deep inelastic scattering processes, again with multiple pions in the final state, are backgrounds to the search presented here. Accordingly, the accurate simulation of atmospheric neutrino events in SK is essential to properly estimate the proton decay background. In this paper, the atmospheric neutrino MC is the same as used in other SK analyses [2, 17]. The primary flux is taken from the Honda model [18] and atmospheric neutrino interactions are gener-

ated within the detector using the NEUT simulator [19, 20]. Kaon regeneration is not considered in the atmospheric neutrino MC because the fraction of K^0 production in these events is negligibly small. For each of the SK run periods presented here, independent about 200 year MC samples were used to compute the background rates for the present search. Two-flavor neutrino oscillation effects with $\sin^2 2\theta_{23} = 1.0$ and $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$ are included in the background prediction. A more detailed explanation of the atmospheric neutrino MC is presented in [2, 17].

IV. DATA SET AND REDUCTION

The current data set corresponds to a 91.7 kton-years (1489.2 days) exposure from SK-I, a 49.2 kton-years (798.6 days) exposure during SK-II, and a 31.9 kton-years (518.1 days) exposure from SK-III. The data acquisition trigger threshold used in this data analysis during these periods corresponds to the energy deposited by 6 MeV electron during SK-I and SK-III and 8 MeV electron during SK-II. Most events above this threshold are cosmic ray muons or low energy backgrounds from radioactivity in detector materials. To remove these backgrounds the data are passed through several reduction stages before detailed reconstruction processes (described in Sec. V) are applied. To summarize, the starting point of the data analysis is the fully contained (FC) fiducial volume (FV) data sample, which contains events passing the following cuts:

- the number of hit PMTs in the highest charge cluster of PMTs in the OD is less than 10
- the total visible energy in the ID is greater than 30 MeV
- the reconstructed vertex's distance to the ID wall is greater than 2 m

After these cuts the FCFV event rate is about eight events per day. Non-atmospheric neutrino backgrounds are estimated to represent less than 1% of this sample. Details of the data reduction can be found in [17].

V. EVENT RECONSTRUCTION

Event reconstruction programs are applied to the FCFV sample described in the previous section. For the K_S^0 searches, the standard event reconstruction [17, 21] used in the SK atmospheric neutrino oscillation analyses and proton decay searches is used. However, relative to the previous version of this analysis [5], several improvements to the reconstruction algorithms have been made. The search for K_L^0 events makes use of new event reconstruction methods, which are explained in detail below.

The event reconstruction for the K_S^0 searches is:

- vertex reconstruction

The event vertex is initially determined by using the time of flight (TOF)-subtracted timing distribution of

hit ID PMTs assuming all light originated from a single point (point fit). An initial direction for the event is then estimated as the sum of vectors drawn from this vertex to each hit PMT and weighted by its observed charge. Defining this direction as the particle's trajectory, the distribution of observed charge as a function of the opening angle to this axis is used to determine the edge of the brightest Cherenkov ring in the event. With the ring edge in hand, the vertex position and particle direction are refined using the timing residual distribution, but assuming that PMTs within the ring are illuminated by photons generated along the particle track and other PMTs receive light generated at the event vertex.

- ring counting

Based on the reconstructed vertex, additional ring candidates in the event are searched for using a technique based on the Hough transform [22]. Possible ring candidates returned by the Hough mapping are tested using a likelihood method to determine if the existence of a second ring better describes the observed PMT hit pattern than a single ring alone. If a second ring is found, the procedure is iterated up to a total of five rings. At each step the likelihood is based on a comparison of the observed charge in the event against the expectation from the number of proposed rings. With respect to the previous analysis there have been improvements to the probability density function (PDF) for the expected charge that are used in the present analysis. More details are presented below.

- PID (e/μ separation)

After the number of rings has been determined each ring's particle type (PID) is estimated taking into account the effects of light scattering in the water and reflection off PMT surfaces. Two likelihood functions are used to separate electromagnetic shower type (e -like) rings from muon type (μ -like) rings. The first is a pattern matching algorithm that exploits topological differences in the PMT hit pattern that arise from the scattering and pair production processes an electron experiences, but that the primarily unperturbed muon does not. A second method makes use of the difference in the observed Cherenkov angle between the two particles as a result of their largely different masses. For the final estimation of a ring's PID, the two methods are combined.

- decay electron search

Electrons produced from the decay of muons in the detector can occur in the same trigger timing gate with the primary event or delayed. The search for decay electrons extends to both cases.

- momentum reconstruction

The momentum of each ring is determined using the sum of its assigned charges after correcting for the attenuation of Cherenkov light in water and the incident

angle dependence of the PMT acceptance. Depending upon the result of the PID estimation, the momentum is then assigned based on the amount of corrected charge expected for the fitted particle type. A pionic momentum (π -like) that relies on the expected Cherenkov angle as well as the total corrected charge is also used in this analysis. The time variation of the light attenuation length and the PMT gain, as measured with cosmic rays traversing the detector, is incorporated into the momentum reconstruction.

Improvements made to the single photoelectron response functions used to predict the expected charge in each PMT have led to improvements in the ring counting, PID, and momentum estimations for this analysis.

The uncertainty in the detector's energy calibration (the energy scale) is one of the most important for the proton decay searches. It is estimated by systematic studies of the differences between the absolute momenta of data and MC in several control samples. At SK these control samples are chosen to probe a variety of energies where neutrino interactions and nucleon decay searches are relevant, among which are cosmic ray muons that stop in the detector, their associated decay electrons (Fig. 1), and π^0 s produced in neutral current atmospheric neutrino interactions (Fig. 2). The uncertainty of the absolute energy scale is estimated to be less than 0.74%, 1.60%, and 2.08% for SK-I, SK-II, and SK-III, respectively. The time variation of the reconstructed momenta of these muon and electron samples during each of the SK run periods (Fig. 3) is also taken into account. Overall, the uncertainty on the energy scale is 1.1%, 1.7%, and 2.7% in SK-I, SK-II, and SK-III, respectively. Further, the directional dependence of decay electron momenta is used to estimate the asymmetry of the energy scale. During SK-I, SK-II, and SK-III, the asymmetry was estimated to be 0.6%, 0.6%, and 1.3% respectively. These errors on the SK energy scale are incorporated into the proton decay analysis as discussed in Sec. VI-B-2.

A. K_L^0 event reconstruction

The K_L^0 event reconstruction needs two vertices, one for the μ^+ candidate from the proton decay and another for particles produced in the delayed K_L^0 decay. The difference between the two vertices is used to distinguish the K_L^0 decay signal from the atmospheric neutrino background. However, the standard reconstruction described cannot by itself reconstruct two vertices. For instance, the standard ring counting algorithm uses a cut on the PMT hit timing after correcting for the time of flight taken from the initial vertex to help isolate genuine Cherenkov rings. Since the light from the particles emerging from the K_L^0 is both delayed in time and spatially separated from this initial vertex, the inclusion of this PMT timing cut degrades the performance of the ring counting algorithm on these events. Therefore, we developed a specialized reconstruction. In the first step of the K_L^0 reconstruction, the standard reconstruction algorithm is applied without making any cut on the PMT hit

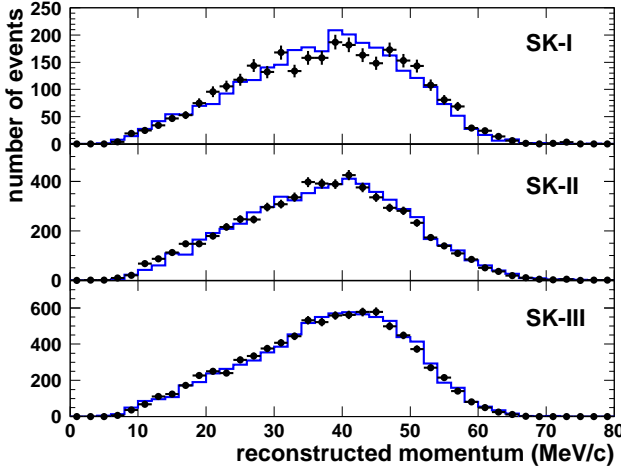


FIG. 1: The momentum distribution of decay electrons of the data (dot) and MC (solid line) for SK-I, SK-II, and SK-III from top to bottom, respectively. MC events are normalized by the number of observed data events. The mean values of the data distributions agree with those of the MC within 0.6%, 1.6%, and 0.8% for SK-I, SK-II, and SK-III, respectively.

timing during the ring counting stage. It outputs an initial vertex, the number of candidate rings, and a direction for each ring in much the same way as the standard reconstruction.

In the second step of the reconstruction [23], an event's hit PMTs are divided into two groups for each ring found by the first step. The first, called the inner domain, is a collection of hit PMTs that fall within a cone that is 10° larger than the ring's reconstructed Cherenkov angle. The second group, called the outer domain, are the remaining collection of hit PMTs that are not part of the inner domain. The charge and time information of PMTs in the outer domain are zeroed and part of the standard reconstruction is reapplied using only information from PMTs in the inner domain. At this stage the vertex reconstruction, PID, and momentum reconstruction are repeated, and the result is stored. A precise vertex fit, which adjusts the initial candidate vertex along the ring's reconstructed momentum using the expected charge distribution for a particle with the ring's new PID, is applied. The vertex resolution is about 0.3 m [17]. Finally, an algorithm designed to distinguish protons from muons [24], is applied to provide an additional PID handle. Once the μ^+ candidate from the original proton's decay is identified, this precision vertex will be identified as that of the initial decay. The secondary vertex from the K_L^0 decay, is estimated by zeroing the charge and time information of the inner domain PMTs and applying the point fit algorithm to the outer domain. Since π^\pm from the K_L^0 de-

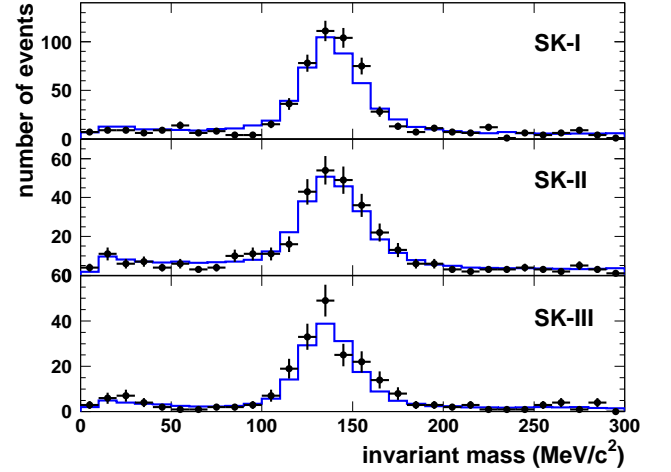


FIG. 2: Invariant mass distribution of neutrino-induced π^0 events of the observed data (dot) and the atmospheric neutrino MC events (solid line) for SK-I, SK-II, and SK-III from top to bottom, respectively. MC events are normalized by the livetime of the observed data. The peak positions of the data distributions agree with those from the MC within 0.7%, 1.3%, and 0.3% for SK-I, SK-II, and SK-III, respectively.

cay may be just above Cherenkov threshold, these pions may not appear in the detector as clear Cherenkov rings. Using the outer domain to perform the secondary vertex fit in this way incorporates light from even these particles to provide a better estimate of the point where the K_L^0 decays. These reconstructions in the second step are repeated for each ring found by the first step.

For each event, the ring with μ -like momentum closest to 326.5 MeV/c is chosen as the μ^+ candidate. A vertex separation parameter is defined as the distance between the μ^+ (primary) candidate vertex and the K_L^0 (secondary) vertex along the μ^+ candidate's momentum vector. This parameter is used to define a cut to help reduce atmospheric neutrino backgrounds and is described below. Figure 4 shows the typical correlation between the true vertex separation, extracted using MC information, and the reconstructed vertex separation for $p \rightarrow \mu^+ K_L^0$ decay MC events. A clear correlation between the two can be seen. A typical event display from one MC event showing both the primary and secondary fitted vertices appears in Fig. 5. In this case the reconstruction has correctly identified the μ^+ (thick cyan ring) and the primary and secondary vertex are represented by the blue triangle and green circle, respectively.

The difference between the reconstructed and true vertex separation is shown in Fig. 6 for proton decay events in each

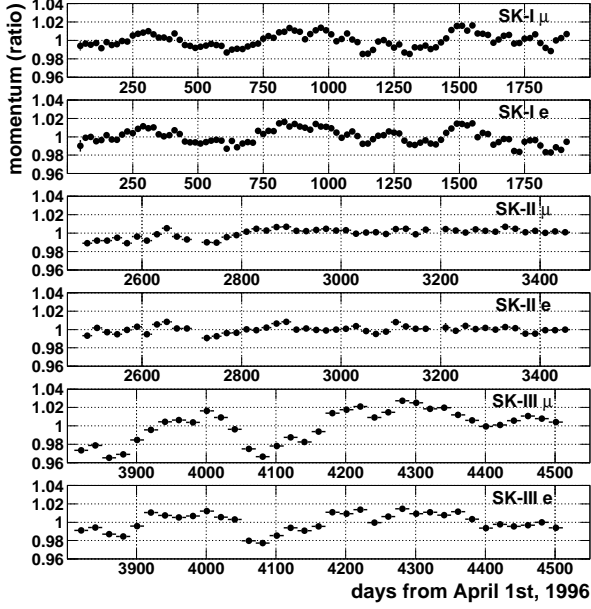


FIG. 3: The time variation of the reconstructed momentum/range of stopping muons and the reconstructed momentum of decay electrons as a function of elapsed days with respect to the mean value for SK-I, SK-II, and SK-III from top to bottom, respectively. The largest variation (RMS) among these two calibration sources during SK-I, SK-II, and SK-III was 0.88%, 0.55%, and 1.79%, respectively. The time variation was relatively larger in SK-III due to its poorer water quality.

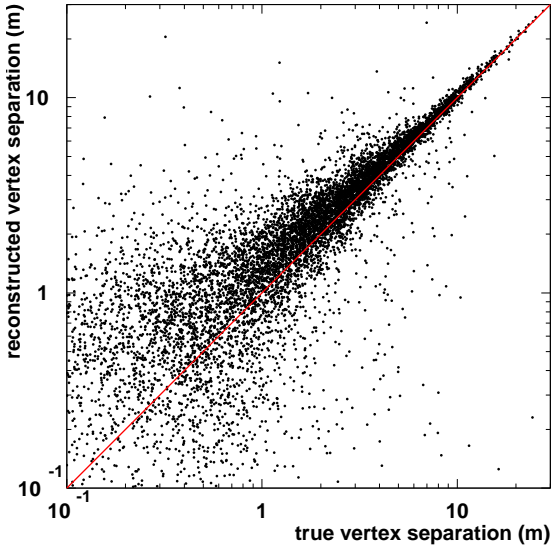


FIG. 4: Correlation between true and reconstructed vertex separations for the $p \rightarrow \mu^+ K_L^0$ decay MC events in SK-I after the event selections (D1-D5) described in Section VI-A.

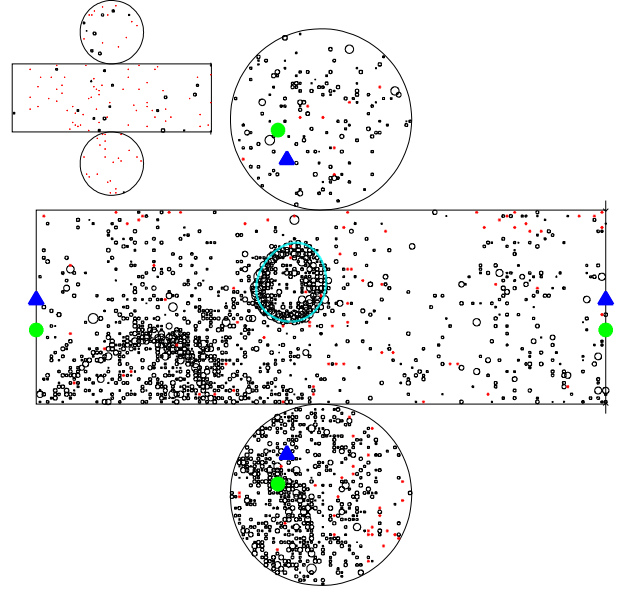


FIG. 5: Typical event display of $p \rightarrow \mu^+ K_L^0$, $K_L^0 \rightarrow \pi^+ e^+ \nu$ MC event in SK-I. The upper (lower) visible ring are from true μ^+ (e). The cyan thick circle shows the μ^+ candidate ring. The blue triangle and green circle show the reconstructed vertex position horizontally and vertically projected on the detector wall for the μ^+ and remaining particle candidates, respectively. For this event, reconstructed and true vertex separations are 6.58 m and 6.33 m, respectively.

of the SK run periods. A slight bias in this distribution, represented by the shift of the peak away from zero, is used to estimate the uncertainty coming from the vertex separation cut discussed in Sec. VI-B-2. This shift is typically $O(10)$ cm for both proton decay and atmospheric neutrino MC events. The vertex separation resolution for these two MC sets are about 0.8 m and 1.1 m, respectively. Due to the cleaner back-to-back event topology of the K_L^0 decay events, the separation resolution for the proton decay events is slightly better than that for the atmospheric neutrino events. Most of this resolution comes from the application of the point fit algorithm in determining the secondary vertex.

VI. DATA ANALYSIS

A. Event Selection

The search for $p \rightarrow \mu^+ K^0$ decay is performed by searching for decays into $\mu^+ K_S^0$ and $\mu^+ K_L^0$ separately. The FCFV events (Sec. IV) are first passed through the K_S^0 selection and failing events at the K_S^0 selection are then additionally subjected to the K_L^0 search. The K_S^0 search criterion are not changed with respect to the previous analysis [5], but are reviewed here for completeness.

To maximize the analysis' sensitivity to the K_S^0 mode, three distinct selections designed to extract events corresponding to each of the K_S^0 decay's final states are used. It should be noted

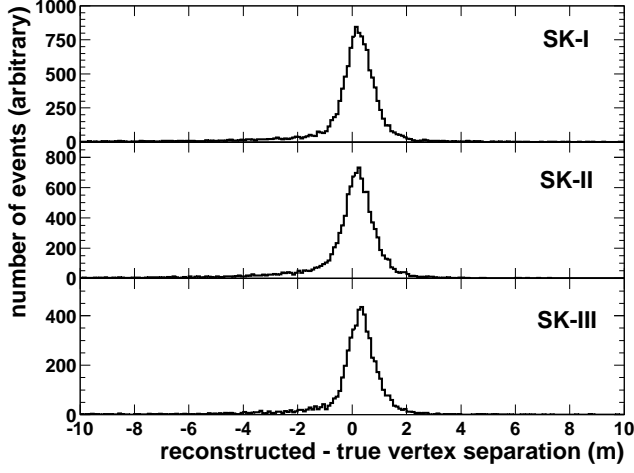


FIG. 6: Reconstructed - true vertex separation for the $p \rightarrow \mu^+ K_L^0$ decay MC events in SK-I, SK-II, and SK-III (from top to bottom), respectively, after the event selections (D1-D5) described in Section VI-A.

that by construction there is no kinematic overlap among the methods. For $K_S^0 \rightarrow \pi^0 \pi^0$ decays (30.7% branching fraction), the proton decay selection criteria are as follows:

- (A1) 3-5 rings, corresponding to the initial μ^+ and the gammas emerging from the π^0 decays
- (A2) one μ -like ring, to be identified as the μ^+ candidate, and the other rings in the event are e -like
- (A3) one Michel electron, from the decay of the μ^+
- (A4) $150 \text{ MeV}/c < p_\mu < 400 \text{ MeV}/c$
- (A5) $400 \text{ MeV}/c^2 < m_{K^0} < 600 \text{ MeV}/c^2$
- (A6) $p_p < 300 \text{ MeV}/c$
- (A7) $750 \text{ MeV}/c^2 < m_p < 1000 \text{ MeV}/c^2$

Here p_μ refers to the μ^+ candidate momentum, m_{K^0} is the reconstructed K^0 invariant mass using only the e -like rings, and p_p (m_p) is the total momentum (invariant mass) using all rings in the event. Figure 7 shows the m_p and p_p distributions after applying these criteria (A1-A5). Under the hypothesis of proton decay, initial proton momenta of up to $300 \text{ MeV}/c$ are considered in the search because the Fermi momentum of protons in ^{16}O nuclei may reach about $200 \text{ MeV}/c$. This, in addition to the possibility of missing gammas from the π^0 decay, is similarly the reason for the small lower bound on the m_p cut.

After this event selection the remaining background consists primarily of events from ν_e or ν_μ charged current (CC) multiple pion production interactions, and neutral current (NC) deep inelastic scattering processes, from the atmospheric neutrino MC. These backgrounds often have a single μ -like ring back-to-back with several e -like rings and are consistent with the expected event signature of the signal.

To search for proton decays in which the K_S^0 decays into $\pi^+ \pi^-$ (69.2% branching fraction) two different methods are used. The first method (Method 1) is designed to search for events where one of the outgoing pions does not produce a clear Cherenkov ring, for instance when its momentum is below the Cherenkov production threshold, or when it captures on a ^{16}O nucleus. The search criteria are:

- (B1) two rings
- (B2) both rings are μ -like, one from the μ^+ and another from one of the charged pions
- (B3) two Michel electrons, from the decays of the primary μ^+ and that from the charged pion
- (B4) $250 \text{ MeV}/c < p_\mu < 400 \text{ MeV}/c$
- (B5) $p_p < 300 \text{ MeV}/c$

In this method the most energetic μ -like ring is taken to be the μ^+ emerging from the initial proton decay and is assigned a μ -like momentum. On the other hand, the second energetic ring is assumed to be the charged pion and is assigned a π -like momentum. Figure 8 shows the p_μ and p_p distributions after applying these criteria (B1-B3). The second method (Method 2) searches for proton decays with $K_S^0 \rightarrow \pi^+ \pi^-$ in which all of the emerging charged particles produce Cherenkov radiation in the detector. In this case the selection cuts become:

- (C1) three rings
- (C2) one or two Michel electrons
- (C3) $450 \text{ MeV}/c^2 < m_{K^0} < 550 \text{ MeV}/c^2$
- (C4) $p_p < 300 \text{ MeV}/c$
- (C5) $750 \text{ MeV}/c^2 < m_p < 1000 \text{ MeV}/c^2$

Figure 9 shows the m_p and p_p distributions that result from applying the criteria (C1-C3). The primary background to this search arises from ν_μ CC interactions with single- or multiple-pions produced in the final state.

To search for proton decays with a K_L^0 decay the following criteria are applied:

- (D1) $500(100) \text{ pe} < \text{total charge} < 8000(3000) \text{ pe}$ in SK-I,III(SK-II),
- (D2) the number of rings without the PMT hit-timing cut > 1
- (D3) at least one μ -like ring that is neither e -like nor proton-like
- (D4) the number of Michel electrons > 0

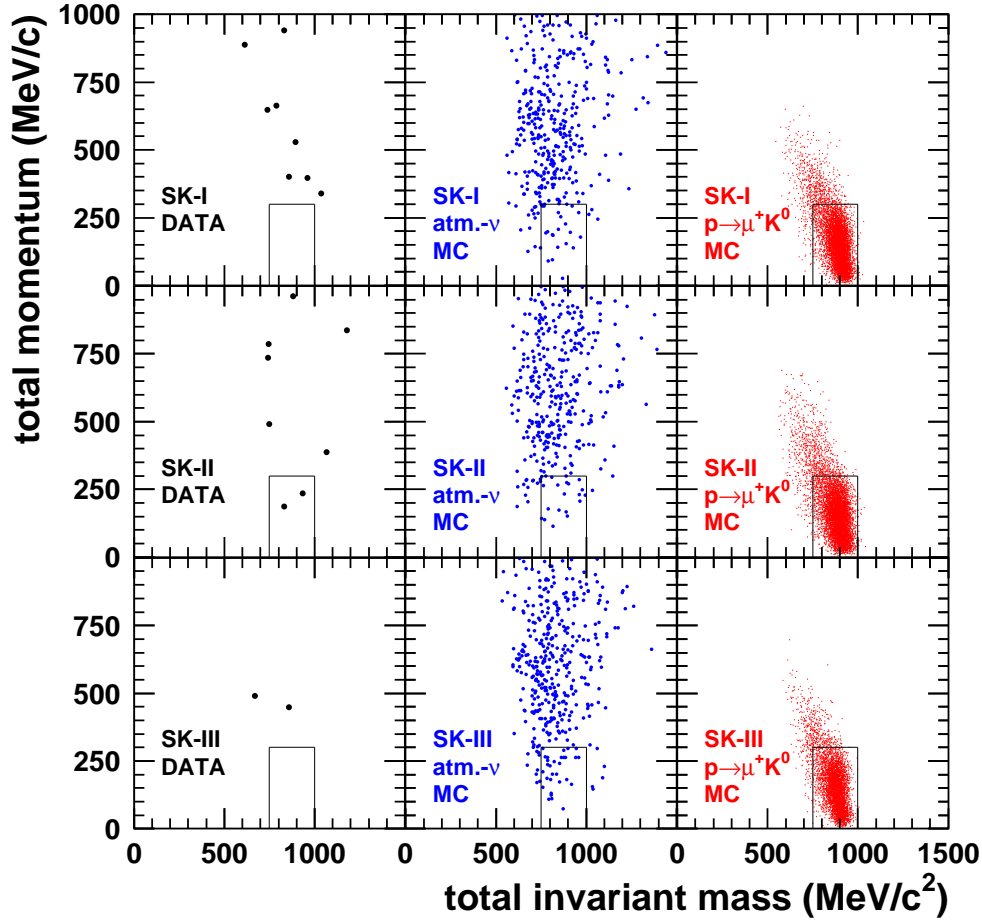


FIG. 7: Total invariant mass and momentum for events that satisfy criteria (A1-A5) in SK-I, SK-II, and SK-III from top to bottom. The box shows criteria (A6, A7). From left to right, data (1489 days, 799 days, 518 days), atmospheric neutrino MC (200 years, 172 years, 194 years), and $p \rightarrow \mu^+ K^0$ MC are shown.

- (D5) $260 \text{ MeV}/c < p_\mu < 410 \text{ MeV}/c$
- (D6) vertex separation between μ^+ candidate and K_L^0 decay is greater than 2.3 m

The μ^+ -candidate is taken to be the μ -like ring with momentum closest to $326.5 \text{ MeV}/c$. At the third cut (D3), the following criteria are required to increase purity of the μ -like rings.

In addition to requiring a μ -like classification by the standard PID, the result of the proton ID algorithm must also be μ -like. Further, the Cherenkov opening angle is required to be greater than 30° . The cut value at (D6) has been chosen to maximize this analysis' sensitivity to the proton partial lifetime based on studies of the proton decay and atmospheric neutrino MC. Figure 10 shows the vertex separation distribution after apply-

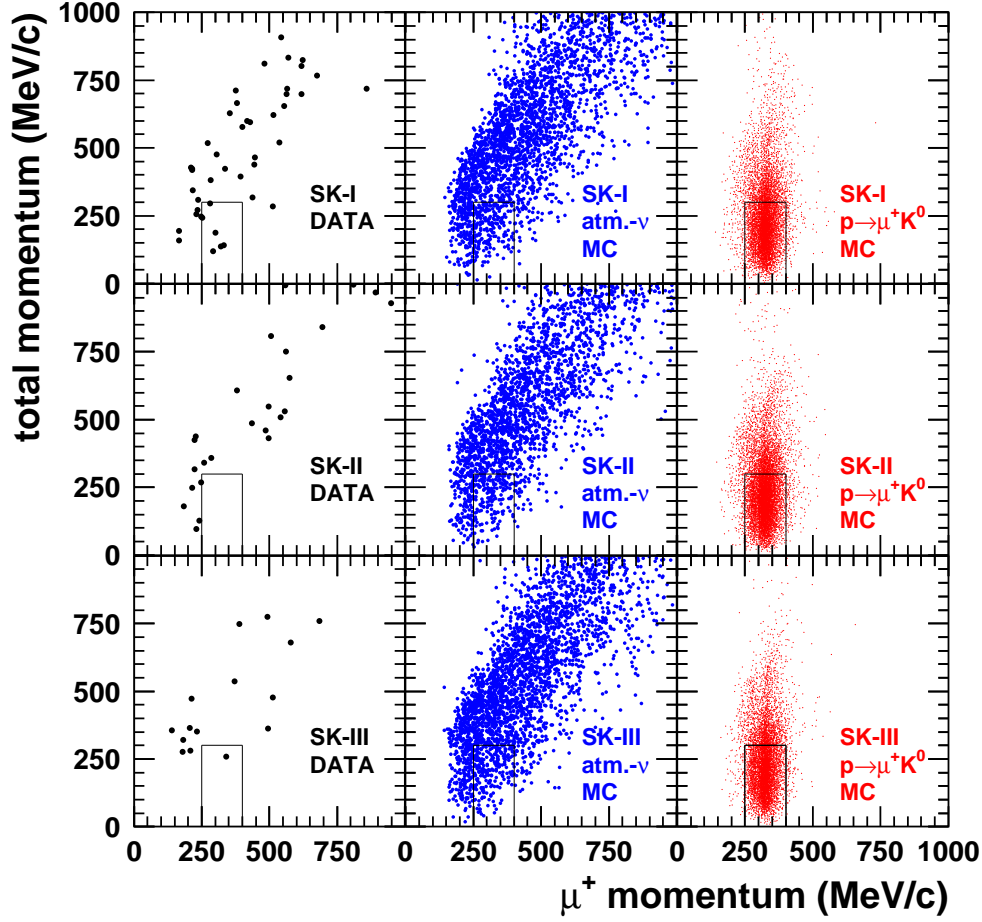


FIG. 8: μ^+ momentum and total momentum for events that satisfy criteria (B1-B3) in SK-I, SK-II, and SK-III from top to bottom. The box shows criteria (B4, B5). From left to right, data (1489 days, 799 days, 518 days), atmospheric neutrino MC (200 years, 172 years, 194 years), and $p \rightarrow \mu^+ K^0$ MC are shown.

ing criteria (D1-D5). The net decay length of the $p \rightarrow \mu^+ K_L^0$ MC is about 2 m because roughly 70% of the K_L^0 undergo hadronic interactions in the water before decaying. There is good agreement between the data and the atmospheric neutrino MC.

The dominant background sources after the event selection are primarily ν_μ CC quasi-elastic and single-pion production

interactions. In these backgrounds the recoiling proton from the neutrino interaction is above Cherenkov threshold and is selected as the μ^+ -candidate. For this reason the primary vertex can be pulled along the direction of the μ^+ candidate momentum, increasing the separation between the two reconstructed vertices. Figure 11 shows a typical event display of these backgrounds. In this particular event the reconstructed

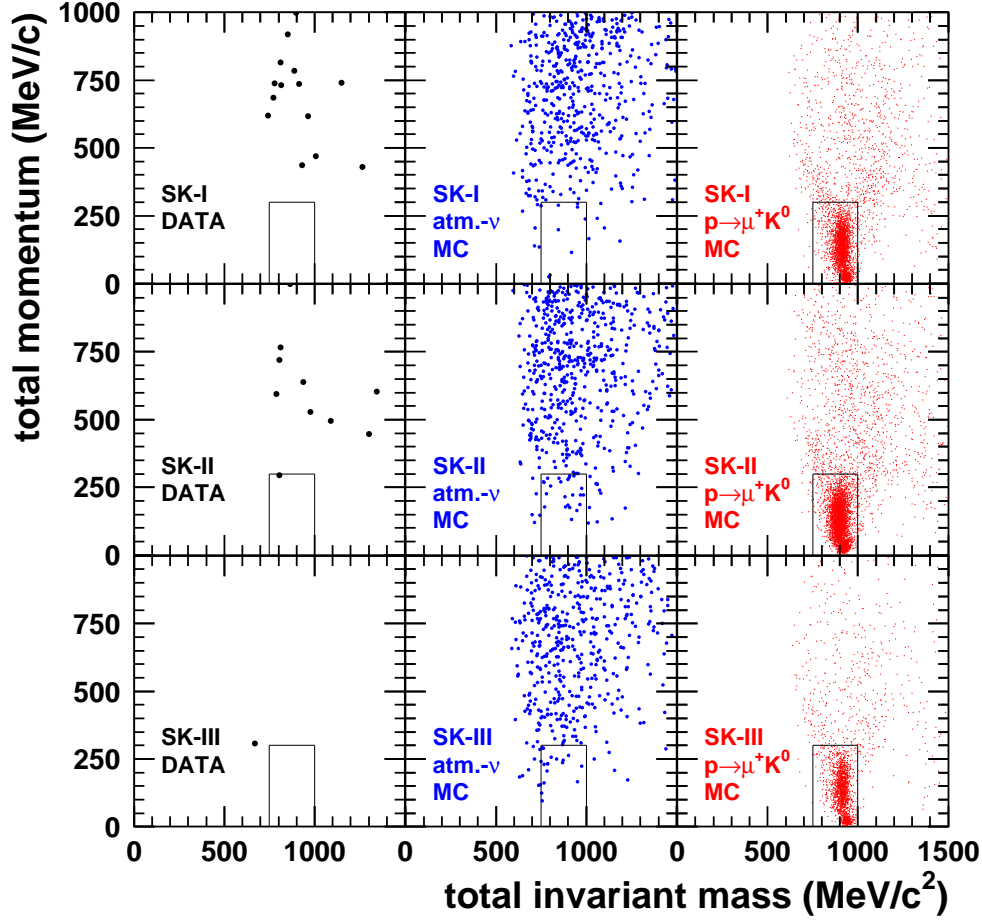


FIG. 9: Total invariant mass and total momentum for events that satisfy criteria (C1-C3) in SK-I, SK-II, and SK-III from top to bottom. The box shows criteria (C4, C5). From left to right, data (1489 days, 799 days, 518 days), atmospheric neutrino MC (200 years, 172 years, 194 years), and $p \rightarrow \mu^+ K^0$ MC are shown.

vertex separation is 3.9 m.

B. Result

The signal detection efficiency, the expected atmospheric neutrino background rate, and the number of candidate events

for each of the search methods are summarized in Table I.

The detection efficiencies in SK-II are lower than in SK-I and SK-III and their differences are at most 20% as shown in Table I. The estimated background rates of SK-I, SK-II, and SK-III are on the order of a few events and the dominant source of uncertainty is the MC statistical error as described in Sec. VI-B-2. For instance, the statistical error on the back-

detector (exposure)	search method	efficiency (%)	background	candidate	lower limit ($\times 10^{33}$ years)
SK-I (91.7 kton-years)	$K_S^0 \rightarrow \pi^0 \pi^0$	7.0 ± 0.5	0.37 ± 0.05 (4.0 ± 0.5)	0	0.92
	$K_S^0 \rightarrow \pi^+ \pi^-$ Method 1	10.6 ± 1.0	3.0 ± 0.5 (33 ± 5)	6	0.42
	$K_S^0 \rightarrow \pi^+ \pi^-$ Method 2	2.5 ± 0.2	0.12 ± 0.08 (1.3 ± 0.9)	0	0.32
	K_L^0	3.8 ± 0.7	3.5 ± 1.1 (38 ± 12)	2	0.30
SK-II (49.2 kton-years)	$K_S^0 \rightarrow \pi^0 \pi^0$	6.2 ± 0.7	0.20 ± 0.05 (4.1 ± 1.0)	2	0.19
	$K_S^0 \rightarrow \pi^+ \pi^-$ Method 1	10.3 ± 1.2	1.6 ± 0.4 (33 ± 8)	0	0.71
	$K_S^0 \rightarrow \pi^+ \pi^-$ Method 2	2.4 ± 0.2	0.23 ± 0.08 (4.7 ± 1.6)	1	0.11
	K_L^0	3.3 ± 0.6	1.4 ± 0.5 (29 ± 10)	0	0.21
SK-III (31.9 kton-years)	$K_S^0 \rightarrow \pi^0 \pi^0$	6.7 ± 0.7	0.19 ± 0.04 (6.0 ± 1.3)	0	0.30
	$K_S^0 \rightarrow \pi^+ \pi^-$ Method 1	10.3 ± 1.8	1.2 ± 0.2 (38 ± 6)	1	0.32
	$K_S^0 \rightarrow \pi^+ \pi^-$ Method 2	3.0 ± 0.2	0.09 ± 0.02 (2.8 ± 0.6)	0	0.14
	K_L^0	3.8 ± 0.7	1.3 ± 0.6 (41 ± 19)	1	0.11
SK-I+SK-II+SK-III (172.8 kton-years)	combined				1.6

TABLE I: Summary of the $p \rightarrow \mu^+ K^0$ search. Systematic errors are shown in the signal efficiencies and background rates (see Table II for more detail). The numbers in the parentheses of the background columns show the expected background rates in Megaton-years $^{-1}$.

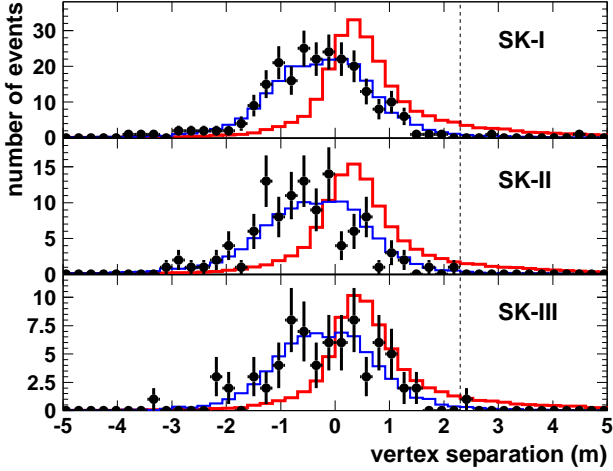


FIG. 10: Vertex separation distributions for events that satisfy criteria (D1-D5) in SK-I, SK-II, and SK-III from top to bottom. Positive values of the vertex separation indicate that the point fit vertex is separated from the μ^+ vertex in the direction opposite of the μ^+ . Data (black dot), atmospheric neutrino MC (blue thinner histogram), and $p \rightarrow \mu^+ K^0$ MC (red thicker histogram) are shown. The MC samples are normalized to data by entries. The cut value corresponding to (D6) is shown as broken line.

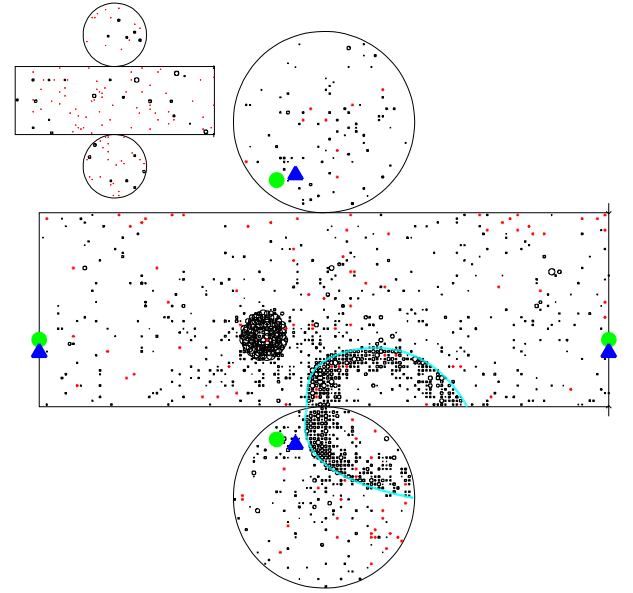


FIG. 11: Typical event display of the remaining atmospheric neutrino background MC event in the K_L^0 search in SK-I. This is from ν_μ charged current quasi-elastic interaction. The right (left) visible rings are from true proton (muon). The cyan ring shows the μ^+ candidate reconstructed ring. The blue triangle and green circle show the reconstructed vertex position horizontally and vertically projected on the detector wall for the μ^+ and remaining particle candidates, respectively.

ground in the $K_S^0 \rightarrow \pi^+ \pi^-$ Method 2 search is 20-40%.

The number of data and the expected background and signal efficiencies at each step of the event selection are compared for all four searches. For example, Figures 12 shows the K_L^0

search. After each event selection, the number of remaining events in the data is consistent with the background expectation in each of the SK run periods. The Poisson probability to observe the number of candidates after all event selections for each search was calculated. For example, the only probability smaller than 5% is seen in the SK-II $K_S^0 \rightarrow \pi^0 \pi^0$ search (2%). However, the number of candidates is smaller than the expected backgrounds in SK-I and SK-III for this search. The sums of the expected backgrounds and the number of candidates from all SK run periods for the K_S^0 and K_L^0 searches are 13.2 and 13, respectively. They are consistent and therefore we conclude that there is no evidence for proton decay found in this analysis.

All the candidate events in Table I were inspected by hand. By checking event display with the reconstructed information, all the events show Sub-GeV (visible energy is less than 1330 MeV) back-to-back multi visible rings and no obvious mis-reconstruction. For example, Figure 13 shows typical real data candidate event in the K_L^0 search. This event looks consistent with the ν_μ background where the visible proton is identified as the μ^+ candidate ring (see Figure 11).

1. Lifetime Limit

In the absence of significant excess of observed data above the background expectation we calculate a lower limit on the proton partial lifetime using a Bayesian method [25]. The calculation used here follows the one from the previous analysis [5].

The decay of the proton is assumed to follow a Poisson probability, $P(\Gamma|n_i)$, and is expressed as:

$$P(\Gamma|n_i) = \int \int \int \frac{e^{-(\Gamma\lambda_i\epsilon_i + b_i)} (\Gamma\lambda_i\epsilon_i + b_i)^{n_i}}{n_i!} P(\Gamma)P(\lambda_i)P(\epsilon_i)P(b_i)d\lambda_i d\epsilon_i db_i$$

where n_i is the number of candidate events in the i -th proton decay search ($i = 1, 2, 3$, and 4 for $K_S^0 \rightarrow \pi^0 \pi^0$, $K_S^0 \rightarrow \pi^+ \pi^-$ Method 1, $K_S^0 \rightarrow \pi^+ \pi^-$ Method 2, and K_L^0 searches, respectively, in SK-I, $i = 5-8$ in SK-II, and $i = 9-12$ in SK-III in Table I), Γ is the total decay rate, λ_i is the detector exposure, ϵ_i is the detection efficiency including the meson branching ratio, and b_i is the number of expected background events. The probability density function, $P(\Gamma)$, describing the prior expectation of decay rate is taken to be $P(\Gamma) = 1$ for $\Gamma > 0$ and zero otherwise.

Introduction of systematic error effects is done through prior probabilities for the detector exposure $P(\lambda_i)$, efficiency $P(\epsilon_i)$, and background expectation $P(b_i)$. They are all assumed to be truncated Gaussian distributions of the form,

$$P(x_i) \propto \begin{cases} \exp\left(-\frac{(x_i - x_{0,i})^2}{2\sigma_{x_i}^2}\right) & (x_i > 0) \\ 0 & (x_i \leq 0) \end{cases} \quad (x_i = \lambda_i, \epsilon_i, b_i)$$

where $\lambda_{0,i}$ (σ_{λ_i}), $\epsilon_{0,i}$ (σ_{ϵ_i}) and $b_{0,i}$ (σ_{b_i}) are the estimates (systematic errors) of the exposure, the detection efficiency, and

the background, respectively. Here $\epsilon_{0,i}$ and $b_{0,i}$ correspond to the i -th searches efficiency and background contamination, respectively. These values are summarized in Table I. The parameters σ_{ϵ_i} and σ_{b_i} correspond to the total systematic error on the signal and background composition for the i -th search. Systematic error estimations are discussed in the next section and Table II summarizes the errors for each run period and search mode. Finally, $\lambda_{0,i}$ represents the detector exposure, taken to be product of the number of target protons in the detector and the livetime of each SK run. The corresponding uncertainty on the exposure, σ_{λ_i} , is assumed to be 1%.

We calculate the lower limit of the nucleon decay rate, Γ_{limit} , using a 90% confidence level (CL) as:

$$\text{CL} = \frac{\int_{\Gamma=0}^{\Gamma_{\text{limit}}} \prod_{i=1}^N P(\Gamma|n_i) d\Gamma}{\int_{\Gamma=0}^{\infty} \prod_{i=1}^N P(\Gamma|n_i) d\Gamma}$$

where N ($= 12$) is the number of searches. The lower lifetime limit:

$$\tau/B_{p \rightarrow \mu^+ K^0} = \frac{1}{\Gamma_{\text{limit}}}$$

is set to be 1.6×10^{33} years at 90% CL. The result of the limit calculation for each search method and data taking period is shown in Table I.

2. Systematic Error

Table II summarizes the systematic errors on the $K_S^0 \rightarrow \pi^0 \pi^0$, $K_S^0 \rightarrow \pi^+ \pi^-$ Method 1, $K_S^0 \rightarrow \pi^+ \pi^-$ Method 2, and K_L^0 searches, respectively.

As for the physics simulation, following uncertainties are taken into account. In the signal efficiency, differences in the Fermi momentum modeling [8, 19] and uncertainties in the correlated decay probability [5], the $K_L^0 \rightarrow K_S^0$ regeneration probability, as well as the charged pion-nucleon cross section in water [5] are considered. The dominant systematic error sources are correlated decay and the pion-nucleon cross section. For the $K_L^0 \rightarrow K_S^0$ regeneration, the signal efficiencies for the default probability (about 0.1%) and about 0.2% or 0% (corresponding to $\pm 100\%$ error on the default probability) are compared and difference of the efficiencies is used as the systematic error (less than 1% for all the searches). Total physics simulation errors are several percent in all four searches in SK-I, SK-II, and SK-III. In the background rate, major systematic error sources used in the SK atmospheric neutrino data analyses [17]; neutrino flux, neutrino cross sections, and pion-nucleon interaction in oxygen, are taken into account and the total simulation errors are about 10-20%.

As for the SK detector, uncertainty of the event selection cut value at each event selection step is considered as well as the energy scale uncertainty. Any detector uncertainty such as light attenuation and scattering in water is taken into account in the systematic error estimations which compare the cut efficiencies between control sample data and MC. In the signal efficiency, the total detector errors are several percent in the K_S^0 searches. In the $K_S^0 \rightarrow \pi^0 \pi^0$ and $K_S^0 \rightarrow \pi^+ \pi^-$ Method 1

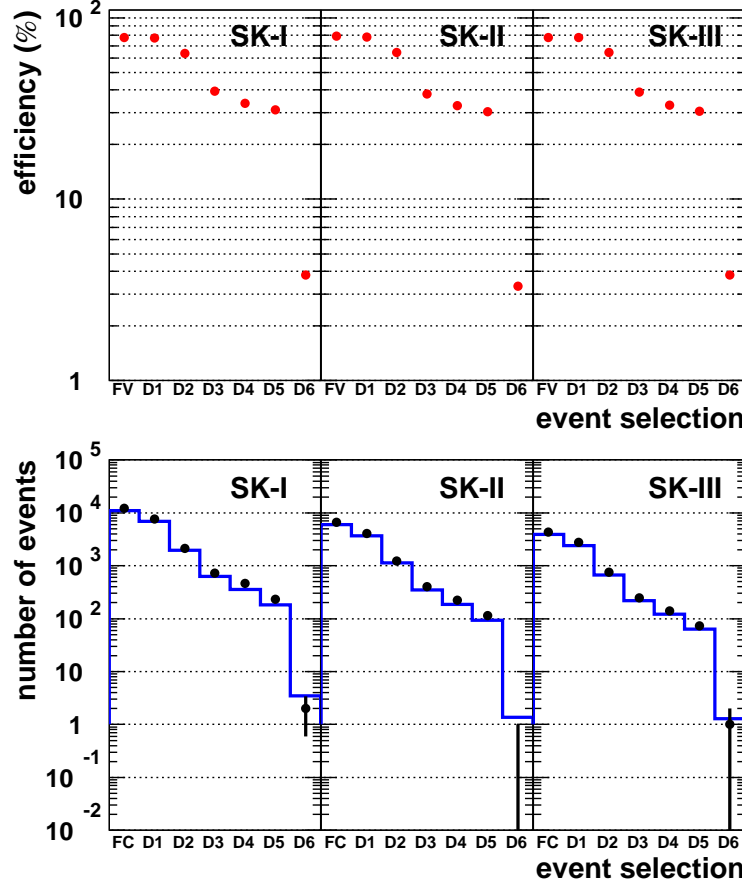


FIG. 12: The K_L^0 search; (upper plot) the signal efficiencies along event selections are shown in SK-I, SK-II, and SK-III from left to right, respectively (“FV” stands for the number of $p \rightarrow \mu^+ K^0$ MC events generated in true fiducial volume (22.5 kton). The events selected by the K_S^0 searches are excluded), (lower plot) the number of data candidates (black circle) and the expected atmospheric neutrino background rate (blue histogram) along event selections are shown in SK-I, SK-II, and SK-III from left to right, respectively (“FC” stands for the FCFV events described in Sec. IV). Only statistical errors are shown. There are no events remaining in the SK-II data after selection (D6).

searches, the errors in SK-III are larger than those of SK-I by a factor of 2~3. The larger errors in SK-III are due to its poorer water quality which resulted in larger energy scale and ring counting systematics. The total detector error in the K_L^0 search (a few 10%) is mostly due to the vertex separation. The vertex separation error is estimated by changing the cut value corresponding to the difference between true and reconstruction described in Sec. V-A. In the background rates, the dominant error (about 20-60%) comes from statistics of the atmospheric neutrino events after all the event selections in the $K_S^0 \rightarrow \pi^+ \pi^-$ Method 2 search. The other dominant error (about 20-40%) is from the vertex separation in the K_L^0 search.

C. Comparison with Previous Result

In this section we describe the differences between the present analysis and the previous result [5]. For the estimation of the signal efficiency the previous analysis only considered the $p \rightarrow \mu^+ K_S^0$ channel while the present work accounts for the entire $p \rightarrow \mu^+ K^0$ channel including the K_L^0 contribution. This contribution coupled with improvements to the event reconstruction has resulted in an efficiency increase from 5.4% to 7.0% in the $K_S^0 \rightarrow \pi^0 \pi^0$ search and from 7.0% to 10.6% in the $K_S^0 \rightarrow \pi^+ \pi^-$ Method 1 search. Signal efficiencies and the background rates for the other searches are consistent within the systematic errors of the two analyses.

Similar systematic error sources are incorporated in both

search method	detector	efficiency (%)	background (%)
		total (physics, detector)	total (physics, detector)
$K_S^0 \rightarrow \pi^0 \pi^0$	SK-I	7.5 (6.8, 3.2)	14.2 (11.0, 9.2)
	SK-II	10.8 (6.8, 8.4)	23.4 (11.5, 20.4)
	SK-III	10.0 (6.8, 7.4)	19.1 (9.5, 16.5)
$K_S^0 \rightarrow \pi^+ \pi^-$ Method 1	SK-I	9.8 (8.8, 4.2)	15.8 (15.2, 4.3)
	SK-II	11.6 (8.8, 7.6)	22.8 (16.5, 15.8)
	SK-III	17.7 (8.9, 15.3)	20.6 (16.2, 12.7)
$K_S^0 \rightarrow \pi^+ \pi^-$ Method 2	SK-I	7.5 (6.9, 2.8)	63.7 (19.8, 60.5)
	SK-II	7.1 (6.9, 1.8)	34.4 (12.7, 32.0)
	SK-III	7.9 (7.2, 3.4)	24.6 (11.6, 21.7)
K_L^0	SK-I	17.2 (9.6, 14.3)	31.9 (9.9, 30.3)
	SK-II	19.2 (9.7, 16.6)	38.9 (9.9, 37.6)
	SK-III	18.4 (9.4, 15.8)	48.4 (9.4, 47.5)

TABLE II: Summary of systematic errors. The total systematic errors on the efficiency and background are shown in the third and fourth columns, respectively. The “physics” and “detector” in the parentheses represent the systematic errors from uncertainty of the physics simulations and the SK detector, respectively.

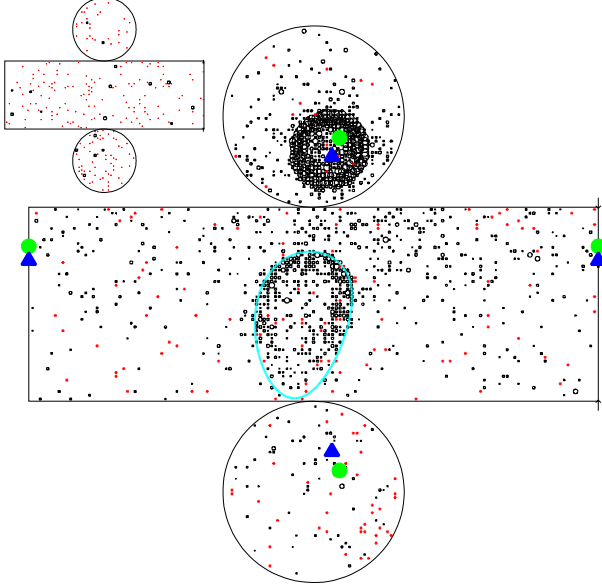


FIG. 13: Typical event display of the real data candidate event in the K_L^0 search in SK-I. The cyan ring shows the reconstructed ring edge of the μ^+ candidate ring. The blue triangle and green circle show the reconstructed vertex position horizontally and vertically projected on the detector wall for the μ^+ and remaining particle candidates, respectively. The reconstructed vertex separation for this event is 4.6 m. The reconstructed Cherenkov angle is 30.6° while the expectation from the μ -like momentum (291 MeV/c) is 37.6° .

analyses. For instance, the error on the signal efficiencies is about 10% in both. However, the systematic error on the background rate in this analysis, ranging from 20% to 60% across the searches, is improved over the previous work’s, which ranged from 40% to 80%. Most of this improvement

is derived from the smaller statistical error on the atmospheric neutrino MC sample used in the present analysis.

If the K_L^0 search is excluded from the lifetime limit computation and the data set restricted to the SK-I period, the result is slightly worse than the previous analysis, 1.1×10^{33} years compared to 1.3×10^{33} years. Despite the higher signal efficiencies and reduced systematic uncertainty on the expected background rates in this analysis, the increase in the number of observed candidate events in the $K_S^0 \rightarrow \pi^+ \pi^-$ Method 1 search degrades the lifetime limit. The three candidates found in the former analysis are also found here, but three additional events that were previously just outside of the signal region have now migrated in. Under the older reconstruction, their momenta fell slightly below the cut value of 250 MeV/c and thus failed to meet condition (B4) from Sec. VI-A. The improved reconstruction has increased their estimated momenta beyond this threshold. The μ^+ candidate momentum reconstruction has been checked using the atmospheric neutrino MC and the shift in the reconstructed momentum relative to the true momentum, and the momentum resolution are both smaller in the present work. The new result represents an improvement to the analysis.

VII. CONCLUSION

The SK $p \rightarrow \mu^+ K^0$ decay search presented in [5] has been updated to include improved event reconstruction algorithms and an additional 81.1 kton-years of data. A search for proton decay into K_L^0 has also been added. There is no significant excess of proton decay candidates found and the data remain consistent with the expected atmospheric neutrino background rates for both the $p \rightarrow \mu^+ K_S^0$ and $p \rightarrow \mu^+ K_L^0$ searches. Therefore a partial lifetime lower limit is set at $\tau/B_{p \rightarrow \mu^+ K^0} > 1.6 \times 10^{33}$ years at the 90% confidence level

using 172.8 kton-years of data. The lifetime limits obtained by the K_S^0 and K_L^0 searches alone are 1.37×10^{33} years and 0.55×10^{33} years, respectively. This result gives further constraints on relevant SUSY GUT models.

VIII. ACKNOWLEDGMENTS

We gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. The Super-Kamiokande experiment has been built and operated from funding by the Japanese Ministry of Education, Culture, Sports, Science and Technology, the United States Department of Energy, and the U.S. National Science Foundation. Some of us have been supported by funds from the Korean Research Foundation (BK21), the National Research Foundation of Korea (NRF-20110024009), the State Committee for Scientific Research in Poland (grant1757/B/H03/2008/35), the Japan Society for the Promotion of Science, and the National Natural Science Foundation of China under Grants No.10575056.

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