PROCEEDINGS OF SCIENCE

Measurement of the charge ratio and polarization of cosmic-ray muon using the tagged decay-e events in Super-Kamiokande

Yuuki Nakano,[a,*] Tomoaki Tada,[b] Hussain Kitagawa[b] and Yusuke Koshio[b] for the Super-Kamiokande collaboration

[a] *Kamioka observatory, Institute for Cosmic-Ray Research, the University of Tokyo, Higashi-Mozumi 456, Kamioka-cho, Hida-city Gifu 506-1205, Japan.*

[b] *Okayama university, Tsushima-naka 1-1-1, Kita-ku, Okayama-city Okayama 700-8530, Japan*

E-mail: ynakano@km.icrr.u-tokyo.ac.jp

Neutrinos and muons from cosmic-ray interactions in the atmosphere originate from mesons, such as pions and kaons, in air-showers. An accuracy of the absolute atmospheric neutrino flux and its flavor ratio are limited due to the uncertainty of meson productions in hadronic interaction models. In order to reduce such uncertainty, measurements of the charge ratio and the polarization of cosmic-ray muons are important as new inputs to theoretical models which simulate the atmospheric neutrino flux. In this proceedings, we present the results of the charge ratio (R) and polarization (P^{μ}_{0}) of cosmic-ray muon measurements using the decay electrons collected from 2008 September to 2022 June by the Super-Kamiokande (SK) detector. We measured muon charge ratio to be $R = 1.32 \pm 0.02$ (stat.+syst.) and the muon polarization at the production location to be $P^{\mu}_{0} = 0.52 \pm 0.01$ (stat.+syst.). The SK detector uniquely measured the polarization of cosmic-ray muons with energies more than 1 TeV at sea-level because of its underground location.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

[*] Speaker

PoS(ICRC2023)212

1. Introduction

Three-flavor neutrino mixing is generally parameterised by three mixing angles, two neutrino mass squared differences, and one CP-violating phase [1]. However, several oscillation parameters remain unknown; the mass hierarchy of Δm^2_{23}, the octant of θ_{23}, and the value of CP-violating phase. For measurements of three unknown parameters using atmospheric neutrino, a precise knowledge of the ratio of neutrinos to anti-neutrinos ($\nu/\bar{\nu}$), and their energy spectrum from meson decays are of particular importance.

The cosmic-ray muon charge ratio, which is defined as the ratio of the number of positive muons to negative muons, is related with the ratio of atmospheric neutrino to anti-neutrino. This charge ratio is expected to increase as energy increases above 100 GeV because of the large contribution of positive kaon decays at high energies [2, 3]. The left panel of Figure 1 shows the muon charge ratio expected by two theoretical models [2, 4].

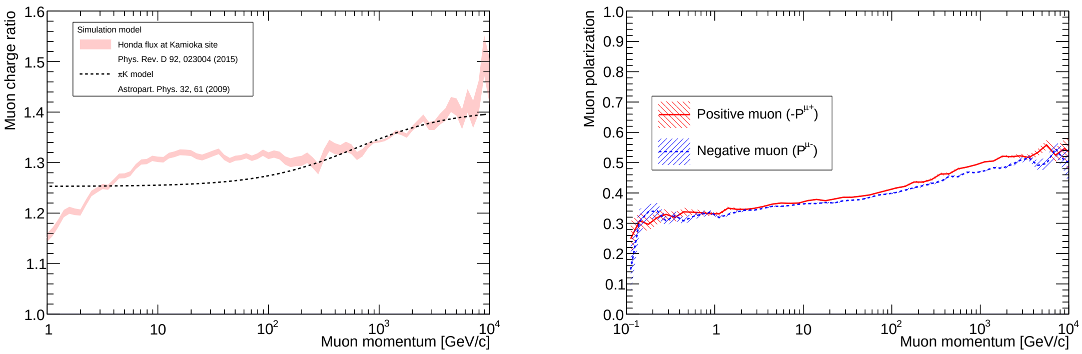

Figure 1: Left: The expected charge ratio of cosmic-ray muon from two simulations; the Honda flux model in the red band [4] and πK model in the black dashed line [2]. Right: The expected polarization of cosmic-ray muon simulated by the Honda flux model [4]. Since a positive muon has a negative helicity, the sign of polarization of positive muon in the y-axis is inverted in this figure.

In addition to the charge ratio, the polarization of cosmic-ray muons is also important to determine the energy spectrum of atmospheric neutrinos, because the kinematics of muon decays depends on their polarization [5]. The polarization of muons from kaon decays is larger than those from pion decays, because the polarization reflects the rest mass of the parent meson [6]. Hence, a measurement of the magnitude of muon polarization gives the relative contribution from kaons and pions to the muon flux [7]. The right panel of Figure 1 shows the energy dependence of the muon polarization simulated with Honda flux model [4].

Those observables are important to be measured because they can reduce the uncertainties of atmospheric neutrino simulation models by constraining hadron models at atmosphere, the energy spectrum of neutrinos, and the ratio of neutrinos to anti-neutrinos. In this proceedings, we present the current status of the measurement of charge ratio and polarization of cosmic-ray muons by analyzing the decay electron observed in the underground neutrino detector, Super-Kamiokande.

2. Super-Kamiokande detector

Super-Kamiokande (SK) is a water Cherenkov detector located underground in Japan [8]. The detector was constructed 1000 meter (m) underground, which corresponds to 2700 m water equivalent. It is a cylindrical stainless tank structure and contains 50 kiloton (ktons) of ultra-pure water. The detector is divided into two regions by the tank structure, separated optically by Tyvek sheets: one is the inner detector (ID) and the other is the outer detector (OD). The ID serves as the target volume for neutrino interactions and the OD is used to veto external cosmic-ray muons as well as γ-rays from the surrounding rock. Further details of the detector can be found elsewhere.

The SK data set is separated into seven distinct periods, from SK-I to SK-VII. From SK-IV, starting in September 2008, new front-end electronics denoted QBEEs [9] were installed. These are capable of very high speed signal processing, enabling the integration and recording of charge and time for every PMT signal. This system stores all PMT signals by opening a [−5, +35] μs window around the trigger time. This window is long enough to capture the vast majority of electrons from muon decay. In this proceedings, data collected from SK-IV to SK-VI (from 2008 September to July 2022), where the QBEE electronics are used, are presented.

3. Analysis

In this section, we briefly describe the development of the MC simulation and the procedure of the analysis to determine the charge ratio and the polarization of cosmic-ray muon by using the decay electron sample in the Super-Kamiokande detector.

3.1 Simulation

The Cherenkov light technique enable us to measure the charge ratio and polarization of cosmic-ray muon by tagging the decay electron sample in the SK detector. The muon charge ratio can be statistically determined by measuring the decay time of stopping muons since negative muons tend to have a shorter decay time due to the formation of muonic atom with Oxygen in water. For the muon polarization measurement, the opening angle distribution between the parent muon and the decay electron gives the magnitude of the muon polarization after correcting the residual polarization in water.

In the case of free muon decay the direction of the emitted electron is highly correlated with the spin of the parent muon, due to maximally violating nature of parity in the weak interaction. The expected decay rate (Γ) is described as

$$\frac{d^2\Gamma}{dx\, d\cos\theta} \sim N(x)[1 + P^{\mu}\beta(x)\cos\theta], \quad (1)$$

where $x = 2E_e/m_\mu$ is the reduced energy of the emitted electron (E_e is the total energy of the electron and m_μ is the mass of muon), θ is the angle between the spin-direction of the parent muon and that of the emitted electron momentum, $N(x)$ is the expected energy spectrum, P^{μ} is the polarization of the parent muon, and $\beta(x)$ is the degree of correlation between the electron momentum and the muon spin direction. The left panel of Figure 2 shows the energy dependence of the asymmetry parameter $\beta(x)$; the distribution of negative muon is distorted because of bound decays at $x > 0.5$. The right panel of Figure 2 shows the expected energy spectrum of emitted electrons, obtained by integrating Eq. (1) over $\cos\theta$. Those difference caused by muon's charge is considered in the MC simulation.

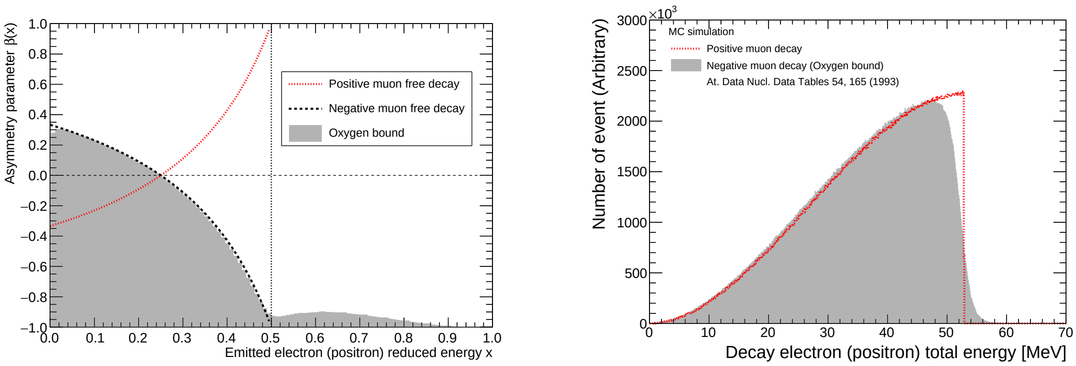

Figure 2: Left: The degree of correlation between emitted electron momentum and parent muon spin direction ($\beta(x)$ in Eq. (1)) for both free and bound muon decays, as a function of the reduced energy x [10]. The red dotted line, black dashed line, and gray filled histograms show the $\beta(x)$ parameter for free positive muon decays, free negative muon decays, and decays of negative muons bound with Oxygen, respectively. Right: The energy distribution of decay electrons, used as input for the MC simulation. The red dashed line shows the energy distribution for free decay of muons. The gray filled histogram shows the energy distribution of electrons emitted in the decay of negative muons atomically bound with Oxygen [10].

After muons lose their energy in water, some of them lose their original polarization depending on their charge by forming muonium (or muonic atom) for positive (negative) muons. De-polarization mechanisms before the muon decay affect positive and negative muons differently, so each must consider separately in the MC simulation. Table 1 summarizes the probability to keep the original polarization in water[1].

Table 1: Summary of probabilities for keeping the original polarization of positive and negative muon in water. The combined value is calculated by taking the weighted mean of measured results.

Muon charge	Probability [%]	Reference
Positive	71.8 ± 0.7	Ref. [11–13]
Negative	5.2 ± 0.4	Ref. [14–16]

3.2 Chi-square definition

To determine the charge ratio and polarization from the observed data, the decay times of tagged decay electrons, the energy spectra of tagged decay electrons, and the $\cos\theta$ distribution between the direction of incoming cosmic-ray muons and that of emitted decay electrons are simultaneously fit to the distributions derived from the MC simulation. The definition of total chi-square (χ^2_{Total}) is

$$\chi^2_{\mathrm{Total}}\,(R, P^{\mu}_{0}) = \chi^2_{\mathrm{Time}} + \chi^2_{\mathrm{Energy}} + \chi^2_{\cos\theta}, \tag{2}$$

[1]The detail of de-polarization mechanisms is omitted in this proceedings due to the page limit

where χ^2 is chi-square for each distribution, R is the given charge ratio, P_0^μ is the polarization of cosmic-ray muons at the production site. We assumed that the magnitude of polarization of positive and negative muons are equal while the sign is inverted ($P_0^\mu = -P_0^{\mu^+} = P_0^{\mu^-}$) because of low residual polarization of negative muon as listed in Table 1. The χ^2 for each distribution are defined as,

$$\begin{cases} \chi^2_{\text{Time}} = \sum_i^{n_{\text{Time}}} \frac{\left(N_i^{\text{Data}} - N_i^{\text{MC}}\right)^2}{(\sigma_i^{\text{Data}})^2 + (\sigma_i^{\text{MC}})^2 + (\sigma_i^{\text{Syst.}})^2}, \\ \chi^2_{\cos\theta} = \sum_i^{n_{\cos\theta}} \frac{\left(N_i^{\text{Data}} - N_i^{\text{MC}}\right)^2}{(\sigma_i^{\text{Data}})^2 + (\sigma_i^{\text{MC}})^2 + (\sigma_i^{\text{Syst.}})^2}, \\ \chi^2_{\text{Energy}} = \sum_i^{n_{\text{Energy}}} \frac{\left(N_i^{\text{Data}} - N_i^{\text{MC}}\right)^2}{(\sigma_i^{\text{Data}})^2 + (\sigma_i^{\text{MC}})^2} + \left(\frac{1-p}{\sigma_i^{\text{E-scale}}}\right)^2, \end{cases} \tag{3}$$

where N_i^{Data} (N_i^{MC}) is the number of selected events in i-th bin of the observed data (MC) distribution, n is the number of bins, σ_i^{Data} (σ_i^{MC}) is the statistical uncertainty on each bin of the observed data (MC), and $\sigma_i^{\text{Syst.}}$ is the systematic uncertainty on each bin, respectively. Since the energy scale of decay electrons affects the value of χ^2_{Energy}, the pull term is introduced only for χ^2_{Energy}, where $\sigma_i^{\text{E-scale}}$ is the systematic uncertainty of the energy scale.

4. Results

In this section, the measurement results by the SK detector are reported and compared with other past experimental results.

4.1 Results from the Super-Kamiokande

We calculated the χ^2 defined in Eq. (2) and then extracted the difference between each value and the minimum value of χ^2, which is expressed as $\Delta\chi^2(R, P_0^\mu) = \chi^2(R, P_0^\mu) - \chi^2_{\text{Min}}$, where χ^2_{Min} is the minimum value of χ^2. Figure 3 shows the result of $\Delta\chi^2$ calculation using SK-IV, SK-V, and SK-VI data sets. The measured charge ratio and polarization among three different data set are consistent within their uncertainties. By combining the results from three different SK phases, we determined the charge ratio and the polarization as $R = 1.32 \pm 0.02$ (stat.+syst.), and $P_0^\mu = 0.52 \pm 0.01$ (stat.+syst.), respectively.

4.2 Comparison with other experimental results

The charge ratio and polarization of cosmic-ray muon have been experimentally measured at the various locations. Figure 4 shows the comparison of the charge ratio in the left panel and the polarization of cosmic-ray muons in the right panel. The measured charge ratio is consistent with the expectation derived from two simulations within 2σ of estimated uncertainty.

The polarization has been mainly measured below 15 GeV by apparatus on ground [17, 22–28] while the SK detector, as well as the Kamiokande-II detector [17], uniquely measured the polarization of cosmic-ray muons with energies more than 1 TeV at sea-level because of its underground location. This measurement provides a new constraint on the hadronic interaction models for atmospheric neutrino flux, in particular the contribution of kaon decay in the neutrino production.

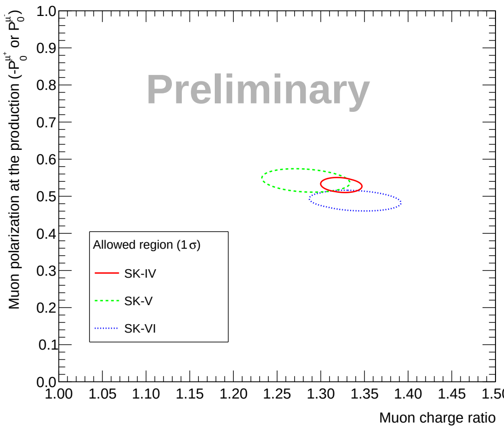

Figure 3: The allowed regions of the charge ratio and the polarization at the production using SK-IV (red solid), SK-V (green dashed), and SK-VI (blue dotted) data sets, where total livetime of each sample are 2970.1 days, 379.2 day, and 560.6 days, respectively.

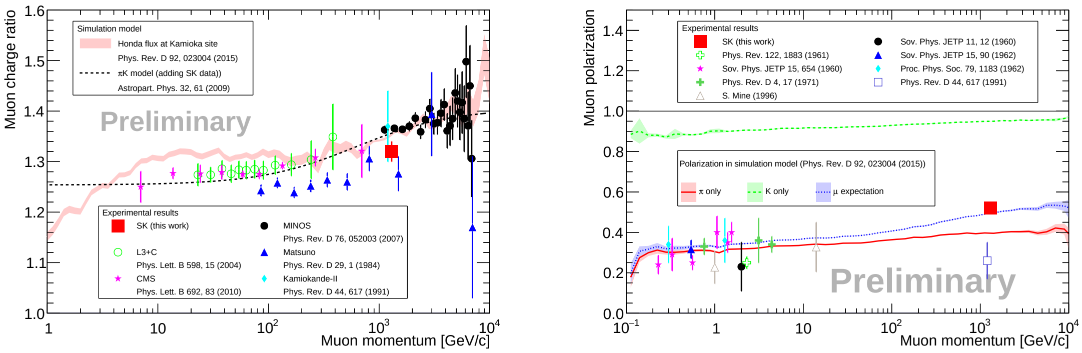

Figure 4: Left: The muon charge ratio as a function of the muon energy together with the expectations from simulation models. The red square point shows the SK's data and other symbols with different colors show the experimental data measured by other groups [17–21]. Right: The experimental data of the polarization of the cosmic-ray muon as a function of the muon energy. The red square point shows the SK's data and other symbols with different colors show the experimental data measured by other groups [17, 22–28]. Red solid and green dashed lines with band show the expected muon's polarization from π decay only and K decay only. The blue line shows the expected muon's polarization.

5. Summary

The energy spectrum of atmospheric neutrinos reflects the charge ratio and polarization of cosmic-ray muons because of their origin. For providing new inputs for atmospheric neutrino simulations, the charge ratio and the muon polarization of ciosmic-ray muons are experimentally measured in the SK detector. The muon charge ratio is measured through the analysis of the decay curve of stopping muons and found to be $R = 1.32 \pm 0.02$ (stat.+syst.). This result is in agreement with past measurements at Kamiokande-II at the almost same depth within their uncertainties. The polarization of the cosmic-ray muon is also measured by evaluating the angle between the parent muon and the decay electron. The magnitude of the cosmic-ray muon polarization at the production is obtained to be $P_0^{\mu} = 0.52 \pm 0.01$ (stat.+syst.).

Acknowledgments

We gratefully acknowledge cooperation of the Kamioka Mining and Smelting Company. The Super-Kamiokande experiment was built and has been operated with funding from the Japanese Ministry of Education, Science, Sports and Culture, and the U.S. Department of Energy. This work is supported by MEXT KAKENHI Grant Number 21K13942.

References

[1] Z. Maki, M. Nakagawa and S. Sakata, *Remarks on the unified model of elementary particles*, *Prog. Theor. Phys.* **28** (1962) 870.

[2] P.A. Schreiner, J. Reichenbacher and M.C. Goodman, *Interpretation of the Underground Muon Charge Ratio*, *Astropart. Phys.* **32** (2009) 61 [0906.3726].

[3] T.K. Gaisser, *Spectrum of cosmic-ray nucleons, kaon production, and the atmospheric muon charge ratio*, *Astropart. Phys.* **35** (2012) 801 [1111.6675].

[4] M. Honda, M. Sajjad Athar, T. Kajita, K. Kasahara and S. Midorikawa, *Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model*, *Phys. Rev. D* **92** (2015) 023004 [1502.03916].

[5] P. Lipari, *Lepton spectra in the earth's atmosphere*, *Astropart. Phys.* **1** (1993) 195.

[6] S. Hayakawa, *Polarization of Cosmic-Ray μ Mesons: Theory*, *Phys. Rev.* **108** (1957) 1533.

[7] J.L. Osborne, *Cosmic-ray muon polarization studies of the K/π ratio*, *Nuovo Cim.* **32** (1964) 816.

[8] The Super-Kamiokande collaboration collaboration, *The Super-Kamiokande detector*, *Nucl. Instrum. Meth. A* **501** (2003) 418.

[9] H. Nishino, K. Awai, Y. Hayato, S. Nakayama, K. Okumura, M. Shiozawa et al., *High-speed charge-to-time converter ASIC for the Super-Kamiokande detector*, *Nucl. Instrum. Meth. A* **610** (2009) 710 [0911.0986].

[10] R. Watanabe, K. Muto, T. Oda, T. Niwa, H. Ohtsubo, R. Morita et al., *Asymmetry and Energy Spectrum of Electrons in Bound-Muon Decay*, *At. Data Nucl. Data Tables* **54** (1993) 165.

[11] R.A. Swanson, *Depolarization of Positive Muons in Condensed Matter*, *Phys. Rev.* **112** (1958) 580.

[12] D. Walker, Y. Jean and D. Fleming, *Muonium atoms and intraspur processes in water*, *J. Chem. Phys.* **70** (1978) 4534.

[13] P. Percival, E. Roduner and H. Fischer, *Radiolysis effects in muonium chemistry*, *Chem. Phys.* **32** (1978) 353.

[14] J. Buckle, J. Kane, R. Siegel and R. Wetmore, *Negative-Muon Depolarization in low-Z Elements and Hydrogen Compounds*, *Phys. Rev. Lett.* **20** (1968) 705.

[15] A.A. Dzhuraev, V.S. Evseev, Y.V. Obukhov and V.S. Roganov, *Depolarization of Negative Muons in Water and in Aqueous Solutions*, *Sov. Phys. JTEP* **35** (1972) 1156.

[16] A.A. Dzhuraev, V.S. Evseev, Y.V. Obukhov and V.S. Roganov, *Depolarization of negative muons in condensed molecular media*, *Sov. Phys. JTEP* **39** (1974) 207.

[17] The Kamiokande collaboration collaboration, *Measurements of the charge ratio and polarization of 1.2-TeV/c cosmic ray muons with the KAMIOKANDE-II detector*, *Phys. Rev. D* **44** (1991) 617.

[18] The CMS collaboration collaboration, *Measurement of the Charge Ratio of Atmospheric Muons with the CMS Detector*, *Phys. Lett. B* **692** (2010) 83 [1005.5332].

[19] The L3 collaboration collaboration, *Measurement of the atmospheric muon spectrum from 20-GeV to 3000-GeV*, *Phys. Lett. B* **598** (2004) 15 [hep-ex/0408114].

[20] The MINOS collaboration collaboration, *Measurement of the atmospheric muon charge ratio at TeV energies with MINOS*, *Phys. Rev. D* **76** (2007) 052003 [0705.3815].

[21] S. Matsuno et al., *COSMIC RAY MUON SPECTRUM UP TO 20-TEV AT 89-degrees ZENITH ANGLE*, *Phys. Rev. D* **29** (1984) 1.

[22] N. Kocharyan, Z. Kirakosyan, E. Sharoyan and A. Pikalov, *POLARIZATION OF HIGH ENERGY μ^+ MESONS IN COSMIC RAYS*, *Sov. Phys. JETP* **11** (1960) 12.

[23] C. Johnshon, *Polarization of Cosmic-Ray Muons at Sea Level*, *Phys. Rev.* **122** (1961) 1883.

[24] A. Alikhanyan, T. Astiani and E. Matevosyan, *INVESTIGATION OF THE POLARIZATION OF COSMIC-RAY μ MESONS*, *Sov. Phys. JTEP* **15** (1962) 90.

[25] B. Dolgoshein, B. Luchkov and V. Ushakov, *Polarization of Low-Energy Cosmic Ray Muons at Sea Level*, *Sov. Phys. JTEP* **15** (1962) 654.

[26] S. Sen Gupta and M. Sinhat, *Decay Asymmetry of Cosmic Ray Muons*, *Proc. Phys. Soc.* **79** (1962) 1183.

[27] R. Turner, C. Ankenbrandt and R. Larsen, *Polarization of Cosmic-Ray Muon*, *Phys. Rev. D* **4** (1971) 17.

[28] S. Mine, *Systematic measurement of the spin polarization of the cosmic ray muons*, Ph.D. thesis, The university of Tokyo, 1996.

Full Authors List: Super-Kamiokande Collaboration

K. Abe,[1,46] C. Bronner,[1] Y. Hayato,[1,46] K. Hiraide,[1,46] K. Hosokawa,[1] K. Ieki,[1,46] M. Ikeda,[1,46] J. Kameda,[1,46] Y. Kanemura,[1] R. Kaneshima,[1] Y. Kashiwagi,[1] Y. Kataoka,[1,46] S. Miki,[1] S. Mine,[1,6] M. Miura,[1,46] S. Moriyama,[1,46] Y. Nakano,[1] M. Nakahata,[1,46] S. Nakayama,[1,46] Y. Noguchi,[1] K. Sato,[1] H. Sekiya,[1,46] H. Shiba,[1] K. Shimizu,[1] M. Shiozawa,[1,46] Y. Sonoda,[1] Y. Suzuki,[1] A. Takeda,[1,46] Y. Takemoto,[1,46] H. Tanaka,[1,46] T. Yano,[1] S. Han,[2] T. Kajita,[2,46,22] K. Okumura,[2,46] T. Tashiro,[2] T. Tomiya,[2] X. Wang,[2] S. Yoshida,[2] P. Fernandez,[3] L. Labarga,[3] N. Ospina,[3] B. Zaldivar,[3] B. W. Pointon,[5,49] E. Kearns,[4,46] J. L. Raaf,[4] L. Wan,[4] T. Wester,[4] J. Bian,[6] N. J. Griskevich,[6] S. Locke,[6] M. B. Smy,[6,46] H. W. Sobel,[6,46] V. Takhistov,[6,24] A. Yankelevich,[6] J. Hill,[7] S. H. Lee,[8] D. H. Moon,[8] R. G. Park,[8] B. Bodur,[9] K. Scholberg,[9,46] C. W. Walter,[9,46] A. Beauchêne,[10] O. Drapier,[10] A. Giampaolo,[10] Th. A. Mueller,[10] A. D. Santos,[10] P. Paganini,[10] B. Quilain,[10] T. Nakamura,[11] J. S. Jang,[12] L. N. Machado,[13] J. G. Learned,[14] K. Choi,[15] N. Iovine,[15] S. Cao,[16] L. H. V. Anthony,[17] D. Martin,[17] N. W. Prouse,[17] M. Scott,[17] A. A. Sztuc,[17] Y. Uchida,[17] V. Berardi,[18] M. G. Catanesi,[18] E. Radicioni,[18] N. F. Calabria,[19] A. Langella,[19] G. De Rosa,[19] G. Collazuol,[20] F. Iacob,[20] M. Mattiazzi,[20] L. Ludovici,[21] M. Gonin,[22] G. Pronost,[22] C. Fujisawa,[23] Y. Maekawa,[23] Y. Nishimura,[23] R. Okazaki,[23] R. Akutsu,[24] M. Friend,[24] T. Hasegawa,[24] T. Ishida,[24] T. Kobayashi,[24] M. Jakkapu,[24] T. Matsubara,[24] T. Nakadaira,[24] K. Nakamura,[24,46] Y. Oyama,[24] K. Sakashita,[24] T. Sekiguchi,[24] T. Tsukamoto,[24] N. Bhuiyan,[25] G. T. Burton,[25] F. Di Lodovico,[25] J. Gao,[25] A. Goldsack,[25] T. Katori,[25] J. Migenda,[25] Z. Xie,[25] S. Zsoldos,[25,46] A. T. Suzuki,[26] Y. Takagi,[26] Y. Takeuchi,[26,46] J. Feng,[27] L. Feng,[27] J. R. Hu,[27] Z. Hu,[27] T. Kikawa,[27] M. Mori,[27] T. Nakaya,[27,46] R. A. Wendell,[27,46] K. Yasutome,[27] S. J. Jenkins,[28] N. McCauley,[28] P. Mehta,[28] A. Tarant,[28] Y. Fukuda,[29] Y. Itow,[30,31] H. Menjo,[30] K. Ninomiya,[30] J. Lagoda,[32] S. M. Lakshmi,[32] M. Mandal,[32] P. Mijakowski,[32] Y. S. Prabhu,[32] J. Zalipska,[32] M. Jia,[33] J. Jiang,[33] C. K. Jung,[33] M. J. Wilking,[33] C. Yanagisawa,[33,2] M. Harada,[34] Y. Hino,[34] H. Ishino,[34] Y. Koshio,[34,46] F. Nakanishi,[34] S. Sakai,[34] T. Tada,[34] T. Tano,[34] T. Ishizuka,[35] G. Barr,[36] D. Barrow,[36] L. Cook,[36,46] S. Samani,[36] D. Wark,[36,41] A. Holin,[37] F. Nova,[37] B. S. Yang,[38] J. Y. Yang,[38] J. Yoo,[38] J. E. P. Fannon,[39] L. Kneale,[39] M. Malek,[39] J. M. McElwee,[39] M. D. Thiesse,[39] L. F. Thompson,[39] S. T. Wilson,[39] H. Okazawa,[40] S. B. Kim,[42] E. Kwon,[42] J. W. Seo,[42] I. Yu,[42] A. K. Ichikawa,[43] K. D. Nakamura,[43] S. Tairafune,[43] K. Nishijima,[44] A. Eguchi,[45] K. Nakagiri,[45] Y. Nakajima,[45,46] S. Shima,[45] N. Taniuchi,[45] E. Watanabe,[45] M. Yokoyama,[45,46] P. de Perio,[46] S. Fujita,[46] K. Martens,[46] K. M. Tsui,[46] M. R. Vagins,[46,6] J. Xia,[46] S. Izumiyama,[47] M. Kuze,[47] R. Matsumoto,[47] M. Ishitsuka,[48] H. Ito,[48] Y. Ommura,[48] N. Shigeta,[48] M. Shinoki,[48] K. Yamauchi,[48] T. Yoshida,[48] R. Gaur,[49] V. Gousy-Leblanc,[49,3] M. Hartz,[49] A. Konaka,[49] X. Li,[49] S. Chen,[50] B. D. Xu,[50] B. Zhang,[50] M. Posiadala-Zezula,[51] S. B. Boyd,[52] R. Edwards,[52] D. Hadley,[52] M. Nicholson,[52] M. O'Flaherty,[52] B. Richards,[52] A. Ali,[53,49] B. Jamieson,[53] S. Amanai,[54] Ll. Marti,[54] A. Minamino,[54] and S. Suzuki[54]

[1]Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu 506-1205, Japan
[2]Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
[3]Department of Theoretical Physics, University Autonoma Madrid, 28049 Madrid, Spain
[4]Department of Physics, Boston University, Boston, MA 02215, USA
[5]Department of Physics, British Columbia Institute of Technology, Burnaby, BC, V5G 3H2, Canada
[6]Department of Physics and Astronomy, University of California, Irvine, Irvine, CA 92697-4575, USA
[7]Department of Physics, California State University, Dominguez Hills, Carson, CA 90747, USA
[8]Institute for Universe and Elementary Particles, Chonnam National University, Gwangju 61186, Korea
[9]Department of Physics, Duke University, Durham NC 27708, USA
[10]Ecole Polytechnique, IN2P3-CNRS, Laboratoire Leprince-Ringuet, F-91120 Palaiseau, France
[11]Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan
[12]GIST College, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea
[13]School of Physics and Astronomy, University of Glasgow, Glasgow, Scotland, G12 8QQ, United Kingdom
[14]Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA
[15]Institute for Basic Science (IBS), Daejeon, 34126, Korea
[16]Institute For Interdisciplinary Research in Science and Education, ICISE, Quy Nhon, 55121, Vietnam
[17]Department of Physics, Imperial College London, London, SW7 2AZ, United Kingdom
[18]Dipartimento Interuniversitario di Fisica, INFN Sezione di Bari and Università e Politecnico di Bari, I-70125, Bari, Italy
[19]Dipartimento di Fisica, INFN Sezione di Napoli and Università di Napoli, I-80126, Napoli, Italy
[20]Dipartimento di Fisica, INFN Sezione di Padova and Università di Padova, I-35131, Padova, Italy
[21]INFN Sezione di Roma and Università di Roma "La Sapienza", I-00185, Roma, Italy
[22]ILANCE, CNRS - University of Tokyo International Research Laboratory, Kashiwa, Chiba 277-8582, Japan
[23]Department of Physics, Keio University, Yokohama, Kanagawa, 223-8522, Japan
[24]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
[25]Department of Physics, King's College London, London, WC2R 2LS, UK
[26]Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan
[27]Department of Physics, Kyoto University, Kyoto, Kyoto 606-8502, Japan
[28]Department of Physics, University of Liverpool, Liverpool, L69 7ZE, United Kingdom
[29]Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan

[2]also at BMCC/CUNY, Science Department, New York, New York, 1007, USA.

[3]also at University of Victoria, Department of Physics and Astronomy, PO Box 1700 STN CSC, Victoria, BC V8W 2Y2, Canada.

[30]Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Aichi 464-8602, Japan
[31]Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Aichi 464-8602, Japan
[32]National Centre For Nuclear Research, 02-093 Warsaw, Poland
[33]Department of Physics and Astronomy, State University of New York at Stony Brook, NY 11794-3800, USA
[34]Department of Physics, Okayama University, Okayama, Okayama 700-8530, Japan
[35]Media Communication Center, Osaka Electro-Communication University, Neyagawa, Osaka, 572-8530, Japan
[36]Department of Physics, Oxford University, Oxford, OX1 3PU, United Kingdom
[37]Rutherford Appleton Laboratory, Harwell, Oxford, OX11 0QX, UK
[38]Department of Physics, Seoul National University, Seoul 151-742, Korea
[39]Department of Physics and Astronomy, University of Sheffield, S3 7RH, Sheffield, United Kingdom
[40]Department of Informatics in Social Welfare, Shizuoka University of Welfare, Yaizu, Shizuoka, 425-8611, Japan
[41]STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory, Warrington, OX11 0QX, United Kingdom
[42]Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea
[43]Department of Physics, Faculty of Science, Tohoku University, Sendai, Miyagi, 980-8578, Japan
[44]Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
[45]Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
[46]Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba 277-8583, Japan
[47]Department of Physics,Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan
[48]Department of Physics, Faculty of Science and Technology, Tokyo University of Science, Noda, Chiba 278-8510, Japan
[49]TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T2A3, Canada
[50]Department of Engineering Physics, Tsinghua University, Beijing, 100084, China
[51]Faculty of Physics, University of Warsaw, Warsaw, 02-093, Poland
[52]Department of Physics, University of Warwick, Coventry, CV4 7AL, UK
[53]Department of Physics, University of Winnipeg, MB R3J 3L8, Canada
[54]Department of Physics, Yokohama National University, Yokohama, Kanagawa, 240-8501, Japan