20th Anniversary of Super-Kamiokande

June 17, 2016

Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo
Super-Kamiokande Collaboration
Preface はじめに

Twenty years have passed since we started the Super-Kamiokande (SK) experiment on April 1st, 1996. There have been several phases of the experiment and many discoveries over those 20 years. At the time SK started, the solar neutrino puzzle as seen by Homestake and Kamiokande and the atmospheric neutrino anomaly as seen by Kamiokande and RNB were important unresolved problems in particle physics. In 1998, SK discovered that the atmospheric neutrino anomaly was due to neutrino oscillations. Then, in 2001, by comparing SK solar neutrino data with that of the SNO experiment in Canada, it was shown that the solar neutrino problem was due to solar neutrino oscillations. Around the same time, the world’s first long-baseline accelerator neutrino experiment, which centered on Super-Kamiokande, was started. The K2K (KEK to Kamioka) experiment began in 1999 and in 2002 confirmed the existence of atmospheric neutrino oscillations using Kamland neutrinos. Later, the T2K (Tokai to Kamioka) experiment, which began in 2008, discovered the three-neutrino appearance phenomenon in 2011, thereby establishing the third type of neutrino oscillation, using a tunnel neutrino beam. Recently, the oscillation-induced appearance of tau neutrinos has been observed in Super-Kamiokande using atmospheric neutrino events collected over many years. In addition, extended observation of solar neutrinos has established a difference in the daytime and nighttime solar neutrino fluxes due to the effects of the Earth’s matter. For these reasons it would be no exaggeration to say that these 20 years were a period in which Super-Kamiokande spearheaded the revolution in neutrino oscillations.

Up until this point, research at SK has been mainly focused on the investigation of the nature of the neutrino as an elementary particle. However, SK is also sensitive to atmospheric neutrinos and through this has not been a supernova explosion within our galaxy in the last 20 years, if one were to occur, SK would detect many thousands of neutrino events and would be able to reveal the details of the star’s explosion mechanism. Through future improvements to the detector we also plan to observe neutrinos created by supernova explosions that have occurred throughout the lifetime of the universe. Further, the T2K experiment plans to investigate the difference between neutrino and antineutrino oscillations, which may provide insight into the evolution of the universe. Thus, essential research at SK continues.

We are greatly indebted to the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the University of Tokyo, the U.S. Department of Energy (DOE), the U.S. National Science Foundation (NSF), Department of Defense, the Japanese Ministry of Education, Culture, Sports, Science and Technology, and SK collaborating institutes for their support and understanding. In addition, we owe a debt of gratitude to the Kamioka Mining and Smelting Company as well as several other companies. Super-Kamiokande was constructed and operated under the strong leadership of Professor T. Takahashi and was successfully recovered from an accident in 2001 because of his self-sacrificing efforts. Further research at SK will continue. We would appreciate your continued support and cooperation.

June 17, 2016
Director, Kamioka Observatory, JKNR, The University of Tokyo
Spokesperson, Super-Kamiokande Collaboration
Masayuki Nakahata

スーパーカミオカンデ(SK)は、1996年4月1日に実験を開始してから今年で20年になります。この20年間は、 NOAAタイタントラブル、カミオカンデ異常など、さまざまな難問を乗り越えてきました。SKは、太陽中性子発生の研究を始め、さらに、カミオカンデ異常の研究を進めてきました。これらの研究は、太陽中性子発生の研究に深く関わっており、また、カミオカンデ異常の研究は、太陽の極円運動を解明するためにも重要です。今後も、SKは、さらに、これからの20年間をさらに発展させるため、たくさんの研究を行い、さらに、多くの成果を上げることを目指しています。
The International collaboration of the Super-Kamiokande experiment was started when the Kamiokande and IMB groups united in 1982. In the 20 years since then a total of 51 Institutes and approximately 400 researchers have participated in the experiment. At present the collaboration is composed of about 120 people and 36 institutes from Japan, the United States, Poland, South Korea, China, Spain, Canada and the United Kingdom.

**Collaboration Institutes**

Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo  
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University of British Columbia  
University of California, Irvine  
Chonnam National University  
Junior College, Fukuoka Institute of Technology

Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, The University of Tokyo  
Boston University  
Brookhaven National Laboratory  
California State University  
Duke University  
George Mason University  
Gwangju Institute of Science and Technology  
Imperial College London  
Kanagawa University  
Kobe University  
Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU)  
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University of Maryland  
University of Minnesota Duluth  
Nagoya University  
Niigata University  
Okayama University  
University of Oxford  
University of Regina  
University of Sheffield  
State University of New York at Stony Brook  
Tohoku University  
Tokyo Institute for Technology  
University of Toronto  
Tsinghua University  
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## Members

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2006
60 Three flavor neutrino oscillation analysis of atmospheric neutrinos in Super-Kamiokande,
Number of citations: 32

41 Solar neutrino measurements in Super-Kamiokande-I,
Number of citations: 474

2005
42 Observation of the Anisotropy of 10 TeV Primary Cosmic Ray Muon Flux with the Super-Kamiokande I Detector,
Number of citations: 110

43 Search for nucleon decay via modes favored by supersymmetric grand unification models in Super-Kamiokande-I,
Number of citations: 137

44 Measurement of Atmospheric Neutrino Oscillation Parameters by Super-Kamiokande-I,
Number of citations: 398

2004
40 Evidence for an auxiliary signature in atmospheric neutrino oscillation,
Number of citations: 827

46 Search for Dark Matter WIMPs using Upward-Through-going Muons in Super-Kamiokande,
Number of citations: 356

47 Limit on the Neutrino Magnetic Moment Using 1464 Days of Super-Kamiokande I Solar Neutrino Data,
Number of citations: 68

48 Precise Measurement of the Solar Neutrino Day/Night and Seasonal Variation in Super-Kamiokande-I,
Number of citations: 251

2003
49 A search for periodic modulations of the solar neutrino flux in Super-Kamiokande-I,
Number of citations: 62

50 The Super-Kamiokande Detector,
Number of citations: 648

51 Search for anti-electron-muons from the Sun at Super-Kamiokande-I,
Number of citations: 61

52 Search for Supernova relic Neutrinos at Super-Kamiokande,
Number of citations: 265

2002
53 Search for neutrinos from Gamma-Ray Bursts using Super-Kamiokande,
Number of citations: 182

54 Determination of Solar Neutrino Oscillation Parameters using 1496 Days of Super-Kamiokande-I Data,
Number of citations: 935

2001
55 Constraints on Neutrino Oscillations Using 1598 Days of Super-Kamiokande Solar Neutrino Data,
Number of citations: 778

56 Solar e^+ and e^- Neutrino Measurements from 1258 Days of Super-Kamiokande Data,
Number of citations: 1196

2000
58 T2K neutrino favored over sterile neutrino in atmospheric neutrino oscillations,
Number of citations: 304

1999
59 Neutrino-induced upward-going muons in Super-Kamiokande,
Number of citations: 287

60 Search for proton decay through p → e^+ + K^0 in a large water Cherenkov Detector,
Number of citations: 160

61 Observation of the East-West Anistropy of the Atmospheric Neutrino Flux,
Number of citations: 107

62 Measurement of muon concentrations at Super-Kamiokande,
Number of citations: 466

63 Constraints on neutrino oscillation parameters from the measurement of day-night solar neutrino fluxes at Super-Kamiokande,
Number of citations: 495

64 Measurement of the flux and search angular distribution of upward through-going muons by Super-Kamiokande,
Number of citations: 775

65 Measurement of the Solar Neutrino Energy Spectrum Using Neutrino-Electron Scattering,
Number of citations: 606

66 Calibration of Super-Kamiokande using an electron LINAC,
Number of citations: 111

1998
67 Evidence for oscillation of atmospheric neutrinos,
Number of citations: 4784

68 Measurements of the Solar Neutrino Flux from Super-Kamiokande’s First 300 Days,
Number of citations: 827

69 Search for Proton Decay via p → e^+ + n in a Large Water Cerenkov Detector,
Number of citations: 168

70 Study of the atmospheric neutrino flux in the multi GeV energy range,
Number of citations: 850

71 Measurement of a small atmospheric, ν_s / ν_o, ratio,
Number of citations: 902

1997
72 Improvement of 20 ln diameter photomultiplier tubes,

73 Proof of hybrid circuit for Super-Kamiokande,
Following a five year construction period the 90 kiloton Super-Kamiokande water Cherenkov detector began observations in April 1998. The experiment is led by the University of Tokyo, Institute of Cosmic Ray Research and its research is conducted in cooperation with 36 collaborating institutes from Japan, the United States, Poland, South Korea, China, Spain, Canada, and the United Kingdom.

One focus of Super-Kamiokande's research is the study of the neutrino, an elementary particle produced at the center of the sun, in the atmosphere, and during supernova explosions. If neutrinos are massive we can expect them to oscillate or change from one type to another. In 1998 observations of atmospheric neutrinos in Super-Kamiokande showed for the first time that neutrinos do indeed oscillate and therefore have mass. Later, in 2001, the oscillations of solar neutrinos were discovered. These discoveries indicate that the Standard Model of particle physics, which assumes neutrinos are massless, is imperfect and thereby point to the existence of new, more complete theories. Super-Kamiokande observes about 3.500 atmospheric neutrino events and about 7,000 solar neutrino events per year. As a result, the detector has accumulated large atmospheric and solar neutrino data sets over the history of its operation and these have enabled precise studies of neutrino oscillations.

While neutrino oscillations were discovered using neutrinos produced in nature, research using neutrinos produced in particle accelerators is essential to their study. The first long-baseline neutrino experiment in the world, the K2K experiment, was conducted from 1999 to 2004 and it sent a beam of neutrinos produced at the KEK proton accelerator to Super-Kamiokande, located 290 km away. In 2004, K2K confirmed the existence of neutrino oscillations using these muon neutrinos. Similarly, the T2K experiment, which uses neutrinos produced with the high intensity proton beam at J-PARC, has been sending a neutrino beam over a distance of 285 km to Kamioka since 2008. During its operation T2K has not only discovered a third neutrino oscillation mode but has made precise measurements of neutrino oscillation parameters.

Super-Kamiokande is also searching for evidence of proton decay, a phenomenon in which a proton spontaneously converts into a set of lighter particles. Though the proton is considered to be stable in the Standard Model, its decay is both possible and necessary in Grand Unified Theories. In the same manner as the discovery of the neutrino's finite mass, an observation of proton decay would lead to dramatic advances in our understanding of the fundamental particles.
Atmospheric neutrinos
大気ニュートリノ

Atmospheric neutrinos are produced from the collisions of cosmic rays with nuclei in the atmosphere and come predominantly in two flavors, electron neutrinos and muon neutrinos. Since neutrinos only rarely interact with matter, they pass easily through the Earth, making it possible for Super-Kamiokande to detect atmospheric neutrinos on the opposite side of the planet. After two years of observation, it was clear in 1998 that while the number of such electron neutrinos agreed well with the model predictions, the number of muon neutrinos was much smaller than expected.

After careful analysis of the observed data, Super-Kamiokande collaborators concluded that the deficit could be explained by “neutrino oscillations,” a phenomenon in which neutrinos change their type during flight (Figure 1). In the atmosphere, nearly half of the atmospheric muon neutrinos created on the opposite side of the Earth change (oscillate) into another type of neutrino that is not observed in the detector. This discovery of neutrino oscillations confirmed that neutrinos have mass, thereby providing decisive evidence for physics beyond the Standard Model, which assumes neutrinos are massless.

While it was clear that the observed atmospheric neutrino disappearance favored the oscillation interpretation, further analysis was needed to fully describe the phenomenon. In the year 2000, Super-Kamiokande determined that the oscillations were most likely from muon to tau neutrinos and that this was supported by the observed rate of atmospheric neutrino events. This result was presented in 2002 (Figure 2), confirming the hypothesis.

In 2013, Super-Kamiokande published the first observation of tau neutrinos (Figure 3), providing final confirmation of the oscillation theory. This work culminated in the 2016 Nobel Prize in Physics.

Super-Kamiokande’s atmospheric neutrino data have also been used to search for dark matter annihilation in the center of celestial objects, to measure the atmospheric neutrino flux itself, and to test a variety of exotic physics models. In addition, atmospheric neutrinos are now being used to study particle antimatter symmetries in nature, a topic central to the formation of the universe, and to determine the ordering of the neutrino masses. Finally, as the dominant background to searches for proton decay, precision atmospheric neutrino research at Super-Kamiokande will be essential to the discovery of new phenomena in the future.
Solar neutrinos
太陽ニュートリノ

The Sun is the most powerful neutrino source in our vicinity.
太陽の中心部では核融合反応により個々の数の電子型ニュートリ
ノが生成されており、その多くが太陽ニュートリノとして宇宙空間に
拡散しています。これにより地球を含む惑星周辺のニュートリノが観測され
てきました。観測されたニュートリノ強度は一部の理論を除き予想され
た値より著しく小さいものでした。2001年に、スープーナー・ミサノオア
（SK）とスーパーヒアルオクロット素粒子（SNOLAB）で行なわれた太陽ニュートリ
ノ研究において、観測された太陽ニュートリノ強度が小さな原因が、電
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の角変位の理論は更に進展しています。

SKは大規模ニュートリノ発生を確認するため、観測結果を
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Proton decay
陽子崩壊

Protons are one of the fundamental constituents of matter and are found in all nuclei throughout the universe. Though it seems possible for protons decay into other particles such an event has never been observed. As a result, they are stable in the Standard Model. However, processes like proton decay are thought to have played an essential role in the formation of the universe. Grand Unified Theories (GUTs) not only address deficiencies in the Standard Model, but they also predict the unification of the fundamental forces of nature as well as proton decay. For these reasons they may provide insight into the early universe and accordingly, the search for proton decay is a main line of research at Super-Kamiokande.

Among the proton decay modes predicted by GUT models, decay into a positron, the antiparticle of the electron, and a neutrino is often the most probable. Super-Kamiokande has an exceptional ability to detect such proton decay events among atmospheric neutrino backgrounds as shown in Figure 1. In 1988, after only two years of running, Super-Kamiokande released results from its first search for proton decay in this channel. Though no evidence for a signal was found, the resulting lower limit on the proton’s lifetime, 1.5 x 10^25 years, was a factor of three times stronger than previous limits. In the intervening 18 years there has been no indication of a signal and Super-Kamiokande’s current limit 1.7 x 10^25 years, is the world’s most constraining.

In 1999 Super-Kamiokande published its second proton decay result, finding no evidence for decay into a neutron and a charged lepton, thereby establishing the world’s stringent lifetime limit for this mode. Since then the search for proton decay has expanded to include analysis of more than 20 modes, all of which resulted in world-leading limits (Figure 2). These limits have ruled out GUT models and are constraining several others.

A few analyses have even yielded candidate events, but as they cannot currently be distinguished from atmospheric neutrino interactions they do not yet constitute evidence for proton decay. As a result, though Super-Kamiokande has already provided stringent limits on the proton’s lifetime, work is ongoing to further remove backgrounds and extract a signal that may be waiting just around the corner.
K2K/T2K long-baseline neutrino oscillation experiments
K2K/T2K 長基線ニュートリノ振動実験

Accelerator-based long-baseline neutrino experiments are well suited to detailed neutrino oscillation studies because in these experiments not only can the neutrino energy and flight distance be optimized to observe a particular effect, but the neutrino beam can also be measured precisely before any oscillations occur.

K2K (Kamiokande-II), the world's first long-baseline neutrino oscillation experiment, collected beam neutrino data from 1996 to 2004. The beam neutrinos were produced by the proton accelerator at KEK in Tsukuba and were observed 250 km away in Super-Kamiokande. Using these neutrinos, K2K definitively confirmed (>99.9%) the existence of neutrino oscillations.

Following the success of K2K, the T2K (Tokai-to-Kamioka) experiment started taking data in 2010 with an intent to further extend neutrino oscillations using a more powerful neutrino beam, T2K is the world’s first off-axis long-baseline neutrino experiment: an intense neutrino beam is produced using a series of world-class proton accelerators at J-PARC in Tokai and its axis directed 255 degrees away from Super-Kamiokande, located 250 km away. This configuration produces a neutrino beam at Super-K which is enhanced in a narrow range of energies where the neutrino oscillation effect is maximal.

The primary aim of T2K was the discovery of the appearance of electron neutrinos in a muon neutrino beam, a phenomenon which is driven by the then unknown mixing between the first and third generations of neutrinos. T2K first observed a clear indication of electron neutrino appearance in 2011 and later fully established it in 2013 (Figure 1). This was an unprecedented achievement as it was the first time a transition between neutrino flavors had been confirmed where both the initial and final flavors were observed in the experiment.

T2K’s discovery of electron neutrino appearance has opened the door to searches for possible differences in the oscillations of neutrinos and antineutrinos, an effect called “neutrino CP violation,” which could be the key to explain why our present universe is made of only matter and no antimatter. Currently, when combined with the results from other experiments, T2K’s data shows a hint of this CP violation (Figure 2). To further study CP violation in neutrino oscillations, T2K started to take data with an antineutrino-enhanced beam in 2014. So far the experiment has measured the disappearance of muon-antineutrinos with world-class precision (Figure 3), but whether there are differences between neutrino and antineutrino oscillations remains to be seen.

加数を用いて人工的に生成したニュートリノシミュレーションを用いる長期基準ニュートリノの実験は、基準のニュートリノエネルギーを変化させることで、観測を可能にする。この実験において、ニュートリノ振動が確認されている確率は99.9%以上、という肯定的な結果が得られました。

基準の真実値を正確に、さらに常に新たな観測結果を導くため、ニュートリノシミュレーションを基準に研究する長期基準実験として、T2K（Tokai-to-Kamioka 実験）が2010年にデータ収集を開始しました。東海村のJ-PARC（世界最高の強力な陽子加速器）を用いて生成した強力なニュートリノシミュレーション方法は、物理のエネルギーに最大となる約10万倍のエネルギーに至ったニュートリノをよりよく理解しています。

T2K実験の目指す目標は、世界で初めて現実となるみそ1-3世代のニュートリノをもとに質量を検出したニュートリノから電子ニュートリノへの変換を観測することでした。2011年に発表され、2015年にその存在を確認しました。ニュートリノの種類とエネルギーを変えることで、基準の振動がどのように影響を及ぼすかを検証することを試みましたが、この結果は、ニュートリノのエネルギーに最大となるエネルギーに至ったニュートリノをよりよく理解しています。

T2K実験における電子ニュートリノ出現の拡大は、現在の科学で反応を模倣できるということが幼児期の重要な一歩であると見なす。ニュートリノのCP対称性の破れを察知する可能性の検証に新たなエネルギーを向けていました。この結果は、エネルギーの変換を観測することで物理のエネルギーを変えることで、基準の振動がどのように影響を及ぼすかを検証することを試みましたが、この結果は、ニュートリノのエネルギーに最大となるエネルギーに至ったニュートリノをよりよく理解しています。

Figure 1: Energy spectrum of electron neutrino events observed by T2K. The red and blue histograms show the expectation with and without electron neutrino appearance, respectively. The data show clear evidence for neutrino oscillations, indicating that a significant fraction of muon neutrinos are transformed into electron neutrinos.

Figure 2: Posterior probability for sin^2(2θ) (a parameter indicating the violation of CP symmetry) obtained by T2K. In combination with results from other experiments, the hatched regions show 90% and 99% confidence intervals. The most preferred value of sin^2(2θ) is 0.02, when CP symmetry is maximally violated.

Figure 3: Allowed antineutrino oscillation parameter region obtained from T2K’s muon-antineutrino disappearance measurement. The black dashed curve shows the 90% (95%) confidence level. Cobalt-60 neutrino source shows clear evidence of CP violation.

In the 2015-16 period, T2K reached the 100% appearance of muon-antineutrino with world-class precision (Figure 3). However, no differences between neutrino and antineutrino oscillations have been seen so far.
Supernova neutrinos
超新星ニュートリノ

Stars with at least eight times more mass than our Sun will eventually collapse under their own weight. When that happens, most of the gravitational energy of the star is held in the form of neutrons, and the star explodes. Even though the resulting light from such a supernova explosion is brighter than an entire galaxy, the neutrons carry more than 99% of the total energy. More than a billion times the energy output of the Sun, if a supernova were to occur at the center of our galaxy, Super-Kamiokande would record about 10,000 neutrinos over the course of last ten seconds. Not only would these neutrons offer new insights into the dynamics of the explosion, but the high intensity of neutrinos inside the exploding star would test our understanding of neutrino interactions with other neutrinos.

Such supernovae in our own galaxy are rare, about a few per century, but they are frequent in the entire universe (one per second). Due to the large distances to other galaxies, Super-Kamiokande expects to see supernovae only a few times per year. From about ten years of Super-Kamiokande data, the supernova neutrino flux above 17.3 MeV of neutrino energy must be less than about three neutrinos/cm²/s.

An exclusion contour from SK data in Supernova (SN) neutrino luminosity vs neutrino temperature parameter space (Mh). The Irvine-Michigan-Brookhaven (IMB) and Kamiokande allowed areas for supernova 1987A are also shown (arbitrarily) from Phys. Rev. D 45, 5920-27 (2012).

*Note:* The image contains scientific diagrams and data related to supernova neutrinos and their detection by Super-Kamiokande. The text explains the basic concept of supernovae and their implications for neutrino detection. The diagram illustrates the energy distribution and exclusion contour for supernova neutrinos, providing a visual aid to the theoretical discussion. The data and exclusion contours are based on observations and theoretical models, offering insights into the universe and cosmic events.
Super-Kamiokande (SK) has enjoyed a remarkably successful two decades of operation. But, what does the future hold, and with twenty years of data already collected, how can our famous detector continue to produce new and interesting results well into the future? First proposed in an article in Physical Review Letters (83:171101 (2004)), the answer comes in the form of loading 10,000 tons of a soluble gadolinium (Gd) salt into the water of SK. By adding gadolinium sulfate to the SK water, the dissolved gadolinium, which has a tremendous affinity for absorbing thorium neutrinos and emits a large flash of light when it does so, will allow us to efficiently see and positively identify these previously hard-to-detect neutral particles.

Gadolinium will greatly reduce limiting backgrounds to many of our existing studies, such as proton decay searches and solar neutrino measurements. It will improve neutrino-antineutrino discrimination for atmospheric and long-baseline oscillation studies. It will enable SK to measure antineutrinos from nuclear reactors located both inside and outside Japan. In the case of a galactic supernova explosion, it will allow the flavors of the SK neutrinos to be separated, doubling SK’s pointing accuracy back to the exploding star. Perhaps most significantly, within a few years of enlisting the SK water, Gd's efficient neutron detection will allow us to make the world’s first observation of the diffuse supernova neutrino background flux, the neutrinos emitted by all historical supernova explosions since the onset of stellar formation in the early universe.

Since 2008 Gd loading has been demonstrated in a dedicated underground laboratory near SK called EAGOS - Evaluating Gadolinium’s Action on Detector Systems. It contains a 200-ton scale model of SK as well as custom-built water filtration and measuring equipment, and can be seen in Figures 1 and 2. The extremely promising results obtained in EAGOS led to the SK and 12K Collaborations formally endorsing the plan to add Gd to SK, officially known as SK-Gd. Preparatory work is already underway, a large new experiment hall (Hall G) has been excavated near SK to contain the required new water handling equipment. It can be seen in Figure 3.

Adding gadolinium to SK will rapidly produce many new and improved kinds of data. As a result, following twenty years of great success, Super-Kamiokande’s future looks bright indeed.
Recent awards / 近年の受賞

The Nobel Prize in Physics 2015
Professor Takaaki Kajita, ICRR, The University of Tokyo
2015年ノーベル物理学賞受賞
ICRR 桐生隆章教授

Professor Kajita was awarded the 2015 Nobel Prize in Physics for the discovery of atmospheric neutrino oscillations. The observation of atmospheric neutrino oscillations was published in 1988 by the Super-Kamiokande collaboration.

In 1988 at the Neutrino International Conference held in Takayama, Gifu, Professor Kajita showed the analysis results that compared the number of atmospheric neutrinos coming downward from about 30 km in the sky above the detector to the number of neutrinos coming upward through the earth from about 10,000 km away. The number of atmospheric neutrinos coming upward was reduced by about one half, which provided strong evidence for atmospheric neutrino oscillations. When finished, Professor Kajita received a standing ovation from the international researchers gathered in the hall.

Neutrino oscillations can only occur if neutrinos have mass. For this reason the observation of neutrino oscillations became conclusive evidence that the neutrino mass is non-zero. The discovery of atmospheric neutrino oscillations revolutionized the theory of elementary particles and opened the door to a new physics. The atmospheric neutrino oscillation analysis was published after 7 years of data taking, since Super-Kamiokande started operation in 1986. Professor Kajita, as one of the leaders of the analysis group, led the Super-Kamiokande collaboration to reach the scientific conclusion about neutrino oscillations.

桜田教授は1988年にスーパーカミオカンデグループが発表した大気ニュートリノ異常の発見により、2015年ノーベル物理学賞を受賞されました。1988年の高山で行われたニュートリノ国際会議において、桜田教授は上空から来る下向きニュートリノを計測し、地球の貫通によって下向きニュートリノの数が減少していることを示し、それがニュートリノ異常の具現化であることを発表しました。その後の研究者たちはニュートリノ異常の検出という新たな物理学の領域を築き上げました。ニュートリノ異常の検出はニュートリノの質量を持つことを示す重要な発見でした。ニュートリノ質量の実験は新たな核物理の歴史的な大きなきっかけとなるもので、受賞を果たした大気ニュートリノ異常の検出結果は、スーパーカミオカンデ実験室が1986年にスタートし、1992年に発表されたものです。桜田教授は桜田グループの代表者として、研究者を鼓舞して革命的な知識へと進み上りました。
2002.12
restart as SK-I with a half density of PMTs
 menosの電子増幅器をSK-IIにとして運用開始

2004.6
confirmation of atmospheric neutrino oscillation
by the K2K experiment using beam neutrinos
K2K 実験でスパイクを観察した
大気ニュートリノ振興を確認

2004.7
direct observation of an oscillatory signature
in the atmospheric neutrino sample
大気ニュートリノの振興パターンの直接観察

2005.10
reconstruction work for full recovery
of the PMT density
対電子増幅器の数を元に戻す完全再構作業開始

2006.7
completion of full reconstruction and
the start of SK-II
完全再構作業完了、全ての電子増幅器で観測開始

2008.9
replacement of front-end electronics
and data acquisition system (DAQ)
データ処理システムの更新

2009.4
start of the T2K (Tokai to Kamioka) experiment,
the first off-axis neutrino oscillation experiment
T2K 実験開始

2010.6
launching a test facility for the SK-Gd project
SK-Gd計画に向けて実験装置開始

2011.6
discovery of electron neutrino appearance
in the T2K experiment
T2K 実験で電子ニュートリノ出現事象の発見

2012.7
proton decay 9-10^-18 lifetime limit published
by SK exceeds 10^29 years
スキの研究が10^29年を超えた

2013.7
measurement of electron neutrino appearance
in the T2K experiment
T2K 実験で電子ニュートリノ出現事象の観測と決定

2015.11
2016 Breakthrough Prize in Fundamental Physics
awarded to Prof. Yoichiro Suzuki,
Prof. Takashi Kajita and SK Collaborators,
and Prof. Koichiro Nishikawa
and K2K/T2K Collaborators
Breakthrough賞受賞

2015.12
The 2013 Nobel Prize in Physics
awarded to Prof. Takaaki Kajita
■ 原子核ニュートリノ物理学賞受賞

20th Anniversary of Super-Kamiokande