Yoji Totsuka (1942–2008) and the Discovery of Neutrino Mass

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Abstract

Yoji Totsuka, a leading figure in the discovery of neutrino mass, died in 2008. His leadership of the Super-Kamiokande experiment and subsequent leadership of the High Energy Physics Laboratory (KEK) in Japan helped to lay the foundation for the current worldwide experimental and theoretical program in neutrinos.

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1. INTRODUCTION

In 1998, at the Eighteenth International Conference on Neutrino Physics and Astrophysics held in Takayama, Japan, the Super-Kamiokande experiment announced that it had found evidence for neutrino oscillations. The news of this discovery spread instantly around the world. On the day after the conference, then–U.S. president Bill Clinton mentioned this discovery in his commencement address at the Massachusetts Institute of Technology. He said, "Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories—from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands. . . . The larger issue is that these kinds of findings have implications that are not limited to the laboratory. They affect the whole of society—not only our economy, but our very view of life, our understanding of our relations with others, and our place in time" (1).

The discovery of neutrino mass changed the future direction of scientific inquiry into neutrinos and led to a number of experimental and theoretical studies to understand the nature behind the neutrino masses. The current Standard Model of elementary particle physics assumes that neutrinos are massless; thus, the discovery of a nonzero neutrino mass has led us to physics beyond the Standard Model.

Yoji Totsuka, who had been the spokesperson of Super-Kamiokande and a leading figure in neutrino physics, died on July 10, 2008 after a long battle with cancer. Totsuka was born on March 6, 1942 and grew up in Fuji City, Japan. He attended the University of Tokyo, where he received his undergraduate, masters, and doctoral degrees. His PhD thesis work involved the study of high-energy muon bundles observed underground; this work was largely related to the composition of cosmic rays.

Following completion of his doctorate, Totsuka worked as a research associate with the University of Tokyo. He began his lifelong career in elementary particle physics at the DESY laboratory in Germany, where he participated in the experiment on electron–positron collisions. He became an associate professor at the University of Tokyo in 1979 and obtained a professorship there in 1987.

In 1988, Totsuka moved from the University's graduate school to its Institute for Cosmic Ray Research (ICRR), where he organized a core group to promote the Super-Kamiokande project. The construction budget for Super-Kamiokande was approved by the Japanese government in 1991, and its construction began in the fall of that year.

Super-Kamiokande took five years to build. Its huge water Cherenkov detector is 39 m in diameter and 42 m in height, containing 50,000 tons of water. To reduce background caused by cosmic rays, the detector was placed 1000 m underground in Mount Ikenoyama. Approximately 11,000 50-cm-diameter photomultiplier tubes (PMTs) are spaced 70 cm apart on the entire inner surface of the detector, viewing 32,000 tons of the inner volume. Encompassing the inner volume is an outer detector volume, equipped with 1885 20-cm-diameter PMTs. This outer volume is used for an active veto against incoming particles. The inner volume is further constrained by software to a 22.5-kton fiducial volume. This fiducial volume is used for most of the physics analyses.

Super-Kamiokande is sensitive to energies ranging from 5 MeV to $\sim$100 TeV, spanning more than eight orders of magnitude. Given this extensive range of sensitivity, Super-Kamiokande can be used to study solar neutrinos, whose energies are less than 15 MeV, and to study atmospheric neutrinos and high-energy neutrinos of extragalactic origin, whose energies are a few hundred megaelectronvolts and above.

Construction of this huge detector was motivated by the two mysteries then surrounding neutrino physics: the so-called solar neutrino problem and the atmospheric neutrino anomaly. The solar neutrino problem was identified by Raymond Davis, Jr. in the early 1970s. Using his chlorine detector, located in the Homestake Mine in South Dakota, Davis observed that the solar neutrino flux was approximately one-third as great as that predicted from solar models. In 1988, an early experiment known as Kamiokande confirmed the solar neutrino problem for the first time in a real-time experiment. Kamiokande began in 1983 with an inner detector volume of 3000 tons. The experiment's original goal was to look for proton decay, but in 1987 it succeeded in lowering its energy threshold to 9 MeV (later 7 MeV) and was therefore able to observe low-energy neutrinos coming from the Sun. The observed rate of solar neutrino events in Kamiokande was 0.3 per day, whereas the Super-Kamiokande detector, with a 5-MeV threshold, was expected to observe $\sim$15 events per day.

The second mystery was the atmospheric neutrino anomaly observed in the Kamiokande experiment in 1988. This neutrino deficit could not be explained by systematic errors or by uncertainties in the neutrino flux calculations. The atmospheric neutrinos were produced by the decay of mesons that arose from the interaction between primary cosmic rays and molecules in the atmosphere. In the low-energy limit, where muons (produced as daughters of pions and kaons) decay before they reach the surface of the earth, the ratio of ν_μ:ν_e is 2:1. This ratio increases as the energy rises. Kamiokande observed that the double ratio of $(\nu_\mu/\nu_e)_{\mathrm{data}}$ to $(\nu_\mu/\nu_e)_{\mathrm{expected}}$ was approximately 60%, indicating either a deficit of ν_μ or an excess of ν_e. The detector mass of Kamiokande was too small to observe the zenith-angle distributions of the atmospheric neutrinos, which later proved crucial both in demonstrating the deficit and in understanding the nature of the process in which the neutrinos disappeared.

2. THE DISCOVERY OF NEUTRINO OSCILLATIONS

In 1987, Totsuka became the leader of the Kamiokande experiment after Masatoshi Koshiba, a founder of Kamiokande, retired from the University of Tokyo. The study of both solar and atmospheric neutrinos became Totsuka's lifelong work.

We now know that both the solar neutrino problem and the atmospheric neutrino anomaly are due to neutrino oscillations. In neutrino oscillation, a neutrino changes from one form to another during its flight from the neutrino-production source to the detector. This oscillation arises from the neutrino's finite mass and mixing: $|\nu_l\rangle = \Sigma U_{li}|\nu_i\rangle$, where $l = e$, μ, and τ and where $i = 1$, 2, and 3. The oscillation wavelength is directly proportional to the energy of the neutrinos and inversely proportional to the square of the mass difference: $\lambda_{\mathrm{osc}} = 4\pi E/\Delta m^2$. For example, we now know that the atmospheric neutrino oscillation is predominantly caused by $\nu_\mu \rightarrow \nu_\tau$ oscillation with a mass difference $\Delta m^2 \sim 2 \times 10^{-3}$ eV^2 and almost full mixing. The wavelength of the oscillation is $\sim$500 km for 1-GeV neutrinos.

The first definitive evidence for neutrino oscillations was obtained from the Super-Kamiokande data of atmospheric neutrinos. The earlier indication of the ν_μ deficits (or ν_e excess) by Kamiokande depended upon flux calculations and therefore was not conclusive. Flux calculation–independent evidence was necessary, and it was obtained by Super-Kamiokande. Because the earth is transparent for atmospheric neutrinos with an energy of less than ~10 TeV, the zenith-angle distribution of such neutrinos should be symmetric for those energies above 1–2 GeV. Those neutrinos produced by cosmic ray interactions in the atmosphere above the detector that were observed going down through the detector should be the same as those produced by cosmic ray interactions in the atmosphere on the other side of the Earth that were observed going up through the detector.

For those atmospheric neutrinos below a few gigaelectronvolts, a small asymmetry is introduced by the geomagnetic cutoff introduced by the low-energy primaries. Furthermore, the lepton angles produced by the interaction of such low-energy neutrinos smear out the zenith-angle distributions. Thus, the zenith-angle distribution in higher energies is crucial for the study of neutrino oscillation. The zenith-angle distribution of electronlike events was observed to be symmetric, whereas the zenith-angle distribution of muon neutrinos was conclusively not symmetric. A striking deficit of upward-going high-energy neutrinos was observed. Analysis showed that muon neutrinos were oscillating into tau neutrinos that were not observable in the Super-Kamiokande detector, leading to the failure to detect upward-going muon neutrinos. These findings provided compelling evidence for neutrino oscillation.

Continued analysis of the atmospheric neutrino data in Super-Kamiokande has produced additional evidence for neutrino oscillation. Through selection of events whose travel distance and energy were relatively well known, it was possible to plot the data as a function of the L/E oscillation parameter. The prominent dip in the plot is a function of Δm^2, and it demonstrates the oscillatory behavior convincingly enough to exclude other nonoscillation hypotheses, such as decoherence and neutrino decay.

Although tau neutrinos are essentially invisible in Super-Kamiokande, researchers have located the few interactions that do occur and that can be identified. Although it is not possible to make a tau neutrino determination on an event-by-event basis, a statistical analysis has been performed through selection of a tau-enriched sample, whereby Super-Kamiokande has so far obtained 2.4-σ evidence for tau production.

Just as the atmospheric neutrino anomaly was resolved as a manifestation of neutrino oscillations, the missing solar neutrinos were also explained in terms of neutrino oscillations. We now know that the missing solar neutrinos were produced as electron neutrinos that converted into tau neutrinos and muon neutrinos, both unobservable in Davis's detector. The first definitive evidence was finally obtained through comparison of the Super-Kamiokande neutrino electron scattering measurement to the first SNO charged-current measurement in 2001. Whereas the neutrino electron scattering in Super-Kamiokande is sensitive to all neutrino flavors, but with a reduced sensitivity of 15% for ν_μ and ν_τ, the SNO data came from pure ν_e charged-current interactions. Through comparison of those two measurements, the non–electron neutrino component of solar neutrinos in the Super-Kamiokande data was revealed.

Soon after the discovery of solar neutrino oscillations, a tragic accident occurred in Super-Kamiokande that caused 6777 PMTs to be destroyed within two seconds. The shock wave initiated by the implosion of one of the PMTs at the bottom of the water tank created a chain reaction that spread the damage throughout the detector. Under Totsuka's strong leadership, we were able to rebuild Super-Kamiokande in approximately one year. Totsuka had announced to the world on the day after the accident that Super-Kamiokande would be reconstructed within one year, and 13 months after the accident, Super-Kamiokande restarted. This accident occurred just one year after Totsuka's first surgical treatment for his cancer.

Before the evidence for atmospheric oscillations was announced, Totsuka foresaw the necessity for a confirmation experiment, preferably one performed with a controlled beam from an accelerator. He was responsible for the discussions that led to the founding of the K2K experiment. In 1999, the man-made neutrino beam created by the 12-GeV KEK proton synchrotron was directed through the Earth to Super-Kamiokande, 250 km away. This was to be the first long-baseline experiment. The goal of the experiment was to test the neutrino oscillation hypothesis as an explanation for the atmospheric neutrino observations. If the oscillation interpretation was correct, the K2K experiment expected to observe a 30% reduction in the muon neutrino beam from Super-Kamiokande. In 2004, after five years of running, K2K observed 112 muon neutrino events. The expected number of events was 156; thus, the atmospheric neutrino oscillation results were confirmed.

Since that time, the worldwide experimental neutrino program has grown rapidly. The current MINOS experiment at Fermilab has once again confirmed the atmospheric neutrino results and is in the process of improving our knowledge of the oscillation parameters. New experiments will probe the remaining unknown parameters.

Although the Super-Kamiokande detector was predominantly motivated by neutrino physics, this was certainly not the case for the first large water Cherenkov detectors, IMB and Kamiokande. These detectors were built to search for proton decay. In that capacity, they showed that the lifetime predictions of the SU(5) Grand Unified Theory (GUT) were not correct. Theorists, however, soon developed other theories that predicted a lifetime longer than the lifetime that could be searched for with IMB and Kamiokande. However, the enormous Super-Kamiokande detector provided a tenfold increase in sensitivity, and the search was able to be continued. Unfortunately, the Super-Kamiokande search for nucleon decay has not yielded any positive evidence, but the absence of nucleon decay, now extended into the decade between 10^{33} to 10^{34} years' lifetime, has provided stringent constraints that must be addressed by any proposed GUT. Certain new theories include features that make the lifetime arbitrarily long, for example the separation of quarks and leptons by extra spatial dimensions. Other theories involving extra dimensions predict surprising new modes. However, a large number of current GUTs that allow a finite nucleon lifetime predict decay rates not greatly exceeding current limits. Clearly, the search for nucleon decay remains a valuable discriminating experiment for understanding the fundamental nature of particles and forces.

From 2003 to 2006, Totsuka served as the director general of Japan's high-energy physics organization, KEK. During this period, Totsuka oversaw the K2K experiment and supervised the Belle *B* factory, which studied the differences between matter and antimatter. Kobayashi and Maskawa were awarded the Nobel Prize for Physics in 2008 for their theoretical work on *CP* violation.

As his illness progressed, Totsuka stepped down from his position at KEK and became director of the Research Center for Science Systems at the JSPS. In this capacity, Totsuka mentored young scientists until the very end of his life.

Totsuka received international recognition for his work, including the Asahi Prize (1987), the Nishina Prize (1988), the Rossi Prize of the American Astronomical Society (1989), the Inoue Prize (1990), the European Physical Society Special Prize (1995), and the Benjamin Franklin Medal (2007). He received the most prestigious prize in Japan, the Order of Culture, in 2004. He was a member of the Physical Society of Japan and the Astronomical Society of Japan, as well as a fellow of the American Physical Society. He held the title of professor emeritus at the University of Tokyo and at KEK.

As the strong and inspirational leader of Super-K, Totsuka helped to lay the foundation for the current worldwide experimental and theoretical program in neutrinos. We miss his great vision and leadership.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

LITERATURE CITED

1. Clinton WJ. *Remarks by the President at Massachusetts Institute of Technology 1998 commencement*. Lincoln, MA: Mass. Inst. Technol. **http://clinton2.nara.gov/WH/New/html/19980605-28045.html** (1998)