

Physics Nobel Prize honors the discovery of neutrino flavor oscillations

The hard-won result that the elusive particles can change their identities has far-reaching implications.

This year's Nobel Prize in Physics goes to Takaaki Kajita and Arthur McDonald for their work on ground-breaking experiments that conclusively demonstrated that neutrinos oscillate among their three flavors—electron, muon, and tau. Kajita led the data analysis team of the Super-Kamiokande experiment, shown in figure 1a, when, in 1998, the collaboration clinched the case for oscillation of neutrinos created in Earth's upper atmosphere. McDonald was the director of the Sudbury Neutrino Observatory (SNO), shown in figure 1b, which in 2001 and 2002 revealed the oscillation of neutrinos coming from the Sun.

The discoveries resolved the mystery of several earlier experiments that detected neutrinos in unexpectedly small numbers. In fact, the neutrinos were rendering themselves invisible by transforming into a different flavor. The results also imply that neutrinos have mass: For neutrinos to change their flavor unprovoked, they must be superpositions of propagating states of different mass.

The solar problem

Detecting neutrinos at all is no mean feat. Although they're more abundant than any other elementary particle apart from photons, neutrinos are immune to both the strong nuclear and electromagnetic forces. They're detected via their weak interactions, which, as the name suggests, are feeble: There's just a 10% chance that, during your lifetime, a passing neutrino will interact with an atom in your body.

To scrape together a usable signal, neutrino researchers construct their detectors from many tons of material, which they monitor for months or years for any telltale sign of a neutrino interaction. To cut down on background from cosmic rays, they typically bury the detectors deep underground, often in old mines. Neutrinos have no trouble penetrating the hundreds of meters of soil and rock, but the flux of other particles is attenuated.



Kajita



McDonald

SNOLAB

In the early 1960s, theorist John Bahcall and experimenter Raymond Davis Jr teamed up to try to understand how many neutrinos were coming from the Sun. Bahcall developed a model that encompassed the various nuclear processes hosted by the Sun—from proton-proton fusion to reactions involving beryllium, boron, carbon, nitrogen, and oxygen—and estimated the number of neutrinos (all of them electron neutrinos) that each process should produce. Meanwhile, Davis devised and built a detector: a tank filled with 600 tons of tetrachloroethylene (C_2Cl_4) in the Homestake gold mine in South Dakota. An electron neutrino interacting with a chlorine nucleus could transform it into a nucleus of radioactive argon-37. Every few months, Davis extracted the ^{37}Ar atoms from the tank and counted them. He found only one-third the number Bahcall had predicted.

That discrepancy would later be known as the solar-neutrino problem. Something was wrong with Bahcall's model, Davis's experiment, or physicists' understanding of neutrinos. The first possibility seemed the most likely. (See *PHYSICS TODAY*, March 1968, page 73.)

In the 1980s and 1990s, other experiments started detecting solar neutrinos in numbers that showed a similarly large shortfall relative to the model's predictions. Among them was Kamiokande, the predecessor of Super-Kamiokande, located in the Kamioka Mining and

Smelting Company's Mozumi mine in Japan. Because Kamiokande had directional sensitivity, it confirmed that the neutrinos Davis had detected were indeed coming from the Sun. For their work, Davis and Kamiokande's first spokesperson, Masatoshi Koshihara, each received a share of the 2002 Nobel Prize. (See *PHYSICS TODAY*, December 2002, page 16.)

Because the new experiments used different materials for their detectors, they were sensitive to different combinations of the Sun's neutrino-generating processes. The water-based Kamiokande detector, for example, could see only the rare highest-energy neutrinos created by beta decay of boron-8 nuclei. Gallium-based detectors and Davis's C_2Cl_4 detector, on the other hand, had lower energy thresholds that admitted neutrinos from several processes.

If the problem with the solar model was that it had the wrong ratios between the rates for various solar processes—perhaps there was much less 8B in the Sun's core than Bahcall had predicted—then the measurements from several detectors would have made it possible to work out what the correct ratios should be. However, it soon became clear that no amount of tweaking could produce a model compatible with all the experimental results: One or more of the solar processes would need to contribute a negative number of neutrinos to the total flux. Either the experiments were wrong or there was some-

thing strange about the physics of neutrinos. (See the article by John Bahcall, Frank Calaprice, Arthur McDonald, and Yoji Totsuka, *PHYSICS TODAY*, July 1996, page 30.)

Super-Kamiokande

Kamiokande collected data not only on solar neutrinos, but also on atmospheric neutrinos, and there the researchers found another puzzle. Cosmic rays—high-energy protons and other charged particles—entering Earth's stratosphere generate showers of pions, which decay into electrons, muons, and neutrinos. Despite the complexity of the decay chain, the process should always yield two muon neutrinos for every electron neutrino.

Atmospheric neutrinos, at one to several GeV, are orders of magnitude more energetic than solar neutrinos, which rarely exceed 10 MeV. At such high energies, Kamiokande could not only detect both the electron and muon flavors of neutrino—it could also tell them apart. A so-called water-Cherenkov detector such as Kamiokande registers a neutrino when it reacts with a nucleon or electron to yield a fast-moving

charged lepton (an electron or muon or one of their antiparticles). The lepton, traveling faster than the speed of light in water, creates the optical equivalent of a sonic boom. The resulting ring of Cherenkov radiation is projected onto the wall of the water tank, where it's picked up by photomultiplier tubes.

The shape of that ring reveals the neutrino's flavor. Relatively heavy muons, created by muon neutrinos, fly straight, and they yield clean, crisp rings. The lighter electrons, created by electron neutrinos, get batted around, so their rings are fuzzier. Between 1987 and 1994, Kamiokande detected 200 atmospheric neutrinos, enough to reach a clear conclusion. Rather than the expected 2:1 ratio of muon neutrinos to electron neutrinos, the ratio was much closer to 1:1. (See *PHYSICS TODAY*, October 1994, page 22.)

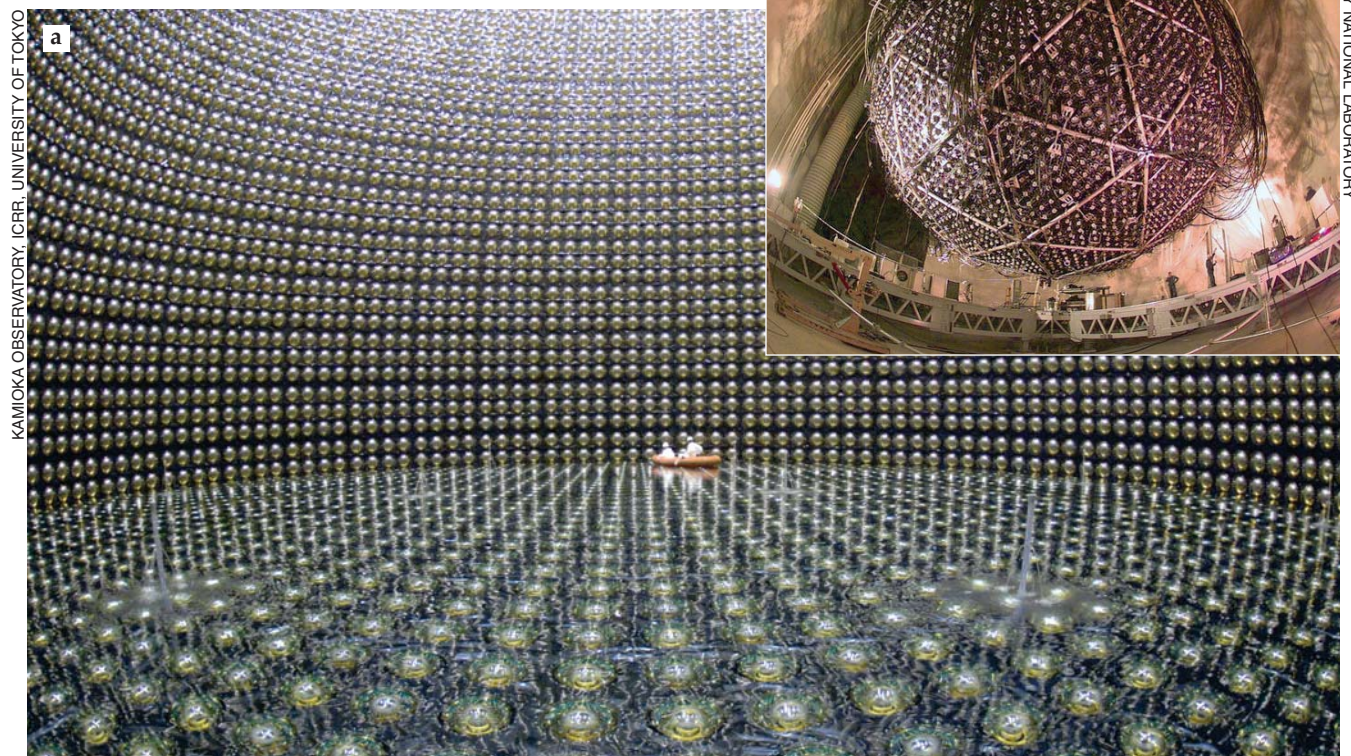
Solving the mystery in a reasonable amount of time would require a much larger detector—both to catch more neutrinos and to fully contain more of their Cherenkov tracks. Whereas the Kamiokande detector used 3000 tons of ultrapure water, its successor, Super-Kamiokande, located in the same mine,

used 50 000 tons, contained in a cylindrical tank 40 meters wide and 40 meters tall. Under the leadership of Yoji Totsuka of the University of Tokyo, the Super-Kamiokande team grew into a collaboration of more than 100 researchers across Japan and the US.

The experiment was scheduled to begin in April 1996—in fact, the construction was completed slightly early. Chang Kee Jung of Stony Brook University, a member of the collaboration, recalls that Totsuka “waited until midnight on April 1st to push the button, so he could say he was ready on time.”

It didn't take long for a pattern to emerge, as shown in figure 2: Electron neutrinos from all parts of the atmosphere were detected at equal rates, but the flux of muon neutrinos depended markedly on direction and energy. Neutrinos coming from directly overhead, having traveled just 15 km or so, appeared in approximately the expected 2:1 ratio. But for those coming up from below, which had been created on the far side of the world and had traveled thousands of kilometers through solid Earth, muon neutrinos

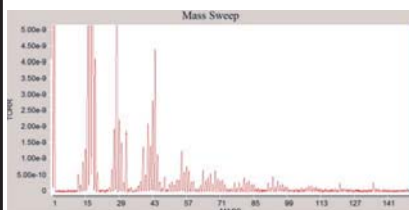
Figure 1. With huge, subterranean detectors, the case for neutrino oscillation was made. (a) Super-Kamiokande used a cylindrical tank filled with 50 000 tons of ultrapure water. While the tank fills, team members travel by raft to clean and check the photomultiplier tubes on the tank's perimeter. **(b)** The Sudbury Neutrino Observatory, or SNO, used a 12-meter-diameter acrylic sphere to hold 1000 tons of heavy water.



Evactron® EP Plasma Cleaning

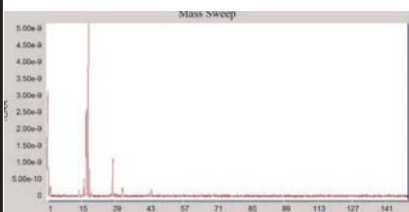


**“The
Hydrocarbon
signatures are
gone in the RGA
analysis!
Evactron
cleaning worked
in minutes!”**



↑ RGA of Vaseline contamination

↓ After 2 min. of Evactron cleaning



Evactron®

By XEI Scientific

www.Evactron.com/pt

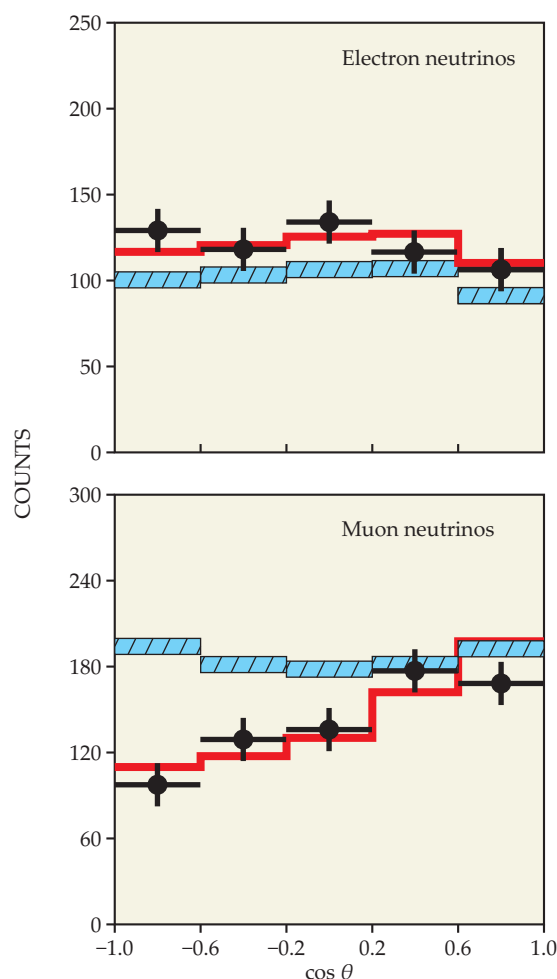


Figure 2. Atmospheric neutrinos with energies between 400 MeV and 1.3 GeV as detected by Super-Kamiokande, as a function of the angle θ measured from the local zenith. Data points and their error bars are shown in black, the blue blocks are the results of a Monte Carlo simulation that assumes no neutrino flavor oscillations, and the red stepped lines are the best fits of the data to a model that includes oscillations. Neutrinos coming from overhead ($\cos \theta = 1$) have little time to oscillate; for those coming up from below ($\cos \theta = -1$), the effect of oscillation is significant. (Adapted from ref. 1.)

appeared depleted relative to the electron neutrinos.

The missing muon neutrinos were, the researchers concluded, transforming into some undetectable species (now known to be tau neutrinos), and the farther they traveled, the greater the probability of transformation. That the transformation probability decreased as energy increased can be understood in terms of special relativity: As a particle approaches the speed of light, its internal clock runs more slowly.

Kajita, as the lead data analyst, presented the collaboration's results to the public for the first time at the Neutrino '98 conference. (See *PHYSICS TODAY*, August 1998, page 17.) "Until I finished my presentation," he says, "I did not think that the talk could have such a tremendous impact." But, as Jung recounts, the result represented the first hint of physics beyond the standard model of particle physics, which provides no mechanism for nonzero neutrino masses. "It immediately became something really big—a major, major revolution." The team's 1998 paper¹ remains the

most highly cited in experimental particle physics.

In November 2001 Super-Kamiokande suffered a severe setback when an accident destroyed more than half of the detector's photomultiplier tubes. (See *PHYSICS TODAY*, January 2002, page 22.) "I felt we were lucky," says Kajita, "because Yoji Totsuka made the decision to rebuild. He devoted his time to practical ways of recovery." By October 2002 the experiment was running again. It remains operational, with plans under way for a million-ton "Hyper-Kamiokande" detector.

SNO

Super-Kamiokande had shown that muon neutrinos could change their identities. That finding didn't directly solve the solar-neutrino problem, because electron neutrinos—the kind produced by the Sun—weren't observed to oscillate. But solar neutrinos travel much farther to reach Earth than atmospheric neutrinos do. Electron-neutrino oscillation along the way could still be responsible for the missing solar neutrinos.

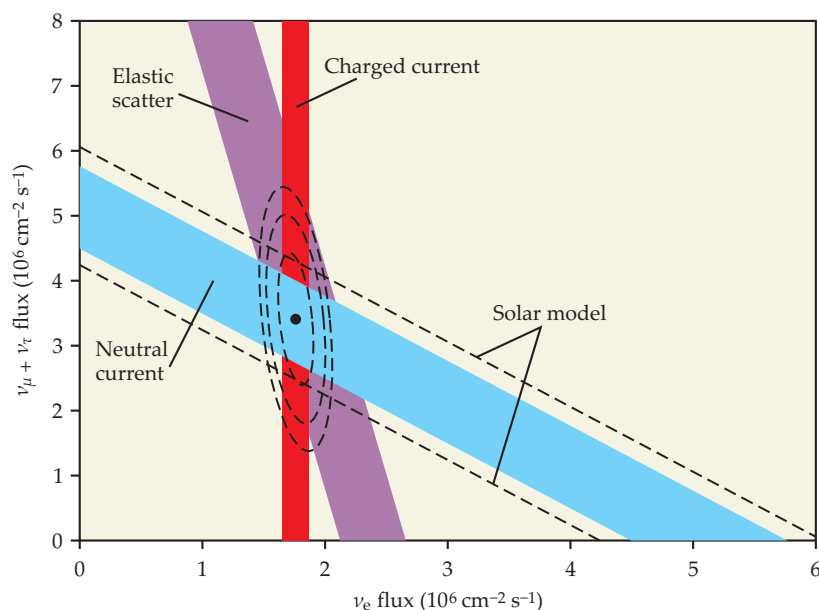


Figure 3. Solar neutrinos as detected by the Sudbury Neutrino Observatory (SNO). The detector measured three distinct neutrino-interaction mechanisms. The charged-current interaction is sensitive only to electron neutrinos (ν_e), whereas the neutral-current interaction is sensitive to electron, muon, and tau neutrinos (ν_e , ν_μ , and ν_τ). The elastic-scatter mechanism, whereby a neutrino scatters off an electron, is sensitive to all neutrino flavors, but not equally. From the intersection of the three bands, one can infer the fluxes of electron and non-electron neutrinos; the dashed ovals represent error margins of one, two, and three standard deviations. The dashed lines are the maximum and minimum total flux predicted by the standard solar model. (Adapted from ref. 3.)

In the mid 1980s, Herbert Chen proposed that a 1000-ton heavy-water detector could be ideally suited for studying solar neutrinos. Deuterons, or heavy-hydrogen nuclei, are rather loosely bound; it takes just 2.2 MeV to break one apart. A neutrino of any flavor, as long as it has sufficient energy, can split a deuteron into a proton and a neutron. Furthermore, an electron neutrino can react with a deuteron to yield two protons plus an electron. Those two mechanisms—called the neutral-current and charged-current interactions, respectively—allow the electron-neutrino flux and total neutrino flux to be measured independently by the same experiment.

Chen never saw his vision realized. After his untimely death in 1987, the project—the eventual SNO—was carried on by McDonald, George Ewan, David Sinclair, Hamish Robertson, and others in Canada, the UK, and the US.

Heavy water is plentiful in Canada, thanks to the country's history with heavy-water-moderated nuclear reactors, but it doesn't come cheap. The 1000 tons of it, worth \$300 million, had to be borrowed from Atomic Energy of Canada, Ltd. Ewan had arranged for a

2-km-deep detector site in Creighton mine in Sudbury, Ontario, an active mine that produces a significant fraction of the world's nickel.

Because the detector would be sensitive to relatively low energies, background levels had to be tightly controlled. A stray radioactive atom could emit a gamma ray with enough energy to split a deuteron and mimic a neutrino signal. To minimize that possibility, the researchers classified the entire detector chamber—which, at 22 m by 38 m, was the largest ever excavated at that depth—as a clean room. Among other precautions, no one could enter without first showering and changing clothes.

Data collection began in 1999. The charged-current interaction—sensitive to electron neutrinos but no other flavors—was straightforward to detect: The nascent electron carried off most of the incident neutrino's energy, so it could be detected via its Cherenkov radiation.² (See *PHYSICS TODAY*, August 2001, page 13.) The telltale neutrons from the neutral-current interaction—the measure of the total flux of all neutrinos—proved harder to see. A deuteron capturing a neutron releases a characteristic 6.25-MeV gamma ray, but the

JANIS

Cryogenic Wafer Probe Stations



- Applications include nano science, materials and spintronics
- 3.2 K - 675 K; high vacuum or UHV
- Up to 8 probes, DC to 67 GHz, plus fiber optics
- Zoom optics with camera and monitor
- Cooling options: liquid helium, liquid nitrogen or cryogen free
- Horizontal, vertical or vector magnetic field options are available

Contact us today:

sales@janis.com

www.janis.com/ProbeStations.aspx

www.facebook.com/JanisResearch

capture probability is low, so it took much longer to obtain a conclusive measurement.

"So that our data analyzers weren't biased by any preconceived result," explains McDonald, "we blinded ourselves by not looking at part of the data set until our analysis criteria were fully defined." When the researchers took the blinders off, they found that the flux of muon and tau neutrinos—that is, electron neutrinos that had changed flavor—was greater than zero with a statistical significance of more than five standard deviations. Says McDonald, "It was a real Eureka moment."

The result, shown in figure 3, was an impressive confirmation of the solar model.³ (See PHYSICS TODAY, July 2002, page 13.) Because the flux of ^8B neutrinos depends on the 24th power of the Sun's core temperature, the excellent agreement between the predicted and observed fluxes meant that the temperature was correct to within 1%. After enduring decades of skepticism, Bahcall's theoretical work turned out to have been right all along.

The SNO detector took its last data in 2006. "The heavy water was expensive to insure," explains Robertson, "so we had to give it back." But the mine

continues to host several other international experiments that benefit from the low-radioactivity subterranean site. And plans are under way to refurbish the SNO equipment for a new 1000-ton neutrino detector, called SNO+, filled with linear alkyl benzene, an organic liquid scintillator, instead of heavy water.

Answers and questions

Subsequent experiments clarified the oscillation picture and its broader implications. The Kamioka liquid-scintillator antineutrino detector (KamLAND), which detects neutrinos originating from nuclear reactors around Japan, was the first to reveal an actual oscillatory signal: electron neutrinos disappearing and reappearing as a function of energy and distance. That result ruled out the possibility—which had always been considered unlikely—that neutrinos were not oscillating but rather irreversibly transforming.

It's now known that each neutrino flavor can transform into each of the others (see PHYSICS TODAY, May 2012, page 13). That means each flavor state—electron, muon, and tau—is the superposition of three different mass states, at least two of which must have

nonzero mass; the oscillation arises from the evolving relative phases between those states. Oscillation measurements have revealed the differences between the squares of the masses, but not their absolute values, nor even which is largest. From observations of the cosmic microwave background, researchers have deduced that the average of the masses must be less than 0.3 eV—less than a millionth of the mass of the electron.

Where do those masses come from, and why are they so small? In the standard model of particle physics, mass arises via the Higgs mechanism (see PHYSICS TODAY, September 2012, page 14). But that model bestows no mass on the neutrinos. Understanding the mechanism that gives neutrinos their mass could go a long way toward a more complete theory that fills in some of the standard model's gaps.

Every neutrino ever observed has been left-handed—that is, its momentum and spin are antiparallel—and has had a speed indistinguishable from the speed of light c . But because neutrinos are massive particles, their speed must be less than c . It's therefore possible, at least theoretically, to catch up with a neutrino and overtake it, which would

PRECISION MEASUREMENT GRANTS

The National Institute of Standards and Technology (NIST) expects to make two new Precision Measurement Grants that start on 1 October 2016, contingent on the availability of funding. Further guidance will be provided on the Web when the funding level is resolved. The grants would be in the amount of \$50,000 each per year and may be renewed for two additional years for a total of \$150,000. They are awarded primarily to faculty members at U.S. universities or colleges for research in the field of fundamental measurement or the determination of fundamental physical constants.

Applications must reach NIST by **2 February 2016**. Details are on the Web at: physics.nist.gov/pmg.

For further information contact:

Dr. Peter J. Mohr, Manager
NIST Precision Measurement Grants Program
100 Bureau Drive, Stop 8420
Gaithersburg, MD 20899-8420
301-975-3217

NIST

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

take flight with MASTERBOND aerospace adhesives

Follow Max on his animated adventures

Catalog on adhesives for the aerospace industry

Products meet NASA low outgassing standards

WATCH THIS ad come to life

Hackensack, NJ 07601, USA • +1.201.343.8983 • main@masterbond.com

www.masterbond.com

reverse its helicity from the observer's point of view. (See the article by Alfred Goldhaber and Maurice Goldhaber, *PHYSICS TODAY*, May 2011, page 40.)

So although right-handed neutrinos have never been seen, they must exist. Theoretical explanations abound. One, the so-called seesaw mechanism, postulates a fixed product of the left-handed and right-handed neutrino masses. Because left-handed neutrinos are much lighter than the other elementary particles, right-handed neutrinos would be much heavier—possibly too heavy to detect.

If the seesaw mechanism is correct, an intriguing consequence is that neutrinos must be Majorana particles—that is, their own antiparticles. Several experiments, including SNO+, seek to test that possibility by looking for neutrinoless double-beta decay (see *PHYSICS TODAY*, January 2010, page 20). A radioactive nucleus undergoing beta decay emits one electron and one antineutrino; the occasional double-beta decay emits two of each. If neutrinos are their own antiparticles, it's possible for the two neutrinos to effectively annihilate, leaving the electrons to carry off the entire energy of the decay.

Neutrinoless double-beta decays, if they occur at all, represent at most a tiny fraction of the already rare double-beta decays. Observing them requires both a large quantity of the decaying isotope and a detector with excellent energy resolution for capturing the emitted electrons. If found, the decays provide a measurement of the absolute neutrino masses (the rate of neutrinoless events is related to the neutrino mass squared) and could also lead to an understanding of why the universe contains so much more matter than antimatter. (See the Quick Study by Rabi Mohapatra, *PHYSICS TODAY*, April 2010, page 68.)

Valuable players

Nobel Prizes can't be awarded posthumously, and they can't be shared by more than three people. So Bahcall (1934–2005) and Totsuka (1942–2008) are necessarily excluded from this year's honor, as are most of the many dozens of scientists who have contributed to Super-Kamiokande and SNO over the years. Jung contrasts the situation to a sports championship: "When a team wins the championship, the whole team shares the trophy," he says. "But then there's also an award for the most valuable player."

Takaaki Kajita was born in 1959 in Higashimatsuyama, Saitama, Japan. He

earned his undergraduate degree from Saitama University in 1981 and his PhD from the University of Tokyo in 1986. He has been affiliated with the University of Tokyo ever since, where he worked on both the Kamiokande and Super-Kamiokande experiments. In 1999 he became the director of the Center for Cosmic Neutrinos at the Institute for Cosmic Ray Research. Since 2008 he has been director for the entire institute, which oversees Super-Kamiokande and several other experiments.

Arthur McDonald was born in 1943 in Sydney, Nova Scotia, Canada. After obtaining bachelor's and master's degrees from Dalhousie University in Nova

Scotia, he earned his doctoral degree in physics from Caltech in 1969. From 1970 until 1982 he worked as a research officer at Chalk River Nuclear Laboratories in Ontario. After seven years on the faculty at Princeton University, he moved to Queen's University in Kingston, Ontario. He has been director of the SNO collaboration since 1989.

Johanna Miller

References

1. Y. Fukuda et al., *Phys. Rev. Lett.* **81**, 1562 (1998).
2. Q. R. Ahmad et al., *Phys. Rev. Lett.* **87**, 071301 (2001).
3. Q. R. Ahmad et al., *Phys. Rev. Lett.* **89**, 011301 (2002).

Digital holography takes to the skies

The technique allows researchers to image the small-scale structure of clouds.

Viewed from afar, clouds can look like floating, wispy puffs of cotton. Up close, micrometer- to millimeter-sized droplets of liquid water are buffeted by turbulent winds as dry air surrounding a cloud mixes with the moisture-laden air inside. The continually morphing shapes of clouds are visible manifestations of that turbulent mixing.

Cloud physicists have long wanted to know how turbulent mixing affects the size and spatial distribution of cloud droplets at centimeter or smaller length scales. Those are the scales at which the droplets collide and merge, evaporate,

and interact with aerosols. Such microphysical processes profoundly shape large-scale cloud properties, among them the likelihood of producing rain and other precipitation and their ability to reflect incoming sunlight back into space.

To get a definitive three-dimensional picture of cloud structure at the scale of a few cubic centimeters, Raymond Shaw of Michigan Technological University, Jacob Fugal of the Max Planck Institute for Chemistry, Jeff Stith of the National Center for Atmospheric Research, and their colleagues have turned to digital holography. On two separate



Figure 1. The Holographic Detector for Clouds, or HOLODEC, is shown mounted to the underside of the leading edge of a research aircraft's wing. The black-tipped instrument takes holographic snapshots of liquid water droplets in a cloud. (Courtesy of the National Center for Atmospheric Research.)