2016 Breakthrough Prize in fundamental physics goes to five neutrino experiments

November 9 2015, by Paul Preuss

SNO captured all flavors of neutrinos with an acrylic vessel (center) filled with a thousand metric tons of heavy water, surrounded by almost 10,000 photomultiplier tubes (PMTs). Berkeley Lab designed and built the support structure for the PMTs. Credit: Roy Kaltschmidt, Berkeley Lab

At a gala ceremony held in Silicon Valley on November 8, the Sudbury Neutrino Observatory (SNO), the Kamioka Liquid-scintillator Antineutrino Detector (KamLAND), and the Daya Bay Reactor Neutrino Experiment (Daya Bay) were among five neutrino experiments awarded the 2016 Breakthrough Prize in Fundamental Physics. All three were made possible by essential contributions from scientists and engineers at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab). The other honored experiments were Super-Kamiokande (Super-K) and KEK-to-Kamioka/Tokai-to-Kamioka (K2K/T2K).

The Breakthrough Prizes, which honor advances in Fundamental Physics, Life Sciences, and Mathematics, were founded in 2012 by technology VIPs Sergey Brin and Anne Wojcicki, Jack Ma and Cathy Zhang, Yuri Milner and Julia Milner, and Mark Zuckerberg and Priscilla Chan. The $3 million prizes are the richest in their fields, often awarded to more than one activity in each category and acknowledging the contributions of their team members.

"That the Lab played important roles in three of the five experiments honored by the Breakthrough physics prize is quite remarkable, considering that Berkeley Lab was not much involved in neutrino physics until the late 1980s," says James Symons, the Lab's Associate Laboratory Director for Physical Sciences, who was director of the Nuclear Sciences Divison (NSD) during much of the Lab's participation in the SNO and KamLAND experiments. "However, once we got started

with SNO, the progression to KamLAND and then to Daya Bay was a natural one, as the neutrino's properties were slowly unveiled."

Kevin Lesko of the Physics Division has focused on neutrinos since first joining Berkeley Lab's NSD over 30 years ago. "The five Breakthrough Prize experiments, taken together, have done a superb job in defining the oscillations among neutrino families and helping us understand fundamental neutrino properties," he says, referring to the phenomenon of three families or "flavors" of neutrinos mixing properties and changing, one into another, as they stream through everything in the universe.

SNO provided the first direct evidence of flavor change, among neutrinos generated by nuclear fusion in the heart of our sun. KamLAND, observing antineutrinos from nuclear reactors, confirmed that the flavor-change mechanism is oscillation. Daya Bay discovered the surprisingly large value of the last unknown neutrino "mixing angle."

Neutrino flavor, neutrino oscillation, neutrino mass

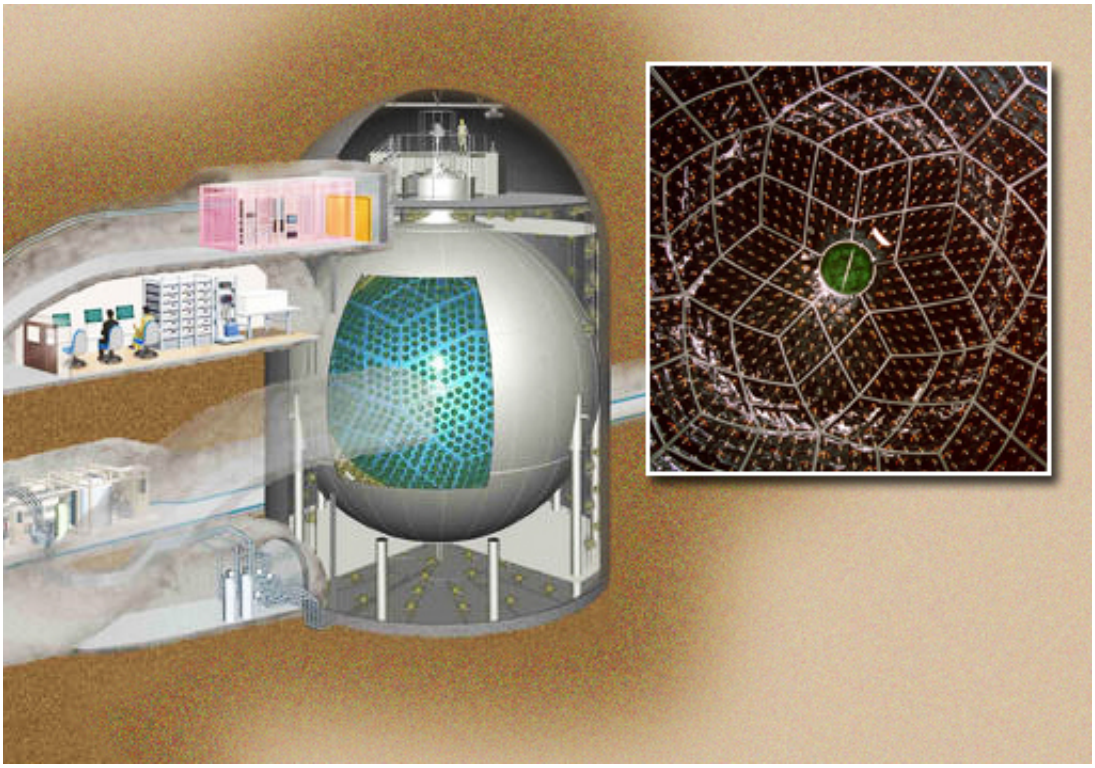
Neutrinos were first proposed in 1930 to account for energy missing in radioactive decays involving electrons. Like photons, neutrinos were thought to have no mass and travel at the speed of light. Unlike photons, they interact via the weak force (hardly at all), not electromagnetism. They weren't detected until the mid-1950s, in events triggered by antineutrinos (their near identical counterparts) from a nuclear reactor.

Electrons have heavier cousins called muons; in 1962, muon-associated neutrinos were found in an accelerator experiment. A much heavier electron cousin, the tau particle, appeared in 1975; researchers assumed it had a neutrino partner, although it took 25 years to find it. Thus the three flavors: electron, muon, and tau neutrinos.

In the late 1960s, deep in the Homestake Gold Mine in South Dakota, experimenter Ray Davis laid a neutrino trap, a 100,000-gallon tank of chlorine-rich cleaning fluid; catching enough neutrinos would prove the sun was fusion-powered. He found only a third the expected number; the so-called "solar neutrino problem" was born.

Since chlorine interacts only with electron-flavored neutrinos, theorists argued that Davis's missing neutrinos were there but undetectable, having oscillated into other flavors en route from the sun—a heretical idea, because nothing with mass can travel at light speed, and it was thought no massless particle could change its identity. Oscillating neutrinos must have mass, however slight.

SNO proves it



KamLAND, buried deep underground near Toyama, Japan, is the largest scintillation detector ever constructed. Berkeley Lab and UC Berkeley members

provided front-end electronics and calibration systems for the detector, a vessel filled with scintillating mineral oil and lined with photomultiplier tubes

In 1998, Japan's Super-K reported indirect evidence for oscillation. In counts of muon neutrinos created when cosmic rays collide with the atmosphere, Super-K found half as many from below as from above; since Earth's 13,000-kilometer diameter allowed room for neutrino oscillation, half were assumed to have gone undetected.

SNO, in Canada, found direct evidence three years later. SNO was built to solve the solar neutrino problem. SNO's Berkeley Lab group, led by Lesko from 1989, designed an intricate array of almost 10,000 photomultiplier tubes (PMTs) to search for faint, telltale flashes of blue light, which tagged neutrino events in the inner sphere of the huge underground detector. The PMT support structure was originally meant to be aluminum, until NSD scientists showed aluminum was sufficiently radioactive to cause false signals. The structure was built of stainless steel in the Bay Area, disassembled, and trucked to the SNO site.

Alan Poon of NSD played a leading role in SNO's physics analysis. He says, "SNO was unique in using heavy water, which could catch electron neutrinos, muon neutrinos, and tau neutrinos with equal efficiency." This all-flavor channel matched the numbers predicted for total solar neutrinos. A separate channel caught only electron neutrinos, and collected far fewer: the others had changed into muon or tau neutrinos on their way from the sun, the first direct evidence of neutrino flavor transformation.

However, says Lesko, "To understand the phenomenon of neutrino oscillation, we needed a full set of experiments using solar neutrinos, antineutrinos from nuclear reactors, and neutrinos produced in particle

accelerators."

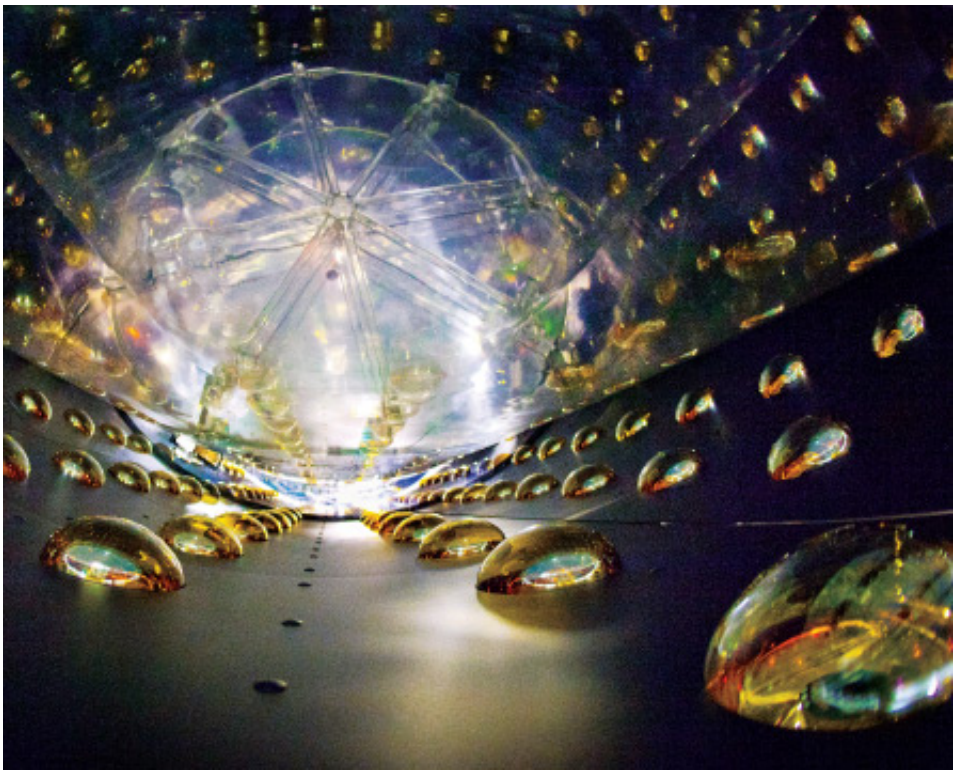
KamLAND nails it down

The late Stuart Freedman of NSD inaugurated and led U.S. participation in KamLAND. KamLAND captured antineutrinos from more than 50 nuclear reactors, some nearby, some hundreds of kilometers away. Its detector, buried deep underground like all such experiments, held a kiloton of pure liquid scintillator surrounded by almost 1,900 PMTs.

NSD's Brian Fujikawa, KamLAND group leader, says that one contribution by Berkeley Lab's NSD and Physics Division team was the front-end electronics to convert signals from KamLAND's photomultiplier tubes from analog to digital, using a chip developed for the IceCube neutrino telescope at the South Pole.

"Instead of neutrinos from the sun, KamLAND observed the flavor changes of antineutrinos from commercial power reactors, artificial sources much better understood than the sun," says Fujikawa. A laboratory-style experiment with both sources and detector controlled, KamLAND revealed the clean signature of actual oscillations.

An unanswered question



Eight detectors like this one, filled with liquid scintillator and surrounded by photomultiplier tubes, were deployed under the mountains near the six immensely powerful nuclear reactors at Daya Bay. Berkeley scientists and engineers designed the experiment's key components. Credit: Kaltschmidt

Neutrinos oscillate, but how? By 2004, the leading theory of flavor mixing had largely been confirmed, but there were significant gaps. The differences among neutrino masses could be estimated, but the masses themselves—and which neutrino was heaviest—were unknown. Two of the three mixing angles had been measured but not the third, called theta one-three; without knowing theta one-three, questions like what part neutrinos played in the excess of matter over antimatter in the universe couldn't be approached.

To plug the gap, members of the Lab's Physics Division conceived the experiment that became Daya Bay. Physicist Kam-Biu Luk identified

the ideal site, six powerful nuclear reactors of the China Guangdong Nuclear Power Group, some 50 kilometers northeast of Hong Kong. Under the mountains that abutted the reactors, groups of detectors would be placed at intervals inside two kilometers of tunnels. Supported by DOE, the plan was realized in partnership with China, other nations, and other U.S. institutions.

Natalie Roe, Director of the Physics Division, says, "The success of this experiment hinged on precise control of the systematic errors between the near and far detector measurements of the neutrino flux, and I remember that there were many in the particle physics community who were skeptical. But in the end, the Daya Bay experiment's careful design and execution met and even exceeded these requirements."

By counting the antineutrinos the reactors produced—a million quadrillion every second—and calculating how many should be visible to the detectors—a thousand per day at the nearby sites, a hundred a day at the far site—and then comparing the smaller number actually detected, theta one-three could be determined with precision.

The first Daya Bay results were released in 2012, even before construction was complete. "We were still two detectors shy of the complete experimental design, but we had extraordinary success," said Luk. Theta one-three, once feared to be near zero, was "comparatively huge."

Luk reflects that "the first definitive proof that the neutrino mixing angle theta one-three is sizable unlocked the floodgate for new experiments that will unveil the order of the neutrino masses and look for differences in the way neutrinos change identities with their antineutrino partners."

The fifth winners of the physics prize, K2K and T2K, were accelerator experiments in Japan that sent beams of muon neutrinos hundreds of

kilometers to the Super-K detector. In 2011, T2K hinted at the first observation of muon neutrinos oscillating to electron neutrinos. The March 2011 earthquake interrupted the search, but in 2013 the observation was firmly established.

Berkeley Lab's contributions to the Breakthrough Prize winners and many other neutrino experiments around the world have involved members from NSD, Physics, Accelerator Technology and Applied Physics, Engineering, Computing Sciences divisions, and others. Berkeley Lab plays an important part in a new generation of experiments, planned or already underway, to investigate profound mysteries such as the role of neutrinos in matter-antimatter asymmetry. From the answers, we may yet learn how it is possible that humans are here to ask such questions.

Provided by Lawrence Berkeley National Laboratory

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