A Nobel Prize for the Two-Neutrino Experiment

The prize honors an experiment that pioneered a new research technique, and that was a key step toward unification

IN RECOGNITION OF an experiment carried out more than a quarter-century ago, the 1988 Nobel Prize in physics has been awarded to Leon Lederman, director of the Fermi National Accelerator Laboratory; Melvin Schwartz, now the president of Digital Pathways, Incorporated, in Mountain View, California; and Jack Steinberger, senior physicist at CERN, the European Center for Particle Physics. Their experiment pioneered the use of high-energy neutrinos as probes of the fundamental interactions. At the same time, it helped provide an empirical basis for unified field theories by proving the existence of at least two kinds of neutrino.

"I think you'll find that the general view of the community is very positive," says Harvard University's Sheldon Glashow, who shared the 1979 Nobel Prize for his own work on unified theories. "[Their experiment] was the birth of a whole new way of doing high-energy physics." Indeed, the neutrino beam technique has become a mainstay at accelerators around the world.

From all reports, however, the prize is not just an honor to three individuals, but a testament to the unique post-war flowering of physics talent at Columbia University, where Lederman, Schwartz, and Steinberger were working at the time. This is the sixth independent physics Nobel to be awarded for research done at that institution within a single 15-year span, from the late 1940s to the early 1960s.*

"It was a very remarkable period, almost like art in the Netherlands in the 1600s," says Schwartz. "I think in large measure it was because of two great people. [The late Isidor I.] Rabi was the guy who brought people in, and who was constantly goading us to greater achievements." (Rabi had himself won the 1944 Nobel prize for his work in nuclear magnetic resonance.) And later there was T. D. Lee, "the sparkplug of the department," who shared the 1957 Nobel Prize for discovering that a quantity known as parity was not conserved in the weak interactions.

Indeed, Schwartz is quick to give Lee the credit for inspiring the neutrino beam experiment in the first place. "It all started in November 1959 at a coffee hour at Columbia, which we had in the physics department from 3:00 to 3:30 every day," he says. He had come down that day from Nevis Laboratory, Columbia's center for high-energy physics research located just north of New York City. "T. D. Lee was leading a discussion group at the blackboard, and he asked, 'Is there any way to study the weak interactions at high energy?' "

Lee's point was that a study of high-energy weak interactions ought to be fruitful for several reasons, not the least being that the weak force itself was utterly mysterious. It was an exceedingly feeble sort of interaction, one that was negligible compared to the electromagnetic forces between particles, and infinitesimal compared to the so-called strong forces that bind the atomic nucleus. It was known to cause a form of radioactivity called beta decay, in which a neutron converts itself into a proton by emitting two particles: an electron and a neutrino. And it was known to cause similar decays in certain other short-lived particles. But no one could say for sure what the weak force was actually *doing* to cause the decays.

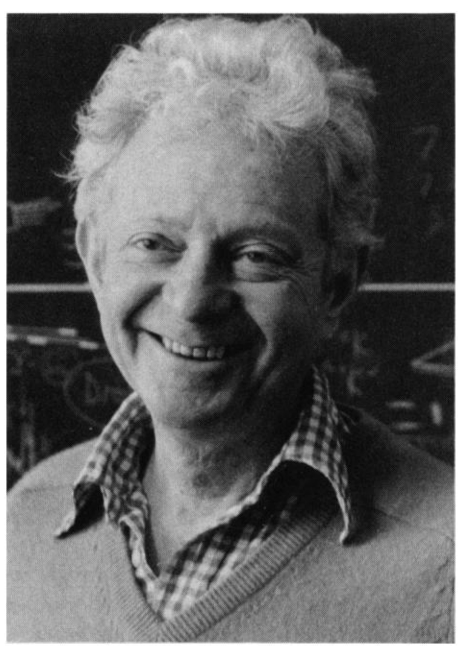
Worse, the weak force as it was then understood seemed to violate one of the most fundamental principles of quantum mechanics. The observed properties of beta decay were described quite accurately by a phenomenological expression first written down in the 1930s by the late Italian physicist Enrico Fermi. Under certain circumstances, however—most notably, when particles were colliding at very high energies—Fermi's equation predicted quantum-mechanical probabilities that were greater than one, which was clearly absurd. So Fermi's equation would have to break down at that point. Some new phenomenon would have to come into play at higher energies, something that would surely illuminate what was really going on in the weak interactions.

Three decades later Lee's argument sounds remarkably prescient, says Schwartz. High-energy studies of the weak interactions did prove to be amazingly fruitful. And as a result, the Fermi model has indeed been replaced: the now accepted "standard model" not only unifies the weak interactions with electromagnetism, but explains beta decay and the high-energy behavior alike in a completely satisfactory way. On that November afternoon at Columbia, however, Lee's simple-sounding question was a major challenge.

"We all tried to think of various subtle processes" that would allow a probe of high-energy weak interactions, says Schwartz, "but none were satisfactory." The essential problem was that the weak force was so very weak. In any kind of particle collision that the physicists around the blackboard could think of, its effects would be lost in a firestorm of electromagnetic and strong interactions.

"So I came home still thinking about it," says Schwartz, "and in a crazy way it just hit me: use neutrinos! Neutrinos do nothing *but* weak interactions." Indeed, that is why neutrinos are so hard to detect in the first place. Ghostly objects with little or no mass and zero electric charge, they can pass through ordinary matter as if it were not there. In fact, they could easily pass through about a light year of lead.

Nonetheless, on very rare occasions neutrinos do interact via the weak force. Moreover, as Lee had pointed out, their probability of interacting rises in proportion to their energy. If one could somehow shine a high-energy beam of neutrinos onto a target,



Leon Lederman

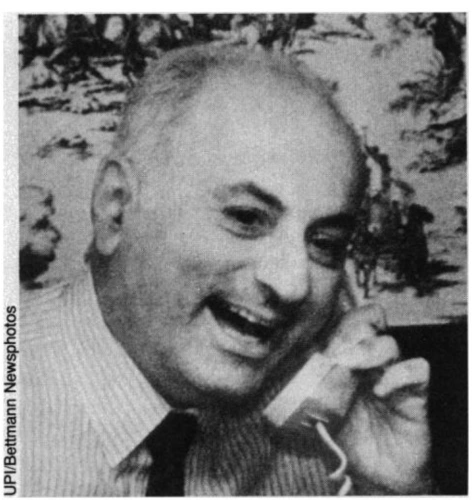
*The other five have gone to Willis E. Lamb, Jr., for his measurement of the fine structure of hydrogen (1955); Ploykarp Kusch for his measurement of the magnetic moment of the electron (1955); T. D. Lee for pointing out the non-conservation of parity in the weak interactions (co-winner, 1957); Charles Townes for the invention of the maser (co-winner, 1964); and James Rainwater for work on collective motions in nuclei (co-winner, 1975). According to many observers—Steinberger, for one—Columbia's C. S. Wu should have shared the 1957 prize since it was she who experimentally confirmed the violation of parity.

thought Schwartz, the result would be a series of pristine weak interactions uncontaminated by any other processes—exactly what he and his colleagues had been looking for all afternoon.

So how does one make a neutrino beam? By a kind of particle cascade, he realized. First, take an accelerator's proton beam and direct it into a target of some kind—say, a block of beryllium. The beam will then blast loose a spray of subatomic debris. Now, among the most copious products of any proton collision are the charged pi mesons, or pions. And as Schwartz well knew, these particles are unstable, decaying in less than a microsecond to form two new particles. One of these new particles—the mu meson, or muon—is a kind of heavy version of the electron. The other is exactly what Schwartz was after: a neutrino. Taken together, these pion-produced neutrinos would give him his neutrino beam.

"It was really a simple idea," says Schwartz. "I called T. D. Lee that night and told him I had a way to do it."

In the days that followed, the team of Lederman, Schwartz, and Steinberger formed quickly. "We yelled and screamed at each other for awhile," says Lederman, "and then we decided, 'Hey! This is a doable experiment.' "



Melvin Schwartz

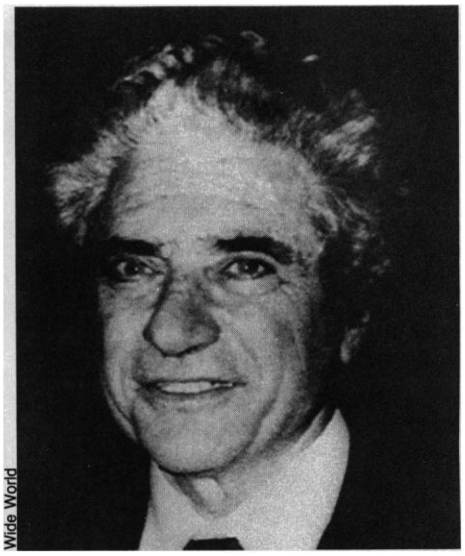
The obvious place for the experiment was the Alternating Gradient Synchrotron (AGS) accelerator, which was then nearing completion at Brookhaven National Laboratory on Long Island; with a proton beam energy of 30 billion electron volts (GeV) and an intensity of some 100 billion protons per second, it was to be the most powerful accelerator in the world. However, the creation of a useful neutrino beam was by no means as simple in practice as it was in concept. To begin with, the neutrinos were going to come flying out of the accelerator accompanied by muons and assorted other trash. All of it would have to be filtered out if there was to be any hope of detecting pure neutrino interactions. To accomplish this, the researchers accordingly bought up armor plate from the battleship U.S.S. *Missouri*, which had been decommissioned and was being cut up for scrap. Then they stacked the massive slabs across the path of the neutrino beam to form a wall of steel nearly 10 meters thick. The neutrinos, of course, would pass right through. Virtually everything else would stop dead. (Lederman recalls a fierce argument with one colleague whose apparatus was going to have to share space with the barrier: "You are *not* going to put that rusty iron next to my beautiful experiment!" They did anyway.)

Then there was the matter of a detector. Behind the barrier the researchers built a 10-ton spark chamber, which would respond to a neutrino collision by creating a trail of sparks behind every electrically charged particle created in the collision. Building the steel barrier was really quite trivial compared with the chamber, says Schwartz. The device had been invented only a year or so before. And yet it was the only detector they knew of that could analyze the collision products in sufficient detail.

By this time, in mid-1960, the researchers had decided that for their first experiment they would attempt to resolve the so-called two-neutrino question. This had emerged as a major issue in weak interaction physics because of an argument first made back in the 1950s by Columbia theorist Gerald Feinberg, and then later generalized by Lee.

Suppose, they said, that there is only one kind of neutrino. That is, suppose that the neutrino emitted along with an electron in beta decay is identical to the neutrino emitted along with a muon in pion decay. Then a certain weak reaction—the decay of a muon into an electron and a gamma ray—ought to occur at an easily detectable rate. And yet that reaction had never been seen. Therefore, concluded Feinberg and Lee, the supposition must be wrong. The two neutrinos must be distinguished by some ineffable "electron-ness" and "muon-ness," even though they otherwise seemed identical. The trick was to prove it.

As it happens, the neutrino beam method was ideal for this purpose. Since the neutrinos in the beam were produced by pi decay, they were clearly of the muon type. And if these muon neutrinos were in fact the same as electron neutrinos, then it was easy enough to show that, when they interacted in the detector, they would produce electrons and muons with equal probability. But if they were different, then they would produce muons only. The experimental signature could not be cleaner.



Jack Steinberger

One can get a sense of how rare neutrino interactions really are from the fact that Lederman, Schwartz, and Steinberger spent 8 months irradiating their target with hundreds of billions of neutrinos, while obtaining less than 50 events. But that was enough. Only muons appeared, not electrons. The two-neutrino hypothesis was proved.

In the wider physics community the announcement caused a sensation, to put it mildly. As Harvard's Glashow points out, "most people at the time did *not* believe in two neutrinos, so the discovery was a shock."† In hindsight, moreover, it was seminal. Especially later on in the 1960s, as it became apparent that particles such as protons, neutrons, and pions are in fact made up of more basic building blocks known as quarks, physicists began to realize that the fundamental particles fall naturally into groupings, or "families." These families are distinguished from one another by their masses, but are otherwise identical. Thus, the lightest family comprises the electron, the electron neutrino, and two quarks designated by the names "up" and "down." The next heavier family comprises the muon, the muon neutrino, and two quarks designated "strange" and "charmed." And so it goes. This duplication of particle families is still not well understood. But the family structure itself has nonetheless become a central tenet of the unified theories constructed by Glashow and others in the 1960s and 1970s. Indeed, the theories would be mathematically inconsistent if the particles did not come in families with this kind of structure.

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†Since the mid-1970s there has also been strong evidence for the existence of a third kind of neutrino.