If Las Vegas took bets on physics results, the odds on LSND’s 1995 announcement would have been very, very long. While no one could quite say what was amiss, few believed the experiment had detected a neutrino mass. When the LSND team made the rounds, giving talks at universities, conferences, and the national labs, it was a tough sell.

There is no original truth, only original error.
Gaston Bachelard (1884–1962)
Neutrinos feel gravity’s tug, but too weakly to be of use experimentally.  

1Neutrinos might be massless, but neutrino oscillations would settle the question period ran longer than the talk itself. Some thought it was complete rubbish, others were very excited," he says. "In the end, all I could say was his is the data . . . take it or leave it." Many preferred to leave it, thinking it would just go away. Previous experience suggested it might.

For one, the Standard Model of particle physics states unequivocally that neutrinos are massless, and the Standard Model had yet to be proved wrong. Although the notion that neutrinos might have mass was not new—measurements of atmospheric- and solar-neutrino rates pointed to a similar conclusion—the LSND result didn’t coincide with many physicists’ expectations. Most theoretical models had to be stretched quite a bit to accommodate it; three sets of data; there just didn’t seem to be room for yet another positive result. (See the article “The Evidence for Oscillations” on page 116.)

Pressed to pick the wrong results on the lineup, many in the field suspected LSND’s. Rather than wait for neutrinos from the heavens, LSND argued the odds were only 1 in 1,000 that their results were wrong. Still, no one was placing bets.

LSND—A Walking Tour

Los Alamos, with its long history of defense work, may seem an odd place for the delicate task of weighing the neutrino. Above ground, in the foothills of the Jemez Mountains, there is little to betray the intricate machinery. The accelerator lies buried under a kilometer-long mound of dirt. Seen from an airplane, it recalls the inhumanly large constructions of the ancient Mayas, designed to catch the eyes of the gods. At its far end, metal blocks, planks, and bricks are stacked several meters high like the abandoned toys of a giant toddler. Most are recycled relics from long since: the cold war—iron from magnets at Oak Ridge Lab, steel from chopped-up battleships, and counterweights from missile silo doors. In their retirement, they shield a giant underground neutrino detector from cosmic rays and an occasional rattlesnake seeking refuge in the cracks.

The detector is so well shielded that it is all but impossible to get to. In a small shack nearby, a ladder leads through tens of meters of dirt and concrete, some of the neutrinos enter the LSND detector: a large, cylindrical tank filled with 52,000 gallons of mineral oil. This is the heart of LSND, where over a thousand phototubes fixed to the walls of the tank stare unblinkingly into the oil, watching for the tiny flashes of light that signal the presence of a neutrino. If a phototube fails, it’s left for dead. Once the tank has been stuffed into the underground tunnel, only neutrinos and cosmic rays can get inside.

Fortunately, after years of trouble-shooting by humans, the detector can essentially take care of itself. Most of the time, it clicks happily away, analyzing the electronic pulses from the phototubes with an elaborate array of hardware and then writing the data to magnetic tapes half the size of a cigarette pack. When a tape is full, the detector swaps it for a new one. If something goes drastically wrong, it pages a physicist for help. And if, somewhere among the millions of cosmic rays, it senses the pattern of lights that could signal a neutrino, it writes the information to a computer disk so that the forty LSND collaborators can log-in from their distant desks at universities coast to coast and check on the day’s catch.

How to Weigh a Neutrino

Neutrinos have mass, it is so slight that it hardly impedes their motion. Were it possible to produce a neutrino that stood perfectly still, the tiniest tap would suffice to send it fleeing to the ends of the universe at, or close to, the speed of light. And because the neutrino is electrically neutral, it cannot be grasped with electric or magnetic fields the way electrons or protons can. The only possibility of detecting neutrinos at all is through the weak force, which is roughly one hundred million times feebleer than the electromagnetic force. 3 The weak force is the agent behind all neutrino behavior—how they produce flashes of light in the tank, how they move, and even, perhaps, how they are “weighed.”

Since it is impossible to sit a neutrino on a scale or to determine its mass by running it through the magnetic fields of a spectrometer, the neutrino can only be weighed indirectly. LSND, like atmospheric and solar experiments, looks for neutrinos to “oscillate,” a strange behavior that can betray their mass.

Neutrinos come in three varieties—the electron neutrino, the muon neutrino, and the tau neutrino. Each neutrino also has an antimatter counterpart, called the electron, muon, and tau antineutrinos. When neutrinos (or antineutrinos) oscillate, they undergo a kind of identity crisis. An electron neutrino made in the Sun, for instance, may transform itself into a muon neutrino or a tau neutrino. The probability of observing one neutrino type or another varies periodically as the neutrino travels, hence the term oscillation. Oscillations can occur only if neutrinos have mass. Definitive observation of neutrino oscillations would settle the
neutrinos oscillate, the probability of observing a given neutrino type varies with distance. An idealized oscillation experiment would consist of a neutrino source that produces only one type of neutrino, here muon antineutrinos (blue) on pion decay. Enroute to the detector, he muon antineutrino transforms into an electron antineutrino (red), which can interact with a proton in the detector to reate a positron and a neutron. These particles are taken to be the signatures of the electron antineutrino.

Los Alamos Science
Number 25  1997

Feeling Around in the Dark

All neutrino oscillation experiments follow the same conceptual blueprints (see Figure 2). At the level of a sketch one might make on a napkin, there are only two components: a “source”, which like a pitching machine, hurls out neutrinos. (LSND searches for the latter experiment.) The death is swift, if rare. The neutrino disappears, replaced by new particles that generate telltale patterns of light in the oil. The “disappearance” is really just a change in identity. The weak force tugs on the neutrino and the protons in the tank, and can occasionally “transfer” the weak charge of one proton to the neutrino. In the process, the proton becomes an (electrically uncharged) neutron, and the electron antineutrino becomes a positively charged electron (called a positron).

Both the neutron and the positron generate flashes of light in the oil which draw the attention of a roomful of electronics. The “disappearance” is really just a change in identity. The weak force tugs on the neutrino and the protons in the tank, and can occasionally “transfer” the weak charge of one proton to the neutrino. In the process, the proton becomes an (electrically uncharged) neutron, and the electron antineutrino becomes a positively charged electron (called a positron).

But most neutrinos fly straight through the detector, so oscillation experiments can be chalked up to oscillations. All neutrino oscillation experiments lie a single all-important equation that gives the probability that a neutrino beginning its journey as one type will be observed as another type.

The quest is made still more difficult because an experiment essentially only measures one number (here the number of electron antineutrinos) but seeks information about two quantities ($\Delta m^2$ and $\sin^2 2\theta$). If, after a year, an experiment saw nothing, it could mean that the mixing angle is very small (and hence $A$, which functions like a “volume” control, squelches the probability of observing an electron antineutrino) or it could mean that the detector happened to sit at a distance where the oscillation probability was low (a distance very much smaller than the wavelength length for example, a meter or a centimeter). One can do is to rule out the values of $\sin^2 2\theta$ or choices of $\Delta m^2$ that would have given an observable number of electron antineutrinos. Figure 4 shows the values that had been searched and ruled out by experiments before LSND began taking data in 1993.

Bluprints

All neutrino oscillation experiments...
impossible to sort out how much of the scission was due to $A$ and how much $\propto \Delta m^2$. In fact, it wouldn’t even be

leat that oscillations had produced the lepton antineutrinos. The appearance of electron antineutrinos could also be

interpreted, perhaps more interestingly, s evidence for a new, bizarre decay of the muon, forbidden by the accepted

laws of physics.1

This was the strange limbo that eset LSND following the 1995

announcement. Although LSND results howed the appearance of electron

antineutrinos in a flood of muon anti-

teurinos, the measurement had been made at only one distance. Without

seeing the number of detected electron

tineutrinos rise and fall periodically s

a function of the distance $s$ or as

function of the energy $E$, few were

willing to write massive neutrinos into

the textbooks.

The LSND collaborators themselves

greed that one point did not make an

scillation. To address this, LSND had

een designed to see oscillations in a

ccond way, by looking for the transfor-
mation of muon neutrinos into electron

teutrinos, the “matter” counterpart of its

rimary antimatter analysis. This second

nalysis would later provide an inva-

uable cross-check on LSND results, but

n 1995 it was not yet complete.

Like all neutrino oscillation experi-

ments, LSND was a shot in the dark. If

he experiment had indeed observed

scliations, it would have been a lucky

apparence that the source-to-detector

istance was right.

Or of course, it could have been a

mistake. The best-designed detectors

re imperfect and can be duped by elec-

trons (muons), or by other particles from

the beam, or by the unrelenting rain of cos-

mic rays. Understanding these “back-

rounds” formed the linchpin for the

SND experiment and was the focus of

te questions that filled the air unless

LSND researchers presented their re-

ults. While a seminar audience could

ot judge in an hour what had taken

years to put together, many feared that

the experimenters, too, had somehow
duped.

Celestial vs Terrestrial Neutrinos

LSND is the fifth in a series of

neutrino experiments at Los Alamos, and

its design draws heavily on the experience of its predecessors. Most

importantly, it has inherited a decade-

old high-intensity neutrino source based on the Los Alamos Neutron Science Center, or LSANCSE accelerator. An

old warhorse, LSANCSE is still the highest-intensity proton accelerator in

the world for its energy. Physicists are

as familiar with its behavior as a soloist

is with a well-rehearsed piece of music.

Earthbound neutrino sources like

SLSANCSE shine out their celestial coun-

terparts in many respects. From their

far-flung birthplaces, celestial neutrinos

must travel a long way to visit terres-
trial detectors—thousands of light-years

from supernovae, a hundred million

kilometers from the Sun. As messen-
gers, they are invaluable, bringing news of
distant events such as the death of

stars and reactions in the heart of the

Sun; but as sources for oscillation

experiments, their remote and uncertain

origins make them less than ideal.

There is no user’s manual for the Sun

that states exactly what kind of neutrinos

are being produced, no dial to turn to

adjust its output, and no switch to turn it

off. Particle accelerators provide a way

to construct an intense neutrino source

closer to home, a kind of sun-on-earth

that can be tuned and tested.

But even a custom-made neutrino

factory will have flaws. The ideal

source would produce only one neu-

trino type so that oscillations could be

casily identified. Earthbound neutrino

and its antiparticle still leaves four other types (electron neutrinos,

electron antineutrinos, muon neutrinos, and muon antineutrinos) and, unfortu-

nately, LSANCSE makes them all. The

gal, then, is to get rid of one (electron

antineutrinos in this case) to clear a

channel so that oscillations can be

detected. The trick is preventive medi-

cine—to stop electron antineutrinos

before they can decay, so that only a

very few electron antineutrinos are pro-

duced. The positive pions, however,

hang around until they decay into

muons, which in turn decay to produce

abundant neutrinos. Thus the copper

block filters out the negative pions and

keeps the source relatively free of elec-

tron antineutrinos. In the end, the other

neutrino types produced outnumber

electron antineutrinos by a factor of

roughly 10,000 to 1.

It should be noted that a small num-

ber of pions decay in flight before

reaching the copper block. These pions

produce higher-energy neutrinos than

the pions that decay at rest in the

copper block. The “decay-in-flight” (DIF) neutrinos thus become a second, separate source riding piggyback on the first and can be used to cross-check the results from the decay-at-rest (DAR) neutrinos. In fact, the DIF

neutrinos are the subject of the second

analysis alluded to earlier.

LSANCSE loses out to neutrino

sources like the Sun, however, in one

important category. The problem isn’t

physical, it’s fiscal. The sun shines for

1 Some positively charged muons made by the

celebrator decreased into electron antineutrinos, it reduced the number of oscillations that oc-

urred. See the article “The Nature of Neutrinos

Muon Decay and Physics Beyond the Standard

model” on page 128.
ee, but LANSCE eats up about $20 million in electric bills every four months. LANSCE serves several experiments in addition to LSND, but in 1993, the Department of Energy (DOE) threatened to shut down the over-hungry accelerator in order to eed other research efforts.

At the time, LSND researchers were just preparing to take their first ata. If LSND died, LSND would ollow, buried in its underground cypt. At the last minute LANCE was spared, and the researchers, crumbling to finish LSND construc- tion, took a total of six weeks of data uring September and October. Even n this small amount of data, there were signs that a few extra electron stinenuinos had reared their heads. he researchers found eight electron nineutrino-like events1 when they ad expected only 0.9 ± 0.2.

The results, which were published in conference proceedings the next year Louis et al. 1994), drew considerable interest, but more data was needed to onfirm the excess of events. If people new one thing about neutrino physics, ells Richard Imlay, “it was that it was hard. Many people wanted to wait nd see if the results held up.” Despite his cloudy funding picture, LSND was leared to take another three and a half months of data beginning in August f 1994.

At the time, Scientific American evoted a page to the LSND story. Missing Matter Found? it asked. “Not et.” We “feel we have a high burden f proof”, it quoted Hywel White, one of the Los Alamos collaborators, as ritting, “it was that it was hard. Many people wanted to wait nd see if the results held up.” Despite his cloudy funding picture, LSND was leared to take another three and a half months of data beginning in August f 1994.

The creation of the neutron and positron heralds an electron antineutrino event. Both particles lead to the produc- tion of light in the detector, and it is by observing that light that LSND knows an event has taken place. By human standards the light is invisibly faint, but to the 1,220 phototubes that can see a single photon and measure its arrival time to a nanosecond, the light shines like a miniature pyrotechnic display. The positron generates light through two mechanisms. When created, the positron has a velocity greater than the speed of light in the oil and produces an electromagnetic shock wave analo- gous to the wake of a speedboat or to the sonic shock wave of a Concorde breaking the sound barrier. The light, called Cerenkov radiation, forms a cone that expands along the positron’s trajectory like the headlight of a tiny car. The cone has a 47-degree opening angle and forms a shell rather than a solid. Projected onto a flat surface, the cone leaves a telltale ring.

The positron also produces light with the help of a small amount of scintillator that is added to the oil. As the positron travels, it loses energy by inducing atomic excitations in the oil; by a secondary process, the scintillator also gets excited. When the scintillator de-excites, it produces blue light that is detected by the phototubes. The excitation process takes a little time and delays the scintillation light by about 15 nanoseconds relative to the Cerenkov light. Also, because the positron typically travels only about 25 centimeters before it wets itself out, the scintillation light appears as an almost spherical cloud. The ratio of scintillator to mineral oil is selected to give roughly four scintillation photons to every Cerenkov photon. All told, a typical positron produces enough photons to trigger 450 phototubes.

Unlike the positron, which leaves a bright trail of light, the neutron goes quietly, wandering randomly away from the neutrino collision until it comes close enough to a proton to be captured through the reaction

\[ n + p \rightarrow D + \gamma \]

producing a deuterion (D) and a 2.2- MeV gamma ray (that is, a 2.2-MeV photon). On average, the capture takes 186 microseconds, so the 2.2-MeV gamma ray emerges somewhat after the light from the positron. The gamma ray also generates some scintillation light, which fires between 20 and 50 phototubes.

The light generates small electric pulses in the phototubes that then travel along some of the one thousand cables connecting the detector tank to the crates of electronics near the tunnel entrance. Like a brain processing a visual image, the electronics sifts through the light signals, trying to assemble a picture of an electron antineutrino.

The purpose of the data collection electronics is to distinguish electron antineutrinos from the endless stream of cosmic rays that penetrate the detector’s shielding and enter the tank. The probability that an electron anti- neutrino (or any other neutrino) will interact with matter is unimaginably small. Even with 167 metric tons of mineral oil, 99,999,999,999 percent of the neutrinos will pass through the tank unhindered and unnoticed. In a day, only 25 neutrinos will leave their mark.

In the same time period, 300 million cosmic rays will also pass through. For more details on the data collection electronics, see “From Tank to Tape— The LSND Data Acquisition System” on page 112.)

The scenario is summarized in Figure 6. The electron antineutrino penetrates the tank and strikes a proton, giving rise to a neutron and a positron. The positron generates a cloud of blue scintillation light and the characteristic cone from Cerenkov radiation. Then all is quiet for roughly 186 micro- seconds, after which a tiny 2.2-MeV gamma ray signals the presence of a neutron. Taken together, these signals constitute the signature of an electron antineutrino.

The central difficulty in analyzing the data is how to pick out the real electron antineutrinos. After all,
Positrons, Photons, and Impostors

The first problem was how to distinguish a positron from cosmic-ray muons and their by-products. Because most muons betray their identity by leaving a signal in the cosmic-ray veto shield (the outer shell that encloses the main detector tank), they are easy to track. If a muon is energetic enough to make it through the veto shield and into the tank, it tends to make a flashy track, producing a large number of photons and a Cerenkov light signature. Any photon produced by a muon is an impostor, and the positrons need to be distinguished from them.

Occasionally, a cosmic ray can pull off a more convincing impersonation, passing near the tank and knocking a neutron free in the shielding. The neutron can pass undetected through the veto shield and into the tank. There it may strike and propel a proton through the oil. If the proton is energetic enough to make it through the veto shield and into the tank, it tends to make a flash light, producing so much ionization that all 1,220 phototubes light up. Looking more like a positron, these muons are easy to identify.

Figure 8. Accidental Photons

Hotons due to background processes—accidental photons—should appear at random positions in the tank. However, these plots reveal that most accidental photons appeared at the bottom of the tank. Each point represents the position a photon projected onto a two-dimensional plane. The heavy concentration along the bottom was likely due to piece of steel shielding that has some small hole in the shielding through which he electronic cables pass.

Correlated and Uncorrelated Photons

Figure 9. Identifying the Photon from Neutron Capture

Although the photon from neutron capture cannot be distinguished from a random photon, statistically, it has a distinct signature in time, energy, and position. In these graphs, blue lines show the distributions of photons that are correlated with neutrons, whereas red lines show the distributions of photons that are uncorrelated. Cosmic-ray neutrons leave a telltale trace of light when they stop in the tank. They are used to determine the correlation functions.

(a) On average, a neutron is captured 186 microseconds after it is created. Uncorrelated photons show no time correlation to the initiating event.

(b) Background photons have less energy and thus produce less light in the tank. On average, the 2.2-MeV photon lights up about 35 photomultiplier tubes (PMTs).

(c) The neutron wanders about 100 centimeters before it is captured. Photons arising from random processes can occur anywhere in the tank. These distributions are used in the likelihood function $R$ to assess whether a photon is associated with a neutron created from a neutrino event.
Other Things in the Tank: Backgrounds

Despite the shielding that surrounds it, the detector tank remains a bubbling cauldron of activity. Every second, thousands of accidental photons and cosmic rays stream through the oil, leaving trails of scintillation light in their wake. Occasionally, the endless background signals combine to look just like the signature of an oscillation event—a positron followed some 180 microseconds later by a photon. The LSND experimenters have taken great pains to understand how background signals could mimic real electron antineutrino events so they can estimate the number of “false positives” that would make it through the data analysis. Only by finding an excess of oscillation over background events can they state with confidence that they have observed neutrino oscillations.

Non-Beam-Related Backgrounds: Cosmic Rays and Accidental Photons. Cosmic rays are the largest source of background. If every muon antineutrino were to oscillate to an electron antineutrino, cosmic rays interacting in the tank would still outnumber electron antineutrinos by a factor of more than 100,000. Most cosmic rays that reach the earth are muons, produced from the decay of pions created when high-energy protons strike nuclei in the upper atmosphere.

Surrounding most of the detector tank is a cosmic-ray veto shield that is LSND’s main line of defense. The archlike shield has double walls. The inner wall is a 15-centimeter-thick layer of lead shot that absorbs accidental photons and a significant number of cosmic rays. But this dense layer is not enough. Every second, approximately 4,000 cosmic-ray muons pass straight through the lead and enter the tank. Thus, the outer wall of the veto shield is studded with 262 photomultiplier tubes looking inward, and the space between the walls is filled with mineral oil and liquid scintillator. On their way into the tank, cosmic rays leave a trail of scintillation light in the veto shield. Removing events in which more than a few of the veto-shield phototubes fire eliminates 99.99 percent of all cosmic-ray-induced events.

Being very energetic, most cosmic-ray muons that pass through the shield also pass straight through the tank. About 10 percent, however, don’t make it. They stop in the tank and decay, with the positive muons producing positrons and the negative muons producing electrons. (The two particles are treated the same in the data analysis, since they are indistinguishable as seen through the eyes of the detector.) Although the muon is detected by the veto shield, the positron that is born typically 2 microseconds later is not. It appears to come from nowhere, exactly like the positron created from an electron antineutrino event. Thus, in this background process, the muon acts as a kind of Trojan horse for the positron, in effect sneaking it past the defenses of the veto shield.

Most of these positrons, however, are ignored by the data acquisition system (see the box “From Tank to Tape—The LSND Data Acquisition System” on page 112). The system requires that there be no activity in the detector or veto shield for a period equivalent to about 7 muon lifetimes before a positron appears. If any activity occurs during this “all quiet” time, the position is rejected as signaling a potential neutrino event.

Although not all cosmic-ray background events can be detected, their number is relatively easy to estimate: It is simply measured when the accelerator is off. The accelerator does not produce protons continuously but has a regular heartbeat, pumping out 600-microsecond bursts of protons 120 times a second. The beam is on only about 7 percent of the time, and the non-beam-related backgrounds can be studied during the relatively long rest periods that compose the remaining 93 percent. In fact, the data acquisition system does not initially distinguish between beam-on and beam-off events. It only uses that information later, when it assesses which events represent true neutrino interactions. In their 1996 paper, the LSND collaborators estimated that they expected 2.5 ± 0.4 events from beam-off sources to look like electron antineutrinos.

Beam-Related Backgrounds: Neutrinos. The beam contains equal numbers of muon neutrinos, muon antineutrinos, and electron neutrinos. But, for instance, 1 percent of the muon antineutrinos oscillate to electron antineutrinos, they will be outnumbered 300 to 1 by the other neutrino types. Although the other neutrinos cannot easily imitate electron antineutrinos, they can still lead to background events that must be estimated.

A muon antineutrino interacting with a proton produces a positive muon (instead of a positive electron) and a neutron. This process is a potentially dangerous background; the muon can decay in the tank and produce a positron, which, when combined with the other neutrino, would convincingly mimic the oscillation signature of an electron antineutrino. Fortunately, the newly created muon produces Čerenkov and scintillation light in the tank, so the muon is observed by the data acquisition system. The “all quiet” requirement removes these muon decay events. In addition, because the muon weighs a hefty 105 MeV, only the relatively few decay-in-flight muon antineutrinos have enough energy to produce muons. (All decay-at-rest neutrinos have energies below 55 MeV.) In the end, muon antineutrinos constitute a small background that can be reliably calculated.

Electron neutrinos are a background because they can change a carbon atom in the detector’s mineral oil into a nitrogen atom. An electron is also produced in the process: 

$$e^+ + C \rightarrow N + e^-$$

However, since no neutron is produced in this reaction, the process is only a problem in the unlikely event that it coincides with an accidental photon. The largest source of beam-related backgrounds is the electron antineutrinos present in the beam itself. They arise from negative muons that decay in the beam stop before being absorbed. These decay-product neutrinos are essentially indistinguishable from electron antineutrinos produced from oscillations. Fortunately, the decay-product flux is very well known, and this background can also be calculated with confidence. In their 1996 paper, the LSND collaborators estimated the background from electron antineutrinos in the beam to be 0.1 ± 0.2 events and the total background from beam-related events to be 2.1 ± 0.4 events. Thus, all told, backgrounds accounted for a grand total of 4.6 ± 0.6 events.

“accidental” photon, which could come from the small amounts of radioactive elements (thorium, for instance) present in the concrete and earth surrounding the detector or in components used to build the phototubes. Accidental photons tended to have energies below 2.2 MeV and, by definition, appeared uncorrelated in position with the positron. The data plots shown in Figure 9 reveal some of the differences between accidental photons and those associated with neutron capture. The R correlation not only picked out events in which the positron and photon were correlated, but it also rejected events in which the photon looked accidental. Mathematically speaking, R was a “relatively likelihood,” but it worked like a magic box. Feed in the number of photons fixed by the photon and the distance and time between the photon and the positron signals, and out popped a number. Real electron antineutrino events tended to have high values of R, while accidental photon events piled up at low R. Unfortunately, although R could remove 99.4 percent of the accidentals, it did so at a high price: R also removed 77 percent of the real electron antineutrinos.

The final source of background events was neutrons produced in the beam stop. The electron antineutrinos that contaminated the source contributed a few background events, as did the other neutrino types that could, on occasion, leave what appeared to be the signature of an electron antineutrino.

Still, when the LSND collaborators ran through the data from both 1993 and 1994, they found further evidence for electron antineutrino oscillations. The improved analysis let fewer impostors slip through the cracks than before. This time they had nine events that looked like electron antineutrons. The expected number of background events came to only 2.1 ± 0.3. The odds, they calculated, that background could account for the nine events were roughly 1 in 300.
One Experiment, Two Interpretations

These were heady times at LSND, they were also times of trouble. The experiment had driven a wedge between some members of the group. Alfred Mann, one of the original collaborators and a professor at the University of Pennsylvania, withdrew from the collaboration because he saw as a dangerous disregard for the scientific method. Mann eared that the group had lost objectivity. The experimenters wanted to see excesses of events, he believed, so they had unconsciously shaped their analyses. "We reasoned, not to present the results first at Los Alamos, they scheduled an on-site colloquium in advance. Bill Louis, the LSND spokesman, would give the Los Alamos colloquium on Thursday. Hywel White would give the Berkeley talk the following Sunday.

Fit to Print

With preparations underway for the Thursday colloquium, the phone rang with a call that would change everything. It was the New York Times. Someone, perhaps a reporter John Wilford to the LSND results. Wilford called John Gustafson at the Los Alamos public affairs office on Thursday, the phone rang with a call that would change everything. It was the New York Times. Someone, perhaps a reporter John Wilford to the LSND results. Wilford called John Gustafson at the Los Alamos public affairs office, and Gustafson, pleased with the prospect of a New York Times article, approached the LSND group with the idea of letting the Times report on the results. The collaborators on hand at Los Alamos were hesitant about speaking to the press before informing their peers, but in the end they decided it was better to talk to Wilford than to let the Times run a story that could be wrong or overblown. White recalls a sense of helplessness: "It's just like going on a rubber raft," he remembers. "Once you decide to get on, jumping off doesn't make any sense, so you hang on as best you can." The ride was long and rough, and in retrospect, many wished they had kept to higher, drier ground. The Tuesday before the Los Alamos colloquium, the Times ran its story—not buried behind the fashion page in the Science Times section but on page one, just below the fold, making it look like a definitive discovery. "Cosmos's Missing Mass: Wispy Particle Weighs In," the headline read (Wilford 1995)."Looking at the article now, White says it seemed balanced and accurate, but at the time, it made him swallow hard. In the physics community, there is nothing as close to a sin as "publishing in the Times." Colleagues want to have a crack at reviewing new results before they hit the presses. "If they hit the presses as soon as we caught them in the pooh," one physicist remembers thinking after reading the article at breakfast. The incident gave critics a leg to hang their skepticism on.

"My whole experience says that if you’re going to find something new, it energetically rises out of the data and oozes you in the eye," he said.

At the same time, one of Mann’s graduate students, James Hill, had returned to Philadelphia from Los Alamos and was hard at work on his analysis of the LSND data. Hill excised to restrict himself to the 1994 ata and to dispense with B. It made more sense, he argued, to simply cut out photons that appeared in the bottom left the tank or near the tank walls. These hits, however, reduced the data set by a factor of 3. Hill also used less-strictive selection criteria to pick out hotons. In the end, he found five events that looked like electron-antineutrinos. He calculated the background to be 0.6 ± 1.6 events. By his estimate, the excess was a mirage. But the rest of the team weren’t necessarily contradictory. If there were only a few oscillation events, it was entirely possible that they would stand out in analysis but not in another—particularly, the advocates of R argued, the other analysis cut out two-thirds the data and took a simple-minded approach to the results. Perhaps it was a crack at reviewing new results before they hit the presses. "If we hit the presses as soon as we caught them in the pooh," one physicist remembers thinking after reading the article at breakfast. The incident gave critics a leg to hang their skepticism on. The experimenters wanted to see excesses of events, he believed, so they had unconsciously shaped their analyses. "We reasoned, not to present the results first at Los Alamos, they scheduled an on-site colloquium in advance. Bill Louis, the LSND spokesman, would give the Los Alamos colloquium on Thursday. Hywel White would give the Berkeley talk the following Sunday.

Putting it all together, the group had come to striking fueling the physics community as to the credibility of the results. Louis recalls, "They seemed to be saying ‘we don’t know what you’ve got there, but it’s not oscillations.’" One physicist at a Fermilab colloquium said White seemed slick, “like a lawyer who knew his client was guilty.” Vern Sandberg, an LSND experimenter, says that under the circumstances, he could sympathize with the skeptics: “I wouldn’t have believed us either.”

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In politics, debates can drag on indefinitely, without hope of resolution. In physics, there is no arguing with nature. With more data, the truth would out. Eventually.

Back Out to Sea

Fortunately, it looked like there would be more data. Though the nuclear physics division of DOE had terminated LSND (which at the time was called LANSE for Los Alamos Meson Physics Facility) by cutting its funding in 1995, the defense projects division had arranged to assume custody. The new overseers renamed the accelerator LANSE to reflect what it would be its new focus on neutron physics but agreed to allow neutrino production to continue on the side. Jerry Garvey, an LSND collaborator who was watching events from a temporary post at the White House’s Office of Science and Technology, attributed LANSE’s stay of execution to a law of nature. “Good things have a way of continuing,” says Garvey, who had been LAMPF’s director for five years. “If you’re going to find something new, it makes sense, he argued, to simply cut out photons that appeared in the bottom left the tank or near the tank walls. These hits, however, reduced the data set by a factor of 3. Hill also used less-strictive selection criteria to pick out hotons. In the end, he found five events that looked like electron-antineutrinos. He calculated the background to be 0.6 ± 1.6 events. By his estimate, the excess was a mirage. But the rest of the team weren’t necessarily contradictory. If there were only a few oscillation events, it was entirely possible that they would stand out in analysis but not in another—particularly, the advocates of R argued, the other analysis cut out two-thirds the data and took a simple-minded approach to the results. Perhaps it was a crack at reviewing new results before they hit the presses. "If we hit the presses as soon as we caught them in the pooh," one physicist remembers thinking after reading the article at breakfast. The incident gave critics a leg to hang their skepticism on. The experimenters wanted to see excesses of events, he believed, so they had unconsciously shaped their analyses. "We reasoned, not to present the results first at Los Alamos, they scheduled an on-site colloquium in advance. Bill Louis, the LSND spokesman, would give the Los Alamos colloquium on Thursday. Hywel White would give the Berkeley talk the following Sunday.

"My whole experience says that if you’re going to find something new, it energetically rises out of the data and oozes you in the eye," he said.

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reparing their next paper. “People would say, ‘Hello! How are you? Haven’t seen you in a while, so WHAT ARE THE RESULTS?”’ andberg remembers, “but we made hem wait.’ The idea was to write a paper that would hang together with the certainty and logic of a mathemati- cal proof. Publicity had forced intense introspection, and this time the group produced a 24-page tome entitled Evidence for Neutrino Oscillations from Muon Decay at Rest” (C. Athanassopoulos et al. 1996). A colleague praised it as one of the most extensive and exhaustive descriptions of a theory ever published. Around SNB, it is simply referred to as ‘the ig paper.’

The big paper spelled out the analysis in excruciating detail, at the level of a graduate thesis, and went a long way toward restoring LSND’s credibility. Paranoid had paid off.

In the paper, the collaborators also tried cutting out photons in the bottom of the tank as Hill had done. They found six events with a background of 1.7 ± 0.3 events. The odds were about 1 in 100 that the six events could all be background. Responding to Mann’s allegations that they had willfully hidden the excess, they repeated their analysis, varying the requirements for photons and positrons. In each case, they reported an excess of events. But the physics community reason- ably demands a high level of proof before declaring victory. Today Mann, while impressed by the excess, cautions that the results are nothing to yell Eure- ka about: “If you knew your house had a 1 percent probability of burning down, you’d be out buying insurance,” he says.

Mapping out the Territory

Nothing makes a physicist happier than data, and having observed a statistically significant excess of events, the LSND collaborators proceeded to map out the regions of \( \Delta m^2 \) and \( \sin^2 2\theta \) that could have led to the oscillations. Given the detection efficiency, they could calculate the number of electron neutrinos that had passed through the tank without getting caught. By comparing this number to the number of muon antineutrinos that emanated from the source, they estimated that only 0.31 ± 0.13 percent of the muon antineutrinos had oscillated. To unfold the \( \Delta m^2 \) and \( \sin^2 2\theta \) information from the data, the collaborators performed a likelihood fit to all events that contained a positron. The fit took into account the positron’s energy and direction, the photon likelihood \( K \), and the distance to the source for each event. It also took into account the expected distributions of these quantities for electron antineutrinos from oscillations and for background processes.

As shown in Figure 11, the fit does not pinpoint particular values of \( \Delta m^2 \) and \( \sin^2 2\theta \) but rather carves out regions of more likely values. The shapes of the regions are a consequence of the fact that the oscillation probability is the product of two terms, one relating to \( \Delta m^2 \), \( \Delta l \), and the other to \( \sin^2 2\theta \). The spots that spread out like a chain of small islands arise because some oscilla- tion events at relatively high energy tend to exclude \( \Delta m^2 \) while keeping \( \sin^2 2\theta \) fixed. The other way around is just as likely — and even more so, for a few sources of background. Thus, the LSND data allowed a region of parameter space for neutrino masses and mixing angles that was quite limited.

Decay-in-Flight—The Second Analysis

While the LSND collaborators were drawing up Figure 11 and putting the finishing touches on the big paper, they began work on a second analysis that would either confirm or disprove all their previous work. Knowing that an excess of electron antineutrinos was not enough to establish that oscillations could be coming from some equally surprising source, such as an exotic type of muon decay, the collaborators built a second method to look for oscillations. Instead of using the neutrinos from decay-at-rest (DAR) pions and muons, this method looked to a smaller sample of neutrinos produced by the pions that decayed in air on their way to the beam stop. These decay-in-flight (DIF) neutrinos had a much higher energy than the DAR neutrinos and so could be easily distinguished in the detector.

In the production of DAR neutrinos, pions produced in the target travel about a half meter through open space before striking and coming to rest in the copper beam stop (refer to Figure 5). When the still pion decays, it can give at most 53 MeV, or about half of its mass, to one of the resulting neutrinos. Thus all neutrinos used in the DAR analysis had energies below 53 MeV. By contrast, a pion that de- cays in flight before reaching the beam stop passes on some of its kinetic energy to the resulting neutrino, giving it as much as 300 MeV of energy. By considering only neutrinos that had at least 60 MeV of energy, LSND collaborators could essentially tap a second neutrino source, for free.

Figure 12 shows this DIF source and the energy spectrum of the neutrinos produced by it.

Unlike the DAR neutrinos, DIF neutrinos come mainly from pion decay, since there is rarely time in the half-meter journey to the beam stop for the muon produced by the pion to also decay. (Roughly 3 percent of the pions 53 MeV, or about half of its mass, to one of the resulting neutrinos. Thus all neutrinos used in the DAR analysis had energies below 53 MeV. By contrast, a pion that de- cays in flight before reaching the beam stop passes on some of its kinetic energy to the resulting neutrino, giving it as much as 300 MeV of energy. By considering only neutrinos that had at least 60 MeV of energy, LSND collaborators could essentially tap a second neutrino source, for free.

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The DIF analysis sought to look for muon neutrinos to oscillate to electron neutrinos—the “matter” counterpart of the DAR analysis. If the neutrino events were detected above background events. The parameter values allowed by the DIF analysis lie between the two solid lines, whereas the values allowed by the AR analysis are shown in grey. Although there were greater uncertainties associated with the DIF analysis, the allowed values of $\Delta m^2$ and $\sin^2 2\theta$ for the two analyses overlapped.

Epilogue

At the time of this writing, LSND had just begun to make its DIF results public. This time around, reactions are more enthusiastic than condemning, and question-and-answer sessions no longer run an hour. Whereas before, LSND results were often downplayed in neutrino talks, they now take center stage along with the atmospheric and solar data.

Neutrino decay is the key to what LSND found. While there seems to be a growing suspicion in the physics community that neutrinos do indeed have mass, many are still waiting for the day when some experiment sees the cyclic rise and fall of the number of neutrinos from oscillations as the neutrino energy or the distance between the source and the detector is gradually altered. It would be impossible to state those results in the face and deny that neutrinos have mass.

That day would mark the end of one of the oldest quests in the history of particle physics, one that currently stretches over half a century and spans generations of physicists. It would also reserve a place in the history books for LSND, solar, and atmospheric experiments. But even those intimately involved in neutrino work are uncertain exactly when all this might come to pass. White has a page from a word-a-day calendar tucked to the wall of his office, just beside a copy of the troublesome New York Times article.

The word is “Greek” and “Greek” calendar, defined as a time that will never arrive, the next blue moon, or when pigs fly. With the mounting evidence, it may be that such pigs are preparing for takeoff.

Further Reading


Hill, J. E. 1995. An Alternative Analysis of the LSND Neutrino Oscillation Search Data on $\nu_e \rightarrow \nu_x$. Physical Review Letters 75: 2634


Vern D. Sandberg received his Ph.D. in 1975 from the University of Utah, where he studied strong gravitational fields. Following a postdoctoral appointment at CalTech, where he participated in the discovery of quantum non-demolition techniques that circumvented the “quantum limit” for the readout of gravitational wave detectors. In 1979, he joined LAMPF (now LANSE), working with Donald Nagle to develop instruments for precision experiments. The high intensity of LAMPF’s accelerator beam opened up possibilities of experiments with well-defined beams of neutrinos, and soon thereafter he collaborated on the neutrino-electron elastic scattering experiment that measured the interference between weak-neutral current and the charged neutral current in the scattering of electrons by neutrinos. This led to a program to search for neutrino oscillations, which culminated with the LSND experiment. Sandberg is currently involved in the neutrino oscillation physics program, conducting on gravitational wave detectors and building a quantum computer.

D. Hywel White received his B.Sc. in mathematics and physics from the University of Wales in 1953, and earned his Ph.D. in experimental particle physics from Birmingham University, England, in 1956. After a stint on the faculty at Birmingham University, White became an assistant professor at the University of Pennsylvania. In 1964 he was appointed associate professor, and in 1966 professor, at Cornell University. White joined Brookhaven National Laboratory in 1979 as head of experimental facilities on the E821 project, where he began experiments in neutrino physics. In 1986 he came to the Laboratory as a group leader in Nuclear and Particle Physics Research at LAMPF to continue work in experimental neutrino physics. In 1994 the neutrino group observed a signal interpreted as neutrino oscillations, an event that has since dominated their research.

A Thousand Eyes
From Tank to Tape—The LSND Data Acquisition System

Neutrinos interact in the LSND tank at a rate of approximately one an hour. To go lunch, and if you’re lucky, there will be a new neutrino event written to tape when you get back. In that same hour, nearly 15 million cosmic rays will also have left their marks in the tank. That’s a staggering number to contemplate. “You have all this background from cosmic rays,” says Vern Sandberg, the principal designer of the LSND data acquisition system, or DAQ. “But you want to be absolutely sure that a positron, which is the primary thing we look for, is isolated from anything to do with cosmic rays. You need some way to separate the wheat from the chaff, so to speak. The only way you can convincingly sort it all out is by keeping track of what happened before the positron showed up and after it was detected.”

The DAQ keeps track. It is an array of electronics (one circuit board is shown in the photo) that can be thought of as a kind of brain with the single-minded task of identifying potential neutrino events whose signature is a positron followed by a 2.2-MeV gamma ray. When the DAQ identifies a promising positron, it grabs from its short-term memory everything that happened in the tank for 6 microseconds (µs) before the positron was detected. It also records all gamma-like activity that occurs within the next 1 millisecond (ms). Armed with this information, the DAQ tries to make sense of what it saw by correlating, in space, time, and energy, the positron signal with a gamma ray. If the correlation matches the profile of a neutrino interaction, it writes the information to long-term memory (a magnetic tape).

The human brain, with its exceptional pattern recognition ability, evolved over hundreds of millions of years. The DAQ used by LSND was designed and assembled in less than 1 year by Sandberg and a team of students and visiting staff as they scrambled for funding and raced to finish before LANL’s experiment producing neutrinos. By all accounts, the final system was a smashing success. “It’s a unique system,” says Darryl Smith, who was involved in developing the DAQ. “No other data collection system has this look-back capability, to see what was happening in the detector before the triggering signal occurred. If in the future someone asks, ‘Did you check for this, or look for this oddball correlation,’ we can go back to the data and see.”

How the DAQ searches for a neutrino signature is shown in the diagram on pages 114 and 115. In the text that follows, the latter callouts correlate with those on the figure.

The Front End—Selecting Promising Signals. (A) The DAQ perceives the world through 1,220 photomultiplier tubes (PMTs) that line the inside of the detector tank. Like huge eyes, the phototubes watch for the brief pulses of light produced when energetic particles pass through the oil. Outside the tank, 290 more phototubes sit within the cosmic-ray veto shield to signal the arrival of cosmic rays. When any tube is hit by a photon, it sends a tiny current pulse to a digital version of short-term memory called a circular buffer. There is one buffer per PMT.

Conceptually, the circular buffer is analogous to an office Rolodex filled with 2,047 electronic “cards.” At every time slice of 100 ns, the Rolodex is “turned” and the value of the electric charge q in the current pulse and the precise time T that the pulse occurred (accurate to about ±0.5 ns) are written to a card. The card is stamped with the system time T if a tube was not hit, q = 0 and t = 0, but the data are still written to the card, which still receives a timestamp. Because a tube is hit on average only once every 200 µs, the data on most cards are just zeroes.

At 100 ns per card and 2,047 cards, each circular buffer maintains a 204-µs history of its phototube. The DAQ can access any portion of that history by asking the buffer to “dump” the information contained on specific cards, for example, the cards stamped T = 1 through T = 60. Because it has access to data from all 1,512 circular buffers, the DAQ in principle can construct detailed, 204-µs histories of everything that occurred in the tank and veto shield.

But a full history comes at a steep price tag. There are over 15 million pieces of data coming in per second, far too much data for a computer to mullet over in detail. The system needs to quickly pull promising positron signals from the heavy traffic of cosmic rays and other “stuff” that courses through the tank. Thus, the DAQ applies some rules of thumb so that it can react “instinctively.” (B) In addition to producing an analogous current pulse, each phototube when hit by a photon sends a digital pulse to a summing circuit. The digital pulse simply indicates that the tube was hit in the preceding 100 ns, and the sum of the pulses gives the total number of tubes that fired in the tank and the veto shield within that time interval. (Tank and veto shield sums are kept separate.) The information goes to a programmable “trigger” (called the signal flagger) that crudely identifies the signal. For example, if at least 21 phototubes fire in the detector and less than 4 fire in the shield, the signal is flagged as a gamma-ray candidate. If at least 150 tubes fire in the detector and less than 4 fire in the shield, the signal is flagged as a positron candidate.

Cosmic-ray muons normally light up the tank like a Roman candle, setting off 250 to 1,000 or more tubes. Flagged signals, and the times that they occurred, are passed onto a trigger computer charged with the task of selecting promising ones.

The Back End—Reconstructing Events. (F) If the positron signal occurred at time T, the trigger computer monitors and stores signals as they roll in, always on the lookout for a positron candidate. When it sees one, it reviews the signal roster, checking back in time to see if there was any activity in the tank within a 15-µs “all-quiet” period before the positron appeared. If there was activity, it ignores the signal and keeps looking. The reason for the all-quiet condition is to weed out positrons that come from muons.

“Cosmic-ray muons that decay in the tank are the bugaboo of this experiment,” says Sandberg. “They produce a Michel electron that is identical to the positron produced by electron anti-neutrinos.” The average lifetime of the muon is about 2 µs, so if there’s any suspicious activity within about 7 µs lifetimes before a positron signal, we don’t want to waste time checking that positron. “We’re not interested.”

Cosmic rays, beta particles from radioactive decay, neutrons, and muons create a riotous background of activity in the tank, and flagged signals are sent to the trigger computer at an average rate of one every 60 µs or so. Positrons account for about a third of that rate. With the all-quiet condition, the rate of signals that will be examined further is cut down to about one every 10 ms. That rate is slow enough that a large, mainframe “analysis” computer—the cerebrum of the DAQ brain—can examine the selected signals in detail. Because the decision to flag a signal is based on low-level information (the total number of tubes that fired in the tank and veto shield), it can be made quickly. (E) Within about 400 ns of finding a clean positron with no prior history, the trigger computer sends a message to all circular buffers to dump their detailed information.

The analysis computer, which has the tough job of trying to figure out what happened, to leisurely collect the detailed information from each tube. The analysis computer then looks for correlations between the signals from different tubes and produces a rate history. If there’s activity in the time history, the analysis computer tells the DAQ to “dump” the information.
The computer gathers the detailed photomultiplier data from all 1,512 FIFOs and reconstructs the signals. First, it finds the Cerenkov cone and the sphere of scintillation light and determines the positron’s trajectory and position. Next, it finds the position and energy of the gamma rays (by reconstructing their spheres of scintillation light) and then uses the likelihood function $R$ to find a gamma that has the right time, energy, and position to have come from neutron capture. If $R$ is high ($>30$), the sequence of signals—a positron followed by a gamma ray from neutron capture—is taken as the signature of a neutrino event.

Since 1993, the trigger computer has looked at half a billion flagged signals, of which twenty-two were identified as the signature of electron antineutrinos. It was a significant challenge to design a system that could handle such a low, “asynchronous” event rate. The DAQs used in most particle physics experiments operate on a clock that is synchronized with the particle beam, so that the electronics know exactly when to pay attention. By contrast, neutrino oscillation events in the LSND experiment appear at almost random times. The DAQ has to operate continuously, look at all events, but select only a tiny subset. “Traditional experiments threw stuff away,” says Sandberg. “We couldn’t afford to do that. But we also couldn’t afford to keep it all.” The front-end selection of signals and the look-back capability of the DAQ helped solve the problem.

“Because neutrino oscillations have come and gone from decade to decade,” says Smith, “we needed as much credibility as we could bring to the problem. This DAQ is totally solid. It’s built almost entirely from off-the-shelf components. It can live in an enormously noisy environment. It can look back in time. Because it’s built using a standard VME architecture, any graduate student could plunk it into an experiment and get it up and running. It works.”

Through a separate analysis, nineteen electron neutrino events were also identified.