lowest temperature—as low as 20 nK.) They then shine a pulse of resonant laser light through the cloud. The shadow of the cloud provides a map of the atom distributions and hence of the velocity distributions before the expansion. (See figure on page 17.)

While the quest for the Grail has now ended, the study of it is just beginning. Those studies will include laser spectroscopy of the condensate, exploring how light interacts with coherent matter, and experiments analogous to the classic experiments on superfluid helium (persistent sloshing, second sound and so on).

The success or failure of competing groups will also yield valuable information. In the first week of July, a group led by Randall Hulet at Rice University, in Houston, Texas, surprised the BEC community by reporting they had cooled clouds of ^{7}Li to within a factor of 3 of the quantum degeneracy point. As we go to press, Hulet tells us they have now pushed well into the degenerate regime. Hulet's team includes Curtis Bradley, Charles Sackett and Jeffrey Tollett.

The group uses a novel harmonic magnetic trap with permanent magnets. Such a trap doesn't suffer from the hole of a quadrupole trap but only allows much lower evaporation rates than either a quadrupole or TOP trap does. Hulet's group gets around this deficiency by achieving evaporation times as long as 7 minutes. Hulet told us that laser light directed through the coldest and densest clouds produced a diffraction pattern consistent with a small compact core. Further study is needed, however, to substantiate these results.

A condensate of ^{7}Li would be more than just another condensate. ^{7}Li has a negative s-wave scattering length (which contributes an additional attraction in collisions) while that of ^{87}Rb is positive (causing a repulsion). Theorists have shown that in the low-density limit the condensate is stable in equilibrium only for the positive (repulsive) case, but whether a condensate might still form in the negative case has been controversial. Studies comparing ^{87}Rb with ^{85}Rb should also shed light on this issue because ^{85}Rb probably has a negative scattering length.

Yet another approach to BEC is that of Chu and Mark Kasevich at Stanford, who in late summer of 1994 achieved evaporative cooling with all-optical traps. These trap atoms in all spin states, including the lowest-energy spin state, unlike the magnetic traps, which trap only a single spin state and are consequently unstable with respect to spin flips.

Chu points out that the condensate is a source of atoms in a single quantum state. "Once you have that you can start to play all sorts of games. You can think of applications equivalent to an atom laser." He also points out that one could form a degenerate Fermi gas, for example by cooling a mixture of fermionic and bosonic lithium isotopes in a trap like Hulet's. (A purely fermionic sample would be much more difficult to cool.)

But perhaps Theodor Hänsch (University of Munich), one of the inventors of laser cooling of atoms, sums up the prospects the best: "It is like a door that has opened to a new world." Researchers everywhere are saddling up to explore that realm.

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Los Alamos Accelerator Group Reports Its Evidence for Neutrino Oscillation

A handful of muon neutrinos at the LAMPF accelerator appear to have undergone a metamorphosis. If it's true, it tells us that some neutrinos have mass.

Despite its somewhat hectic provenance, the paper submitted to *Physical Review Letters* in June by the Liquid Scintillator Neutrino Detector collaboration[1] at Los Alamos brings us the first serious evidence of neutrino oscillation in an accelerator experiment. All previous substantial hints of neutrino oscillation have come from astrophysical sources, over which experimenters have no control. (See PHYSICS TODAY, April, page 19.) The LSND result, like all the astrophysical evidence, is still inconclusive. But it has set the particle physics and cosmological communities abuzz.

The standard model of particle theory assumes, for simplicity, that all three neutrino varieties (associated respectively with the electron, the muon and the much heavier tau lepton) are massless. But the theory, and the experimental limits, can accommodate small neutrino masses. If neutrinos can be shown to oscillate from one "flavor" to another, the two varieties must differ in mass; they cannot both be massless.

The demonstration of neutrino oscillation would enrich the standard model, perhaps pointing the way to a more unified particle theory. Cosmologists, for their part, are particularly interested in the range of neutrino masses (on the order of an electron volt) indicated by the new Los Alamos result. It suggests that neutrinos may be significant contributors to the "dark matter" required by the cosmologists' own standard model.

Tons of baby oil

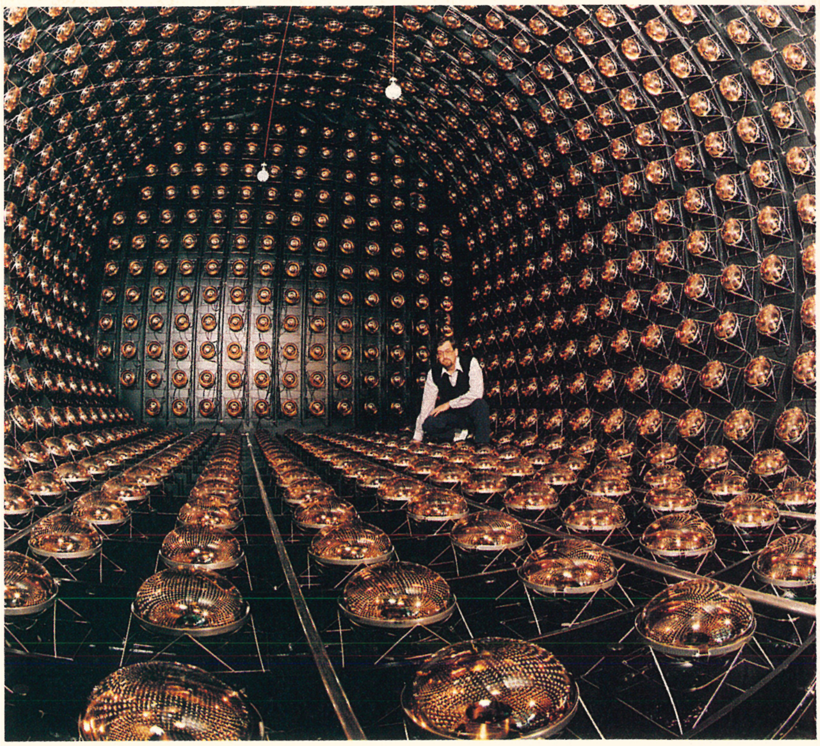
The LSND experiment at Los Alamos, initiated by Hywel White and William Louis, began taking data in 1993. The detector—basically 167 tons of mineral oil spiked with a gallon of scintillator and watched over by more than a thousand photomultiplier tubes—is shown on page 21. It sits 30 meters downstream of a massive beam stop that brings the Los Alamos Meson Physics Facility (LAMPF) accelerator's high-intensity 800-MeV proton beam and its mesonic debris to rest. The lineup of impediments upstream of the detector is designed to produce an abundance of muon antineutrinos ($\bar{\nu}_\mu$) with the least possible contamination of electron antineutrinos ($\bar{\nu}_e$), while keeping everything except neutrinos (and antineutrinos) from reaching the detector.

The task of the phototube array is to look for inverse-beta-decay scattering events inside the detector, that is

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

The only neutrino variety that can induce this telltale reaction is $\bar{\nu}_e$. Ignoring for the moment the tiny contamination of $\bar{\nu}_e$ produced by conventional physics in the beam, one can take the observation of inverse beta-decay events in the detector as evidence of neutrino oscillation, that is to say, the metamorphosis of some $\bar{\nu}_\mu$'s into $\bar{\nu}_e$'s en route to the detector.

Any charged particle traversing the detector generates a cone of Čerenkov light if its velocity exceeds the speed of light in the oil, whose refractive index is 1.47. The Čerenkov light serves to distinguish relativistic positrons (and electrons) from protons, muons and pions, which are generally slower at these energies. The scintillation light generated by the dollop of scintillator in the oil is a measure of the positron energy. The neutron produced in an inverse beta scattering announces itself by emitting a characteristic 2.2-MeV gamma a few hundred microseconds later, when it joins with a proton to form a deuteron.



LIQUID SCINTILLATOR NEUTRINO DETECTOR at Los Alamos, when filled, is essentially a 167-ton tub of mineral oil spiked with a gallon of scintillator and lined with 1220 photomultiplier tubes. Receiving a neutrino beam from the LAMPF accelerator, the detector looks for light generated by neutrino scattering events that would indicate the metamorphosis of muon neutrinos into electron neutrinos.[1]

Nine events

Applying its most stringent criteria for the identification of both the positron and the neutron from an inverse beta scattering, the LSND group reports seeing 9 events where a background of only 2 events would be expected in the absence of neutrino oscillation or some other exotic new physics. Though a 7-event excess may not seem overwhelming, the Poisson probability that this excess could be simply a statistical fluctuation is less than 10^{-3}. With somewhat looser criteria for observing the neutron-capture gamma, the group finds 19 events where 2.7 background events are expected. These excesses imply that about 1 $\bar{\nu}_\mu$ in 300 turns into a $\bar{\nu}_e$ during the journey from the μ^+ decay that gave it birth in the beam stop.

The consensus among the cognoscenti is that the statistical signal is robust. "If their result is wrong," says Stuart Freedman (Berkeley), a veteran rival seeker after exotic neutrino physics, "they can't blame it on a statistical fluctuation. The excess is too big for that. It would have to be some sort of systematic effect they've overlooked or underestimated."

It's the *positive* muons that produce the desired $\bar{\nu}_\mu$'s when they decay. The contaminating $\bar{\nu}_e$'s that simulate the effect the experimenters are looking for come from the much rarer decay of negative muons in this experiment. Why much rarer? The muons come from the decay of pions produced by collisions of the beam protons. Lots of π^-'s are produced, but almost every one is captured in atomic orbits in the beam stop and then quickly swallowed by the nucleus before it has time to decay into a troublesome μ^-. But the positive ions, repelled by nuclear charge, generally decay to μ^+ after they come to rest in the beam stop, yielding a broad $\bar{\nu}_\mu$ energy spectrum that peaks at 52 MeV, its kinematic upper limit. The LSND group estimates that conventional physics in this experiment produces a background of about 1 $\bar{\nu}_e$ for every 2500 $\bar{\nu}_\mu$'s. That's the principal source of background related to the proton beam.

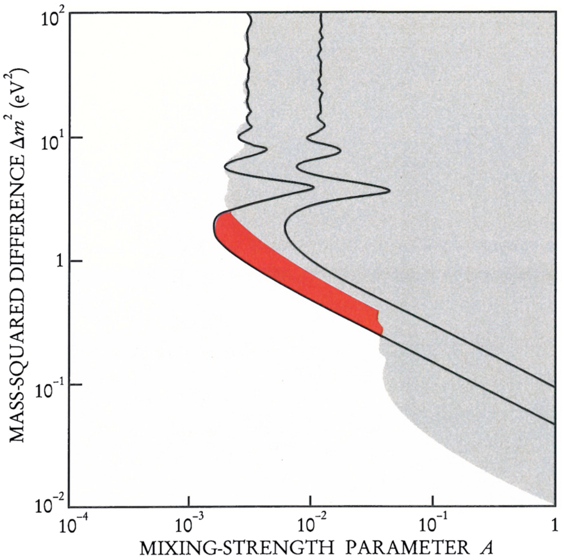
It turns out that more than half of the estimated background is in fact *unrelated* to the proton beam. The LAMPF accelerator sends beam to the beam stop in millisecond pulses, with a duty cycle of only 7%. Events in the detector that look like inverse beta decay are of course rejected as spurious if they occur during the 93% of the time when the beam is off. But these out-of-time events provide an indisputable estimate of the beam-unrelated background when the beam is on. Such background is attributed to cosmic rays, nearby radioactivity and other sources of noise.

To minimize that kind of external background, the group has covered the detector with a liquid-scintillator veto shield. For reasons of space and weight, however, this active veto shield does not cover the bottom of the detector.

Dissension in the ranks

The gaps in the veto shielding caused an unusual defection within the collaboration last spring. When the first version of the LSND preprint was submitted to *Physical Review Letters* in April, three members of the 40-member collaboration talked about removing their names from the paper. They were concerned that the somewhat nonuniform distribution of candidate inverse-beta scattering events over the volume of the detector was an indication that too many of them were induced by cosmic rays, neutron scattering debris or underground radioactivity that had slipped through the gaps in the veto shield.

Further analysis, detailed in the revised June version of the paper, eventually reconciled all but one of the dissenters. The lone holdout, University of Pennsylvania graduate student James Hill, had in April taken the extraordinary step of submitting to *Physical Review Letters* a one-author dissenting preprint that claimed



IN PARAMETER SPACE for neutrino oscillation between $\bar{\nu}_\mu$ and $\bar{\nu}_e$, the difference between their squared masses is plotted against the mixing-strength parameter A. The pair of wavy lines marks the 90% confidence limits of the parameters allowed by the new Los Alamos result.[1] But the gray region had already been excluded by experiments[2,3] that found no oscillation, leaving only the swath shown in red. (Adapted from ref. 1.)

there was no real evidence of new physics in the data. When the two April submissions arrived almost simultaneously, the editors returned them both, suggesting that the collaboration make up its collective mind.

The LSND group's claim of evidence for neutrino oscillation had in fact received considerable attention, and some criticism, several months before the first preprint, with the appearance of a front-page article in the 30 January *New York Times*. That was on the eve of a "town meeting" organized by DOE's Nuclear Science Advisory Committee to gather input for its "long-range plan" for the next five to ten years. Louis and White felt it necessary, they told us, to present their evidence to NSAC before the long-range plan was written in stone, even though their paper wasn't ready yet. The dilemma facing the LSND experiment was the scheduled termination, at the end of the fiscal year, of nuclear science funding for LAMPF. After September the accelerator is to be funded only by DOE's defense-related programs. The LSND collaboration is hoping to find a way to continue running for several more years, with the goal of increasing its data sample by a factor of three or four.

Oscillation parameters

If the excess above background observed in the LSND experiment is real, it might conceivably be due to some sort of new physics other than the neutrino oscillation so many groups are looking for. But if it is indeed neutrino oscillation, the oscillating probability $P(L)$ that a $\bar{\nu}_\mu$ of energy E MeV will have become a $\bar{\nu}_e$ after a flight of L meters is given by

$$P = A \sin^2 (1.27\ \Delta m^2\ L/E)$$

where Δm^2 is the difference (in eV^2) between the squared masses of the two neutrino varieties, and A, which can range from 0 to 1, is the mixing-strength parameter between them.

The detector is 8 meters long, and the neutrino energy for a given event is approximated from the observed positron energy and scattering angle. With only a handful of inverse-beta events, the telltale sinusoidal oscillation doesn't leap out of the data. But the group's maximum-likelihood fit to the distribution of events in L and E points to a swath across the (A, Δm^2) parameter space. (See the figure at left.) The best fit for Δm^2 is about 5 eV^2. But if one excludes the parameter-space regions (shown gray) eliminated by earlier accelerator[2] and reactor[3] experiments that found no evidence of neutrino oscillation, one is left with the red diagonal band centered near $\Delta m^2 = 1\ eV^2$ and $A = 0.01$. If one then assumes that the $\bar{\nu}_e$ mass is negligible (some would call that a prejudice), the Los Alamos result implies that the $\bar{\nu}_\mu$ mass is on the order of an electron volt.

The range of oscillation parameters suggested by the LSND experiment is quite far from those pointed to by astrophysical anomalies like the solar-neutrino shortfall. It may well be that the astrophysical phenomena involve oscillation with tau neutrinos or even with a "sterile" neutrino species impervious to the ordinary weak interactions. The nice thing about the accelerator experiments is that one knows that the oscillation, if it's really happening, is between muon and electron neutrinos.

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Rochester and Naval Research Lab Start Running New Laser Fusion Facilities for Direct-Drive Experiments

Two new facilities for inertial confinement fusion have recently started operation. The University of Rochester's Laboratory for Laser Energetics is now running Omega Upgrade at energies as high as 45 kilojoules (at greater than 60 terawatts), at a wavelength of 351 nanometers, making it the most powerful ultraviolet laser facility in the world. (Typical operation will be at 40 kJ in 1-nano-second pulses.) Omega Upgrade is a frequency-tripled neodymium–glass solid-state laser, as is Lawrence Livermore National Laboratory's Nova, which has produced as much as 45 kJ in a 2.5-ns pulse at 351 nm. (Nova typically operates at 30–35 kJ in 1-ns pulses.) The second ICF facility to recently start running is the Naval Research Laboratory's Nike, a KrF gas laser that produces energies at the target of 3 kJ at 248 nm.

> Direct-drive laser fusion is a decade behind indirect drive, but new laser facilities at Rochester and NRL may reduce the lead. Meanwhile megajoule indirect-drive facilities are planned for Livermore and Bordeaux.

Although many physicists work on ICF because they want to produce an energy source (see the article by John D. Lindl, Robert L. McCrory and E. Michael Campbell in PHYSICS TODAY,