

## Neutrino Physics Probes Mysteries Of 'Flavor' and Origins

Fifty years ago, Fred Reines and collaborators reported (in *Science*) the first confirmed detection of the elusive neutrino. At the meeting,\* physicists marked the anniversary with a flood of new and anticipated neutrino data offering insights into particle physics and astronomy.

Neutrinos are produced abundantly throughout the cosmos. They are generated by cosmic rays striking Earth's atmosphere, by nuclear fusion reactions in the cores of stars, and in supernova explosions and other energetic cosmic processes. There are three known varieties, or "flavors," of neutrinos, associated with the electron, muon, and tau particles (collectively known as leptons).

As they propagate through space, neutrinos travel not as pure flavors but rather as mixtures, sort of like a vanilla-chocolate swirl. Neutrinos beginning a journey as primarily one flavor may end up being detected as another. Such identity switches, or "flavor oscillations," have been confirmed by several neutrino experiments, most recently by an international collaboration known as MINOS.

The MINOS detector, housed in an iron mine in Soudan, Minnesota, measures neutrinos produced at the Fermi National Accelerator Laboratory, 735 kilometers away in Batavia, Illinois. The latest results confirm the disappearance of muon neutrinos

in transit, suggesting a switch of flavors on the way, said Donna Naples of the University of Pittsburgh in Pennsylvania, reporting at PASCOS for the collaboration.

"We see a significant deficit" of muon neutrinos, Naples said. The Soudan detector recorded 215 events in the relevant energy range, compared with more than 300 expected if the neutrinos did not shift flavors. The collaboration's paper with the new data has been submitted for publication and is available online at [arxiv.org/abs/hep-ex/0607088](http://arxiv.org/abs/hep-ex/0607088). Further data, Naples said, will help pin down neutrino properties more precisely, in particular the masses of the three neutrino types and the precise amount of mixing between the flavors.

For astronomy, much of the current neutrino excitement focuses on understanding the more energetic neutrinos that may shed light on the nature of high-energy gamma rays in space and the origin of cosmic rays. "Cosmic rays are totally not understood. We don't know where they come from or how they are accelerated," said neutrino physicist Francis Halzen of the University of Wisconsin, Madison.

Because high-energy neutrinos may be produced in the same processes that create cosmic rays, several experiments are now planned or in progress to seek neutrinos at the top of the energy scale, exceeding 1 trillion electron volts (TeV). Hopes are highest for results from IceCube, a massive detector array partially completed more than a kilo-

**Switcheroo.** Neutrinos from this beamline in Illinois change type in transit to Minnesota.

meter below the ice's surface at the South Pole.

IceCube detects neutrinos produced when muons from cosmic ray showers collide with atoms in the ice and may also be able to measure the arrival of TeV neutrinos from space. If such neutrinos are found, they could help identify the mechanism that produces high-energy gamma rays, reported Matt Kistler of Ohio State University, Columbus. Recent observations from observatories such as HESS in Namibia have revealed the existence of extremely high-energy gamma ray sources in the galaxy. It's unclear whether these high-energy rays are produced by a process involving leptons (electrons colliding with photons) or hadrons (the decay of pions). If pion decay is the cause, high-energy neutrinos would also be produced, and their detection by IceCube or other neutrino experiments could verify the pion-decay explanation, Kistler said.

In any case, neutrino experiments now operating, under construction, or planned promise to turn what was once a hypothetical particle into a powerful astronomical tool—a prospect that Reines himself envisioned at the time of his experimental discovery, Halzen said.

"People at the time didn't know whether [the neutrino] was a mathematical trick to fix up theory or whether it was a real particle," Halzen said. "As soon as Reines discovered a real particle, he suggested that this was a way to do astronomy."

## A Cosmic-Scale Test for String Theory?

Theorists who think nature's ultimate building blocks are vibrating strands of energy called superstrings have always had a big problem converting skeptics. One reason: The strings are far too small to see. In fact, they are supposedly so small that no conceivable microscope (or particle accelerator) could ever render them visible. But some string theorists now believe they've found a way to make superstrings observable: supersize them.

Superstrings that were supertiny shortly after the big bang could have been stretched by the expansion of the universe to cosmic size today, Robert Myers of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada, noted at the meeting. He

\* 12th International Symposium on Particles, Strings, and Cosmology.

described several ongoing investigations of the properties that such cosmic strings would have and how they might be detected.

"I think it's pretty exciting," said Princeton University astrophysicist David Spergel. "It's the potential to see physics from really high energies that we can't get any other way. It's the potential for a really exciting surprise."

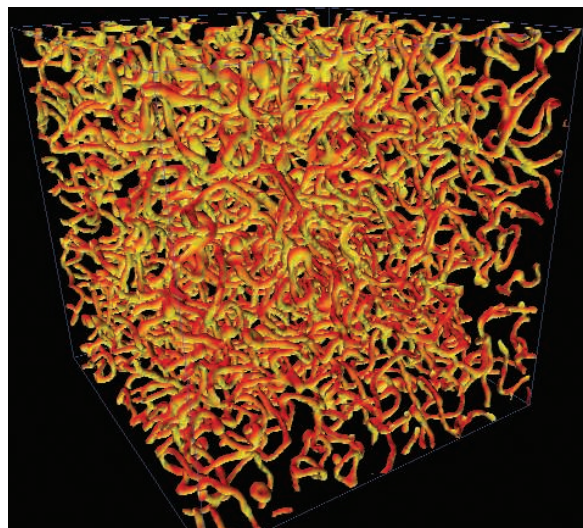
Earlier analyses indicated that strings from the time of the universe's birth would be diluted away by the subsequent expansion or would be too unstable to survive to the current epoch. But advances in recent years have shown that's not necessarily true, Myers said. "We have scenarios where you get, in fact, a rich network of different kinds of strings generated at exit from inflation," the brief burst of superfast expansion following the big bang, Myers said. "So we have the exciting possibility that in certain scenarios, the superstrings might appear in a network of cosmic strings."

One way of detecting cosmic superstrings would rely on precise timing of the spinning rates of fast pulsars, neutron stars that emit blips of radiation at precise intervals. Small variations in the intervals might be the effect of background gravitational waves produced by cosmic string networks.

Another promising approach, Myers said, would be to detect gravitational waves directly by means of experiments such as LIGO, the twin observatories in Louisiana and Washington state (*Science*, 21 April 2000, p. 420). As cosmic strings wiggle, rapid acceleration of their mass can generate powerful gravitational-wave beams. LIGO may not be sensitive enough to detect them, but a planned set of three space-based gravitational wave detectors known as LISA would be a good bet.

Another method would exploit gravitational lensing, the power of massive objects to bend light passing nearby. The gravity of a string in space could bend light enough to split the image of a galaxy in the background, giving astronomers the impression of two identical galaxies sitting side by side.

Finally, physicists might detect distortions imprinted by strings in the cosmic background radiation, the smooth glow of microwaves from the big bang that permeates all of space. Evidence could come from extremely precise measurements such as



**Pumped up.** Computer simulations show that cosmic inflation might have created networks of enormous "superstrings."

those expected from the European Space Agency's Planck Surveyor mission, scheduled for launch next year.

"We have people actually working on looking for string signatures for their thesis," said Spergel. "So maybe we'll detect them."

—TOM SIEGFRIED

Tom Siegfried is a writer in Los Angeles, California.

## Snapshots From the Meeting >>

**Shooting the moon.** Recent observations of a galactic cluster collision seem to rule out modified theories of gravity for explaining dark matter (*Science*, 25 August, p. 1033). But Gia Dvali of New York University reports that other changes to the law of gravity over vast distances are still possible and could explain why the universe appears to be expanding at an accelerating rate.

In fact, such modifications would produce observable variations in the orbit of the moon around Earth, Dvali pointed out. Deviations on the order of 1 millimeter would be a sign that mysterious "dark energy" is not needed to explain cosmic acceleration. Such precise measurements may be within the



reach of a new generation of laser-ranging experiments, in which researchers bounce laser beams off reflectors that Apollo astronauts left on the moon.

"It would be absolutely amazing," Dvali said. "By looking at the moon, you can derive information about dark energy."

**Dark possibilities.** In the cosmos, invisible, unidentified "dark" matter outmasses the ordinary "baryonic" matter known on Earth about 10 to 1. That may sound like a big difference, but to physicists it's mystifyingly close. It suggests that dark matter and ordinary matter were originally produced by related mechanisms.

At the meeting, physicist Leszek Roszkowski of the University of Sheffield in the U.K. discussed the possibility that both forms of matter owe their origin to Q balls, exotic objects possibly formed in the early universe. A Q ball is basically a bag of squarks, hypothetical partner particles to ordinary quarks predicted by a theory known as supersymmetry. If Q balls decayed into both ordinary matter and dark matter, it would explain why the amounts of the two forms of matter are similar.

That idea doesn't work if the dark matter is composed of WIMPs: weakly interacting massive particles that supersymmetry also predicts. Accelerator experiments and searches for dark matter using underground detectors rule out the mass range for WIMPs predicted for Q-ball decay. But Roszkowski and collaborator Osamu Seto of the University of Sussex, U.K., calculate that those objections to the Q-ball scenario can be avoided if Q-ball decay produces another supersymmetric particle called the axino. If so, the axino's mass would be about the same as the proton's—much less than the mass predicted for WIMPs and not detectable by current underground experiments.

"That's bad news for WIMP dark-matter searches," said Roszkowski. But it's possible that evidence for axinos could be produced in the Large Hadron Collider, scheduled to begin operation outside Geneva next year. —T.S.