explain theoretically. "We suggest a model in which charge exchange between ions is the pumping mechanism, and an instability of the plasma produces fast jets," Kunze says. His group is proceeding with experiments using a variety of other capillary materials.

—GRAHAM P. COLLINS

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ANOMALOUS COSMIC-RAY DATA SUGGEST OSCILLATION BETWEEN NEUTRINO FLAVORS

When high-energy cosmic ray protons and nuclei hit the top of the atmosphere, they generate showers of mesons that quickly decay to muons, electrons, positrons and neutrinos. A few kilometers below the surface of the Earth, nothing remains but the most energetic muons and almost all of the neutrinos. Irrespective of the complicated details, unimpeachable particle theory dictates that these hadronic showers produce, on average, twice as many muon-flavored neutrinos (ν_μ and $\bar{\nu}_\mu$) as electron-flavored neutrinos (ν_e and $\bar{\nu}_e$). The details leave wiggle room for only a few percent departure from this predicted 2:1 ratio.

But for the last six years underground neutrino detectors have been providing tantalizingly inconclusive evidence that the observed ratio

$$R_{\rm obs} = (\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$$

is close to 1 instead of the expected 2. If this anomaly is real, the likeliest explanation is the much-sought-after phenomenon of "neutrino oscillation": Mu neutrinos, it would seem, are metamorphosed into some other flavor en route from the top of the atmosphere to the detector deep underground. (In the detector, on the rare occasions when they deign to collide with nuclei, electron neutrinos usually produce electrons or positrons, but never muons. For mu neutrinos it's just the other way around.) Definitive evidence of neutrino oscillation would tell us, among other things, that not all neutrinos are massless.

New results

The strongest statistical evidence for the cosmic-ray neutrino anomaly, over the years, has come from the 3-kiloton Kamiokande water Čerenkov detector inside a Japanese zinc mine. The 1 September issue of *Physics Letters B* brought news of an important, if still inconclusive, new result from Kamiokande.[1] This is the first extensive report on cosmic-ray neutrinos with energies above 1 GeV. The new data exhibit just the kind of energy and angular dependence one would expect for neutrino oscillation. But the statistics are still far from overwhelming. Neutrinos are notoriously unobtrusive: In seven years of exposure, the 3-kiloton detector has harvested barely 200 usable interactions of GeV neutrinos.

In June, at the Neutrino '94 conference in Israel, the Anglo-American Soudan collaboration, whose 1-kiloton iron tracking calorimeter sits deep inside a northern Minnesota iron mine, reported a preliminary new result supporting the reality of the cosmic-ray anomaly.[2] That result is perhaps more important than the relatively little statistical weight it adds to the accumulated Kamiokande data: In the past the principal support for the Kamiokande anomaly has come from the Irvine–Michigan–Brookhaven collaboration's 8-kiloton water Čerenkov detector (now retired) in an Ohio salt mine. A 1-kiloton segmented iron calorimeter (also now retired) in the Frejus tunnel in the French Alps, on the other hand, showed no real evidence of the alleged cosmic-ray anomaly. Therefore in the absence of the Soudan result a skeptic might well write off the anomaly as a spurious artifact of water Čerenkov detectors.

Now there's a new player in the game. In a tunnel 3 kilometers under the summit of the Gran Sasso d'Italia in the Apennines, the Italian–American MACRO detector has just been completed. But at various stages of completion it has already been taking data since 1989. Unlike Kamiokande, IMB, Soudan and Frejus, all of which began life in the 1980s as proton-decay detectors, MACRO is a large-area, low-density array of scintillators and streamer tubes originally designed primarily to detect traversing magnetic monopoles.[3] But now that the cosmic-ray neutrino anomaly has attracted so much interest, MACRO's excellent capacity for tracking muons that pass through it *from below* makes it particularly useful for examining the collision products of cosmic-ray neutrinos with energies on the order of 10 GeV. In its first announcement of cosmic-ray neutrino results, last July,[4] the MACRO collaboration reported that the flux of high-energy muons traversing the detector from below was about 25% less than what one would expect, in the absence of neutrino oscillations, from mu neutrinos interacting in the rock just below the detector. That's less of a shortfall than the Kamiokande and IMB groups have found for lower-energy neutrinos. But the meager MACRO statisics at this early stage are still compatible with either a 50% shortfall *or* no shortfall at all.

Ratio of ratios

Something else besides low statistics complicates the interpretation of the early MACRO data, or any other experiment that sets out to look at neutrinos above 10 GeV. Particle theory predicts the 2:1 *ratio* of mu neutrinos to electron neutrinos produced in the hadronic cosmic-ray showers with an uncertainty of only about 4%. But predicting the absolute fluxes of the two neutrino flavors is a much shakier business, requiring detailed assumptions about meson-production cross sections and the like. That's why all the lower-energy-detector groups report their results in terms of the ratio of ratios

$$\mathfrak{R} = R_{\rm obs}/R_{\rm MC}$$

where $R_{\rm MC}$ is the value of the μ/e neutrino ratio R predicted by Monte Carlo calculation using standard particle theory *without* any neutrino oscillation. This ratio of ratios takes account of detector idiosyncrasies as well as canceling out much of the uncertainty due to flux normalization and shower phenomenology.

But because MACRO, unlike the other detectors, looks primarily for through-going charged particles rather than neutrino collisions within the detector, it almost never sees the short-range electrons produced by electron neutrinos in the adjacent rock. Therefore MACRO only measures the absolute flux of mu neutrinos, a number that's harder to compare with theory than is the ν_μ / ν_e ratio. On the other hand, MACRO has unique access to the high-energy end of the cosmic-ray neutrino spectrum, which comes from the decay of mesons and muons whose flight lengths can exceed the thickness of the atmosphere.

In the absence of neutrino oscillations or other "new physics," $\mathfrak{R}$ should be close to unity. The new Kamiokande paper gives $\mathfrak{R} = 0.60 \pm 0.07$ for the updated sub-GeV data and 0.57 ± 0.10 for the new higher-energy data. Two years ago the IMB collaboration reported $\mathfrak{R} = 0.54 \pm 0.13$ for its low-energy data set.[5]

Such low values of $\mathfrak{R}$ by themselves do not necessarily imply a disappearance of mu neutrinos. They might alternatively be pointing to an excess of electron or positron tracks in the detector. In that context the first thing that comes to mind in these old proton-decay detectors is, of course, the decay of protons to positrons and neutral pions. That would be new physics with a vengeance. But to the extent that one can predict absolute neutrino event rates from the primary cosmic-ray flux at the top of the atmosphere, the proton-decay hypothesis turns out to fit the observed low μ/e ratio less well than does the hypothesis of neutrino oscillation.

Zenith angle

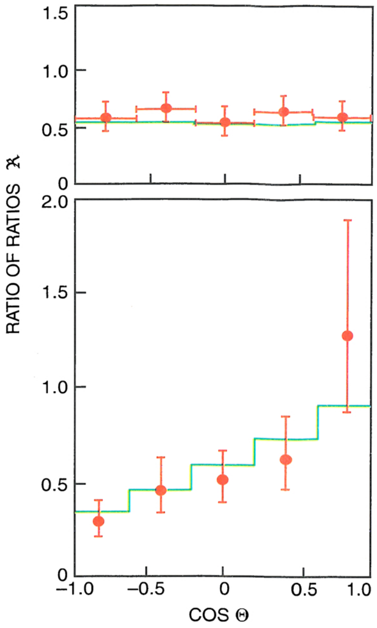
The angular dependence of the high-energy Kamiokande data adds intriguing new evidence in favor of neutrino oscillation. The top part of the figure on this page shows the zenith-angle dependence of $\mathfrak{R}$ for Kamiokande's sub-GeV events. One doesn't really know the direction of the incident neutrino, but the direction of the muon, electron or positron produced by the collision approximates it well enough for the broad bins of the figure. Neutrinos coming straight down from the zenith produce events near $\cos\Theta = +1$, and neutrinos that come straight up through the center of the Earth correspond to $\cos\Theta = -1$. We see that $\mathfrak{R}$ remains at about 0.6, irrespective of whether the neutrino traveled a mere 20 kilometers from the top of the atmosphere or 13 000 kilometers through the entire Earth.

But the lower part of the figure, displaying the zenith-angle dependence of $\mathfrak{R}$ for Kamiokande events with energies above 1 GeV, looks quite different. The average neutrino energy here is about 5 GeV. Ignoring for the moment the sizable error bars, we see $\mathfrak{R}$ falling from above unity for downward neutrinos to less than 0.5 for upward neutrinos entering the detector from below.

The theory of neutrino oscillation in vacuum (or in the Earth, which comes to much the same thing) offers a ready explanation for the difference between the two distributions. If two neutrino flavors, say ν_μ and ν_e, do indeed mix, the probability that a ν_μ will have become a ν_e by the end of a journey of length L oscillates between zero and some maximum like $\sin^2(L/\lambda)$. The characteristic wavelength λ of this oscillation is proportional to the neutrino energy divided by Δm^2, the difference between the squared masses of the two neutrino species. (If both are massless there is no oscillation.)

Suppose, as the new Kamiokande data suggest, that λ is only a few times 20 km (the height of the atmosphere) for typical neutrino energies in the sub-GeV data. Then every $\cos\Theta$ bin in the top part of the figure will span many cycles of neutrino oscillation, and $\mathfrak{R}$ will therefore always take the same average value between no effect and maximal ν_μ disappearance, irrespective of zenith angle. But because λ is proportional to energy, the situation in the bottom part of the figure is different. Now the typical λ is closer to 1000 km, so that the rightmost bin ($\cos\Theta > +0.6$) includes only events with L much smaller than λ and therefore very little neutrino metamorphosis. In that bin, therefore, $\mathfrak{R}$ would be close to unity.

"This apparent departure from isotropy at higher energy is exciting," says Alfred Mann, a member of the University of Pennsylvania contingent at Kamiokande. "It's strongly suggestive of neutrino oscillation, but at this statistical level it's not yet compelling." The green lines in the two plots display a joint Monte Carlo fit to the high- and low-energy Kamiokande data assuming oscillation between ν_μ and ν_e. These fits yield a Δm^2 of about 0.01 eV^2 and a mixing parameter close to unity, the theoretical maximum. The group gets just about as good a fit with the alternative assumption that the oscillation is between ν_μ and ν_τ, the third (and presumably heaviest) neutrino variety.



Ratio of ratios, $\mathfrak{R}$, as a function of zenith angle Θ, for Kamiokande cosmic-ray neutrino events with energies less than (top) and greater than (bottom) 1 GeV. $\mathfrak{R}$ is the observed ratio of ν_μ to ν_e collisions, divided by the Monto Carlo prediction of the same ν_μ/ν_e ratio assuming *no* neutrino oscillations. So in the absence of any "new physics," $\mathfrak{R}$ should always be 1. Cos $\Theta = +1$ denotes neutrinos coming down from the zenith, and $\cos\Theta = -1$ corresponds to neutrinos coming straight up into the detector from below. The green lines indicate a joint fit to both data sets, this time assuming oscillation between ν_μ and ν_e. (Adapted from ref. 1.)

The other anomaly

Kamiokande is also a player in the other game that has yielded serious evidence of neutrino oscillation, namely the measurement of the apparent solar-neutrino deficit. (See PHYSICS TODAY, August 1992, page 17.) The attractive theory invoked to explain the solar-neutrino shortfall involves resonant matter-induced neutrino oscillation inside the Sun, as distinguished from the vacuum oscillation discussed above. Nonetheless both phenomena would ultimately be governed by the same two parameters: Δm^2 and the neutrino mixing parameter. So one may well ask if there is any sign of convergence between what is suggested by the solar neutrino deficit on the one hand and the cosmic-ray neutrino anomaly on the other. The various solar neutrino experiments seem to be pointing to a Δm^2 several orders of magnitude smaller than what one gets from the Kamiokande cosmic-ray fits. But that would not be inconsistent if the electron neutrinos made in the solar core are changing into something other than mu neutrinos, or if the cosmic-ray mu neutrinos are becoming tau neutrinos. One fit to the aggregate solar neutrino data points to a mixing parameter on the order of 1%. That would make particle theorists happier than the large mixing parameter suggested by other solar neutrino fits and seemingly demanded by the cosmic-ray anomaly. Theoretical prejudice favors the smaller mixing parameter because it is more in line with the measured mixing of the various quark species.

Detectors old and new

Because none of the detectors that have yielded positive or negative findings on the cosmic-ray neutrino anomaly was designed for that purpose, the central experimental issue of discriminating between muons and electrons has been problematic. The essential difference at these energies is that muons have fairly long ranges in material, whereas the much lighter electrons and positrons initiate showers of photons and e^+e^- pairs. But the distinction can be clouded, for example, by the production of pions in the neutrino collisions. There is also concern that muons can be lost in water detectors because of Čerenkov threshold effects exacerbated by Fermi motion in the oxygen nuclei. In recent months the Kamiokande and IMB groups have been availing themselves of a 1-kiloton water Čerenkov test module at Japan's KEK laboratory to check how well their own detectors have been identifying muon and electron events. Each group has deployed photomultiplier tubes throughout the test tank in a pattern like that of its home detector and then directed muon and electron beams from the KEK accelerator into the water. The tests thus far have produced no surprises: Preliminary analysis indicates that Kamiokande has been identifying muon and electron events about as well as had been assumed. The IMB test is still under way. These tests should, of course, be done with a neutrino beam, but KEK does not as yet have one.

If one wants to find out whether neutrinos really do oscillate from one flavor to another, cosmic-ray showering is not a very suitable neutrino source. Nor, for that matter, is the Sun. Ideally one wants to start with an intense, well-characterized neutrino beam of known initial flavor, let it travel a specified distance and then look for any flavor change by directing the beam through a detector designed for the purpose.

One such new experiment, named CHORUS, is already under way at CERN: A 25-GeV ν_μ beam from the Super Proton Synchrotron is directed at almost a ton of photographic emulsion 600 meters downstream. Emulsion may sound quaint, but this is in fact a very modern detector with highly automated microscopic scanning. One is looking for telltale track kinks a few hundred microns from neutrino collision vertices. Such kinks, if they are found, would indicate decays of the heavy, short-lived tau lepton. Tau leptons could have been produced only by collisions of tau neutrinos, in a beam that originally had none. The CHORUS group expects to report first results next year.

Beam length and energy determine what regions of the neutrino-oscillation parameter space an experiment can probe. Mann and collaborators at Brookhaven are proposing to send a ν_μ beam through three detectors on a 24-km journey across eastern Long Island. Groups at Fermilab, CERN and KEK want to direct higher-energy ν_μ beams over much longer distances. Those beams, unlike the proposed Brookhaven beam, would be energetic enough to make tau leptons. But because neutrino beams are poorly collimated, their longer distances would require much bigger detectors. One of the CERN schemes calls for a neutrino beam to travel 730 km through the Earth to a new detector in the Gran Sasso underground laboratory. A comparable distance would be spanned in Fermilab proposals to direct a beam at the Soudan or IMB site. The Japanese are thinking about sending a neutrino beam 250 km from KEK to Super Kamiokande, the 50 000-ton water Čerenkov detector now under construction in the Kamioka mine.

Confirming the reality of neutrino oscillations would be much more than an interesting curiosity. The spectacularly successful but manifestly incomplete "standard model" of the elementary particles can accommodate a variety of schemes with nonzero masses and mixing among the three "generations" of neutrinos. Knowing whether Nature has chosen one of those schemes should help point the way to a grand unification beyond the standard model.

—Bertram Schwarzschild

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Theory of Everything

You test the weight of your theory,
toss it up, a perfect arc
from palm to palm.
You keep your eyes focused
straight ahead, concentrating
out of the corners of your eyes.
Electromagnetism shuttles
back and forth.

When you feel confident you move to two,
adding the Weak Force
to your equation.
They pass in the center,
one thrown over the other.

You juggle for a while
then move to three,
the Strong Force flying
smoothly with the others
in perfect syzygy.

Feeling cocky
you add Gravity
too soon.
Your timing off,
all your theories fall,
bouncing slightly as they disappear
under the lab tables
and behind the door.

Sometimes you think you'll never juggle
four.

— Lawrence Schimel