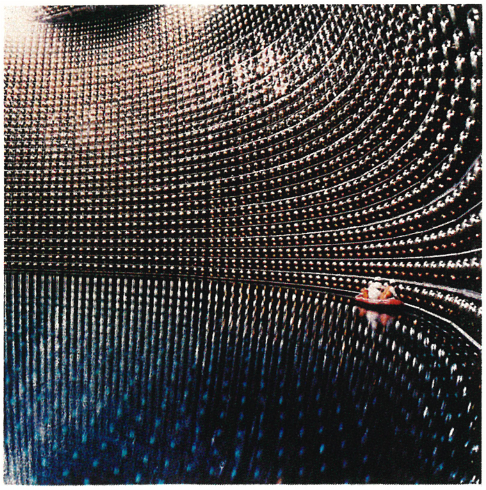
Cosmic Ray Showers Provide Strong Evidence of Neutrino Flavor Oscillation

To prolonged ovation at the recent Neutrino '98 conference in a ski resort west of Tokyo, the Japanese–American Super Kamiokande collaboration reported by far the most convincing evidence to date of oscillatory metamorphosis between different neutrino flavors.[1] Super Kamiokande is the gargantuan 50-kiloton water-Čerenkov neutrino detector buried 1 kilometer under a mountain not far from the conference site. The collaboration is headed by Yoji Totsuka of Tokyo University's Institute for Cosmic Ray Research.

The best-advertised purpose of the two-year-old, $100 million underground superdetector is to elucidate the solar neutrino problem, presumably in terms of neutrino flavor oscillation. (See PHYSICS TODAY, July 1996, page 30.) But this powerful new evidence of neutrino oscillation has no obvious connection to the solar-neutrino problem. The neutrinos in question come not from the Sun, but from the decay of short-lived particles produced by cosmic-ray showers in the atmosphere. In fact, Super Kamiokande's atmospheric neutrino data point to oscillation between neutrino varieties that have nothing to do with electron neutrinos, the only kind made in the core of the Sun.



SUPER KAMIOKANDE

AS SUPER KAMIOKANDE, under a mountain west of Tokyo, was filling up in 1996 with 50 kilotons of ultrapure water, technicians had to move around by raft to clean the faces of its 13 000 photomultiplier tubes before they were submerged.

In the bowels of a zinc mine, 13 thousand phototubes keeping watch over 50 thousand tons of water have provided the strongest evidence yet of neutrino oscillation, and therefore of neutrino mass.

The neutrinos (and antineutrinos) we know about come in three "flavors": ν_e, ν_μ and ν_τ, associated, respectively, with the electron, the muon and their much heavier (1.8 GeV) sibling, the tau lepton, discovered in 1976. In the minimal standard model of the fundamental particles, there is no metamorphosis from one neutrino flavor to another, because all the neutrinos are massless and lepton flavor is rigorously conserved.

For all its uninterrupted success, however, the standard model is manifestly incomplete; it is held together by too many empirical parameters that the theory cannot predict. For a quarter of a century, particle physicists have been urgently looking for some small deviation from the standard model that might point the way to a more encompassing theory that properly unifies the strong and electroweak sectors and explains the masses of the leptons and quarks.

Oscillation

An attractive and relatively painless extension of the standard model is to posit that all or some of the neutrino species have small but nonvanishing masses, and that the states are mixed—that is to say, the basis formed by the three mass eigenstates is somewhat rotated from the basis formed by the three weak-flavor eigenstates. We already know of an analogous mixing rotation between the mass eigenstates of the quarks and their strong-flavor (strangeness, charm *etc.*) eigenstates.

If two different neutrino flavors, call them ν_1 and ν_2, have different masses and a finite mixing angle, then the oscillating probability that a neutrino starting out as a ν_1 will have become a ν_2 after a journey of length L through vacuum, air or earth is

$$P_{12}(L) = S_{12}\sin^2(L/\lambda)\,, \qquad (1)$$

where the mixing strength parameter S_{12} lies somewhere between 0 and 1, depending on the mixing angle. The characteristic length λ is given in kilometers by

$$\lambda = E/1.27\Delta m^2\,, \qquad (2)$$

where E is the neutrino energy in GeV and $\Delta m^2 \equiv m_1{}^2 - m_2{}^2$ is in eV^2. It doesn't matter which neutrino is heavier, but unless the two masses are different there is no oscillation.

What Super Kamiokande appears now to have confirmed is that a significant fraction of the muon neutrinos produced in atmospheric cosmic-ray showers are rendered invisible to the detector by just this sort of flavor oscillation.

The atmospheric anomaly

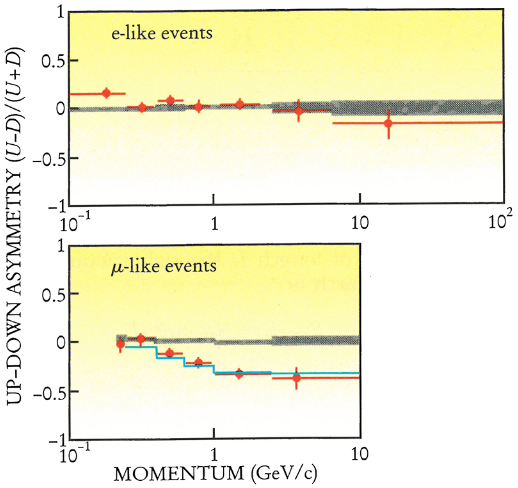
When high-energy cosmic-ray protons and nuclei hit the atmosphere, they generate showers of mesons that quickly decay to muons, electrons, positrons and neutrinos. A kilometer below the Earth's surface, nothing remains but a few energetic muons and almost all of the neutrinos. Despite the complicated details, unimpeachable showering theory dictates a surprisingly simple result: Such showers must, in the end, create twice as many muon neutrinos $(\nu_\mu + \bar\nu_\mu)$ as electron neutrinos $(\nu_e + \bar\nu_e)$, give or take a few percent.

For more than a decade, however, various groups have been reporting evidence that the ratio

$$R_{obs} \equiv (\nu_\mu + \bar\nu_\mu)/(\nu_e + \bar\nu_e)$$

reaching their underground detectors is close to 1 instead of the expected 2. The first explanation that sprang to mind was, of course, neutrino oscillation—assuming the reported atmospheric neutrino anomaly was real. But the detectors were relatively small, so that statistics were painfully meager and the telltale charged lepton produced by neutrino scattering was often not fully contained in the detector when the neutrino's energy was above average.

When a neutrino produces a



UP-DOWN ASYMMETRY $(U-D)/(U+D)$ for electron-like events (top) and muon-like events (bottom) in Super Kamiokande, plotted against the charged lepton's momentum. Above 10 GeV/c, most muon tracks are not fully contained in the detector. U and D are, respectively, the number of events instigated by neutrinos coming *up* from below and *down* from above. The gray bars are Monte Carlo predictions in the absence of new physics, and the blue line indicates the best-fit prediction for oscillation between muon neutrinos and an unseen species. (Adapted from ref. 1.)

charged lepton by colliding with a nucleus, that lepton is the signature of the incident neutrino's flavor: Electron neutrinos create electrons and muon neutrinos create muons. Cosmic-ray shower neutrinos are generally energetic enough (1 GeV is typical) to produce measurable muon, electron and positron Čerenkov light cones when they collide with the nuclei in a water-Čerenkov detector. Furthermore, the charged lepton's energy and direction is a fair indicator of the parent neutrino's incident energy and direction.

Far more solar neutrinos than atmospheric neutrinos rain onto the detector. But solar neutrinos are much less energetic; only the most energetic of them can be identified in a water-Čerenkov detector, and then only by the recoil of elastically scattered electrons.

Little old Kamiokande

Before Super Kamiokande, the best evidence of atmospheric neutrino oscillation came from Kamiokande, its 3-kiloton predecessor. In 1994, the Kamiokande collaboration reported the first study of atmospheric neutrino interactions above 1 GeV. Observing these higher-energy neutrinos is important, because the characteristic oscillation length λ is proportional to the neutrino's energy (see equation 2). If λ is comparable to the height of the atmosphere or the diameter of the Earth, one might hope to see a telltale directional dependence of the atmospheric neutrino flux.

And that, indeed, is what Kamiokande reported in 1994, albeit with marginal statistics. (See PHYSICS TODAY, October 1994, page 22.) For $E < 1$ GeV, the muon/electron ratio R_{obs} was close to 1, and therefore only *half* its expected value, for all neutrino arrival directions. But for the higher-energy atmospheric neutrinos, R_{obs} exhibited a pronounced dependence on the zenith angle Θ: It increased from about 1 for neutrinos coming up from the center of the Earth ($\cos\Theta \approx -1$) to about 2 for neutrinos coming directly down from the zenith ($\cos\Theta \approx +1$).

How would neutrino oscillation explain this angular and energy dependence? The zenith angle of an incident neutrino is an indicator of how far it has traveled since its creation in the atmosphere. Suppose Δm^2 is something like 0.01 eV^2 for oscillation between muon neutrinos and some other neutrino variety. Then, for a typical high energy of 5 GeV, equation 2 gives a λ of about 400 km, much longer than the effective height of the atmosphere, but much smaller than the Earth's diameter. So atmospheric muon neutrinos from directly above would have very little opportunity to change flavor, and the detector would see the $R_{obs} = 2$ we expect in the absence of any oscillation. On the other hand, a muon neutrino produced in the atmosphere halfway round the world would traverse many oscillation lengths on its way to the detector. Therefore, if we suppose that the mixing strength S is close to the maximum 1, we should find that, on average, half of all those upward-coming muon neutrinos have changed flavor, because the average of $\sin^2(L/\lambda)$ over a complete oscillation is $\frac{1}{2}$. Essentially the same goes for the sub-GeV neutrinos, with λ comparable to the height of the atmosphere.

With only about 200 usable interactions of GeV neutrinos harvested by 1994, after seven years of exposure to cosmic-ray showers, the Kamiokande collaboration presented its evidence for depletion of the muon neutrino flux by flavor oscillation, with Δm^2 of order 0.01 eV^2 and the mixing parameter S close to 1. But the statistics were insufficient to tell whether the muon neutrinos were reappearing as electron neutrinos or disappearing as tau neutrinos or some other undetectable species.

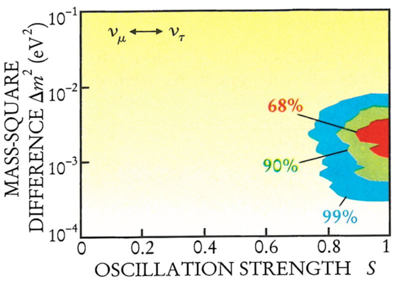
The tau lepton's short lifetime and high production threshhold energy make it very hard to identify in a water-Čerenkov neutrino detector. And there is good reason to believe that no still heavier standard-model charged lepton (and its corresponding neutrino) is waiting to be discovered. But many of the speculative theories that venture beyond the standard model predict the existence of "sterile" neutrino species that are impervious to the ordinary weak interaction but can nonetheless participate in neutrino oscillation.

Super Kamiokande

In the same zinc mine that housed Kamiokande, excavation began in 1991 for its enormously larger successor. After the 13 000 photomultiplier tubes that monitor for Čerenkov light were installed, filling with 50 kilotons of ultrapurified water began early in 1996. (See the photo on page 17.)

The 50-cm-diameter phototubes that monitor the inner fiducial volume are so unusually large that all 11 000 of them had to be blown by hand. Another 2000 smaller phototubes, scavenged from the old IMB (Illinois-Michigan-Brookhaven) detector in an Ohio salt mine, face outward to the surrounding 2-meter-thick shell of water that serves to veto spurious events coincident with charged particles entering the detector from the outside. Because the phototubes lining the detector have to monitor its entire volume, the water has to be kept so pure that its light attenuation length is almost 100 meters. For ordinary tap water, it's less than 3 meters.

At Neutrino '98, the Super Kamiokande collaboration reported the analysis of its first 18 months of data taking. In that time, the detector harvested almost 3000 atmospheric neutrino interactions of the most useful kind: events in which the charged-lepton trajectory is fully contained within the inner detector and there is only a single cone of Čerenkov light. It turns out to be quite easy to distinguish a muon from an electron of the same energy by the neatness of the ring its Čerenkov light cone makes where it intersects the wall of phototubes. Electrons, being much lighter than muons, suffer a lot of electromagnetic showering and small-angle multiple scattering as they make their way through the water. Therefore they produce much more ragged rings than the muons. The collaboration can distinguish muons from electrons (and positrons) with something like 98% efficiency. Muons also have longer tracks,



FITTING NEUTRINO OSCILLATION parameters Δm^2 and S to 535 days of Super Kamiokande atmospheric-neutrino data yields the confidence-level contours shown in the parameter plane. This fitting assumes that muon neutrinos are oscillating with tau neutrinos or some sterile species the detector cannot see. The alternative hypothesis—that the oscillation partner is the electron neutrino—yields a much poorer fit. (Adapted from ref. 1.)

for a given energy, than electrons. Therefore they are hard to contain in a small detector. An important benefit of Super Kamiokande's great size is that it can fully contain 8-GeV muon tracks.

Because the water's index of refraction is 1.33, a relativistic charged particle generates a 42° forward cone of mostly blue Čerenkov light. The light intensity is a measure of the particle's energy, and its direction is determined by the spatial and temporal pattern of phototube hits.

Convincing ratios

Super Kamiokande's first major atmospheric-neutrino result was to confirm emphatically the anamolously low R_{obs} suggested by most of the earlier detectors. For both sub-GeV and higher-energy events, the group found that R_{obs} was only about 64% of what is predicted by an elaborate Monte Carlo simulation that assumes no new physics beyond the standard model but does take account of two minor effects: the slight energy dependence of the expected 2:1 neutrino-flavor production ratio in cosmic-ray showers, and small differences in the detection efficiency for muon and electron events. For many of the uses to which the group puts it, this Monte Carlo simulation is saddled with a 20% uncertainty in the absolute flux of cosmic-ray primaries striking the atmosphere. But in the case of the muon/electron ratio, this normalization uncertainty cancels out.

It also cancels out for another important ratio: the asymmetry between events coming down from above and those coming up from below the detector. An anomalously low R_{obs} may be a harbinger of new physics; but it is certainly not enough, by itself, to clinch the case for neutrino oscillation. For that, one must also examine carefully the dependence of the anomaly on L and E. The zenith angle Θ is a good indicator of L. The figure on page 18 contrasts the observed energy dependence of the up–down asymmetry $(U-D)/(U+D)$ for muon-like and electron-like events. U and D are, respectively, the number of events with $\cos\Theta < -0.2$ and $> +0.2$.

At all energies, the electron-event data are consistent with the zero asymmetry one would expect in the absence of new physics (the gray bars). The muon data start out the same way—at the lowest energies. But with increasing energy, the asymmetry grows steadily toward an asymptotic value of about ⅓. That agrees quite well with the blue line indicating what one expects for neutrino oscillation with the parameters determined by the best global fit to all the data.

That best fit yields $\Delta m^2 = 0.0022$ eV^2 and $S = 1$. (See the figure above.) So, over the entire energy range, half the muon neutrinos coming up through the Earth are lost by metamorphosis, because for them the path length is always much larger than λ. By contrast, very few of the neutrinos coming down from above change flavor when their energy is high enough for λ to become greater than the thickness of the atmosphere.

Metamorphosis to what?

What is the oscillation partner of the ν_μ in these atmospheric shenanigans? The Super Kamiokande data appear to exclude ν_e, because there seems to be no evidence of electron (or positron) neutrinos created by oscillation. Quite generally, the zenith-angle distributions agree well (in both shape and normalization) with maximal oscillation for the muon events in all energy bins, whereas the corresponding electron event distributions show no serious departures from old-fashioned standard model physics. Despite the rather large uncertainty in the absolute cosmic-ray flux normalization, the collaboration finds only a very improbable fit to the hypothesis $\nu_\mu \leftrightarrow \nu_e$. On the other hand, the best global fit to the hypothesis that the muon neutrinos are oscillating with some species that Super Kamiokande cannot easily see—ν_τ or a sterile neutrino—is very good, with a minimum χ^2 of 65 for 67 degrees of freedom.

If the oscillation partner is not ν_e, then the atmospheric anomaly has no immediate bearing on the famous solar neutrino shortfall. The nuclear fusion processes in the Sun produce only electron neutrinos. So do the fission processes in a reactor. Therefore the failure of the recent CHOOZ reactor experiment[2] in France to see a loss of electron neutrinos can be taken as a confirmation that $\nu_\mu \leftrightarrow \nu_e$ is not happening, at least not with a large oscillation amplitude $S_{e\mu}$. The CHOOZ and Super Kamiokande results do not, however, exclude $\nu_\mu \leftrightarrow \nu_e$ oscillation at the very small mixing strength ($S_{e\mu} \approx 0.01$) suggested by the controversial Los Alamos accelerator data (see PHYSICS TODAY, August 1995, page 20). With three standard-model neutrino flavors plus possible sterile species to speculate with, one can suppose that all the different regimes of apparent neutrino oscillation involve different pairings of players.

How heavy?

At the 90% confidence level, the Super Kamiokande collaboration finds that the mixing strength S exceeds 0.82 and that Δm^2 lies somewhere between 5×10^{-4} and 6×10^{-3} eV^2. If one makes the simplifying assumption that the lighter of the two mass eigenstates is much lighter than the other, one gets something like 0.05 eV for the mass of the heavier neutrino. If the mixing strength is indeed close to maximal, implying that the mass states have roughly equal admixtures of the two weak-flavor eigenstates, it makes little sense to speak specifically of "the mass of the mu (or tau) neutrino."

Even though neutrinos are thought to outnumber protons and neutrons in the universe by a factor of 10^9, a neutrino mass of order 0.05 eV would make little difference to cosmological closure or structure formation. But the oscillation data cannot exclude the possibility that Δm^2 is much smaller than m^2. If, for example, the two neutrino masses are both near 3 eV, with a very small difference between them, they would provide enough mass to constitute the "hot dark matter" component cosmologists are nowadays looking for.[3]

Cosmological implications are only a part of the story. If the atmospheric neutrino oscillation result holds up, it is arguably the most important experimental result of the decade in the physics of elementary particles. It would certainly be a major milestone in the history of neutrino physics, and our first direct glimpse beyond the standard model. "One profound consequence of the nonzero neutrino mass," says University of Maryland theorist Rabi Mohapatra, "is that the weak interactions must become parity conserving at very high energies."

"Uncertainties in the flux prediction, cross sections and experimental biases are ruled out as explanations for the observations," the Super Kamiokande collaboration asserts.[1] And, after 18 months of abundant data, so are statistical fluctuations. "More important than another year's worth of data," says University of Delaware theorist Tom Gaisser, who made major contributions to the neutrino-flux calculations, "will be another year of working to understand possible systematic uncertainties in the measurements and the calculations, especially the normalization."

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Strings May Tie Quantum Gravity to Quantum Chromodynamics

Might we learn more about the strong interactions by studying string theory? That's one possibility raised by recent work showing that string theories and gauge field theories are flip sides of the same coin.

Although string theorists explore bizarre multidimensional spaces filled with tiny loops and membrane-like objects, they are ultimately seeking a description of the real world. They may have come close with a recent hypothesis that links a ten-dimensional string theory to a gauge field theory in the four dimensions of our ordinary world. The theorists' great hope is that this connection extends to the specific gauge theory describing quantum chromodynamics (QCD), which governs the strong interactions.

String theorists have been quite excited about this hypothesis since about February—which is when they realized the import of a paper that Juan Maldacena of Harvard University had posted in November on the Los Alamos e-print archive server.[1] By the time of the international Strings '98 conference,[2] held in late June at the Institute for Theoretical Physics at the University of California, Santa Barbara, over a hundred papers had elaborated upon and extended the basic idea, and it became the focus of the meeting.

Maldacena identified a duality between a particular string theory, which inherently includes gravity, and a particular gauge theory, which does not. The duality says that the string theory on a particular curved spacetime background maps onto the gauge theory. The best part of the duality is that the two theories overlap when the coupling between fields in the gauge theory is strong. That's precisely where it is difficult to do calculations in the gauge theory and, fortuitously, just where it is easy to do calculations in the string theory. (For a background on superstrings and duality, see two articles by Edward Witten in PHYSICS TODAY: April 1996, page 24, and May 1997, page 28.)

Extensions and refinements

Since Maldacena's paper, others have suggested ways to translate between the two theories, relating observables in one to those in the other. In particular, Steve Gubser, Igor Klebanov and Alexander Polyakov (all at Princeton University)[3] and, independently, Witten (Institute for Advanced Study in Princeton)[4] have proposed a precise version of this correspondence, which relates quantities in the interior of a region (spacetime) to quantities in a gauge theory located at the boundary.

As originally formulated, Maldacena's duality was limited to gauge theories that are supersymmetric—that is, theories in which each of the known bosons (fermions) has a supersymmetric fermionic (bosonic) partner with identical properties except for the spin. The duality was also restricted to conformal, or scale-invariant, gauge theories, those having additional symmetries besides translation and rotation. Thanks to work by a number of other theorists, Maldacena's duality has by now been freed of these two restrictions.

Before Maldacena's work, many theorists had worked out specific cases of duality between gravity and two dimensional conformal theories. Their calculations lent some credibility to the proposal, and a host of other calculations since Maldacena put forth his thesis have provided additional supporting evidence for it. Some papers have offered formal proofs of the conjectured duality, albeit in specific rather than more general spacetime geometries.

Leonard Susskind (Stanford University) is among many who are ecstatic about the new developments in string theory. Not too many years ago, he recalls, people were discouraging others from going into quantum gravity because it was not expected to lead to anything. Maybe now, he speculates, everything will turn on its head, and quantum gravity can give insight into particle physics.

Polyakov is more cautious in his reaction: "If this idea works in the nonsupersymmetric case, it will provide the theory of quark confinement. If not, it will remain an unimportant curiosity. I hope the answer will not take too long, but it is too early now to celebrate."

The large N limit

Doing calculations in the strong-coupling limit of QCD has long been a dream of theorists. Unlike in quantum electrodynamics, one cannot do a perturbative expansion to calculate quantities in QCD: There is no small coupling constant in which to expand. One trick is to assume that quarks come in a large number (N) of colors instead of the three that have been observed. (Quarks also come in three families of flavors such as the up/down one.) Because the interactions between N colored quarks would be transmitted by $N^2 - 1$ different gluons, the large N limit would correspond to the strong-coupling limit.

In 1974, Gerard 't Hooft (Utrecht University in The Netherlands) suggested that one could expand the equations for QCD in the variable $1/N$, taking N to be large. His suggestion led to some insights but fell short of solving the problems of interest in QCD. (See the article by Witten in PHYSICS TODAY, July 1980, page 38).

But 't Hooft also predicted that one should be able to find a string theory describing QCD, in which $1/N$ would play the role of some coupling constant. (Around the same time, Kenneth Wilson realized that, in the strong coupling limit of QCD, the Faraday flux lines behave as strings and confine quarks by tying them together.) In 1981, Polyakov (then at the L. D. Landau Institute in Moscow) realized that the appropriate string theory might be in five dimensions. But neither he nor many others who looked could find the string theory anticipated by 't Hooft.

Witten thinks that the string theory identified in the recent duality is substantially closer to what is needed for understanding the $1/N$ expansion than anything yet found. As evidence to support this claim, Witten notes that the duality has been used to give explanations of quark confinement and the hadronic mass gap—two of the main mysteries of QCD—that are