of C_{60}. Nevertheless, comparing their data to the three-dimensional calculations, the researchers found that the peak in T_c did not coincide with a peak in the density of states. They concluded that the density of states might not be the dominant determinant of T_c.

The Bell Labs team next measured the resistivity of their C_{60} crystal above T_c because the normal-state resistivity reflects the coupling strength of electrons or holes to phonons. Arthur Hebard of the University of Florida reminded us of the old adage, “Bad metals make good superconductors.” Lead, for example, is a superconductor; gold is not. The Bell Labs experimenters compared an electron metal, made by gate doping C_{60} with electrons above T_c, to a similarly produced hole metal that had the same critical temperature. The resistivity of the hole metal was as much as six times higher than that of the electron metal, indicating that its charge–phonon coupling is much stronger. Schön, Kloc, and Batlogg conclude that the stronger coupling contributes significantly to the difference in T_c.

Dusting off old theories

Schön and his colleagues point out two factors of C_{60} that should give rise to a high critical temperature. First, the frequency spectrum of the C_{60} intramolecular vibrations extends to energies as high as 200 meV; the coupling of some of these vibrations to electronic states provides intramolecular electron–phonon coupling. Second, the density of electronic states is higher for holes than for electrons because it derives from a fivefold degenerate molecular orbital state rather than a threefold degenerate state in the case of electrons. But those are qualitative arguments. To explain the observed behavior in detail, many theorists have invoked the traditional Bardeen-Cooper-Schrieffer (BCS) theory of electron–phonon coupling. Still, as Hebard points out, some aspects of the data remain unexplained.

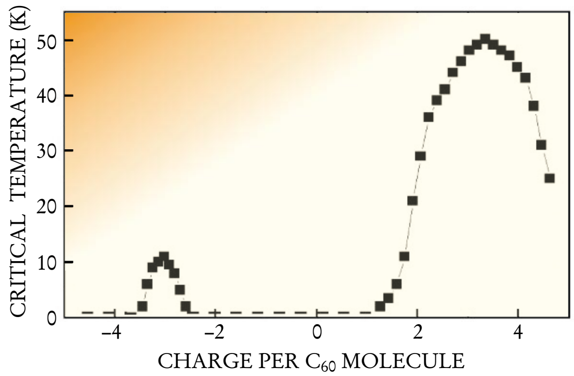

FIGURE 2. PEAKS IN THE CRITICAL TEMPERATURE T_c. Data were taken when charges were added to C_{60} crystals by gate doping. Peaks are seen when the ratio of charges to C_{60} molecules is near three for both electrons and holes. The peak for hole-doped C_{60} is higher and wider than that for electron doping. (Adapted from ref. 3.)

The results on hole-doped C_{60} are bound to revive interest in theories of electron–electron correlations as a mechanism for superconductivity. The case for electron interactions was made in 1991 by Sudip Chakravarty and Steve Kivelson of UCLA, along with Martin Gelfand (now at Colorado State University).[4] Two aspects of the hole-doped data further strengthen the case against a phonon mechanism, say Chakravarty and Kivelson. First, it's hard to get a T_c as high as 52 K from phonon coupling alone without introducing instabilities. Second, it's hard to explain by phonon mechanisms alone what the two theorists believe is a rather sharp drop-off in T_c as a function of doping. Others agree that electron–electron correlations have a large enough energy scale to yield a high T_c, but the challenge is to get the required attractive pairing out of repulsive interactions. A number of observers think that the answer may well lie in a combination of the two mechanisms.

Batlogg points out that phonons in the doped buckyballs exist in a new regime—one in which their energies are comparable to the Fermi energy. This new regime requires a new approach even to BCS models because the conventional method of calculating T_c involves expansion in the ratio of the phonon to the Fermi energy.[5]

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Disappearing Atmospheric Neutrinos Don't Seem to be Turning Sterile

> Super-Kamiokande data strongly disfavor hypothetical sterile neutrinos as partners in the oscillation of neutrinos from cosmic-ray showers.

For some time now, we've had overwhelming evidence that a significant fraction of the muon neutrinos (ν_μ) produced by decays in cosmic-ray showers in the upper atmosphere are somehow disappearing before they can get to an underground neutrino detector. Four years of data from Super-Kamiokande, the 50-kiloton water-Čerenkov detector in Japan, have made a strong case that these missing atmospheric ν_μ's are being transformed by “neutrino oscillation” into neutrinos of some other sort. But there was no good evidence of just what sort these other neutrinos might be. (See PHYSICS TODAY, August 1998, page 17.)

Now, at last, the Super-Kamiokande collaboration has published the results of its assault on this experimentally difficult question.[1] Any new evidence of neutrino oscillation and its detailed character is a subject of considerable excitement, because neutrino oscillation promises to be our first glimpse of new physics beyond the all-too-successful standard model of particle theory.

“We find,” writes the collaboration, “that oscillation between ν_μ and tau neutrinos [ν_τ] suffices to explain all the results in hand.” The paper rejects, at the 99% confidence level, the principal competing hypothesis—namely, that ν_μ is oscillating with a putative “sterile” neutrino species that is impervious to the normal weak interaction. (The data have long since ruled out a third possibility—that the missing atmospheric neutrinos might be turning into electron neutrinos [ν_e].)

Why sterile neutrinos?

Why should anyone entertain something so exotic as a sterile neutrino (ν_s) in the first place, when the theorists already have three perfectly good neutrino flavors to play with: ν_μ, ν_τ, and ν_e? In fact, the high-energy electron–positron collider data have made it quite clear that there can be no additional neutrino varieties participating in the standard weak interactions.

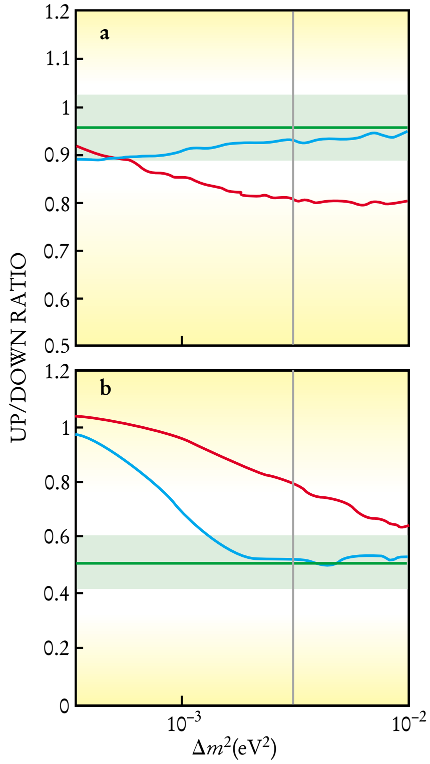
That's the problem! Three neutrino flavors simply cannot suffice to explain the disparate data from all three observational regimes for which evidence of neutrino oscillation has been reported: atmospheric neutrinos, solar neutrinos, and neutrinos produced in accelerators. Suppose you have oscillation between two neutrino flavors, labeled i and j. Then the probability that a neutrino starting out as an i will have become a j after a journey of length L through empty space oscillates like $\sin^2(L/\Lambda)$. The characteristic oscillation length Λ is proportional to $E/\Delta m^2_{ij}$, where E is the neutrino's energy and Δm^2_{ij} is the difference between the squares of the two neutrino masses in question. Neutrino oscillation implies unequal neutrino masses.

Because the measured oscillation parameters of the three observational regimes are so different, it is presumed that each involves a different pairing of neutrino species. But if there are only three species, one confronts an obvious algebraic constraint. By definition,

$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} \equiv 0.$$

The problem is, however, that the accelerator data, where $\nu_\mu \leftrightarrow \nu_e$ is the only possible oscillation pairing, indicate a magnitude of about 1 eV^2 for $\Delta m^2_{\mu e}$. That's orders of magnitude bigger than the mass-squared differences indicated by the solar and atmospheric neutrino oscillation data, making it impossible to satisfy the algebraic identity.

That leaves several possibilities: If one believes all the data, one almost has to invoke a fourth, sterile neutrino species taking part in either the atmospheric or solar neutrino oscillations. (Sterile neutrinos, by the way, appear in a variety of respectable theoretical schemes.) A way out might be to suggest that the data are actually describing messy three-way rather than simple pairwise oscillations. Finally, one could call the data into question. The weakest experimental link is the claimed oscillation of neutrinos within the confines of an accelerator lab. Only one group, working at the Los Alamos LAMPF accelerator, has reported such an observation (see Physics Today, August 1995, page 20). In fact, Fermilab is currently mounting an experiment called Miniboone, specifically to confirm or refute the Los Alamos result.



Up/down ratio observed in Super-Kamiokande for two special subsamples of atmospheric-neutrino scattering events: (a) a sample enriched in neutral-current events, as evidenced by Čerenkov signals suggestive of pions rather than muons, and (b) charged-current events of unusually high neutrino energy (typically 20 GeV), with muon tracks too energetic to stop in the detector. Horizontal lines and shading indicate the measured ratios and their errors. The blue (red) curves shows how the ratio predicted for $\nu_\mu \leftrightarrow \nu_\tau$ ($\nu_\mu \leftrightarrow \nu_s$) depends on Δm^2. The vertical lines indicate the best-fit value of Δm^2 from *all* the charged-current data.

The search

How did the Super-Kamiokande collaboration manage to distinguish ν_τ from a hypothetical sterile species? An unaltered ν_μ can interact with a nucleus in the detector's water in two distinct ways. First, by exchanging charge with the nucleus, the ν_μ can change into a charged muon. The emergence of the muon at the scattering site makes this so-called charged-current (CC) interaction easily visible. Alternatively, the scattering can be a "neutral-current" (NC) interaction, in which the ν_μ retains its invisible identity. NC events are much harder to identify in a water-Čerenkov detector than CC events. Lacking a muon flag, one has to rely on the emission of pions by the struck nucleus.

Almost all of the detailed evidence for atmospheric neutrino oscillation over the years has come from the anomalously anisotropic distribution of the CC events: One sees only about half as many atmospheric ν_μ's coming up through the Earth as one sees coming down from above. In the absence of neutrino oscillation, there should be almost no up/down asymmetry.

The CC oscillation data yield a Δm^2 of about 3×10^{-3} eV^2. But they are of little use for discriminating between ν_τ and sterile neutrinos. Tau neutrinos do have charged-current interactions, but the charged τ leptons they produce are too heavy and too short-lived to be reliably identified in Super-Kamiokande. NC events, on the other hand, should look exactly the same for ν_μ and ν_τ collisions.

Therefore, if the neutrino oscillation is, in fact, $\nu_\mu \leftrightarrow \nu_\tau$, the NC events should exhibit no up/down asymmetry. The probability that an atmospheric neutrino suffers an NC scattering in the detector would be unaffected by metamorphosis into ν_τ. If, on the other hand, disappearing ν_μ's are turning into ν_s's, which do not scatter at all, the NC events should exhibit the same up/down asymmetry as the CC events.

From four years of running, the Super-Kamiokande group has culled a sample of of 791 plausible NC events in which the incident neutrino direction is within about 60° of the vertical. The near equality of upward and downward events in this sample argues against the sterile-neutrino hypothesis. See the top panel of the figure, which compares the measured up/down ratio with what's predicted by the competing hypotheses. Because the predictions depend on Δm^2, one should make the comparison at $\Delta m^2 = 3 \times 10^{-3}$ eV^2.

Passing through matter

There's yet another way of distinguishing ν_τ from ν_s in Super-Kamiokande. Passage through matter would, in general, affect neutrino oscillation, modifying its amplitude and oscillation length. That is presumably what's happening to solar (electron) neutrinos as they make their way out of the Sun. But oscillation between ν_μ and ν_τ would be an exception. Passage through the Earth would have no effect on this oscillation pairing, essentially because these two neutrino varieties have identical forward elastic-scattering amplitudes in matter.

But if the ν_μ's oscillation partner were sterile, with no scattering amplitude at all, passage through matter would modify the oscillation parameters. For typical atmospheric-neutrino energies (a few GeV), this modification would be negligible. But above 15 GeV, it would significantly suppress $\nu_\mu \leftrightarrow \nu_s$ oscillation for atmospheric neutrinos traveling long distances through the Earth.

Therefore the collaboration also examined two subsets of unusually high-energy CC events to see whether they exhibited any suppression of the telltale up/down asymmetry seen in the lower-energy CC data. The figure's bottom panel shows the result for a subset of 127 vertical events with typical neutrino energies of 20 GeV. This high-energy sample turns out to be just as asymmetric as the bulk of the CC events at lower energy. That's what one expects for $\nu_\mu \leftrightarrow \nu_\tau$. The tau-neutrino hypothesis is similarly favored by another subset of events of even higher energy (around 100 GeV), where the CC interaction actually took place in the rock outside the detector and the resulting muon passed clean through the rock and the detector.

Combining the results from the three samples of events that have some ability to discriminate between the tau- and sterile-neutrino hypotheses, the group reports that these data exclude, at the 99% confidence level, a sterile neutrino with the oscillation amplitude and Δm^2 indicated by the bulk of the CC events. The tau-neutrino hypothesis, on the other hand, is quite compatible with these best-fit oscillation parameters.

If sterile neutrinos play no obvious role in the oscillation of atmospheric neutrinos, perhaps such exotics will turn up in the solar-neutrino data at the Sudbury Neutrino Observatory, which began operation last spring in a Canadian nickel mine. With all the deuterons in its core of heavy water, the SNO detector is uniquely sensitive to the neutral-current interactions of the MeV solar neutrinos (see PHYSICS TODAY, July 1996, page 30).

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