

Antineutrinos From Distant Reactors Simulate the Disappearance of Solar Neutrinos

First results from the Kamland detector in Japan home in on the parameters of solar-neutrino flavor oscillation.

After 36 years of solar neutrino experiments, the inescapable conclusion is that a large fraction of the electron neutrinos (ν_e) produced by nuclear processes in the Sun's core are metamorphosing into other neutrino varieties somewhere en route to the detectors on Earth (see *PHYSICS TODAY*, December 2002, page 16). The cause is very likely neutrino oscillation, resulting from the existence of three putative neutrino mass eigenstates with three different masses. But until recently, the data have allowed considerable latitude in the oscillation parameters, leaving open a variety of possible mechanisms as the neutrinos traverse solar and terrestrial matter as well as 150 million kilometers of vacuum.

Now, however, the first results from Kamland—a new kind of reactor-neutrino experiment—have dramatically narrowed the range of possible solar-neutrino parameters and thus made it clear that the decisive metamorphosis takes place in the Sun itself.¹ Kamland, a liquid-scintillator detector deep inside the Kamioka mine in mountains west of Tokyo, exploits electron antineutrinos ($\bar{\nu}_e$) arriving from 22 nuclear power plants within a few hundred kilometers as surrogates for neutrinos from the Sun.

The potential importance of the Kamland results goes well beyond the solar-neutrino problem. Particle theorists hope that the masses and flavor compositions of the neutrino mass eigenstates will help point the way to an encompassing unification beyond today's manifestly incomplete standard model of fundamental particles and their interactions. Detailed knowledge of the neutrino states might also elucidate a central problem of cosmology: How did matter come to dominate over antimatter in the immediate aftermath of the Big Bang? Does the mixing of neutrino states harbor the symmetry-breaking mechanism that could have done the trick?

Oscillating flavors

The three neutrino mass eigenstates are presumed to be different coherent superpositions of the three flavor eigenstates (ν_e , ν_μ , and ν_τ) associated with the three charged leptons: the electron, the muon, and the tau. There is good evidence that only two of the three mass eigenstates contribute significantly to ν_e . In that approximation, one can write

$$P(L) = 1 - A \sin^2(L/\lambda)$$

for the oscillating probability that a neutrino born as a ν_e is still a ν_e after a journey of length L through vacuum.

The characteristic vacuum oscillation length in kilometers is given by

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

where E is the neutrino's energy in

GeV and Δm^2 is the difference between the squared masses of the two relevant mass eigenstates in eV^2 . The amplitude of the probability oscillation is

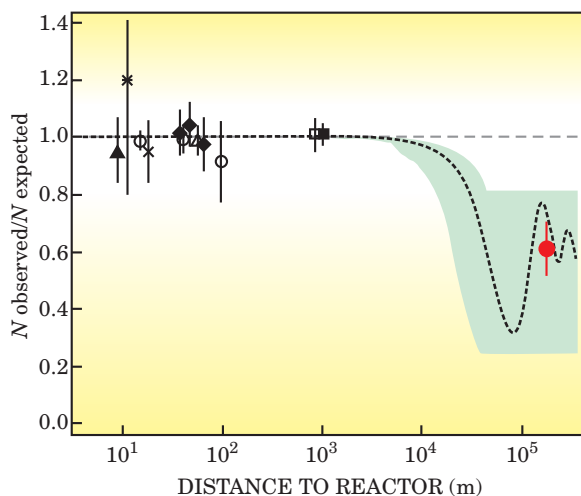
$$A = \sin^2 2\theta,$$

where the “mixing angle” θ is the angle by which the state ν_e is rotated from the lighter of the two solar-neutrino mass states in the Hilbert space spanned by the mass eigenstates.

Because there are, as yet, no data good enough to reveal the very small contribution of the third neutrino mass eigenstate to ν_e , it is customary to summarize solar-neutrino oscillation results in terms of the two parameters θ and Δm^2 . Prior to the Kamland result, the region of parameter space favored by the existing solar-neutrino data was the so-called large-mixing-angle (LMA) solution, with θ ranging from about 25° to 40° and Δm^2 near $5 \times 10^{-5} \text{ eV}^2$.

However, several alternatives to the LMA solution had also survived the experimental gauntlet with statistically respectable, albeit larger, chi-squares. Some, like the LMA solution, had large mixing angles; but they had much smaller Δm^2 , ranging from 10^{-7} eV^2 all the way down to $5 \times 10^{-12} \text{ eV}^2$. Another solution still in play last year gave a θ of only about 1° . So small a mixing angle would suit the theoretical prejudice that neutrino mixing angles ought not to be much bigger than those that describe the mixing of quark flavors among the quark-mass eigenstates. There were also several solutions that incorporated a hypothetical fourth neutrino mass eigenstate that would be “sterile” in the sense that it did not participate in the usual weak interactions.

The highest energy of neutrinos produced in the solar core is only 20 MeV. The third neutrino mass eigenstate, though it contributes little, if anything, to solar-neutrino oscillation, is important for the well-attested oscillation of GeV muon neutrinos produced in the atmosphere by cosmic rays. For atmospheric ν_μ oscillation, the relevant Δm^2 is a few times



Shortfall of reactor neutrinos measured by various experiments. The ratio of observed number of neutrinos to the number expected in the absence of oscillation is plotted against the reactor's distance from the detector. For Kamland (the red point), the plotted distance is a flux-weighted average for 22 reactor sites. The dotted line is the prediction for oscillation parameters from a representative large-mixing-angle fit to the solar-neutrino data, and the shaded area indicates the range of such LMA fits. (Adapted from ref. 1.)

10^{-3} eV^2 (see PHYSICS TODAY, August 1998, page 17).

Twenty-two surrogate Suns

The principal goal of the Kamland experiment is to test and refine the LMA solar-neutrino solution with controlled terrestrial antineutrino sources free of astrophysical complications. The heart of the detector is a kiloton of liquid scintillator in a transparent spherical vessel monitored by a surrounding array of almost 2000 large photomultiplier tubes. It sits, shielded from cosmic-ray muons by a kilometer of rock overhead, in the same cavern of the Kamioka mine that previously housed the first-generation Kamiokande water-Cherenkov solar-neutrino detector. The Japan-US Kamland collaboration, headed by Atsuto Suzuki of Tohoku University in Sendai, began building the detector in 1998.

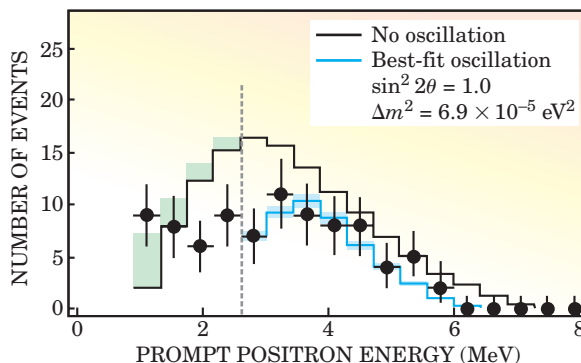
The beta decay of fission fragments in a power reactor produces a continuous, penetrating flux of electron antineutrinos. The 22 reactor sites in Japan and Korea that contribute significant $\bar{\nu}_e$ flux at the Kamland detector range in distance from 80 to 900 km, with the strongest concentration between 160 and 180 km. If the neutrino oscillation parameters do indeed lie within the LMA region, a significant fraction of the reactor antineutrinos will change flavor along the way and become invisible to the detector. Kamland detects arriving neutrinos when they instigate inverse beta decay,



in the liquid scintillator. And that reaction can only be accomplished by electron antineutrinos.

The energy distribution of the neutrinos recorded by Kamland peaks at about 4 MeV. For a neutrino of that energy, the LMA solution gives an oscillation length λ of about 100 km. That's why the Kamland complex is so well suited to probe the LMA region of the parameter space. All of the alternative solutions to the solar-neutrino data have much smaller Δm^2 and thus correspondingly longer λ . Therefore, only the LMA solution predicts that Kamland will record a significant shortfall of reactor neutrinos. And previous reactor-neutrino detectors, none of which was farther than a kilometer from its source reactor, could only have seen a shortfall if Δm^2 were much larger than 10^{-4} eV^2 .

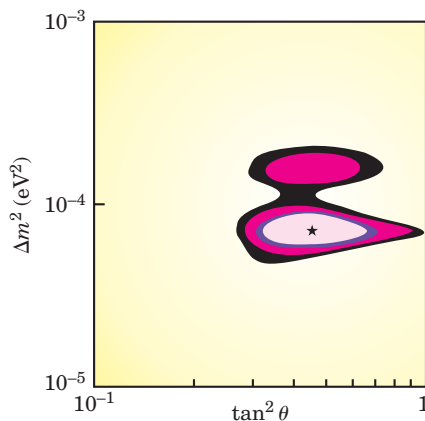
"When Kamland was first pro-



Energy distribution of neutrinos recorded by Kamland. The prompt positron scintillation energy approximates the incident neutrino energy minus 0.8 MeV. The black histogram shows what's expected in the absence of flavor oscillation. The shaded blue histogram is the prediction for the best oscillation-parameter fit to the Kamland data alone. The events with energies below the cut at 2.6 MeV are excluded because of the high probability of simulation (green shading) by radioactive backgrounds. (Adapted from ref. 1.)

posed," recalls Stuart Freedman (University of California, Berkeley), a spokesman for the collaboration's US contingent, "we had a hard time selling it to the community, because most of them were betting on the small-mixing-angle solution, to which Kamland wouldn't be sensitive."

In the first five months of data taking, the Kamland group found a total of 53 $\bar{\nu}_e$ events above an estimated background of only one event. That's only 61% of the 87 events one would expect in the absence of neutrino oscillation. But it's in good agreement with what the LMA solution predicts.



Global neutrino-oscillation fit to the Kamland data and all the solar-neutrino data confines θ and Δm^2 , the mixing angle and mass-squared splitting, to a quite restricted region of the parameter space. The star marks the best-fit parameters, and the surrounding contours indicate confidence levels of 90%, 95%, 99%, and 99.73%. (Adapted from ref. 2.)

The figure on page 14 shows the Kamland shortfall, together with the null results from the earlier reactor-neutrino detectors.

The estimated background of only about one event in the final sample of 54 is impressively low by the standards of neutrino detectors in underground settings rife with radioactive contaminants. It points up a considerable advantage of looking for reactor antineutrinos rather than solar neutrinos. Each inverse beta-decay reaction produces not just one, but a correlated pair of signals that makes it much easier to spot spurious events. First, the slowing and annihilation of the positron produces a "prompt" scintillation signal whose intensity provides a measure of the incident neutrino's energy.

Then, typically a few hundred microseconds later, the neutron can be captured by a proton to create a deuteron and a telltale 2.2 MeV photon.

Energy spectrum

One learns about the oscillation parameters not simply from the overall fraction of neutrinos that have become invisible to the detector, but also from the energy dependence of the shortfall. The figure above shows the distribution of prompt positron-annihilation energies for the 54 events in the final sample. To good approximation, the prompt energy measured by the phototubes is the incident neutrino's energy minus a kinematic correction of 0.8 MeV.

The Kamland group's best-fit oscillation parameters from the observed shortfall and energy distribution are $\theta = 45^\circ$ and $\Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2$. The 32 events in the plot with prompt energies below 2.6 MeV were excluded from the analysis because, below this cutoff, antineutrinos from radioactive uranium and thorium in Earth's crust contribute significantly to the tally of inverse-beta-decay events. At the 95% confidence level, the Kamland data already exclude all the previously surviving alternatives to the LMA solution.

The posting of the first Kamland results on the Web triggered a torrent of analyses by the theorists. (One wag commented that the appearance of five of those papers hours before the Kamland paper constituted evidence of causality violation.) The first order of business was to extract the oscillation parameters from a global fit to all the existing solar-neutrino data together

with the Kamland results. A typical fit of this kind, carried out by John Bahcall (Institute for Advanced Study) and coworkers,² is shown in the lower figure on page 15. “The Kamland results decisively shrink the allowed range of the solar-neutrino parameters,” says Bahcall. “And they limit a possible sterile component to less than 9%.”

The Kamland result is also good evidence that antineutrinos and neutrinos share the same oscillation parameters, as required by fundamental theory. But the theory does allow the neutrino mixing matrix to include a complex phase that might engender a subtle neutrino–antineutrino asymmetry (leptonic *CP* violation) strong enough to explain the upsetting of the matter–antimatter balance in the early cosmos. (See the article by Helen Quinn in *PHYSICS TODAY*, February 2003, page 30.) The triumph of the LMA solution raises the prospect that future long-baseline neutrino experiments may find evidence for leptonic *CP* violation.

The MSW effect

For neutrinos coming from the solar core, the LMA solution implies that vacuum oscillation on the journey to Earth plays second fiddle to an irreversible

flavor change that takes place in high-density regions of the Sun: the Mikheyev-Smirnov-Wolfenstein (MSW) effect. If vacuum oscillation with a λ very much shorter than our distance from the Sun were the dominant process, the energy dependence of the solar-neutrino shortfall would be almost completely washed out. But that’s not the case; the solar-neutrino detectors do see a clear energy dependence.

Because of its association with the electron, a ν_e passing through matter feels an extra interaction energy, proportional to the ambient electron density, beyond the matter-interaction energy common to all the neutrino flavors. In 1986, Stanislav Mikheyev and Alexei Smirnov at the Institute for Nuclear Research in Moscow, using a formalism developed by Lincoln Wolfenstein (Carnegie Mellon University), pointed out that this extra energy term should produce a flavor metamorphosis when a ν_e produced in the core passes through a critical-electron-density region of the Sun. The critical density, and thus the distance from the core at which it’s encountered, depends on the neutrino’s energy. When the neutrino finally emerges from the Sun it is, to good approximation, in a coherent superposition of flavor states

that constitutes a mass eigenstate. A pure mass eigenstate would experience no vacuum oscillation on the rest of the journey to Earth. There is now good evidence that this mass eigenstate, the heavier of the two whose splitting is given by Δm^2 , is roughly an equal superposition of all three neutrino flavors. The MSW mechanism was originally invoked to explain how a *small* mixing angle might cause a large solar-neutrino shortfall.

“I’m sometimes asked whether our first Kamland result is a discovery or just a confirmation of what we already believed,” says Giorgio Gratta (Stanford University), the US contingent’s other spokesman. “I like to compare it to the first creation of spectral lines in the laboratory in the 19th century. Fraunhofer had already found lines in the solar spectrum. But until they were also made on Earth, one couldn’t be sure that they were more than just something that happened only in stars.” **Bertram Schwarzschild**

References

1. K. Eguchi et al. (Kamland collaboration), *Phys. Rev. Lett.* **90**, 021802 (2003).
2. J. Bahcall, M. Gonzalez-Garcia, C. Peña-Garay, *J. High Energy Phys.* **02**, 009 (2003).

X-ray Observations Deepen Mystery of What Happens in the Cores of Galaxy Clusters

Simple physics says huge amounts of gas in cluster cores should cool and collapse. Simple physics is wrong—but why?

A cluster of galaxies looks different at optical and x-ray wavelengths. In the optical band, you see the galaxies themselves—typically about a hundred—in orbit about the cluster’s center of mass. In x rays, you can still see the biggest galaxies, but the smaller ones are lost against a bright background of diffuse plasma that fills intracluster space.

The plasma is a byproduct of cluster formation. In the early universe, vast volumes of dark matter and baryons collapsed under their own gravity to form infant clusters. Following the collapse, most of the baryonic matter ended up as shock-heated plasma. The rest, about a fifth, formed galaxies. Unreactive even with itself, the dark matter presumably lay idle, but it has always dominated the clusters’ gravitational potential. And the gravitational potential, through virialization, is what has heated the plasma in clusters to temperatures of 10^7 K and higher.

The plasma radiates in the x-ray band through a combination of thermal bremsstrahlung and collisionally excited line emission. Both processes depend strongly on density, which, thanks to gravity, is highest in the cluster cores. In 1977–78, three pairs of astronomers independently realized that the plasma in some cluster cores loses so much energy through radiation that it should cool rapidly.¹ Unable to match the pressure of the outer layers, the cooling plasma would slump inward. The phenomenon became known as a cooling flow.

Flow motion

Not all clusters have strongly peaked x-ray emission and, by inference, cooling flows. But analysis of x-ray images in the 1970s and later suggested that, in some clusters, hundreds of solar masses of plasma cool every year. What happened to the cooling plasma? Stars form in cold clouds of gas, so astronomers looked in the cen-

tral regions of clusters for pools of cold material and enhanced star formation. They found some, but not enough by an order of magnitude, to match the cooling plasma’s inferred mass.

Meanwhile, astronomers tried to catch intracluster plasma in the act of cooling by measuring its x-ray spectrum. As in the rest of the universe, hydrogen and helium make up all but a few percent of intracluster plasma, but other elements are present, too. Among the admixtures, iron is an especially good thermometer. Its series of L lines ranges in wavelength from the lithium-like Fe XXIV at 10.6 Å to the neon-like Fe XVII at 16.8 Å. If intracluster plasma were cooling, its spectrum would bristle with emission lines, each indicating a particular temperature range.

Unfortunately, the L lines are closely spaced. The spectrometers aboard such missions as ROSAT (1990–99) and ASCA (1993–2001) couldn’t exploit the lines’ diagnostic power, nor, through other temperature diagnostics, could they find the cooling plasma.

NASA’s Chandra mission, which