

Now you see them, now you don't

David Wark

Evidence has been growing that the fundamental particles known as neutrinos oscillate — one type of neutrino can transform into another type. A well-placed experiment now points to the definitive answer.

Popular descriptions of the history of science are littered with stories of a much-loved theory swept aside by a single key experiment and replaced by a new, very different theory. In reality, it usually doesn't happen like that. Proponents of the existing theory will simply claim that any single experiment is wrong, or try to argue around it. Thus, acceptance relies on effects being seen in a number of experiments that address different aspects of the new and old models. This has certainly been true in neutrino physics, where the case for a radical overhaul of theory has been building for thirty years. Stunning new results from the Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND), announced at a conference last month and now formally published¹, have cut through a thicket of proposed new models, and show that the simplest and most elegant is nature's choice.

The existence of neutrinos was first proposed in 1930, to explain an anomaly seen in experiments on the radioactive β -decay of atomic nuclei. Neutrinos — fundamental particles similar to electrons, but much lighter and with no electric charge — interact only weakly with normal matter and can penetrate a star with negligible attenuation. This led Ray Davis and colleagues to seek the first direct experimental evidence for thermonuclear reactions inside the Sun, by looking for the neutrinos that these reactions produce. When their experiment in the Homestake Mine, South Dakota, measured fewer neutrinos than expected², explanations ranging from experimental error to flaws in solar modelling were proposed.

The most elegant suggestion came from Samoil Bilenky and Bruno Pontecorvo³. In the standard model of particle physics, there are three types (or 'flavours') of neutrino — called electron, muon and tau neutrinos — all with zero mass. Bilenky and Pontecorvo pointed out that if neutrinos did have mass, quantum mechanics would allow the electron neutrinos emitted in the core of the Sun to change into one of the other types of neutrino, and thereby evade detection by the Davis experiment (which was sensitive only to electron neutrinos). They called this phenomenon neutrino oscillations.

At first, this explanation was considered rather speculative, but subsequent solar-neutrino experiments ruled out experimental error or flaws in solar modelling.

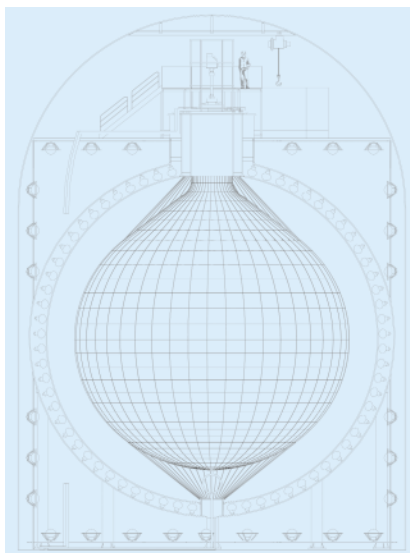


Figure 1 The KamLAND detector, in the Kamioka Mine, Japan. The transparent central balloon holds about 1 kilotonne of scintillating liquid. When an anti-neutrino interacts with protons in the liquid, the light emitted is picked up by the surrounding array of nearly 2,000 photomultiplier tubes, mounted in an 18-m-diameter sphere. The outer, water-filled volume, with more than 200 photomultiplier tubes, acts as a 'veto' for other particles entering the detector from the surrounding rock, especially muons.

Neutrino oscillations gained theoretical credibility when Stanislav Mikheyev and Alexei Smirnov⁴, building on the earlier work of Lincoln Wolfenstein⁵, showed that interactions with matter in the Sun could greatly enhance neutrino oscillations. Further support came from the Japanese Super-Kamiokande experiment, designed to pick up 'atmospheric' neutrinos coming from cosmic-ray interactions in the Earth's atmosphere⁶. The variations in the number of atmospheric neutrinos seen could not be explained within the standard model, but matched exactly the predictions for neutrino oscillations.

In 2001, Bilenky and Pontecorvo's explanation seemed to have been beautifully confirmed by results⁷ from the Sudbury Neutrino Observatory in Canada. In a single experiment, the number, or flux, of all flavours of neutrinos from the Sun was measured, and a separate measurement of

the electron-neutrino flux was also recorded. The total flux did indeed correspond to the number predicted by solar models, but the electron-neutrino flux was only about a third of the predicted value, showing that most of the electron neutrinos had oscillated into other flavours before reaching the Earth.

Or had they? The Super-Kamiokande results clearly established that electron neutrinos disappear, and the Sudbury results implied that they change flavour, but the exact mechanism was still open to question. Never underestimate the creativity of theorists — dozens of other models were proposed to describe the data, with mechanisms ranging from new properties of neutrinos, to the effects of higher dimensions, to violations of the basic assumptions of special relativity⁸. What was needed was an observation of oscillations using neutrinos from a known, well-calibrated source that would really test the key predictions of the model.

KamLAND⁹, an ingenious experiment in Japan, has taken advantage of some good luck to do just that. Like Super-Kamiokande, the experiment is built in an underground cavity in the Kamioka Mine (all these experiments must be located deep underground to screen out other high-energy particles from cosmic rays). KamLAND consists of a spherical volume of liquid scintillator, which emits light when hit by energetic charged particles, surrounded by a buffer liquid and water, which act as a shield against particles produced in radioactive decays in the surrounding rock (Fig. 1). The scintillator is watched by almost 2,000 photomultiplier tubes — light detectors so sensitive that they can detect a single photon.

KamLAND detects not electron neutrinos, but their anti-matter counterpart, electron anti-neutrinos. The anti-neutrinos interact with protons in the material of the detector to produce a neutron and an anti-electron, or positron. The positron immediately generates a tiny flash of light, but the neutron wanders around losing energy until it is captured in the detector material, producing a slightly delayed flash of light. These flashes are detected by the photomultiplier tubes, the second flash signalling that the first flash really was from an anti-neutrino interaction and not from some other, spurious interaction. The amount of light detected gives a measure of the anti-neutrino's energy and, using the timing of signals at

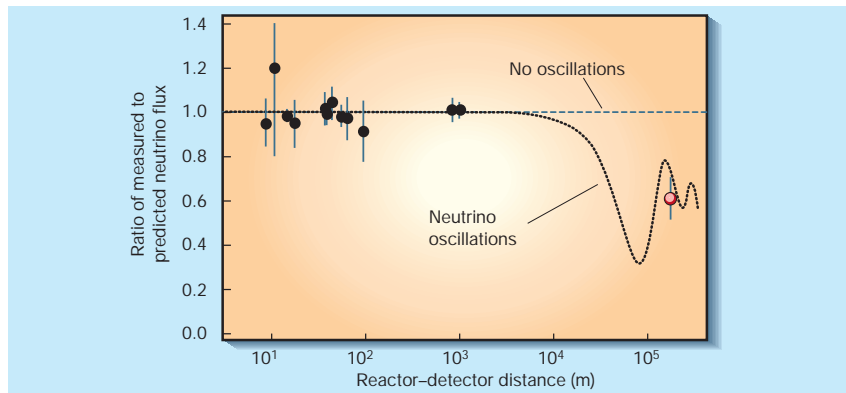


Figure 2 The right place at the right time. Earlier measurements (black points) of the ratio of measured to predicted flux of anti-neutrinos emitted from nuclear reactors have seen no trace of neutrino oscillations — the ratio is always one. But the first data from the KamLAND detector¹, ideally placed at the centre of a circle of reactors, give a lower ratio (red point), exactly as expected if the three types of neutrino can oscillate from one type to another.

the relative positions of the photomultiplier tubes, the location of the anti-neutrino interaction inside the detector can be reconstructed (which is another good way to discriminate against radioactive background signals from the edge of the detector).

None of this is luck — it is good experimental design. The luck is in the source of the anti-neutrinos: nuclear reactors, which are a prodigious source of electron anti-neutrinos and which have been exploited by several experiments around the world. Japan generates a large part of its electricity from nuclear power, and it so happens that KamLAND is surrounded by a number of powerful reactors, all at about the same distance — a lucky accident that means that the effects of oscillations (which vary with the distance the anti-neutrinos travel) will add up rather than average out between the different reactors. By a second lucky accident, this distance turns out to be sufficiently large that oscillations, at the level implied by the solar-neutrino results, should produce a noticeable reduction in the number of electron anti-neutrinos seen in KamLAND.

The KamLAND collaboration of US, Japanese and Chinese physicists has now announced the results from its first 145 days of data-taking¹. They have measured the flux of electron anti-neutrinos and compared it with the predicted value (which is known quite precisely from the power produced by the reactors) — the ratio is 0.61, significantly less than 1 (Fig. 2). What is exciting for neutrino physicists is that this level of suppression is exactly what was predicted, based on the results of solar neutrino experiments. It is, however, not the same level of suppression seen in the solar experiments, where the equivalent ratio for electron-neutrino flux is only 0.35. That is because the Earth, through which KamLAND's anti-neutrinos travel, is much less dense than the Sun and so causes less enhancement of the oscillations. But the two different levels of suppression corre-

spond to the same underlying physics — a coincidence that is true for neutrino oscillations, but not for any of the other mechanisms that theorists have speculated might be the cause of the observed atmospheric and solar neutrino deficits. KamLAND has therefore provided vital confirmation of the real reason for the neutrino disappearance and flavour change seen by the other experiments.

So what next? These results from KamLAND are based on a small sample of data. More data should reveal whether the energy spectrum of the anti-neutrinos is distorted, which is another clear signature of oscilla-

tions and would enable the properties of neutrinos to be determined more precisely. Meanwhile, other experiments are planned or are being built around the world to explore the phenomenon of neutrino oscillations in much greater detail. Hopefully, these efforts will culminate in the building of a 'neutrino factory', which would fire intense neutrino beams at detectors thousands of kilometres away. Such an experiment could show whether the laws that govern neutrino behaviour are different if time moves backwards instead of forwards — an effect that is being sought in all the fundamental laws of physics to explain why there is more matter than anti-matter in the Universe. Thus, the solution to one mystery brings the opportunity to search for the solution to another, and neutrino physics looks set to remain exciting for years to come. ■

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DNA repair

Damage alert

Jiri Bartek and Jiri Lukas

Radiation and other harmful influences frequently damage our genes, potentially causing diseases such as cancer. New work reveals a surprising mechanism that notifies the cellular defence system about DNA damage.

Our genetic blueprint is constantly assaulted by adverse environmental and cellular influences, such as ultraviolet or ionizing radiation and various chemicals¹. Fortunately, these massive attacks on our DNA are largely counterbalanced by promptly deployed, multifaceted surveillance and rescue operations. Among the many types of damage that arise in DNA, the most deadly are double-strand DNA breaks (DSBs), where both phosphate backbones of the double helix are severed. If left unrepaired, such damage can result in chromosomal defects and lead to inborn diseases or cancer¹. On page 499 of this issue, Bakkenist and Kastan² provide eagerly awaited insight into how the vital response to DSBs is initiated in human cells.

Researchers have known for years that the cellular response to DSBs requires the protein kinase ATM — the product of the *ATM* gene,

which is mutated in the human disease ataxia-telangiectasia^{3,4}. People with this disease suffer immune deficiency, partial brain degeneration, sterility, sensitivity to radiation and a higher risk of cancer, and their cells fail to respond to DSBs. In contrast, normal cells that are victim to radiation-induced DSBs can activate ATM, which then adds phosphate groups to (phosphorylates) several target proteins. These proteins are in turn linked into a signalling network that slows the cells' progression through the cell-division cycle, and stimulates DNA repair. If the DNA damage is irreparable, the network eliminates affected cells by a suicide programme^{3–7}.

But what tells ATM when to start phosphorylating its protein targets? How do the 'dormant' and activated forms of ATM differ? And how does this mechanism ensure that proteins throughout the cell nucleus