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The researchers looked at a range of cuprates—from undoped to overdoped—over a range of scattering angles to access excitations of different energies. In every superconducting sample they tried, they found a paramagnon spectrum similar in intensity to the magnon spectrum of the undoped cuprates. Figure 2 shows the spectra for the two extremes in the range of compounds studied.

In fact, says Keimer, "The magnetic excitations were much more intense than we had expected." The biggest challenge, he explains, was in accessing sufficiently low-energy excitations in order to get some overlap with the neutron-scattering experiments, to demonstrate that both techniques were detecting the same excitations. With a clever choice of scattering geometry to minimize the elastic-scattering background, they managed to obtain a few points of overlap.

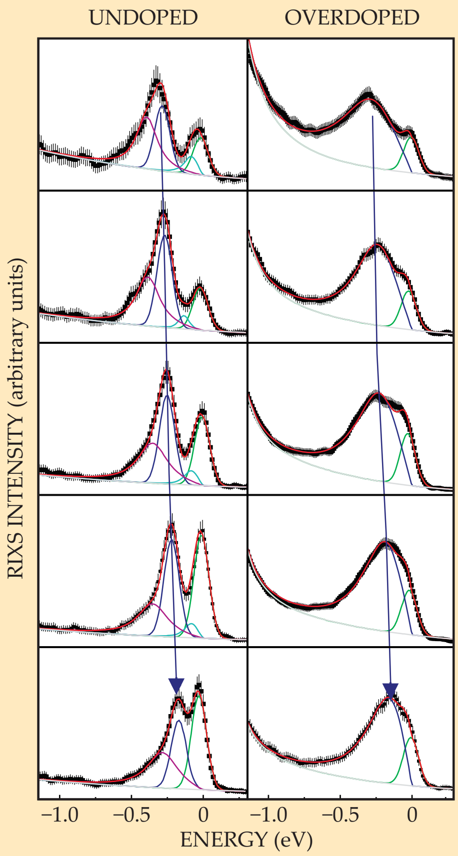

Figure 2. Resonant inelastic x-ray scattering (RIXS) reveals magnetic excitations, or spin waves, in undoped and overdoped cuprates. X-ray photons scattered off the surface of the solid sample excite the quantized waves, which are measured via the photons' loss of energy and change in momentum. Five panels from top to bottom show the spectra for different scattering angles, which access excitations of different energies. The peak of interest, shown in dark blue, indicates a single magnetic excitation. It appears at the same energies, as shown by the blue arrow, in both the undoped and overdoped samples, and in all the other samples studied. (Adapted from ref. 1.)

Critical temperatures

Keimer and colleagues' results show that paramagnons exist across the entire range of cuprates, and with sufficient intensity to mediate superconductivity. That addresses the main source of doubt about paramagnons as the cuprates' pairing glue. But there's still much that remains unclear. A full understanding of cuprate superconductivity will require, among other things, a theory to connect the observed paramagnon spectra to the observed critical temperatures.

The best existing theoretical methods applicable to magnetically mediated superconductivity are still very crude. Keimer and colleagues applied one method—called Eliashberg strong-coupling theory, which is also applicable to conventional superconductors—to their overdoped cuprate and found that it reproduced the critical temperature to within a factor of 2. That's a similar level of accuracy to what Eliashberg theory can achieve for conventional superconductors.

As for further experimental proof that paramagnons not only exist but also mediate cuprate superconductivity, Keimer explains, "The materials chemistry of the cuprates and the physics of strongly correlated electrons are very complex. It would be naive to expect a single smoking-gun experiment. However, the evidence has been accumulating steadily over the past two decades."

Johanna Miller

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Neutrinos from Earth's interior measure the planet's radiogenic heating

Built primarily for fundamental neutrino physics, the KamLAND detector deep inside a Japanese mineshaft proves its usefulness for geology.

Neutrinos interact only very weakly with matter. That makes them hard to detect, but it also makes them worth the trouble even for purposes far removed from fundamental neutrino physics. Neutrinos can travel straight to astrophysical observers from remote sources otherwise veiled by obscuring material or magnetic fields. And since the 1960s, it's been argued that they could do as much for geophysics.

Earth's crust and mantle abound with unstable isotopes of thorium, uranium, potassium, and lesser contributors to the planet's radioactivity. In principle, one could detect the "geoneutrino" flux from their decay chains and thus learn much about Earth's composition and its heat sources. But it was not until 2005 that the KamLAND collaboration reported the first detection of geoneutrinos.[1] Now, with five times as much data in hand, the international collaboration has reported its first substantive geophysics result.[2]

The principal finding is that present-day radioactivity accounts for about half of the total heat flux from Earth's interior. That's no great surprise to geologists. But it does supply the first explicit measurement of the radiogenic heat flux—albeit still with large error bars—for comparison with the broad

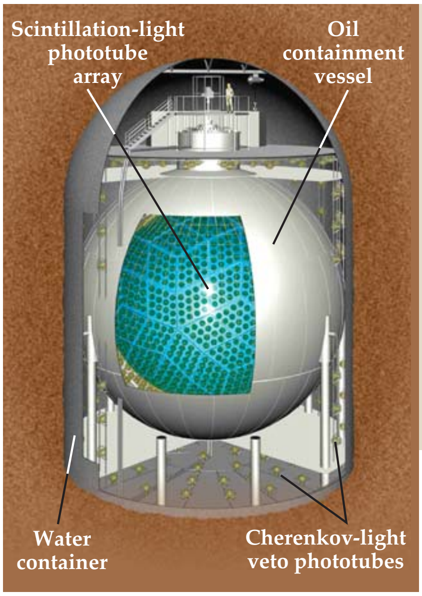

Figure 1. The underground KamLAND antineutrino detector in Kamioka, Japan, detects an energetic electron antineutrino ($\bar{\nu}_e$) from a reactor or from a radioactive decay in Earth's interior by the scintillation light produced when the $\bar{\nu}_e$ interacts with a hydrogen nucleus in the detector's kiloton of scintillator oil. An array of phototubes inside the 18-m-diameter oil-containment vessel records scintillation pulses. To veto scintillation pulses from incident charged particles that mimic $\bar{\nu}_e$ interactions, the containment vessel is immersed in water monitored by phototubes that detect an interloper's Cherenkov radiation.

range of detailed models of Earth's formation and the energy sources of plate tectonics and the geodynamo.

The detector

KamLAND, the Kamioka liquid-scintillator antineutrino detector, shown in figure 1, was completed in 2001, a kilometer underground in the disused Kamioka zinc mine in the mountains west of Tokyo. Its kiloton of liquid scintillator, monitored by thousands of photomultiplier tubes, reveals the interactions in the detector of electron antineutrinos ($\bar{\nu}_e$s) from the beta-decay chains of ^{238}U and ^{232}Th in Earth's crust and mantle—and from dozens of power reactors in and around Japan.

KamLAND's ability to detect geoneutrinos is a byproduct of the facility's primary particle-physics purpose: monitoring the flavor-oscillation disappearance of $\bar{\nu}_e$s that emanate from reactors. In fact, KamLAND's purposeful placement in the midst of so many reactors creates a troublesome background for geoneutrino searches.

When an incident $\bar{\nu}_e$ of sufficient energy interacts with a hydrogen nucleus in the scintillator fluid, the resulting inverse-beta-decay reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

manifests itself by a robust, double-barreled signal: A prompt scintillation signal comes from the positron's brief travel and annihilation in the liquid. It provides a good approximation of the incident $\bar{\nu}_e$'s energy. Then after about 200 μs, a delayed monoenergetic scintillation pulse signals the 2.2-MeV gamma created when the neutron is finally captured by another proton to form a deuteron. Unfortunately, there's no information about the direction from which the $\bar{\nu}_e$ came.

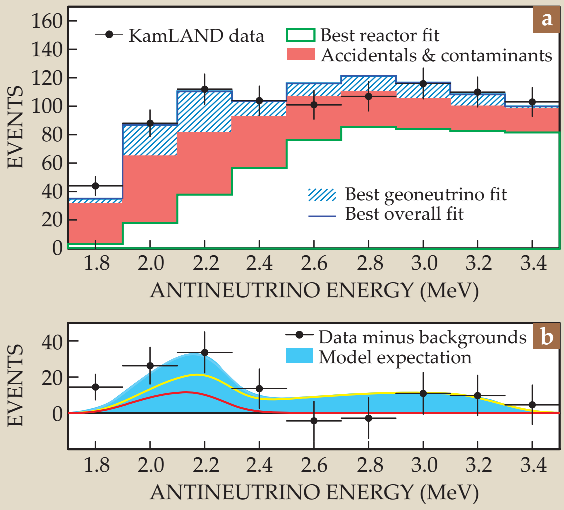

Figure 2. Geoneutrino spectrum. **(a)** The best fit to the spectrum of all 841 geoneutrino candidate events recorded by KamLAND estimates the contributions from true geoneutrinos and from backgrounds due to radioactive contaminants in the detector, accidental scintillator coincidences, and $\bar{\nu}_e$s from reactors in and near Japan. **(b)** With the estimated backgrounds subtracted, the residual measured spectrum is compared with the geoneutrino flux prediction of a reference model.[3] The uranium-238 and thorium-232 decay-chain spectra that together make up the prediction are shown, respectively, as yellow and red curves. (Adapted from ref. 2.)

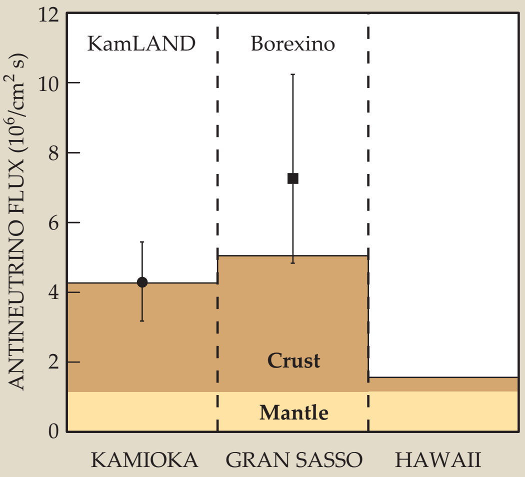

Figure 3. Contributions of Earth's crust and mantle to the geoneutrino fluxes at KamLAND (in Kamioka, Japan) and Borexino (in Gran Sasso, Italy). The contributions are estimated from the best fit of a global model to the fluxes measured by the two detectors. The model prediction is also shown for Hawaii, a typical oceanic-crust site. (Adapted from ref. 2.)

The threshold $\bar{\nu}_e$ energy for the inverse-beta-decay reaction is 1.8 MeV. That renders the detector blind to lower-energy $\bar{\nu}_e$s from the ^{238}U and ^{232}Th decay chains, and to the entire decay spectrum of ^{40}K, the third most important geoneutrino source. At the high-energy end, the geoneutrino spectrum extends up to 3.3 MeV and the reactor spectrum continues out to 8 MeV. Separating the two spectra in their overlap region can't be done event by event. It requires maximum-likelihood fits of a model with free instrumental and geological parameters that incorporate detailed information about the crustal geology around Kamioka and the day-to-day operations of all the relevant reactors.

Only a few events per week pass the double-scintillation-pulse test and survive all other selection cuts—and the majority of those come from the reactors. The recorded time of each event is important because the likelihood function constrains the geoneutrino flux to be constant (within statistical fluctuations), wheras the reactor flux varies with power-station schedules and shutdowns. Ironically, reactor shutdowns due to earthquake damage help the geoneutrino search in two ways: They lower backgrounds, and they provide time tags that help distinguish signal from background.

Figure 2a shows the spectrum of the 841 inverse-beta-decay candidate events accumulated by KamLAND from 2002 through 2009 in the energy range relevant to geoneutrinos. The best fit, shown in the figure, attributes 106 ± 29 of them to geoneutrinos, and the rest to reactor $\bar{\nu}_e$s, radioactive contaminants in the detector, and accidental scintillation coincidences. With those estimated backgrounds subtracted from the data, figure 2b compares what remains with the sum of the ^{238}U and ^{232}Th decay-chain geoneutrino fluxes expected from the team's reference model. (The contributions of all other radioisotopes to KamLAND's geoneutrino signal are thought to be negligible.)

Bulk-silicate Earth

The reference model belongs to the widely accepted class of so-called bulk-silicate-Earth models. BSE scenarios for Earth's formation assume that primordial Earth was a rather homogeneous rocky accumulation of silicates, with the relative abundances of metallic and rare-earth elements close to those of the most primitive meteorites.

About 50 million years later, the scenarios posit, radioactive heating accumulating on top of the planet's residual heat of formation initiated the "iron catastrophe" that created the core when temperatures became hot enough to melt iron. Percolating down through the silicate rock, the liquid iron carried with it most of the siderophilic (iron-loving) elements like nickel and gold, leaving behind lithophilic (rock-loving) elements like U and Th. Thus BSE models assume that very little radioactivity now emanates from Earth's core.

KamLAND's reference model is based on a particularly comprehensive and widely cited 1995 BSE model,[3] augmented by detailed upper-crustal data, especially from the Kamioka region. The model also takes account of the significant fraction of geophysical and reactor neutrinos rendered invisible to KamLAND by flavor oscillation en route.

To find the best geoneutrino fit, shown in figure 2a, the team treated the overall terrestrial abundances of ^{238}U and ^{232}Th as independent, free parameters. But the best-fit parameters turned out to be in good agreement with those of the reference model. The expected geoneutrino spectrum, shown in figure 2b, is calculated directly from the reference model without free geological parameters.

Radiogenic heating

From thermal gradients measured in thousands of deep boreholes all over the globe, geologists conclude that the total heat flux from Earth's interior is about 44 terawatts. Some of that flux is surely of "primordial" origin. As the word is used by geologists, it refers to what's left of the heat from the dissipation of gravitational energy in the formation of the planet and the later infall of its core, and from ancient radioactivity. The remainder, attributable to current radioactive heating, is what the KamLANDers were seeking to determine.

With geoneutrino data from only a single detector site, that's a poorly constrained inverse problem. So the team availed itself of data from Borexino,[4] the only other detector already in the geoneutrino business. Borexino is significantly smaller than KamLAND. But, sitting in a tunnel under Gran Sasso d'Italia, the highest mountain in the Apennines, it provides an excellent complement to KamLAND's site, which straddles the margin of continental and Pacific ocean crust. The floor of the Mediterranean around Italy, by contrast, is thoroughly continental. Furthermore, Borexino, which was originally built to study solar neutrinos, doesn't have to contend with dozens of nearby reactors.

About 40 km thick, Earth's continental crust, formed over eons by repeated vertical migration and remelting, is thought to have 100 times the U and Th concentrations of the 3000-km-deep mantle on which it floats. The U and Th concentrations of the thinner ocean-floor crust are only about 10 times those of the mantle, from which it is continually refreshed.

To estimate the worldwide contribution of the ^{238}U and ^{232}Th decay chains to Earth's heat flux, the KamLAND team fitted its data and Borexino's with a global model incorporating detailed crustal geology near both detectors. Some geological parameters were left free, but the overall ratio of Th to U atoms was held fixed at 3.9, a global number that geologists take to be well determined from meteorite compositions.

For simplicity, the model assumes that Th and U are uniformly distributed throughout the mantle and that their presence in the core is negligible. There are speculations, however, that a local uranium concentration somewhere in the solid inner core might be functioning as a natural fission reactor.[5] The new data put an upper limit of 3 TW on the power of such a putative reactor. Whether the turbulent geodynamo action of the liquid outer core requires ongoing local radioactive heating remains an open question.

Figure 3 compares the total geoneutrino fluxes measured at KamLAND and Borexino with the fitted model's expectations, given separately for the crust and mantle at the two detectors and also at Hawaii, a possible mid-ocean setting for a future detector.

The KamLAND–Borexino fit yields a global ^{238}U plus ^{232}Th heat flux of 20.0 ± 8.7 TW. About 13 TW of that total is attributed to the mantle. "Radioactive heating of the mantle is of particular interest," says KamLAND spokesman Kunio Inoue (Tohoku University, Sendai, Japan), "because it's thought to contribute significantly to mantle convection, which drives plate tectonics and thus earthquakes."

Adding the roughly 4 TW of heating estimated for the ^{40}K decays neither detector can see, one gets a radiogenic contribution of about 24 TW to Earth's total 44 TW heat flux. The data exclude, with a confidence level of 97%, the notion that Earth's primordial heat is already exhausted.

In 1897, knowing that Earth's interior was still giving up heat but not yet aware of radioactivity, Lord Kelvin proclaimed that the planet couldn't be older than 40 million years, much to the annoyance of geologists and Darwinians. If Earth were any older, he argued from a naive conduction model, its heat of formation would already have radiated away.

Even before the geoneutrino results, the notion that the primordial heat of the 4.6-billion-year-old planet might already be exhausted had few adherents. But serious conjectures about the radiogenic fraction of Earth's heat flux range from 30% to 70%. So, more geoneutrino detectors at geologically varied sites are clearly important for probing Earth's interior with increasing precision. Directional sensitivity and lower detection thresholds would also help.

Bertram Schwarzschild

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Precision spectroscopy reveals a highly forbidden electronic transition in helium

Researchers combine optical trapping and frequency comb technology to control and measure the interaction of light with degenerate quantum gases.

Willis Lamb's 1947 measurement of the tiny energy splitting between the 2*S* and 2*P* states of atomic hydrogen largely spawned the development of quantum electrodynamics (QED). Ever since, precision spectroscopy of simple atomic systems has been used to test the theory and refine our understanding of it. In the latest contribution to that effort,[1] researchers led by Wim Vassen (Vrije University Amsterdam) have resolved—to a precision of 1.5 kHz, or 8 parts in 10^{12}—an exceedingly weak IR transition between the triplet and singlet metastable states of atomic helium, $2\,^3S_1$ and $2\,^1S_0$. So highly forbidden is the excitation, which violates both spin and parity selection rules, that it has never before been seen, much less measured to high precision.

Individually, the states are energy levels of different species of helium—orthohelium, in which electron spins are parallel, and parahelium, in which they're antiparallel. The distinct emission spectra of the two spin arrangements were noticed in the late 19th century but not understood until Werner Heisenberg explained them in 1926.

A photon's electric field does not interact directly with the electron spin. Nor can it connect two states of the same parity. Yet for the doubly forbidden excitation to occur, one of the orthohelium spins must flip to form parahelium. Were it not for the photon's magnetic field, which couples to an electron's magnetic moment, such flips