Sterile neutrinos give IceCube and other experiments the cold shoulder

Recent null results heighten the tension between the bulk of neutrino experiments and the few that hint at the putative particle's existence.

FIGURE 1. THE ICECUBE LABORATORY sits under the serene glow of the aurora australis at the South Pole. Kilometers below the Antarctic ice, 5160 photodetectors watch for Cherenkov light from charged particles that are produced when atmospheric neutrinos collide with nuclei in the bedrock or ice. (Photo by Ian Rees, IceCube/NSF.)

Under kilometers of ice at the South Pole, the IceCube Neutrino Observatory's 5160 optical detectors keep watch for neutrinos that have traveled through Earth from the opposite side of the globe. (See the article by Francis Halzen and Spencer R. Klein, PHYSICS TODAY, May 2008, page 29.) The observatory was built primarily to serve as a telescope to study neutrinos from astrophysical sources. However, it also detects neutrinos born in the aftermath of cosmic-ray protons crashing into nuclei in the upper atmosphere. About once every six minutes, one of those atmospheric neutrinos finds its way to IceCube's monitoring zone, collides with a nucleus in the ice or bedrock, and produces a charged particle that can be detected from the Cherenkov light it gives off. Figure 1 shows the IceCube Laboratory, which houses the computers that collect and process raw data.

The standard model of particle physics posits the existence of three flavors of neutrinos. Among IceCube's many scientific quarries are signs that some of the atmospheric neutrinos, during their transit through Earth, transform into sterile neutrinos—hypothetical particles that interact with other matter only via gravity. A recent analysis of 20 145 high-energy atmospheric neutrino events from 2011–12 has yielded no such sign.[1]

Meanwhile, researchers from MINOS (Main Injector Neutrino Oscillation Search) and the Daya Bay Reactor Neutrino Experiment recently joined forces. MINOS is an accelerator-neutrino experiment at Fermilab; Daya Bay is a reactor-based experiment in South China. When the joint collaboration analyzed data from the two experiments, along with data from a third source, the Bugey-3 reactor-neutrino experiment in France, the researchers, too, found no evidence for sterile neutrinos.[2]

Although the results don't rule out sterile neutrinos, they do place stringent limits on how a possible sterile neutrino might mix with the three well-established ones. In so doing, they heighten the tension between a handful of experiments that have tantalizingly hinted at an unseen sterile neutrino and those that are perfectly compatible with the usual three flavors: electron, muon, and tau.

The sterile hypothesis

Neutrino flavors, which are eigenstates of the weak interaction, are quantum mechanical superpositions of mass eigenstates. Because the mass eigenstates have different masses, each one propagates differently. Thus a neutrino born as one superposition, after propagating some distance, can evolve into a different superposition. The flavor- and mass-eigenstate bases are related by the unitary transformation $|\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle$, where $U_{\alpha i}$ is the amplitude for mass state i to be in flavor state α. The matrix elements $U_{\alpha i}$ are conventionally expressed in terms of so-called mixing angles. Oscillations between flavor states are then characterized by the mixing angles and by the differences Δm^2 between the squared masses of the mass eigenstates.

Neutrino-oscillation experiments come in two varieties: those that track the

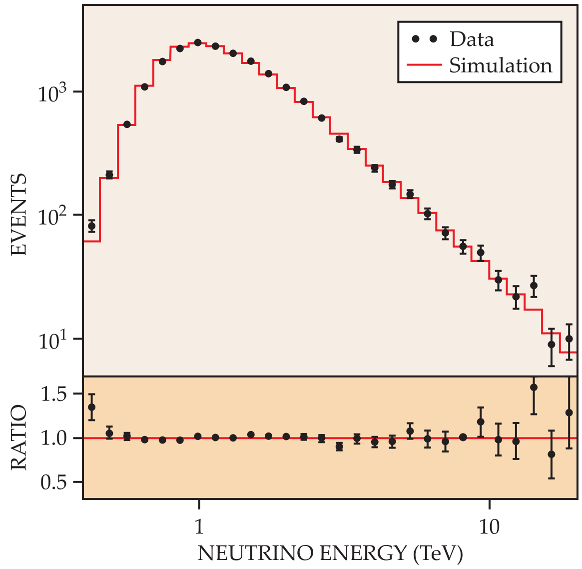

FIGURE 2. ICECUBE ENERGY SPECTRUM. The number of observed atmospheric muon neutrinos compared with a Monte Carlo simulation that assumes no sterile neutrinos. The lower panel shows the ratio of observed to simulated events. If oscillations into sterile neutrinos with a mass of 1 eV were present, a dip in the spectrum would appear at a neutrino energy of 3 TeV. (Adapted from ref. 1.)

disappearance of a particular neutrino flavor while in transit and those that detect the appearance of a neutrino flavor that wasn't present at the source. In the 1990s the appearance-type LSND (Liquid Scintillator Neutrino Detector) experiment at Los Alamos National Laboratory set out to look for electron antineutrinos ($\bar{\nu}_e$) 30 m downstream from where a proton beam slammed into a beamstop to produce muon antineutrinos ($\bar{\nu}_\mu$). (See PHYSICS TODAY, August 1995, page 20.)

In 1995 the LSND team reported finding excess numbers of $\bar{\nu}_e$ in their $\bar{\nu}_\mu$ beam. The result, which implied a $\Delta m^2 \approx 1$ eV^2, has come to be known as the LSND anomaly because the standard three-neutrino model can't reconcile such a large Δm^2 with those deduced from atmospheric- and solar-neutrino experiments, which are an order of magnitude smaller. One attractive way out of that predicament is to augment the model with a sterile neutrino with a mass of roughly 1 eV.

Light sterile neutrinos of the kind implied by LSND were unanticipated. In its simplest form, the leading theoretical treatment of sterile neutrino flavors, called the seesaw model, invokes three TeV-mass-range sterile neutrinos—one partnered with each known neutrino—whose decay properties can account for the matter–antimatter imbalance in the universe. Another idea proposes a keV-mass sterile neutrino as a dark-matter candidate. "There's not a whole bunch of theoretical models that scream that these light sterile neutrinos need to exist," explains Fermilab theorist Boris Kayser. Thus, he says, searches for light sterile neutrinos have been driven largely by experimental hints.

Those hints emerged from the LSND experiment, but they didn't stop there. MiniBooNE, an accelerator experiment at Fermilab, first discounted the LSND results, but then reopened the account when additional measurements showed that the ν_μ to ν_e oscillation might be different from the $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation. (See PHYSICS TODAY, October 2010, page 14.)

Recent improvements in models of $\bar{\nu}_e$ production inside nuclear reactors prompted reevaluations of reactor experiments from the 1990s. Those improved models predicted a 6% greater $\bar{\nu}_e$ flux than the old experiments saw (see PHYSICS TODAY, May 2016, page 16). That reactor antineutrino anomaly could be explained by an eV-mass sterile neutrino.

Also in the 1990s, Gallex (short for Gallium Experiment) at Italy's Gran Sasso National Laboratory and SAGE (Soviet-American Gallium Experiment) at the Baksan Neutrino Observatory in Russia used radioactive chromium-51 (and later argon-37 at SAGE) as a ν_e source to test the performance of their radiochemical solar-neutrino detectors. The two experiments detected 15–20% fewer neutrinos than expected. Called the gallium anomaly, the results are again explainable with an eV-mass sterile neutrino.

Lamppost in the desert

IceCube's principal investigator, Francis Halzen (University of Wisconsin–Madison), says that the space of mass-squared differences and mixing angles that could support a putative sterile neu-

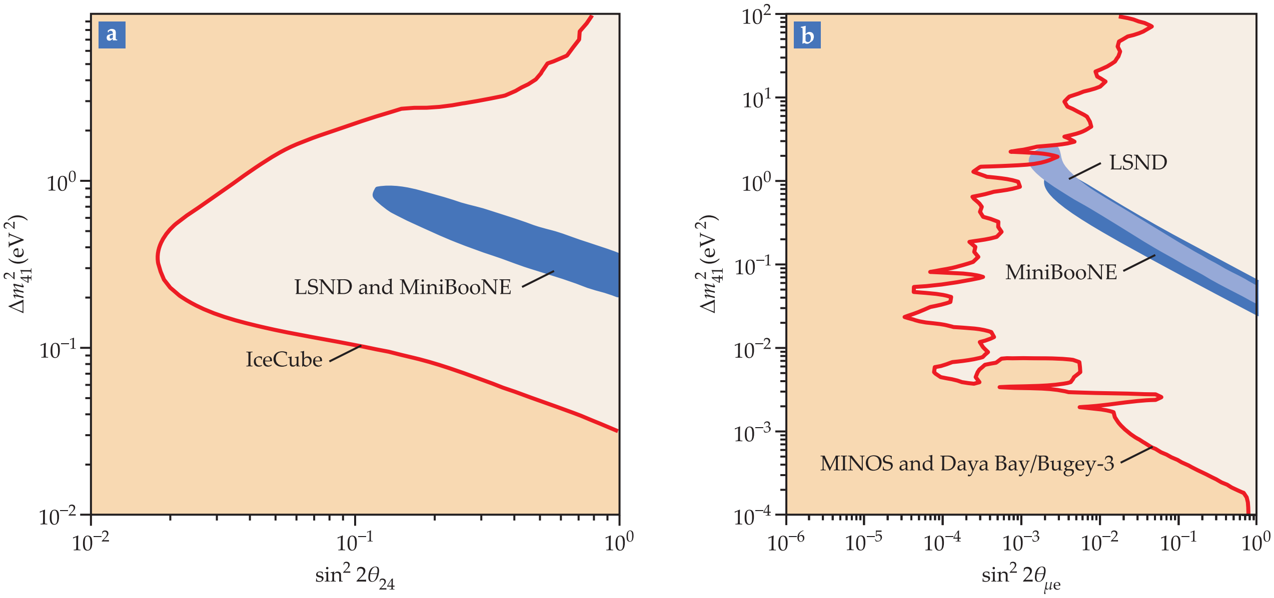

FIGURE 3. THE SIMPLEST EXTENSION of the standard three-neutrino picture adds one sterile flavor state and thus a fourth mass eigenstate. **(a)** Based on that extension, an analysis of atmospheric muon neutrino observations by the IceCube Neutrino Observatory excludes the unshaded region of parameter space to the right of the red line at a 90% confidence level. That exclusion is in conflict with the allowed region for sterile neutrinos from a combined fit of LSND (Liquid Scintillator Neutrino Detector) and MiniBooNE experiments (dark blue). (Adapted from ref. 1.) **(b)** A combined evaluation of the MINOS (Main Injector Neutrino Oscillation Search) accelerator experiment and the Daya Bay and Bugey-3 reactor experiments appears to exclude separately fitted LSND (light blue) and MiniBooNE (dark blue) allowed regions. Similar to panel a, the region to the right of the red line is excluded at a 90% confidence level. The composite parameter $\theta_{\mu e}$ characterizes the oscillation between muon and electron flavor states that involves the fourth mass eigenstate. (Adapted from ref. 2.)

trino is like an infinite desert at night. “Twenty years ago,” he says, “the LSND experiment put a lamppost in this desert of parameters.”

As fortune would have it, IceCube is well suited to test the LSND anomaly. At neutrino energies of 320 GeV–20 TeV, the range that the IceCube researchers analyzed for their sterile search, interactions with matter can resonantly enhance neutrino oscillation. “And it turns out that if you throw in a sterile neutrino, everything changes,” says Halzen.

The IceCube collaboration considered the simplest possible model, one with the three known neutrinos and one sterile neutrino of eV-range mass. For such a model, IceCube’s detectors should see ν_μ events disappear at a 3 TeV resonant energy. Figure 2 shows the ν_μ energy spectrum detected by IceCube. Says Halzen, “This resonance is there or it’s not. And it’s not.”

As shown in figure 3a, the results appear to rule out the region of parameter space consistent with the LSND and MiniBooNE observations. An independent analysis of publicly available IceCube data by Jiajun Liao and Danny Marfatia, both at the University of Hawaii, at Manoa, drew similar exclusions.[3] However, Liao and Marfatia caution that if nonstandard neutrino–matter interactions are sufficiently large, the limits might be evaded. Halzen concedes that more complex models could circumvent the IceCube limits, but he isn’t impressed. If ways around the limits can be conceived, Halzen says, it just means “now it’s the Wild West.”

More no news

The MINOS experiment tracked neutrino disappearance by comparing the ν_μ flux at a detector 1 km downstream from the source with the flux at a second detector 734 km away. Oscillations into sterile neutrinos, depending on the sterile mass, would show up either as a deviation from the expected energy spectrum or as a reduction in total ν_μ flux observed at the two detectors.

Daya Bay monitors electron antineutrinos that originate from six nuclear reactors at the eponymous reactor complex in China’s Guangdong province. The reactor cores are located 300 m to 2 km from the experiment’s eight liquid-scintillator detectors. The presence of sterile neutrinos would distort the $\bar{\nu}_e$ energy spectrum. But given the detector–source distances, Daya Bay is mostly sensitive to Δm^2 less than 0.1 eV^2. Bugey-3 was a reactor experiment carried out in the 1990s that used two liquid-scintillator detectors to measure the $\bar{\nu}_e$ flux from two reactors in a power plant in eastern France. Because Bugey-3 had detectors closer to the reactors, it was more sensitive to Δm^2 in the eV^2 range.

Like IceCube’s analysis, the one by the MINOS–Daya Bay team also considered one sterile flavor and one additional mass eigenstate. And again, the results appear to exclude the portion of parameter space allowed by LSND and MiniBooNE, as shown in figure 3b.

Missing but not gone

Now that IceCube and MINOS–Daya Bay appear to have removed what Halzen calls the LSND lamppost, what’s to be done? As MIT’s Janet Conrad, a member of the IceCube collaboration, points out, “Disappearance experiments also have anomalies.” Including the gallium and reactor antineutrino anomalies and the new IceCube results in global fits of existing oscillation data tends to shift allowed regions to greater Δm^2. “That illustrates how important it is to consider all of the data,” she says. “Sterile neutrinos are slippery little beasts.”

The quest continues. Several planned experiments—the Precision Oscillation and Spectrum Experiment at Oak Ridge National Laboratory, the Detector of Anti-Neutrino based on Solid Scintillator project at the Kalinin Nuclear Power Plant in Russia, and the Stereo experiment at the Institut Laue–Langevin in France—aim to suss out the reactor antineutrino anomaly. At Fermilab, the Short-Baseline Neutrino Program to search for sterile neutrinos will have a complement of three detectors—Imaging Cosmic and Rare Underground Signals detector, MicroBooNE, and the Short-Baseline Near Detector—to monitor an accelerator neutrino source (see PHYSICS TODAY, July 2015, page 23). MicroBooNE began collecting data last October as a standalone experiment. "There's a big global effort to do future experiments," says Kayser. "This is an experimental question. And we really need experiments to settle the issue."

Sung Chang

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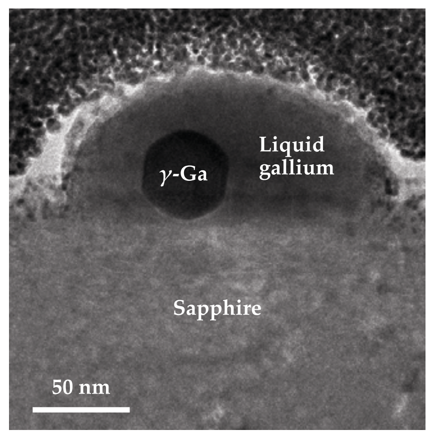
A droplet that won't freeze harbors a crystal that won't melt

The gallium nanodroplet's anomalous phase behavior is a new twist on the maxim "small is different."

To the casual observer, the tiny crystal of gallium visible in the adjacent figure might seem remarkable primarily for its scale, just 40 nm—roughly 100 atoms—in diameter. But for the University of Western Australia's Alexandra Suvorova, who took the transmission electron microscope (TEM) image, the bigger surprise was that the speck of frozen Ga was there at all. According to the metal's phase diagram, the observed crystalline structure—a hexagonally packed arrangement known as the γ phase—occurs only at temperatures below 236 K, far cooler than the ambient temperature at which the image was taken.



A BURIED GEM. At the core of the molten gallium nanodroplet shown here, the metal adopts a crystalline form known as the γ phase. The liquid and solid phases coexist over a temperature range of more than 600 K. Interactions between the droplet and the underlying sapphire substrate are thought to cause the anomalous behavior. (Adapted from ref. 1.)

Moreover, the diminutive lump of solid is enveloped in a shell of molten Ga, which seems to fly in the face of conventional rules of thermodynamics. Those rules stipulate that at a fixed pressure, a pure substance's liquid and solid phases can coexist at precisely one temperature, the melting point. For Ga at atmospheric pressure, that temperature is around 303 K, several kelvin hotter than Suvorova's droplet. Even when the droplet is chilled below 200 K or heated to 800 K, it retains its two-phase character. The finding,[1] newly reported by a team led by Maria Losurdo (CNR-NANOTEC, Bari, Italy) and April Brown (Duke University), has theorists scratching their heads.

Nicola Gaston, a physicist at the University of Auckland, has been studying metal nanoparticles for more than a decade and says she's never seen anything quite like it. Experiments have generated indirect evidence of coexistence, she says, "but they've never produced anything so clear as this."

Gaston adds that the earlier experi-