A Neutrino Bombshell: It Has Mass

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In an old zinc mine 2,000 feet beneath the Japanese Alps, an international team of physicists has discovered that a ubiquitous, ghostly subatomic particle called the neutrino -- previously thought to have no mass at all, like a beam of light -- actually weighs in at about one ten-millionth the mass of the electron.

That may not sound like much. But the long-awaited observation, to be announced in Japan today by the 100-member collaboration using the underground Super-Kamiokande neutrino detector, will force drastic revisions in long-established scientific theory and change the way researchers view a host of phenomena, including the shape of the cosmos.

"These new results could prove to be a key to finding the holy grail of physics, the unified theory" -- the quest for deep, simplifying principles that underlie the profusion of objects and forces in nature, according to John G. Learned of the University of Hawaii, a veteran neutrino hunter in the Kamiokande group.

The discovery strikes a devastating blow to the "Standard Model" of particles and forces, the consensus theory of how nature works at the most basic level. That model, hammered together over the past 75 years, governs the way scientists use nuclear energy, design transistors and lasers, explore space and build medical imaging devices, among scores of other endeavors. But it cannot accommodate a neutrino that has mass without changing several primary assumptions.

"It really does shake up the Standard Model in a serious way," said Nobel physics laureate Leon Lederman, and "it shows us that we really just don't know nothin' " about the processes that give particles their bewildering diversity of masses.

That shake-up, Learned believes, could lead "toward understanding of the origins of the matter from which we are made and the ultimate fate of the universe" -- namely, whether it contains sufficient mass that it will collapse upon itself, or so little that it will expand forever.

There are about 50 billion neutrinos for every electron, and even the most seemingly barren voids of interstellar space contain a whopping 1,500 neutrinos per cubic inch. So if the particles have even a tiny mass, the universe is a much heftier place. Indeed, the collective neutrino mass could easily be "comparable to all the visible stars and the galaxies," said theorist Joel R. Primack of the University of California at Santa Cruz. That's a matter of considerable purport, since astronomers agree that at least 90 percent of the mass of the cosmos is in some unknown, invisible form called "dark matter."

Neutrinos, first theorized in 1930 and undetected until 1956, are arguably the oddest of the 12 fundamental particles that make up all the visible matter known to science.

There are three types, or "flavors," of neutrinos. All of them interact so faintly with ordinary matter that they usually pass unimpeded through space at nearly the speed of light. Tens of thousands stream through every human body every second; most could sail comfortably through a few trillion miles of lead without smacking into anything. As a result, they are almost impossible to detect, even by instruments buried far underground to shield the detectors from other incoming particles.

"It's like trying to measure the mass of a dust particle that's on top of a baseball," said Jordan A. Goodman of the University of Maryland, one of 11 U.S. institutions in the collaboration. In fact, it has so far proven impossible to determine the mass of the neutrino directly. Instead, physicists study the phantom particles' behavior to see whether one type changes into another and back again over time in a process called "oscillation." Neutrinos could not oscillate if they were massless, so evidence of oscillation is tantamount to evidence of mass.

Oscillation is made possible by the maddeningly strange rules of quantum mechanics, the system that governs the conduct of particles and forces at the very smallest dimensions. In the quantum realm, even entities with mass have wave-like properties and may exist in a number of different potential states simultaneously. Thus, viewed from a quantum perspective, a neutrino is not exactly a single particle. Instead, it is a combination of two different but coexisting flavors, each with a different mass. Over time, the waves representing each mass get in and out of sync with each other, and as one wave or the other predominates, the neutrino changes flavor.

Or at least that was the theory developed to explain a couple of embarrassing problems. One is called the "solar neutrino deficit," referring to the fact that only a fraction of the neutrinos known to be created by nuclear fusion in the sun actually arrive on Earth. A similar deficit occurs in neutrinos created in the atmosphere when cosmic rays collide with air molecules. Physicists were obliged to either admit that they didn't understand neutrino production, or to assume that the "missing" neutrinos had oscillated to a flavor their instruments could not detect.

From the 1960s through the '80s, various facilities made progress at observing neutrinos. Then, a few years ago, the Japanese decided to construct a huge detector in a mining site near the city of Kamioka. With assistance from the U.S. Department of Energy, they built a double-walled stainless steel tank the size of a small office building, containing 55,000 tons of ultra-pure water.

Covering the interior walls are 11,146 special light sensors called photomultipliers that watch for the telltale optical signals given off in the rare event that a stray neutrino created by a cosmic ray in the atmosphere smacks into one of the atoms in a water molecule. When it does, the neutrino picks up an electric charge. Because it is traveling much faster than the speed of light in water, the now-charged particle causes the optical equivalent of a sonic boom -- a blast of blue light recorded by the sensors.

One flavor, the electron neutrino, makes a characteristically fuzzy light pattern; another, the muon neutrino, produces a distinctively neat, clean ring. (The third type, the tau neutrino, has never been observed, though physicists are hoping to do so at Fermilab outside Chicago and elsewhere within the next few years.) After recording light patterns for 535 days, the scientists were finally able to show that there were roughly twice as many muon neutrinos coming downward into the detector from the atmosphere directly above than there were coming upward from the other side of the Earth.

The neutrinos "that had traveled the longest seem to be disappearing more frequently," said collaboration member David Casper of the University of California at Irvine. Presumably they had enough time to oscillate into tau neutrinos (or perhaps some still unknown exotic flavor) that did not show up in the detector.

"Massive neutrinos must now be incorporated in the theoretical models of the structure of matter," the collaboration announcement states, and "astrophysicists concerned with finding the 'missing' or 'dark matter' in the universe must now consider the neutrino as a serious candidate."

Discovering Mass

The farther neutrinos travel, the more time they have to change or "oscillate" into different "flavors." By comparing the number Aoming all the way through the Earth to the number coming from close overhead, physicists determine that neutrinos oscillate, which they can only do if they have mass.

The Super-Kamiokande detector

A 12.5-million gallon tank of ultra-pure water buried 2,000 feet underground to filter out other signals that mask neutrino detection.

About once every 90 minutes, a neutrino interacts in the detector chamber, creating a cone of light that registers on the photo-multipliers that line the tank.

Characteristic ring patterns tell what kind of neutrinos interacted and in which direction they were headed.

SOURCE: University of Hawaii