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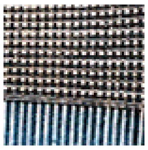
Elusive Particles Continue to Puzzle Theorists of the Sun



By GEORGE JOHNSON

One of the biggest embarrassments of 20th-century science -- the sun’s refusal to emit nearly as many neutrinos as physicists say it should -- inched closer to a possible solution last week when experimenters reported strong new evidence that these weird elementary particles, long thought to be perfectly massless, may have a small amount of heft after all. If neutrinos indeed have mass, the story goes, they can change "flavor" on their flight from the center of the Sun, eluding the electronic snares earthlings have been setting. The neutrinos wouldn’t be missing, but traveling in disguise.

But the "solar **neutrino** deficit," as it is politely called, still is not ready to give up its secrets. Just as the news, reported at the **Neutrino** ’98 conference in Takayama, Japan, seemed to clear up one mystery, it raised another: The same team claiming the existence of **neutrino** mass may have also cast doubt on the most elegant version of the changing-flavor hypothesis, in favor of an alternative that many theorists find ugly and

The Life and Times of the Neutrino
"I ve done a terrible thing," Wolfgang Pauli wrote shortly after inventing an elusive massless particle to solve a mystery about decaying neutrons. "I’ve invented a particle that cannot be detected." The particle he invented, however, has turned out to play a central role in 20th century physics. Here is a short synopsis.

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The dispute is far from resolved. Gathering and interpreting data about these rarefied particles -- inevitably described as "ghostly" and "elusive" -- is among the most delicate and frustrating challenges of physics. For all the excitement over last week’s breakthrough, it may still be years before anyone knows what is going on with the Sun.

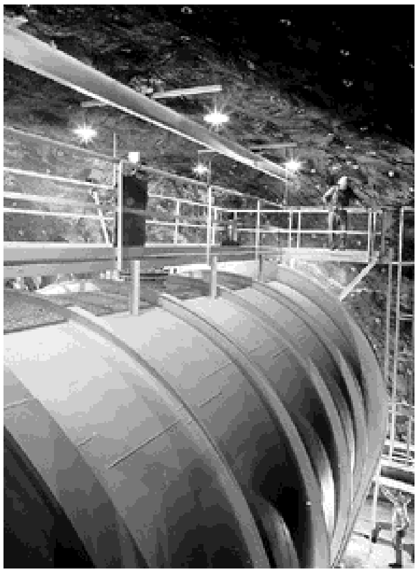
"The solar **neutrino** issue is far from settled," said Dr. John Learned of the University of Hawaii, a member of the international team whose experiments at the Super-Kamiokande **neutrino** observatory in Japan found the evidence of **neutrino** mass. "It drives you nuts because this is such a slow drama."

Adding another twist to the seemingly endless story, results from Super-Kamiokande and other recent experiments suggest the jarring possibility that the three kinds of neutrinos now believed to exist might have to be joined by a fourth, and even a fifth and sixth. Even stranger than their more familiar cousins, which barely interact with other matter, these exotic new "sterile" neutrinos would be even more reclusive: sealed off in their own phantom zone, apparent only by their gravitational pull.

"I think sterile neutrinos are a very ugly concept," lamented Dr. John Bahcall, a theorist at the Institute for Advanced Study in Princeton, N.J., who has spent most of his career trying to solve the solar **neutrino** mess.

"I hope that they will not be needed when all of the experiments now going on are complete.

If they are present, they will greatly



The original solar neutrino detector in the Homestake gold mine.

Credit: Eddie Hausner/The New York Times (Goldhaber); Associated Press (Reines); Photo Researchers

1930 Wolfgang Pauli hypothe-sizes the existence of an unknown particle to account for missing energy when neutrons decay. A year later Enrico Fermi calls the putative particle a **neutrino**.

1956 Fred Reines and Clyde Cowan discover neutrinos coming from a nuclear reactor. (Reines later wins a Nobel Prize for this and other work.)

Dr. Maurice Goldhaber

1957 Maurice Goldhaber and his colleagues find that neutrinos are lefthanded.

1961 Muon neutrinos are discovered at Brookhaven National Laboratory.

1957-62 Bruno Pontecorvo and Shoichi Sakata speculate independently that neutrinos oscillate between the electron and muon varieties.

1965 The first natural neutrinos are complicate the efforts to get a unique solution."

While he and other theorists long for a mathematically elegant explanation of the Sun's obstinacy, the experimenters almost seem to delight in finding more loose ends to be tied together. This kind of rivalry is the driving force behind physics. Without a theoretical framework in which they can be arranged, the data are meaningless. And without the data, the theories are just mathematical bric-a-brac.

How much neater physics seemed in the early 1930's, when there were just neutrons, protons and electrons to worry about. Then physicists found that a process called beta decay, in which a neutron spits out an electron and turns into a proton, of conservation of energy. The amount of energy coming out of the reaction was less than the amount going in. The solution: to invent an invisible particle called the **neutrino**, tailored to carry away just the right amount of missing energy.

Chargeless and thought to be massless, neutrinos were dismissed for decades as mathematical figments, something to make the equations balance, until they were detected in 1956 coming out of a nuclear reactor. In the meantime, scientists realized that if stars are powered by nuclear fusion (and it is hard to see how else they could be), neutrinos must be constantly streaming from the Sun. By their very nature, they would speed through the Earth almost entirely unimpeded.

1965 The first natural neutrinos are observed by Dr. Reines and colleagues in a gold mine in South Africa.

1968 Raymond Davis builds the first solar **neutrino** detector, a vat of cleaning fluid, in the Homestake gold mine in Lead, S.D., but detects fewer neutrinos than theory predicts.

Dr. Fred Reines

1976 The tau particle is discovered by Martin Perl at the Stanford Linear Accelerator in California. Analysis of its decay suggests the existence of a third type of **neutrino**.

1980 sA giant water tank experiment known as IMB (for Irvine-Michigan-Brookhaven) to detect neutrinos from decaying protons is built in the Morton salt mine in Ohio. The Kamioka experiment is built for the same purpose in Japan.

1987 Both Kamioka and IMB detect neutrinos from a supernova explosion in the Large Magellanic Cloud, heralding the birth of **neutrino** astronomy.

1991-92 The SAGE experiment in Russia and GALLEX in Italy confirm the deficit of solar neutrinos.

1998 After analyzing data collected over more than 500 days, the Super-Kamiokande team reports finding oscillations and, thus, mass in muon neutrinos.

Source: University of Hawaii

The only way to detect neutrinos is through their exceedingly rare collisions with ordinary matter. Hoping to snag just a few of the particles, experimenters have placed swimming-pool sized vats of various substances deep inside mines all over the world, where they are shielded from just about everything but the penetrating neutrinos. But after 30 years of measurements, the Sun has been found to be emitting only a third to a half of the neutrinos the theorists predict.

As the detectors have become more refined, and the results harder to dismiss, physicists have been forced to conclude that something is seriously wrong -- with either their understanding of neutrinos or their understanding of how the Sun shines. Many physicists believe they have pretty much ruled out the possibility that their model of the Sun is seriously askew. No reasonable amount of tweaking seems able to get the model to allow for such a feeble breeze of solar neutrinos.

Barring some stupendous discovery -- that the Sun is powered not by nuclear fusion but some unimaginable new phenomenon -- most physicists wager that the fault lies instead with the reigning theory of particles -- called simply the Standard Model. According to this cornerstone of physics, neutrinos, along with electrons and quarks, are the fundamental constituents of all matter. There are three "flavors" of neutrinos: the plain vanilla "electron **neutrino**" (the one involved in beta decay) and the more exotic muon and tau neutrinos. The latter get their names from their association with muons and tau particles, which are sort of like heavy electrons. All three types of neutrinos have long been held, mostly for reasons of mathematical esthetics, to be massless.

Physicists have come to realize that if the Standard Model is wrong on this point and neutrinos have even the slightest mass, they could conceivably change identity ("oscillate" is the preferred term) in mid-flight. Common electron neutrinos could turn into the other, undetected flavors, the muons and taus. The missing neutrinos would be found.

In recent years, theorists have rallied around an elegant version of this hypothesis called the MSW effect, after its inventors, S. P. Mikheyev, Alexei Smirnov and Lincoln Wolfenstein. According to MSW, the oscillations of the solar neutrinos are significantly enhanced as they travel through the matter of the Sun -- by enough to account for the deficit.

"The MSW effect is a beautiful idea," Bahcall said. "It would seem like a cosmic mistake if nature did not use this solution."

For the theory to work, neutrinos must be shown to have mass -- otherwise they can’t oscillate. This may have finally been established, in a backhanded way, by the Super-Kamiokande team.

Here the immediate issue is not solar neutrinos but the neutrinos created when cosmic rays strike the Earth’s atmosphere. The result is a cascade of reactions that is supposed to end in a shower of the muon neutrinos. But detectors tuned to find these "atmospheric" neutrinos also register many fewer than predicted.

According to the results announced last week, the muon neutrinos are disappearing somewhere along the way, presumably oscillating into another flavor -- not electron neutrinos (that would be too easy) but either tau neutrinos or one of the hypothetical sterile neutrinos. If the theoretical infrastructure of physics is sound, then **neutrino** oscillation implies, ipso facto, that the particles have mass. There has to be a difference of mass between the two **neutrino** types for oscillation to occur, according to the rules of quantum mechanics. And that means at least one type of **neutrino** has to have a mass greater than zero.

An experiment at a particle accelerator at Los Alamos National Laboratory in 1995 has also been interpreted as showing **neutrino** oscillation. But the Super-Kamiokande results are considered much more definitive.

It would seem that two birds have been killed with one stone: if the atmospheric **neutrino** deficit can be solved with massive, oscillating neutrinos, then surely the solar **neutrino** deficit can be, too. That's the hope, but other observations at Super-Kamiokande have added complications.

The MSW effect, the favored explanation for the solar deficit, comes in two versions. The first predicts that the deficit should be smaller at night when the neutrinos have to shine all the way through the Earth to get to the detectors. By interacting with the geological layers, electron neutrinos that had changed flavor inside the Sun would be converted back again. So far the Super-Kamiokande team has not been able to find this day-night variation.

A fallback version of MSW does not demand a day-night effect perceptible enough to be measured. But it does require that there be a certain shape to the **neutrino** energy spectrum, the curve that results when the number of neutrinos of different energies is plotted on a graph.

Experimenters at Super-Kamiokande are finding a possible "kink" in the spectrum: more high-energy neutrinos are being produced than predicted by MSW.

"We don't know if the kink will go away as we collect more data, or if it will get bigger," said Dr. Robert Svoboda, a physicist at Louisiana State University and a member of the American Super-Kamiokande team. "So far it seems persistent. Both versions of MSW may be close to being ruled out. Unless something changes dramatically, it's not what's going on."

Smirnov of the International Center for Theoretical Physics in Trieste, Italy, (he's the "S" in MSW) said the data are far too fragile and premature to overturn his theory yet. To judge definitively whether the effect is real, he said, experimenters will have to train their sights on solar neutrinos with lower and lower energies.

"This may take many years," Svoboda conceded. "Patience is a virtue for this type of observation." And it is still possible that the kink is a statistical fluke, or caused by some exotic new physics.

"One can only compensate for things one knows about," Learned said. "The sea of things one does not know about is infinite."

If MSW does not survive, physicists may find refuge in another theory in which the solar neutrinos change identity not while traveling through the mass of the Sun and Earth, but within the vacuum of space. Some kind of "vacuum oscillations" are already needed to explain the atmospheric deficit -- there is not enough matter in the air to cause a significant MSW effect. But getting vacuum oscillations to account for the solar deficit is much trickier. The theory only works if the masses of the various neutrinos just happen to have certain values, and because the Earth just happens to be the right distance from the Sun. Many theorists find these coincidences a little hard to swallow, and the theory is called the Just-So effect, after Rudyard Kipling's tall tales.

Even more repellent to some is the possibility that new neutrinos will have to be invented. Three flavors aren't enough to build a theory so expansive that it can accommodate the solar and atmospheric results as well as the data from the earlier Los Alamos experiment.

A fourth or fifth cousin for the neutrino family?

"If you believe all three of them, you are forced to invent a fourth **neutrino**," said Dr. Sandip Pakvasa, a phenomenologist at the University of Hawaii (one who has a leg in both the experimental and the theoretical sides of physics). And if there is one of these extra neutrinos, he said, there is probably no reason why there cannot be more.

Just nine years ago, scientists excitedly announced that they had determined once and forever that there are three and only three flavors of neutrinos. But the deciding experiment did not address the possibility of "flavorless," sterile neutrinos.

Regular neutrinos are immune to electromagnetism and the strong nuclear force, feeling only the weak nuclear force and gravity. The hypothetical sterile neutrinos would ignore the weak force, too. Once an ordinary **neutrino** changed into a sterile neutrino, it would essentially disappear from the universe, except for its minuscule gravitational field. And a sterile **neutrino** oscillating into a flavorful **neutrino** would seem to pop out of nowhere.

Whether this desperate theoretical dodge is really necessary should become clearer in the next few years as more **neutrino** experiments come on line.

Experimenters working at the Borexino **neutrino** detector at the Gran Sasso underground laboratory in Italy plan to test the Just-So theory by seeing if the number of solar neutrinos, sensitive to the distance between Earth and Sun, varies with the seasons. In the MINOS experiment (Main Injector **Neutrino** Oscillation Search), physicists will shoot a beam of neutrinos from a particle accelerator at Fermilab in Illinois through the Earth to a detector in the Soudan iron mine in northern Minnesota, looking for oscillations. And the Sudbury **Neutrino** Observatory, deep inside a nickel mine in southern Ontario, will be the first tuned to register all three flavors of neutrinos.

In half a decade, Pakvasa predicted, all the data will be in. "We’ll have the facts in front of us," he said. "Then it’s time to start speculating. That might take longer. The theorists are behind in the game."