NEUTRINOS MATTER

Credits
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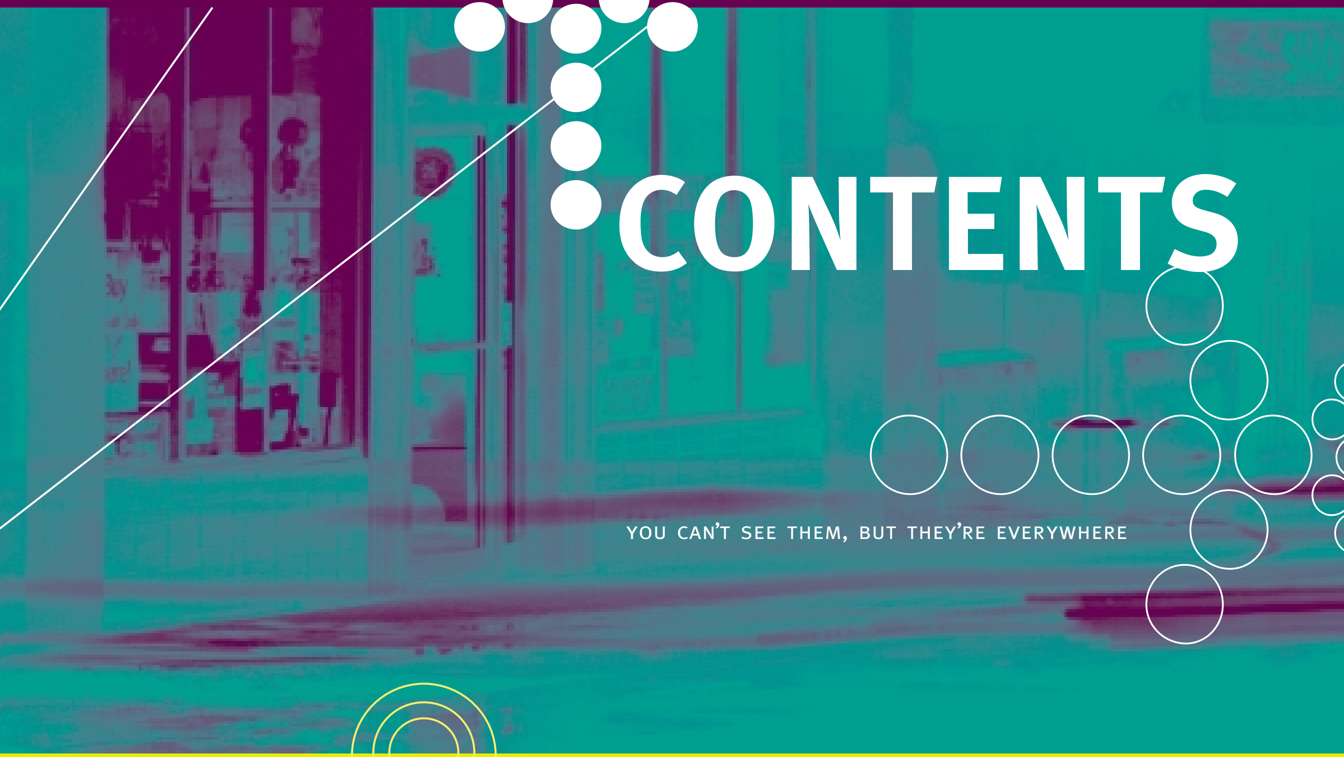
WHAT ARE NEUTRINOS?

HOW DO WE "SEE" NEUTRINOS?

DO NEUTRINOS HAVE MASS?

NEUTRINOS DO MATTER.



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YOU CAN'T SEE THEM, BUT THEY'RE EVERYWHERE

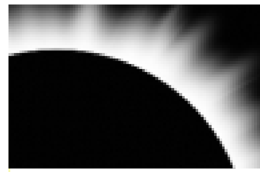

THE STUFF THAT HOLDS OUR UNIVERSE TOGETHER?
they probably shaped the evolution of galaxies

YOU CAN'T SEE THEM, HEAR THEM, OR TOUCH THEM, BUT

NEUTRINOS ARE EVERYWHERE

WHISTLING RIGHT BY YOU—AND THROUGH YOU!—EVEN AS YOU READ THESE WORDS. THERE ARE A MILLION OF THEM IN EVERY GALLON MEASURE OF SPACE, HAVING AN ENORMOUS IMPACT ON OUR EVERYDAY WORLD.

Without them, continents wouldn't drift, volcanoes wouldn't erupt, the sun wouldn't shine.



They probably shaped the evolution of galaxies, and may be the stuff that holds our universe together even as other forces send it flying apart.

Oddly, then, while neutrinos play so lively a part in the world around us, we know very little about them. We don't even know how much they weigh.

INTRODUCTION

WHAT ARE NEUTRINOS?

The stuff of matter

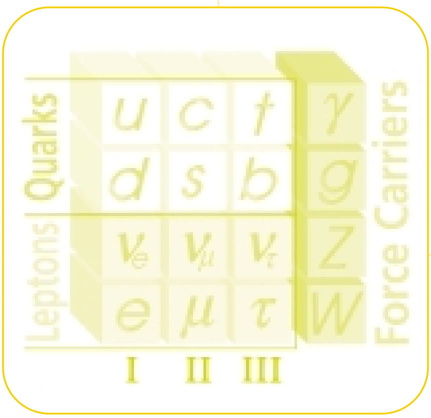
Matter is made up of two kinds of particles: quarks and leptons.

Quarks come in six varieties with whimsical names like up and down, strange and charm, top and bottom. They like to congregate in small groups. Thus, the proton in the core of the atom is a composite of two up quarks and one down quark. The neutron is made up of two down quarks and one up quark.

Leptons—from the Greek word for "light" or "thin"—travel alone. The electron, that familiar particle that creates static electricity (and is, incidentally, the first fundamental particle ever observed), is a lepton. It hovers around the nucleus of an atom solo, unattached.

Some leptons are charged: the electron, for example, has a negative charge. But other leptons—neutrinos—are electrically neutral.

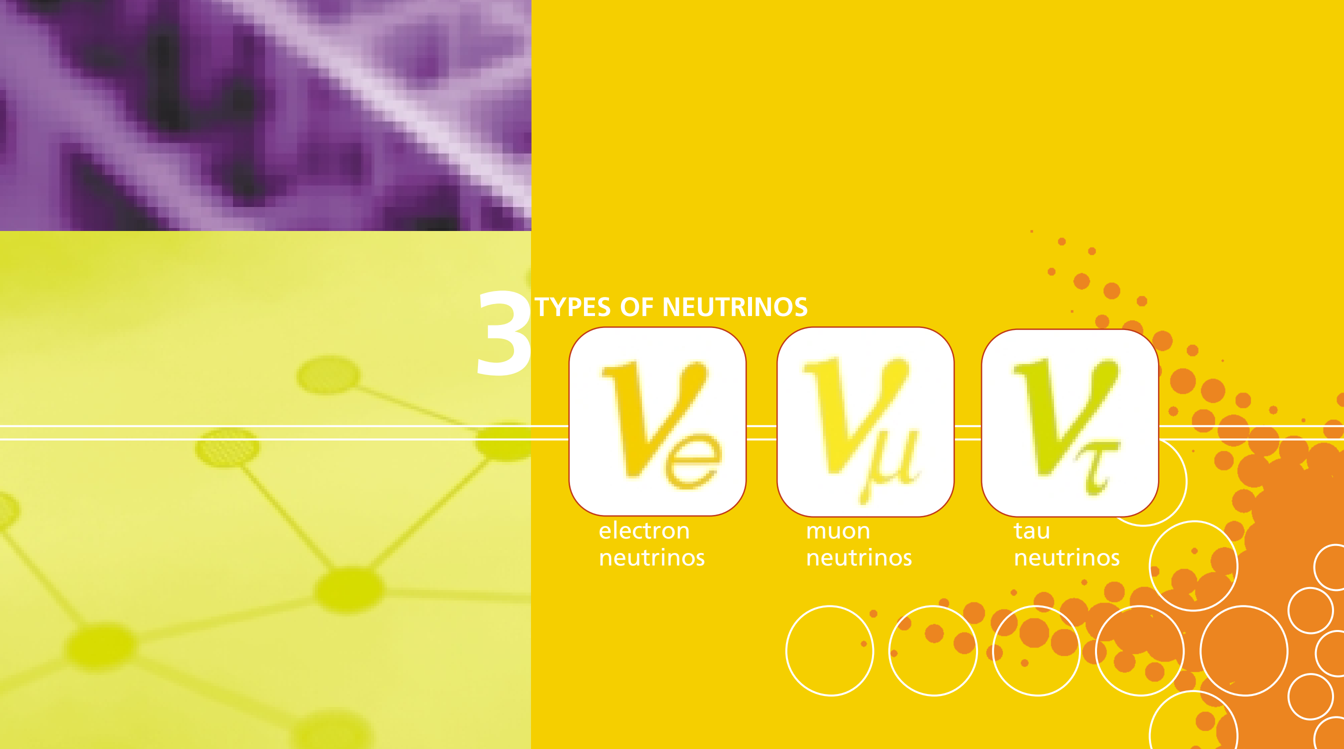
STANDARD MODEL



Fermilab

There are three types of neutrinos: electron neutrinos, muon neutrinos, and tau neutrinos.

These "little neutral ones" were at first only a mathematical invention used to balance an equation. In the early 1900s, scientists had discovered that, in a radioactive process called beta decay, when neutrons fall apart, the time-honored law of energy conservation appears to be violated. According to this law, when particles decay, the energy before the decay, bound up in the masses of the particles, should equal the energy after the decay—that is, the energy in any leftover matter plus the energy of motion, or kinetic energy. By physical law, energy can't vanish. It must be conserved in some form, either as matter or as its equivalent in energy [remember Einstein's equation:



THE EXISTENCE OF A NEW PARTICLE

E (energy) = m (mass) x c^2 (the speed of light squared)].

But scientists found that when a neutron falls apart into a proton and an electron, the energy before and after the decay doesn't add up.

To account for this discrepancy seen in beta decays, Wolfgang Pauli, an eminent theoretical physicist at the renowned Federal Technical Institute in Zurich, Switzerland, proposed in 1933 the existence of a new particle, the neutrino. Without proof, though, his proposal was an embarrassment. "I have done something very bad today in proposing a particle that cannot be detected," Pauli told a friend. "It is something no theorist should ever do."

In fact, rather than present his idea in a talk at a physics conference and open himself up to possible ridicule, he described his thesis in a letter to the conference organizer—and excused himself from giving a talk, saying he had to attend a town ball.

In 1953, however, American physicists Clyde Cowan and Frederick Reines set out to detect neutrinos emitted from a nuclear reactor in Hanford, Washington. Three years and several experiments later, they sent a telegram to Pauli in Zurich saying with confidence, "We are happy to inform you that we have definitely detected neutrinos."

Origins

Neutrinos don’t just materialize out of thin air.

Most of them were created 20 billion years ago, in the earliest moments after the Big Bang. The newborn universe was a hot, dense soup of elementary particles—among them, neutrinos. It is believed that there are today about a billion neutrinos per cubic yard of space that have survived since the days of the early universe.

Neutrinos are also created every day in the hot furnace of the sun. Strong gravitational pressure at the sun's core heats up the nuclei of its hydrogen and helium gases, giving them enough energy to fuse. As they fuse, they release energy and a stream of particles, including X-rays, gamma rays, and neutrinos.

Through similar nuclear reactions, neutrinos are released when stars are just beginning to form from large clouds of gas and dust—or when they reach the end of their lives and explode. One of these dying stars, which are called supernovas, exploded in 1987 some 100,000 light-years away. It emitted 1,000 times more energy than our sun will produce in 4.5 billion years and was 20 times more massive. Researchers in Japan were able to detect 11 neutrinos that emerged from that violent explosion so far away—an astonishing feat! Still, these must have been only a tiny fraction of the neutrinos created during the star’s demise.

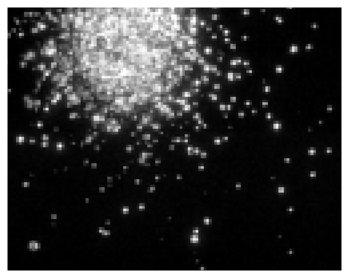
For the most part, neutrinos occur naturally in our universe, but here on Earth physicists also create neutrinos for experimental purposes using high-energy particle accelerators. They might start with a vial of hydrogen and strip away the electron from each atom, leaving behind only the proton that makes up its nucleus. The protons are then accelerated in an electric field to very high energies for such a tiny piece of matter—say, 8 billion electron volts—and aimed at a metal target. The protons interact with the atoms in the metal to create pions, which decay into a stream of charged particles and neutrinos.

AIP Emilio Segre Visual Archives, Goudsmit Collection

WOLFGANG PAULI

Ed Nano, AIP Emilio Segre Visual Archives

FREDERICK REINES

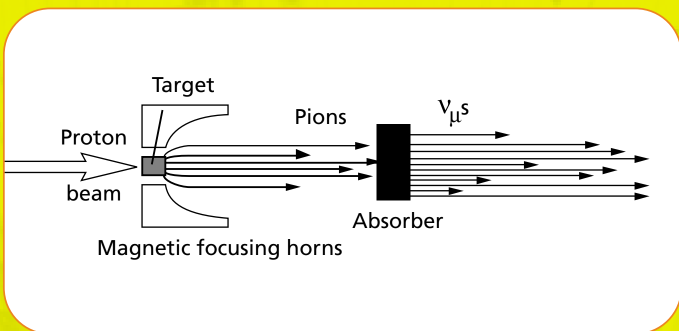


National Aeronautics & Space Administration

The giant galactic nebula NG.

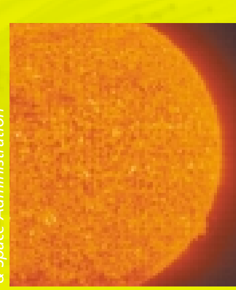
NEUTRINOS don't just materialize out of thin air

BooNE BEAM



Fermilab

IN THE BooNE EXPERIMENT
(the acronym stands for Booster Neutrino Experiment), scientists will use an accelerator called the Booster, at Fermilab, in Illinois, to shoot protons into a metal target. By interacting with the protons and neutrons in the atoms of this metal, the proton beam will generate pions, which subsequently decay into neutrinos and other particles. The other particles are weeded out with an "absorber," yielding a pure beam of muon neutrinos.



National Aeronautics & Space Administration

HOW DO WE “SEE” NEUTRINOS?

“Seeing” neutrinos isn’t easy.

Physicists see particles only when they interact with other particles. But neutrinos are the loners of the universe: they rarely interact with each other or anything else. They rip across the great expanse of the universe unperturbed, sailing right through our bodies, on through the crust of the Earth, and out the other side. Neutrinos can happily pass through a wall of lead several hundred light-years thick. In nature, neutrinos bump into other particles only once in a blue moon.

Big detectors

To see neutrinos, then, physicists need not only a concentrated source of these little neutral ones but big detectors with lots of material inside. The more material standing in the way, the better the chances that a neutrino will collide with another particle instead of just whizzing by. Water, chlorine, and mineral oil are commonly used because they leave behind distinctive, measurable signs when a neutrino knocks into one of their atoms.

How big is “big”? Physicists in Japan studying atmospheric neutrinos use a 50,000-ton detector the size of a cathedral, filled with 12.5 million gallons of ultra-clean water.

A smaller detector, soon to be built at Fermilab, a high-energy physics laboratory in Illinois, will be four stories high, weighing 800 tons—immense by any standards. It will be filled with 250,000 gallons of purified baby oil.

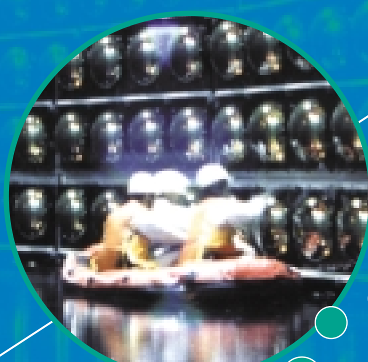
These detectors can’t see neutrinos per se; but when a neutrino bumps into another particle—an atom of hydrogen, for example—it creates a flurry of charged particles, which can be seen. Depending on what kind of detector is used, these charged particles may leave a trail of ionized gas, a pattern of light emitted by excited atoms, or black dots on photographic paper.

SUPER-K DETECTOR
Phototubes lining the 50,000-ton detector used in the Super-Kamiokande experiment in Japan.

ICRR (Institute for Cosmic Ray Research), The University of Tokyo

50,000-TON DETECTOR

the size of a cathedral, filled with 12.5 million gallons of ultra-clean water



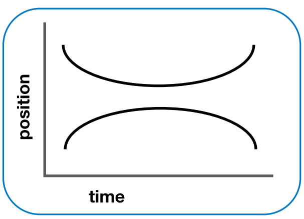
NEUTRINOS
ARE THE

LONERS of the universe

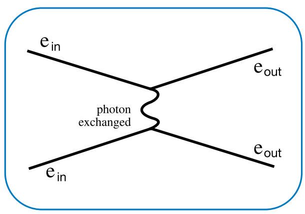
In the 1950s, bubble chambers were the detectors *par excellence.* The photograph to the left is what a neutrino interaction looks like in a bubble chamber. Notice that the neutrino is invisible as it sails through the liquid hydrogen inside the chamber, until it collides with a hydrogen atom (see arrow). The liquid is heated to near its boiling point and kept under just enough pressure to prevent it from boiling. But when the neutrino strikes the hydrogen atom, it creates a track of tiny bubbles (ionized gas) as the liquid momentarily boils. In this picture, the neutrino disintegrates into a stream of positively and negatively charged particles, curving left and right in the surrounding magnetic field.

More modern detectors use huge vats of water or mineral oil. They rely on an odd phenomenon called Cerenkov light. In a vacuum, of course, nothing travels faster than light. But in media like water and mineral oil, photons slow down while subatomic particles hurry on, outstripping the speed of light. In so doing, charged particles create a shockwave, a burst of light much like the sonic boom that occurs when a plane travels faster than the speed of sound. Photons rush outward, producing a characteristic cone of blue light—Cerenkov light—the pattern physicists see in their detectors.

? What does it mean to say a particle "interacts"?



In the classical view, two particles with the same charge—say, two electrons—approach each other and then repel one another.



Particle physicists today picture the same interaction this way: The two electrons (e) interact by exchanging a photon (the particle responsible for electromagnetism, or light).

Neutrinos interact by exchanging particles, too.

Fermilab

THE ELECTRON, THE MUON, THE TAU leave

ALL 3 KINDS OF NEUTRINOS HAVE CERTAIN FEATURES IN COMMON

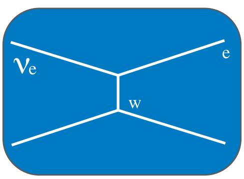
their own distinctive tracks in neutrino detectors

Distinctive tracks

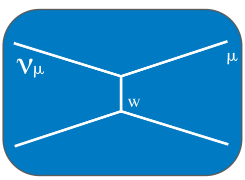
To study neutrinos, physicists not only need to be able to see the particles; they also need to be able to tell one kind from another. All three kinds of neutrinos have certain features in common, just as all flowers have petals, a stamen, and a pistil. But a rose is not a daisy or a daffodil.

The different types of neutrinos are distinguished by the kinds of particles they leave in their wake when they collide with another particle. Thus an electron neutrino leaves behind an electron; a muon neutrino, a muon; and a tau neutrino, a tau. The electron, the muon, and the tau are all charged leptons and leave their own distinctive tracks in neutrino detectors; the muon and tau decay into still other particles.

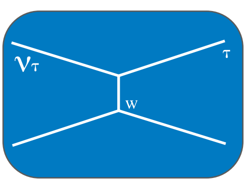
! Different kinds of neutrinos leave different kinds of tracks.



When an electron neutrino interacts with another particle and they exchange a W boson (the particle responsible for the electroweak force), the electron neutrino leaves behind an electron.



A muon neutrino leaves behind a muon.



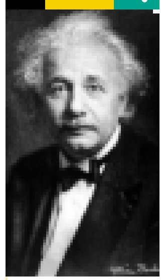
A tau neutrino leaves behind a tau.

Each of these charged leptons—the electron, muon, and tau—produces its own recognizable pattern in the detectors that physicists use to "see" and identify particles.

DO NEUTRINOS HAVE MASS?

Strange as it may seem, there are particles that have no mass—like the photon, responsible for the electromagnetic force and for the light we see. Traveling at the speed of light, the photon is a mere bundle of energy that never sits still.

Physicists long supposed that the neutrino, too, is massless—like the photon, it never sits still. In the last few decades, however, several studies of neutrinos, while not definitive, have suggested otherwise.



Particles can be massless.

Particles are just little bundles of energy.

Energy comes in two forms: rest energy and kinetic energy.

By Einstein's famous equation,
E (energy) = mc^2 (rest energy, or mass, times the speed of light squared) + K (kinetic energy).

If a particle doesn't move, K = 0, and so the total energy of the particle is just its "mc^2."

Alternatively, what if there is kinetic energy but no mass? There is still E, so there is still a particle!

Missing neutrinos

In the 1960s, physicists set out to count the number of neutrinos arriving on Earth from nuclear reactions in the sun. The researchers' detector was a large tank filled with chlorinated cleaning fluid (perchloroethylene). It was buried in an abandoned gold mine in South Dakota to shield it from the bombardment of other particles that might interfere with the neutrino count. The design of the detector relied on the fact that if a neutrino struck the nucleus of a chlorine atom, it would transform the element into an easily identifiable isotope of argon.

Data-taking began in 1968, and, much to the researchers' surprise, they found far fewer neutrinos than they had expected to see. By drawing on various facts—the estimated age of the sun, the temperature of its core, known chemical reactions, the capabilities of their detector, etc.—the scientists estimated that they would see one neutrino per day arriving in their detector. Instead, they saw only one every four days.

Other experiments sought to confirm or refute this observation. All of them found the same curious result: the number of

IF NEUTRINOS HAVE MASS, IT MUST BE VERY TINY

less than the mass of a human hair, less, even, than the mass of an electron, which weighs even less than one quintillionth of an ounce here on Earth

neutrinos arriving on Earth from the sun was far fewer than the laws of physics would predict.

Similar observations were made of neutrinos created by high-energy particles originating deep in space, called cosmic rays.

When cosmic rays strike the Earth's atmosphere, they produce a shower of particles called pions, some with a negative charge, some with a positive charge. The positively charged pions fall apart, yielding a muon and a muon neutrino; the muon disintegrates even further, into an electron, an electron neutrino, and a muon neutrino. Thus, for every two muon neutrinos produced in this cascade of events, there should be one electron neutrino. But several experiments—using detectors submerged under Lake Erie, tucked away in a mine in Minnesota, or hidden under the mountains in Japan—all found this ratio to be closer to one to one.

Again, the number of neutrinos was not what scientists predicted. Neutrinos were missing.

Clearly, they couldn't have simply disappeared.

Lawrence Berkeley National Laboratory

The Sudbury Neutrino Observatory, Canada, where solar neutrinos are studied.

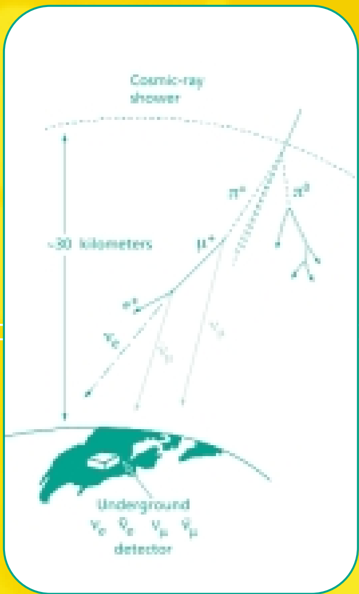
Oscillations?

It is a weird but scientifically well-established fact of quantum mechanics—the science of the invisibly small—that particles also act as waves.

An odd consequence of this fact is that particles can exist in different states and, moreover, can change from one state to another. But they can do so only if, first, the particles have mass, and second, the different states have different masses.

Seeking an explanation for the "missing" neutrinos, physicists think that perhaps one kind of neutrino morphs into another kind, and morphs back again. In the physics jargon, neutrinos "oscillate." Maybe, for example, the muon neutrinos produced by cosmic rays turn into tau neutrinos, and neutrinos appear to be missing because the low-energy tau neutrinos elude detection. Maybe, too, the electron neutrinos from the core of the sun turn into muon neutrinos on their journey to Earth. Again, the electron neutrinos appear to be missing only because the solar-neutrino detectors aren't capable of identifying muon neutrinos.

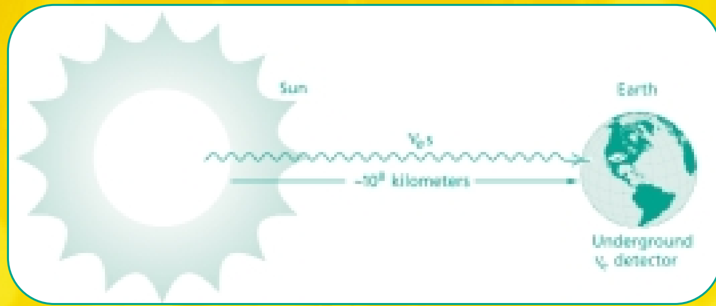
COSMIC RAYS



Los Alamos National Laboratory

Cosmic rays, high-energy particles that constantly bombard the Earth, create neutrinos when they interact with our atmosphere. Physicists "see" only about half the number of atmospheric neutrinos predicted.

SOLAR NEUTRINOS



Los Alamos National Laboratory

Electron neutrinos are produced in the sun's core, as atoms of hydrogen and helium fuse to form still heavier elements. Using large underground detectors, scientists find only about half the number of solar neutrinos that they expect to see.

THE SCIENCE OF THE INVISIBLY SMALL

If neutrinos oscillate, then, by the laws of quantum mechanics, neutrinos must have mass.

But do neutrinos oscillate? No experiment yet has proved that they do—at least not to the satisfaction of the very demanding scientific establishment.

In 1998, though, the results of an experiment called Super-Kamiokande got scientists excited. Researchers in Japan confirmed the deficit in neutrinos generated by cosmic rays, but they went a step further. With more data and better statistics than any other experiment, the scientists counted the number of neutrinos entering their detector from two directions: overhead as well as underneath. The neutrinos entering the detector from underneath had to travel through the Earth an extra 13,000 kilometers, giving them a greater distance in which to change from one kind of neutrino into another. Remarkably, the researchers found an "up-down asymmetry"—a difference in the number of muon neutrinos depending on whether they took the shorter or the longer path to reach the detector.

NEWSPAPER HEADLINES AROUND THE WORLD PROCLAIMED THAT NEUTRINOS HAD MASS, BUT...

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and

Detecting Neutrinos

And Detecting Their Mass

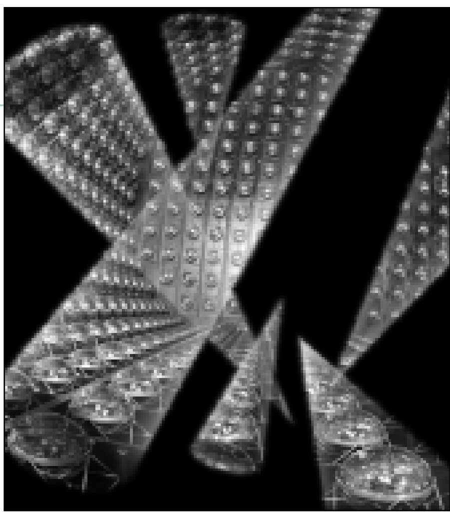
By analyzing the cones of light.

The New York Times, June 6, 1998.

Newspaper headlines around the world proclaimed that neutrinos had mass, but the researchers' colleagues were more reserved. To confirm that this odd phenomenon of neutrino oscillation exists, physicists need more solid evidence: evidence not only that neutrinos are missing, but that a different kind of neutrino has emerged from what was originally a homogenous collection. This kind of evidence can come only from carefully controlled experiments using particle accelerators.

In fact, scientists in some 50 countries throughout the world are either planning or already engaged in accelerator experiments.

One such experiment is MINOS (for Main Injector Neutrino Oscillation Search; the Main Injector is a particle accelerator at Fermilab). Construction of the experimental apparatus is now underway. By 2003, scientists hope to send a beam composed entirely of muon neutrinos all the way from Batavia, Illinois, to a detector 730 kilometers away in an abandoned iron mine in Soudan, Minnesota. That trip will take only 2.5 milliseconds or so, but on the way, scientists expect, at least some of the neutrinos will oscillate. If they do, then the massive detector, weighing the equivalent of nearly 4,600 Ford Taurus cars, should find that some of the muon neutrinos have disappeared, while electron and tau neutrinos have taken their place.



Los Alamos National Laboratory

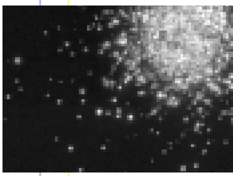
Phototubes lining a neutrino detector at Los Alamos National Laboratory.

NEUTRINOS DO MATTER

As odd and elusive as neutrinos are, they are, in fact, surprisingly common. These invisible particles are all around us, a billion of them in every cubic yard of space, trillions upon trillions hanging on since the early moments of the universe. They emerge daily from the sun, too, and from cosmic rays that strike our atmosphere. Still more neutrinos are created every day as the products of natural radioactive decays: in Fiestaware, in salt and cured ham, in building materials, in isotopes used for medical diagnosis and radiocarbon dating.

And they do matter.

The sun shines, warms our summer afternoons, because nuclear reactions in its interior daily generate neutrinos.

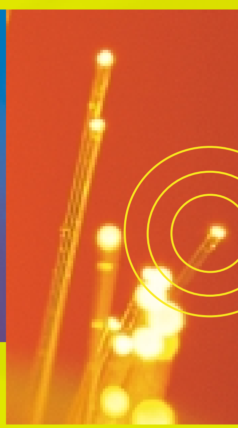


Neutrinos have geological effects, too. The decay of radioactive elements in the Earth's mantle, spewing out neutrinos, is a constant source of heat, producing molten material that slowly churns by convective currents. All this activity just below the ground has caused continents to drift, creating the peaks of the Himalayas and the ring of volcanoes around the Pacific. Were it not for neutrinos, we might still be dwelling in Gondwanaland instead of residing here on the North American continent.

Some scientists think that neutrinos might ultimately decide our fate, if indeed they are the stuff of "dark matter." Dark matter makes up at least 90 percent of the matter in the universe. Scientists can't see dark matter (hence the name), but they see its gravitational effects.

And it has profound cosmological ramifications. How much there is will determine whether the universe goes on expanding forever, or whether it slows down and collapses back on itself.

No wonder, then, that scientists are so eager to study neutrinos.



Postscript: In the hour or so that it took you to read this pamphlet, about

100,000,000,000,000,000,000

NEUTRINOS

ZIPPED THROUGH YOUR BODY UNANNOUNCED

100,000,000,000,000,000,000 NEUTRINOS