NEUTRINO ODYSSEY

THE INCREDIBLE JOURNEY OF DISCOVERY INTO ONE OF NATURE’S MOST ELUSIVE PARTICLES
Their number far exceeds the count of all the atoms in the entire Universe. Although they hardly interact at all, they helped forge the elements in the early Universe, they tell us how the Sun shines, and they may even cause the titanic explosion of a dying star. They may well be the reason we live in a Universe filled with matter – in other words, a reason for our being here.

We have learned much of what we know about neutrinos in just the last decade. We have been challenged to rebuild neutrino theory quickly to keep up with the rapid pace of new discoveries. This booklet tells the story of how far we have come and where we hope to go.
A CRISIS
LOOMED AT THE END OF THE 1920’S – A DECADE ALREADY FILLED WITH REVOLUTIONS. ONE OF PHYSICS’ MOST SACRED PRINCIPLES – THE CONSERVATION OF ENERGY – APPEARED NOT TO HOLD WITHIN THE SUBATOMIC WORLD. FOR CERTAIN RADIOACTIVE NUCLEI, ENERGY JUST SEEMED TO DISAPPEAR, LEAVING NO TRACE OF ITS EXISTENCE.
In a letter to colleagues in December 1930, Wolfgang Pauli suggested a “desperate remedy” to the problem. Pauli postulated that the missing energy was carried away by a new particle. But to solve the problem, the new particle had properties such that it could not yet be detected: it carried no electric charge and it scarcely interacted with matter at all.

Enrico Fermi soon was able to show that while the new particles would be hard to observe, seeing them would not be impossible. What was needed was an enormous number of them, and a very large detector. Fermi named Pauli’s particle the neutrino, which means ‘little neutral one’. More than two decades after Pauli’s letter proposing the neutrino, Clyde Cowan and Fred Reines finally observed neutrinos. Further studies over the course of the next 35 years taught us that there are three kinds, or ‘flavors,’ of neutrinos (electron neutrinos, muon neutrinos, and tau neutrinos) and that, as far as we could tell, they had no mass at all. The neutrino story might have ended there, but developments in solar physics changed everything.
Neutrinos are produced in great numbers by the nuclear reactions in the Sun’s core and can travel unimpeded from the solar center to us. While the light we see from the solar surface represents energy created in the core tens of thousands of years ago, a neutrino created in the Sun right now will reach us in just over eight minutes. In the mid-1960’s theorist John Bahcall showed that neutrinos from the Sun could be observed on Earth. Experimentalist Raymond Davis, Jr. built a detector that could see them.

While he did observe neutrinos, Davis found only roughly 1/3 the number Bahcall had predicted. Many physicists believed it likely that one, or perhaps both, were in error. Physicists puzzled over this problem for the next three decades, and to their surprise, Davis’ results were confirmed again and again by increasingly refined experiments. The best explanation of this mystery was that one kind of neutrino was morphing into another – or “oscillating.”
Evidence of neutrino oscillation has accelerated the growing excitement in neutrino physics.

Much of what we know about these mysterious particles has been learned very recently. In the Standard Model of Particle Physics (ABOVE, RIGHT), the properties and interactions of known particles and forces are described in exquisite detail. But recent neutrino discoveries have exposed a crack in its time-tested edifice – the Standard Model describes neutrinos (OUTLINED IN RED) as having no mass. As you will read, the solution to the problem of Davis and Bahcall’s missing neutrinos suggests otherwise – and is casting a long shadow of doubt on this essential scientific theory.
CONCLUSIVE EVIDENCE THAT NEUTRINOS HAVE MASS MAY BE THE UNDOING OF THE STANDARD MODEL, INSPIRING PHYSICISTS TO RETHINK THE BASIC NATURE OF THE UNIVERSE.
Among the many oddities of the subatomic world, one of the strangest is the fact that fundamental particles can sometimes behave like waves. The wave-like nature of neutrinos is proving to be an important clue to physics beyond the Standard Model.

These waves can be very simple in form, similar to the pure sound of a flute playing a single note. Or waves may be complicated, like the sound of several notes being played as a chord. In this case, the final wave is really the combination of two or more component waves. If the component waves oscillate with patterns that are almost, but not quite, the same, then the overall pattern gets stronger and weaker. Sometimes the component waves add together, sometimes they cancel each other. When two very similar notes are played together, the sound you hear “wobbles” slowly from loud to soft and back again – an effect physicists call “beats.”
Waves have periodic motion – they oscillate. If you add two waves, you will get another wave. Many common waves have multiple components – musical chords, neon lights, etc.

But if the components are similar, the resulting wave exhibits interference. This phenomenon is called “beats.”
Were Davis and Bahcall right – were 2/3 of the neutrinos from the Sun evading detection through oscillation? We can look at these oscillations as “neutrino beats”. The Standard Model sees neutrinos as three distinct particles, but oscillating neutrinos are a combination of three different waves. As a neutrino travels through space, the waves combine in different ways depending on how far the neutrino has traveled and its energy. Sometimes the combination might look like an electron-type neutrino, and then later the waves might combine to look like a muon neutrino. Thus, in any beam of neutrinos, as one type appears to come and go, another type goes and comes.
NEUTRINO OSCILLATIONS CAN ONLY HAPPEN IF THE NEUTRINO WAVE IS MADE OF TWO OR MORE COMPONENT WAVES, WITH SMALL PHYSICAL DIFFERENCES CAUSING THE “BEATS”. THOSE DIFFERENCES ARE THE RESULT OF MASS. IN OTHER WORDS: IF WE SEE NEUTRINO OSCILLATIONS, WE KNOW THAT NEUTRINOS HAVE MASS.
Super-K makes the first discovery of neutrino oscillations.

When high energy particles, created in catastrophic events in the cosmos, collide with the Earth’s atmosphere, they are scattered into showers of particles. Among these particles are so-called “atmospheric” neutrinos. In 1998, the Super-Kamiokande collaboration announced the observation of oscillations of atmospheric neutrinos. Their results, confirming evidence from earlier experiments, showed the oscillation of muon neutrinos. This confirmation of oscillations shook the neutrino world.

Super-Kamiokande also confirmed the observation of the solar neutrino deficit first seen by Davis and Bahcall. In the process, they took the first image of the Sun using neutrinos. Super-K’s data, when combined with data from the SNO collaboration – whose SNO detector resides in the Creighton mine in Sudbury, Ontario – proves without doubt that neutrinos originating in the Sun also oscillate.

These results have two important implications; that neutrinos do have mass; and that the Standard Model is an incomplete description of nature. Several new experiments are now underway to describe neutrino oscillations in detail, and to answer deep questions about our Universe.
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 can 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 pass through a wall of lead several hundred light-years thick without stopping or even slowing down.

There are a million neutrinos – relics of the Big Bang – in every gallon of space throughout the Universe. 60 million neutrinos from the Sun pass through the cubic inch in front of your nose each second. Your body is emitting 200,000 neutrinos each minute from the decay of naturally occurring potassium.
“Seeing” neutrinos isn’t easy.

We can only infer their existence when they collide with material in a detector. In some collisions, the neutrino is converted into an electrically charged particle. Fortunately, distinct charged particles are produced in the collisions of each type of neutrino. A collision of an electron neutrino creates an electron, a muon neutrino produces a muon, and a tau neutrino results in a tau particle. The trace that each charged particle leaves in the detector is distinct, much like rabbit tracks in the snow are different from shoe prints. We “see” neutrinos by seeing these tracks.

In other collisions, the neutrino remains a neutrino. When this happens, we can’t see the neutrino itself, but we can detect how the interaction has affected the other particles in the collision. For example, if a neutrino collides with an electron in our detector, it can transfer energy to the electron just like one billiard ball hitting another. We can detect this energy transfer by measuring the track of the electron.
Capturing Interactions

Many of today’s neutrino detectors use water, oil, or even ice to take advantage of the strange effect of Cherenkov light. When a neutrino interaction produces a charged particle in such material, bursts of blue Cherenkov light signal the interaction. This effect happens because the charged particle debris from the interaction are travelling faster than the speed of light. At first this sounds strange – how can a particle go faster than the speed of light? No particle can – in a vacuum. But in material, light slows down, and a charged particle can outstrip the light that it emits. In this case, the light waves pile up, much like sound waves pile up from a supersonic plane. The “boom” of blue light produced when this happens illuminates the very clear water, oil or ice in the detector.

The detectors’ photomultiplier tubes work like light bulbs in reverse. When a neutrino interaction emits a burst of Cherenkov light, the photomultipliers detect the light and send electrical signals to computers. Physicists study the detailed pattern of these signals to reconstruct the neutrino interaction.

**IMAGE 1**: Artist’s rendering of a Cherenkov light cone passing through the detectors of the IceCube experiment in the Antarctic ice. (IMAGE: Steve Yunck)

**IMAGE 2**: Before advanced detectors and computers, physicists used detectors called bubble chambers – large tanks filled with liquid hydrogen. Here, the energy released by a neutrino’s interaction with a charged particle makes the hydrogen boil. The hydrogen vaporizes and forms tracks of bubbles [arrow] along the spray of the charged particles. These interactions were captured by cameras in photographs like this one. (IMAGE: CERN)

**IMAGE 3**: Modern detectors register neutrino interactions with electronic data. This neutrino event is from the MiniBooNE experiment. The ring of light, registered by some of more than one thousand light sensors inside the detector, indicates the collision of a muon neutrino with an atomic nucleus. (IMAGE: Fermilab)
LEFT: The MINOS Far Detector, in the Soudan mine in Minnesota, is a 5,500 ton sandwich of steel plates and scintillator – a material capable of detecting the tiny interactions between neutrinos and atomic nuclei in the steel. (IMAGE: Fermilab)
Since neutrinos so rarely interact with other particles, “seeing” neutrinos requires two things: a lot of neutrinos, and a big detector with a lot of material inside. The more material standing in the way, the better the chances that a neutrino will collide with a particle instead of just whizzing by. A common type of detector uses Cherenkov light. Another kind of detector looks for scintillation light, produced when fragments from neutrino interactions zip through certain materials. Neutrino detectors are usually built underground (or even underwater). The rock surrounding a mine isn’t enough to stop neutrinos, but it does keep most charged particles produced in the atmosphere from getting into the detector and interfering with the carefully controlled experiments.
In the Sun

A nuclear furnace burns at the core of the Sun and of every shining star. The fuel is hydrogen, and the “ashes” are helium, the next heavier element. Nuclear fusion converts hydrogen to helium. The energy released in this process is enough to power the Sun over its estimated 10 billion year lifetime. Energy is carried away from the Sun in two main ways: by photons of sunlight, and by a huge number of neutrinos.

What happens next for the solar photons and solar neutrinos is very different. The photons interact readily with the extremely dense matter inside the Sun, colliding and struggling for many thousands of years before reaching the solar surface to escape. For the neutrinos, though, this roiling internal plasma is essentially transparent; they zip to the surface in seconds, reaching the Earth in just eight minutes before heading off into the Universe. So when we look at the sunlight reaching us now, we are seeing energy that was created long before the dawn of civilization – but when we look at the neutrinos, we see what is happening inside the Sun today.

In the Earth

Neutrinos are also created beneath our feet, inside the Earth. As Pauli first suggested, neutrinos are produced when some radioactive nuclei decay. The Earth contains radioactive heavy elements, like uranium and thorium, and the decay processes of these elements produce neutrinos. These decays are a major source of heat inside the Earth. As the heated material churns, the continents drift, creating the volcanoes of the Pacific and the peaks of the Himalayas.
In Nuclear Fission

In nuclear fusion, the nuclei of light elements are joined together to create heavier elements. In contrast, the nuclei of heavy elements can break up into lighter elements through nuclear fission. Both fusion and fission produce neutrinos. However, while fusion creates neutrinos, fission decays give rise to antineutrinos – the antimatter partners of neutrinos.

Controlled fission is used to generate electrical power in nuclear power plants. Several important neutrino experiments have used a nuclear reactor as a neutrino source, including Reines and Cowan’s first detection of the antineutrino.

In the Atmosphere

When high energy particles smash into one another, new particles are created out of the debris. Very often the new particles decay quickly, and when they do they often leave behind neutrinos. The source of the high energy particles can be natural – a catastrophic explosion occurring at the center of a far away galaxy, for example. The high energy particles created by natural sources produce showers of neutrinos when they hit the Earth’s atmosphere. The behavior of these “atmospheric” neutrinos was one of the first indications of neutrino oscillations.

In Particle Accelerators

With man-made accelerator beams we can create high energy neutrinos at will, and thus begin to understand in detail what neutrino oscillations are telling us about the microscopic world. So few neutrinos interact with matter that we must create an enormous number in order to measure their properties. To make an accelerator neutrino beam, we aim protons at a target made from an element like copper or tungsten. The

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The Savannah River Neutrino Detector, where Reines and Cowan first detected neutrinos emitted by a nuclear reactor.

Cosmic ray showers, like the one depicted here by the Pierre Auger Observatory, are the source of atmospheric neutrinos.
collisions of the protons with the target often create particles called pions. The pions eventually decay into neutrinos and other particles.

A distinct advantage of man-made accelerators is that they can produce neutrinos in short bursts, lasting far less than a thousandth of a second. It is then easy for experimenters to determine whether a detected interaction was a neutrino or something else just by checking to see if the interaction occurred during the accelerator burst.

In the Cosmos

When a star suffers an explosive death, or matter feeds the black hole lurking at the center of a galaxy, energies are released far beyond what we can achieve on Earth. Of the many fundamental particles that are created in such cataclysmic events, only neutrinos can reach us unscathed, carrying information about how and where they were created. The neutrinos from such astrophysical sources are produced in vast quantities. In a supernova explosion, for example, neutrinos carry away as much energy as the entire mass of our Sun. Astrophysical neutrinos can also be produced with remarkably high energies. Neutrinos born in the center of an active galaxy can arrive on Earth with more energy than we will ever be able to create with a terrestrial accelerator.

The most extraordinary explosion of all, the Big Bang, created more neutrinos than any other source which has existed since. These neutrinos still exist, unaffected since the beginning of time, and surround us and pass through us every instant of every day.
THE DISCOVERY THAT NEUTRINOS HAVE MASS MAY ONLY BE THE TIP OF THE ICEBERG. THREE THEMES HAVE CRYSTALLIZED THAT BROADLY DEFINE THE ONGOING STORY. WITHIN EACH OF THESE THEMES, WE ARE CONFRONTED BY CRITICAL ISSUES AT THE FRONTIERS OF PHYSICS, ASTROPHYSICS, AND COSMOLOGY. A WORLDWIDE EFFORT OF THEORY AND EXPERIMENT IS UNDERWAY TO ANSWER THE QUESTIONS POSED BY NEUTRINOS.
NEUTRINOS AND THE NEW PARADIGM

The neutrino discoveries of the last decade force revisions to the basic picture of the elementary particles and pose a set of well-defined but presently unanswered questions, questions of fundamental importance.

Our best theory of the nature and behavior of the fundamental world must be changed – but how? The neutrino masses are not zero, but their values are uncertain by a factor of 100 – what, exactly, are the masses? And how do we adapt our theory to allow the neutrino to have mass at all? How much do neutrinos mix with each other, allowing one “flavor” of neutrino to change into another? Neutrinos, alone among matter particles, could be their own antiparticles – are they? Why are neutrinos so much lighter than all the other known massive particles? Our newest results offer a glimpse, but we are still missing several crucial pieces to assemble the big picture.
Neutrinos may have properties beyond even our new paradigm. Such properties would again force a profound revision in our thinking.

Neutrinos can probe matter and its interactions more deeply than any other particle. Neutrinos themselves may have even more extraordinary behavior than that already seen. Will we discover new fundamental forces affecting neutrino interactions? Are there more than three flavors of neutrinos? Now that we have found one unexpected property of neutrinos – mass – how many more new properties might we discover? For more than 75 years, neutrinos have been surprising us. If past history is any guide, there is a lot more excitement to come!
Neutrinos originating from the Big Bang and from the cores of stars prompt us to find the connections between these particles and the Universe.

Neutrinos allow us to probe the origin and future of solar energy, upon which all life on Earth depends. Understanding neutrinos is necessary to comprehend supernova explosions, perhaps the origin of the heaviest elements on Earth. Neutrinos may have influenced the large scale structure of the Universe. Neutrinos may be the key to understanding why the Universe contains matter but almost no antimatter. As we understand neutrinos better, they can become tools to pursue these ideas to the fullest.
U.S. PARTICIPATION IN WORLDWIDE COLLABORATIONS

The astonishing discoveries in neutrino physics have led physicists to build detectors on nearly every continent, even Antarctica! The difficulty of detecting neutrinos means that most neutrino experiments must be built and run by collaborations of people from many nations and across many scientific disciplines. Neutrino physics must therefore be considered in an international context. This map shows the experiments that are now collecting data plus those currently under construction. The field is so rich with experiments that only a few can be highlighted here, those with major U.S. participation. Results from these experiments will drive the excitement in the field for at least a decade to come.
Neutrino experiments will soon embark upon an exciting exploration of fundamental physics.

New experiments are being designed to yield the answers we seek: experiments searching for a rare decay mode of nuclear matter, experiments studying neutrinos from nuclear reactors, from particle accelerators, and from the Sun. The planned experiments are physics-rich, diverse, cost effective, and integrated with the worldwide effort to reach an understanding of the neutrino. Each component provides unique information and thereby enhances companion studies in high energy physics, nuclear physics, and astrophysics (see figure on facing page). There are rare moments in science when a clear road to discovery lies ahead and there is broad consensus about the steps to take along that path. This is one such moment.
We live in a time when the light of new discoveries is breaking apart our long-held picture of the Universe.

This revolution began in part with the now widely-confirmed assertion that neutrinos have mass, and it will continue to be waged by neutrino experiments in the U.S. and abroad.

New theoretical models correct the problems of the old Standard Model, and they suggest a Universe never before imagined. The data gathered at current and future neutrino experiments will be instrumental in confirming or correcting these theories, or perhaps in opening unimagined possibilities.

The odyssey into a fundamental understanding of neutrinos – and the Universe as a whole – continues. Our Nation’s support of physics in the years ahead will largely determine the success of this journey, with profound possibilities for science and society.
Learn more online:
www.interactions.org/neutrinostudy