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Neutrinos

The Ghostly Particles

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Contents

Chapter 1: The Discovery of Neutrinos

Chapter 2: Understanding Neutrinos

Chapter 3: Key Characteristics of Neutrinos

Chapter 4: The Science Behind Neutrinos

Chapter 5: Observation and Measurement of Neutrinos

Chapter 6: Important Features of Neutrinos

Chapter 7: Neutrinos in Context

Chapter 8: Modern Understanding of Neutrinos

Chapter 9: Research and Exploration of Neutrinos

Chapter 10: Significant Discoveries About Neutrinos

Chapter 11: Challenges and Mysteries of Neutrinos

Chapter 12: Future Directions in Neutrinos Research

Chapter 13: Fun Facts and Trivia About Neutrinos

Chapter 14: Conclusion: The Significance of Neutrinos

Chapter 1: The Discovery of Neutrinos

These include the beta decay of atomic nuclei or hadrons and natural nuclear reactions such as those that take place in the core of a star. Other mechanisms include artificial nuclear reactions in nuclear reactors, nuclear bombs, or particle accelerators, supernovas, during the spin-down of a neutron star and when cosmic rays or accelerated particle beams strike atoms. The majority of neutrinos which are detected about the Earth are from nuclear reactions inside the Sun.

At the surface of the Earth, the flux is about 65 billion (6.5×1010) solar neutrinos, per second per square centimeter. Neutrinos can be used for tomography of the interior of the Earth. The neutrino was postulated first by Wolfgang Pauli in 1930 to explain how beta decay could conserve energy, momentum, and angular momentum (spin).

In contrast to Niels Bohr, who proposed a statistical version of the conservation laws to explain the observed continuous energy spectra of electrons in beta decay, Pauli hypothesized an undetected particle that he called a "neutron", using the same -on ending employed for naming both the proton and the electron. He considered that the new particle was emitted from the nucleus together with the beta particles (electrons or positrons) and had a mass similar to the electron.

James Chadwick discovered a much more massive neutral nuclear particle in 1932 and named it a neutron also, leaving two kinds of particles with the same name. The word "neutrino" entered the scientific vocabulary through Enrico Fermi, who used it during a conference in Paris in July 1932 and at the Solvay Conference in October 1933, where Pauli also employed it.

The name (the Italian equivalent of "little neutral one") was jokingly coined by Edoardo Amaldi during a conversation with Fermi at the Institute of Physics of via Panisperna in Rome, in order to distinguish this light neutral particle from Chadwick's heavy neutron.

In Fermi's theory of beta decay, Chadwick's large neutral particle could decay to a proton, electron, and the smaller neutral particle (now called an electron antineutrino): Fermi's paper, written in 1934, unified Pauli's neutrino with Paul Dirac's positron and Werner Heisenberg's neutron–proton model and gave a solid theoretical basis for future experimental work.

By 1934, there was experimental evidence against Bohr's idea that energy conservation is invalid for beta decay: At the Solvay conference of that year, measurements of the energy spectra of beta particles (electrons) were reported, showing that there is a strict limit on the energy of electrons from each type of beta decay. Such a limit is not expected if the conservation of energy is invalid, in which case any amount of energy would be statistically available in at least a few decays.

The natural explanation of the beta decay spectrum as first measured in 1934 was that only a limited (and conserved) amount of energy was available, and a new

particle was sometimes taking a varying fraction of this limited energy, leaving the rest for the beta particle. Pauli made use of the occasion to publicly emphasize that the still-undetected "neutrino" must be an actual particle.

The first evidence of the reality of neutrinos came in 1938 via simultaneous cloud-chamber measurements of the electron and the recoil of the nucleus. In 1942, Wang Ganchang first proposed the use of beta capture to experimentally detect neutrinos. In the 20 July 1956 issue of Science, Clyde Cowan, Frederick Reines, Francis B. Kruse, and Austin D. McGuire published confirmation that they had detected the neutrino, a result that was rewarded almost forty years later with the 1995 Nobel Prize.

In this experiment, now known as the Cowan–Reines neutrino experiment, antineutrinos created in a nuclear reactor by beta decay reacted with protons to produce neutrons and positrons: The positron quickly finds an electron, and they annihilate each other. The two resulting gamma rays (γ) are detectable. The neutron can be detected by its capture on an appropriate nucleus, releasing a gamma ray. The coincidence of both events—positron annihilation and neutron capture—gives a unique signature of an antineutrino interaction.

In February 1965, the first neutrino found in nature was identified by a group including Frederick Reines and Friedel Sellschop. The experiment was performed in a specially prepared chamber at a depth of 3 km in the East Rand ("ERPM") gold mine near Boksburg, South Africa. A plaque in the main building commemorates the discovery. The experiments also implemented a primitive neutrino astronomy and looked at issues of neutrino physics and weak interactions.

The antineutrino discovered by Clyde Cowan and Frederick Reines was the antiparticle of the electron neutrino. In 1962, Leon M. Lederman, Melvin Schwartz, and Jack Steinberger showed that more than one type of neutrino exists by first detecting interactions of the muon neutrino (already hypothesised with the name neutretto), which earned them the 1988 Nobel Prize in Physics.

Neutrino detectors are often built underground, to isolate the detector from cosmic rays and other background radiation. The field of neutrino astronomy is still very much in its infancy – the only confirmed extraterrestrial sources as of 2018 are the Sun and the supernova 1987A in the nearby Large Magellanic Cloud. Another likely source (three standard deviations) is the blazar TXS 0506+056 about 3.7 billion light years away. Neutrino observatories will "give astronomers fresh eyes with which to study the universe".

Various detection methods have been used. Super Kamiokande is a large volume of water surrounded by phototubes that watch for the Cherenkov radiation emitted when an incoming neutrino creates an electron or muon in the water. The Sudbury Neutrino Observatory was similar, but used heavy water as the detecting medium. Other detectors have consisted of large volumes of chlorine or gallium which are periodically checked for excesses of argon or germanium, respectively, which are created by neutrinos interacting with the original substance.

Tau leptons decay essentially immediately to either another charged lepton or pions, and cannot be observed directly in this kind of detector.

At low energies, a neutrino can scatter from the entire nucleus of an atom, rather than the individual nucleons, in a process known as coherent neutral current neutrino-nucleus elastic scattering or coherent neutrino scattering. This effect has been used to make an extremely small neutrino detector.

Chapter 2: Understanding Neutrinos

When the third type of lepton, the tau, was discovered in 1975 at the Stanford Linear Accelerator Center, it was also expected to have an associated neutrino (the tau neutrino). The first evidence for this third neutrino type came from the observation of missing energy and momentum in tau decays analogous to the beta decay leading to the discovery of the electron neutrino.

The first detection of tau neutrino interactions was announced in 2000 by the DONUT collaboration at Fermilab; its existence had already been inferred by both theoretical consistency and experimental data from the Large Electron–Positron Collider. In the 1960s, the now-famous Homestake experiment made the first measurement of the flux of electron neutrinos arriving from the core of the Sun and found a value that was between one third and one half the number predicted by the Standard Solar Model.

This discrepancy, which became known as the solar neutrino problem, remained unresolved for some thirty years, while possible problems with both the experiment and the solar model were investigated, but none could be found. Eventually, it was realized that both were actually correct and that the discrepancy between them was due to neutrinos being more complex than was previously assumed.

It was postulated that the three neutrinos had nonzero and slightly different masses, and could therefore oscillate into undetectable flavors on their flight to the Earth. This hypothesis was investigated by a new series of experiments, thereby opening a new major field of research that still continues. Eventual confirmation of the phenomenon of neutrino oscillation led to two Nobel prizes, one to R.

Davis, who conceived and led the Homestake experiment and Masatoshi Koshiba of Kamiokande, whose work confirmed it, and one to Takaaki Kajita of Super-Kamiokande and A.B. McDonald of Sudbury Neutrino Observatory for their joint experiment, which confirmed the existence of all three neutrino flavors and found no deficit.

A practical method for investigating neutrino oscillations was first suggested by Bruno Pontecorvo in 1957 using an analogy with kaon oscillations; over the subsequent 10 years, he developed the mathematical formalism and the modern formulation of vacuum oscillations. In 1985 Stanislav Mikheyev and Alexei Smirnov (expanding on 1978 work by Lincoln Wolfenstein) noted that flavor oscillations can be modified when neutrinos propagate through matter.

This so-called Mikheyev–Smirnov–Wolfenstein effect (MSW effect) is important to understand because many neutrinos emitted by fusion in the Sun pass through the

dense matter in the solar core (where essentially all solar fusion takes place) on their way to detectors on Earth. Starting in 1998, experiments began to show that solar and atmospheric neutrinos change flavors (see Super-Kamiokande and Sudbury Neutrino Observatory).

This resolved the solar neutrino problem: the electron neutrinos produced in the Sun had partly changed into other flavors which the experiments could not detect. Although individual experiments, such as the set of solar neutrino experiments, are consistent with non-oscillatory mechanisms of neutrino flavor conversion, taken altogether, neutrino experiments imply the existence of neutrino oscillations. Especially relevant in this context are the reactor experiment KamLAND and the accelerator experiments such as MINOS.

The KamLAND experiment has indeed identified oscillations as the neutrino flavor conversion mechanism involved in the solar electron neutrinos. Similarly MINOS confirms the oscillation of atmospheric neutrinos and gives a better determination of the mass squared splitting. Takaaki Kajita of Japan, and Arthur B. McDonald of Canada, received the 2015 Nobel Prize for Physics for their landmark finding, theoretical and experimental, that neutrinos can change flavors.

As well as specific sources, a general background level of neutrinos is expected to pervade the universe, theorized to occur due to two main sources: the Big Bang and supernovae. Around 1 second after the Big Bang, neutrinos decoupled, giving rise to a background level of neutrinos known as the cosmic neutrino background (CNB). A second diffuse neutrino background is supernova-originated. Raymond Davis, Jr.

Koshiba's work also resulted in the first real-time observation of neutrinos from the SN 1987A supernova in the nearby Large Magellanic Cloud. These efforts marked the beginning of neutrino astronomy. SN 1987A represents the only verified detection of neutrinos from a supernova. However, many stars have exploded as supernovae in the universe, leaving a theorized diffuse supernova neutrino background. Neutrinos have half-integer spin (1/2ħ); therefore they are fermions.

Neutrinos are leptons; therefore they are colorless fermions that cannot interact with the gluons of the strong force. They have only been observed to interact through the weak force, although it is assumed that they also interact gravitationally. Since they have non-zero mass, some theories permit, but do not require, neutrinos to interact magnetically; as yet there is no experimental evidence for a non-zero magnetic moment in neutrinos.

Chapter 3: Key Characteristics of Neutrinos

The weak force makes neutrinos in three leptonic flavors — electron (νe), muon (νμ), and tau (ντ) — each tied to the correspondingly named charged lepton. Long thought to carry no mass at all, neutrinos in fact come in three discrete masses, and each flavor state is a blend of the three underlying mass eigenstates.

From calculations based on cosmological models, the sum of the three neutrino

masses must be below 0.120 eV/c2. Direct and independent measurements by the Karlsruhe Tritium Neutrino (KATRIN) experiment found the upper limit of the mass of the electron antineutrino as 0.45 eV/c2, which is at least 5 orders of magnitude below the next lightest fermion. This large ratio suggests the possibility that the mass-creation mechanism for neutrinos differs from that of other fermions.

More formally, neutrino flavor eigenstates (creation and annihilation combinations) are not the same as the neutrino mass eigenstates (simply labeled "1", "2", and "3"). As of 2024, it is not known which of these three is the heaviest. The neutrino mass hierarchy consists of two possible configurations. In analogy with the mass hierarchy of the charged leptons, the configuration with mass 2 being lighter than mass 3 is conventionally called the "normal hierarchy", while in the "inverted hierarchy", the opposite would hold.

Several major experimental efforts are underway to help establish which is correct. A neutrino created in a specific flavor eigenstate is in an associated specific quantum superposition of all three mass eigenstates. The three masses differ so little that they cannot possibly be distinguished experimentally within any practical flight path. The proportion of each mass state in the pure flavor states produced has been found to depend profoundly on the flavor. The relationship between flavor and mass eigenstates is encoded in the PMNS matrix.

Experiments have established moderate- to low-precision values for the elements of this matrix, with the single complex phase in the matrix being only poorly known, as of 2016. A non-zero mass means neutrinos could have a tiny magnetic moment. If so, neutrinos would interact electromagnetically, albeit probably undetectably considering their enormous velocities. No such interaction has ever been observed. Neutrinos oscillate between different flavors in flight.

Consider an electron neutrino born in a beta decay: by the time it reaches a faraway detector it may register as a muon or tau neutrino, depending on which charged lepton shows up in the detector. This oscillation occurs because the three mass state components of the produced flavor travel at slightly different speeds, so that their quantum mechanical wave packets develop relative phase shifts that change how they combine to produce a varying superposition of three flavors.

Each flavor component thereby oscillates as the neutrino travels, with the flavors varying in relative strengths. The relative flavor proportions when the neutrino interacts represent the relative probabilities for that flavor of interaction to produce the corresponding flavor of charged lepton. There are other possibilities in which neutrinos could oscillate even if they were massless: If Lorentz symmetry were not an exact symmetry, neutrinos could experience Lorentz-violating oscillations.

Neutrinos traveling through matter can interact with electrons and the interaction differs for electron neutrinos compared to muon- or tau-neutrinos. This difference alters the neutrino oscillations, call the Mikheyev–Smirnov–Wolfenstein effect after the theorists who proposed it. Under certain conditions of electron number density the effect can be amplified. These conditions may be encountered by solar neutrinos at

some point as they travel through the Sun, providing a possible explanation of the observed solar neutrino problem.

For each neutrino, there also exists a corresponding antiparticle, called an antineutrino, which also has no electric charge and half-integer spin. They are distinguished from the neutrinos by having opposite signs of lepton number and opposite chirality (and consequently opposite-sign weak isospin). As of 2016, no evidence has been found for any other difference.

So far, despite extensive and continuing searches for exceptions, in all observed leptonic processes there has never been any change in total lepton number; for example, if the total lepton number is zero in the initial state, then the final state has only matched lepton and anti-lepton pairs: electron neutrinos appear in the final state together with only positrons (anti-electrons) or electron antineutrinos, and electron antineutrinos with electrons or electron neutrinos.

Antineutrinos are produced in nuclear beta decay together with a beta particle (in beta decay a neutron decays into a proton, electron, and antineutrino). All antineutrinos observed thus far had right-handed helicity (i.e., only one of the two possible spin states has ever been seen), while neutrinos were all left-handed.

Nevertheless, because neutrinos have mass, their helicity is frame-dependent, so particle physicists have fallen back on the frame-independent property of chirality that is closely related to helicity, and for practical purposes the same as the helicity of the ultra-relativistic neutrinos that can be observed in detectors. Antineutrinos were first detected as a result of their interaction with protons in a large tank of water. This was installed next to a nuclear reactor as a controllable source of the antineutrinos (see Cowan–Reines neutrino experiment).

Chapter 4: The Science Behind Neutrinos

Researchers around the world have begun to investigate the possibility of using antineutrinos for reactor monitoring in the context of preventing the proliferation of nuclear weapons. Because antineutrinos and neutrinos are neutral particles, it is possible that they are the same particle.

Rather than conventional Dirac fermions, neutral particles can be another type of spin 1/2 particle called Majorana particles, named after the Italian physicist Ettore Majorana who first proposed the concept. For the case of neutrinos this theory has gained popularity as it can be used, in combination with the seesaw mechanism, to explain why neutrino masses are so small compared to those of the other elementary particles, such as electrons or quarks.

Majorana neutrinos would have the property that the neutrino and antineutrino could be distinguished only by chirality; what experiments observe as a difference between the neutrino and antineutrino could simply be due to one particle with two possible chiralities. As of 2019, it is not known whether neutrinos are Majorana or Dirac particles. It is possible to test this property experimentally.

For example, if neutrinos are indeed Majorana particles, then lepton-number violating processes such as neutrinoless double-beta decay would be allowed, while they would not if neutrinos are Dirac particles. Several experiments have been and are being conducted to search for this process, e.g. GERDA, EXO, SNO+, and CUORE. The cosmic neutrino background is also a probe of whether neutrinos are Majorana particles, since there should be a different number of cosmic neutrinos detected in either the Dirac or Majorana case.

Neutrinos can interact with a nucleus, changing it to a different nucleus. This process is used in radiochemical neutrino detectors. In this case, the energy levels and spin states within the target nucleus have to be taken into account to estimate the probability for an interaction. In general the interaction probability increases with the number of neutrons and protons within a nucleus. It is very hard to uniquely identify neutrino interactions among the natural background of radioactivity.

For this reason, in early experiments a special reaction channel was chosen to facilitate the identification: the interaction of an antineutrino with one of the hydrogen nuclei in the water molecules. A hydrogen nucleus is a single proton, so simultaneous nuclear interactions, which would occur within a heavier nucleus, do not need to be considered for the detection experiment.

Within a cubic meter of water placed right outside a nuclear reactor, only relatively few such interactions can be recorded, but the setup is now used for measuring the reactor's plutonium production rate. Very much like neutrons do in nuclear reactors, neutrinos can induce fission reactions within heavy nuclei. So far, this reaction has not been measured in a laboratory, but is predicted to happen within stars and supernovae. The process affects the abundance of isotopes seen in the universe.

Neutrino-induced disintegration of deuterium nuclei has been observed in the Sudbury Neutrino Observatory, which uses a heavy water detector. The three known flavors — electron, muon, and tau — take their names from the partner leptons they travel with in the Standard Model. The current best measurement of the number of neutrino types comes from observing the decay of the Z boson.

This particle can decay into any light neutrino and its antineutrino, and the more available types of light neutrinos, the shorter the lifetime of the Z boson. Measurements of the Z lifetime have shown that three light neutrino flavors couple to the Z.

There are several active research areas involving the neutrino with aspirations of finding: the three neutrino mass values the degree of CP violation in the leptonic sector (which may lead to leptogenesis) evidence of physics which might break the Standard Model of particle physics, such as neutrinoless double beta decay, which would be evidence for violation of lepton number conservation.

International scientific collaborations install large neutrino detectors near nuclear reactors or in neutrino beams from particle accelerators to better constrain the neutrino masses and the values for the magnitude and rates of oscillations between neutrino flavors. These experiments are thereby searching for the existence of CP

violation in the neutrino sector; that is, whether or not the laws of physics treat neutrinos and antineutrinos differently.

The KATRIN experiment in Germany began to acquire data in June 2018 to determine the value of the mass of the electron neutrino, with other approaches to this problem in the planning stages. Despite their tiny masses, neutrinos are so numerous that their gravitational force can influence other matter in the universe. The three known neutrino flavors are the only candidates for dark matter that are experimentally established elementary particles – specifically, they would be hot dark matter.

However, the currently known neutrino types seem to be essentially ruled out as a substantial proportion of dark matter, based on observations of the cosmic microwave background. It still seems plausible that heavier, sterile neutrinos might compose warm dark matter, if they exist. Other efforts search for evidence of a sterile neutrino – a fourth neutrino flavor that would not interact with matter like the three known neutrino flavors.

Gran Sasso National Laboratories (LNGS), Italy, site of Borexino, CUORE, and other experiments. Jiangmen Underground Neutrino Observatory (JUNO), Kaiping, Jiangmen, China

Soudan Mine, home of Soudan 2, MINOS, and CDMS

Kamioka Observatory, Japan, home of Super-Kamiokande (Super-K) and its successor Hyper-Kamiokande, currently under construction.

Nobel laureates Steven Weinberg, George Smoot III, and Carlo Rubbia, and other physicists not affiliated with the experiment, including Michio Kaku, expressed skepticism about the accuracy of the experiment on the basis that the results challenged a long-held theory consistent with the results of many other tests of special relativity. Nevertheless, Ereditato, the OPERA spokesperson, stated that no one had an explanation that invalidated the experiment's results.

Previous experiments of neutrino speed played a role in the reception of the OPERA result by the physics community. Those experiments did not detect statistically significant deviations of neutrino speeds from the speed of light. For instance, Astronomer Royal Martin Rees and theoretical physicists Lawrence Krauss and Stephen Hawking stated neutrinos from the SN 1987A supernova explosion arrived almost at the same time as light, indicating no faster-than-light neutrino speed.

Chapter 5: Observation and Measurement of Neutrinos

While the measured decay width of the Z boson indicates the existence of only three active light neutrinos, sterile neutrinos do not participate in the weak interaction and are therefore not subject to this experimental constraint. The existence of such particles is in fact hinted by experimental data from the LSND experiment.

On the other hand, the currently running MiniBooNE experiment suggested that sterile neutrinos are not required to explain the experimental data, although the latest research into this area is on-going and anomalies in the MiniBooNE data may allow for exotic neutrino types, including sterile neutrinos. A re-analysis of reference electron spectra data from the Institut Laue-Langevin in 2011 has also hinted at a fourth, light sterile neutrino.

Triggered by the 2011 findings, several experiments at very short distances from nuclear reactors have searched for sterile neutrinos since then. While most of them were able to rule out the existence of a light sterile neutrino, the combined results are ambiguous. According to an analysis published in 2010, data from the Wilkinson Microwave Anisotropy Probe of the cosmic background radiation is compatible with either three or four types of neutrinos.

Another hypothesis concerns neutrinoless double-beta decay, which, if it exists, would violate lepton number conservation and show that neutrinos have a non-zero Majorana mass. Searches for this mechanism are underway but have not yet found evidence for it. Cosmic ray neutrino experiments detect neutrinos from space to study both the nature of neutrinos and the cosmic sources producing them. Before neutrinos were found to oscillate, they were generally assumed to be massless, propagating at the speed of light (c).

According to the theory of special relativity, the question of neutrino velocity is closely related to their mass: If neutrinos are massless, they must travel at the speed of light, and if they have mass they cannot reach the speed of light. Due to their tiny mass, the predicted speed is extremely close to the speed of light in all experiments, and current detectors are not sensitive to the expected difference. Also, there are some Lorentz-violating variants of quantum gravity which might allow faster-than-light neutrinos.

A comprehensive framework for Lorentz violations is the Standard-Model Extension (SME). The first measurements of neutrino speed were made in the early 1980s using pulsed pion beams (produced by pulsed proton beams hitting a target). The pions decayed producing neutrinos, and the neutrino interactions observed within a time window in a detector at a distance were consistent with the speed of light.

This measurement was repeated in 2007 using the MINOS detectors, which found the speed of 3 GeV neutrinos to be, at the 99% confidence level, in the range between 0.999976 c and 1.000126 c. The central value of 1.000051 c is higher than the speed of light but, with uncertainty taken into account, is also consistent with a velocity of exactly c or slightly less. This measurement set an upper bound on the mass of the muon neutrino at 50 MeV with 99% confidence.

After the detectors for the project were upgraded in 2012, MINOS refined their initial result and found agreement with the speed of light, with the difference in the arrival time of neutrinos and light of $-0.0006\% \pm 0.0012\%$. A similar observation was made, on a much larger scale, with supernova 1987A (SN 1987A). Antineutrinos with an energy of 10 MeV from the supernova were detected within a time window that was

consistent with the speed of light for the neutrinos.

So far, all measurements of neutrino speed have been consistent with the speed of light. In September 2011, the OPERA collaboration released calculations showing velocities of 17 GeV and 28 GeV neutrinos exceeding the speed of light in their experiments. In November 2011, OPERA repeated its experiment with changes so that the speed could be determined individually for each detected neutrino. The results showed the same faster-than-light speed.

In February 2012, reports came out that the results may have been caused by a loose fiber optic cable attached to one of the atomic clocks which measured the departure and arrival times of the neutrinos. An independent recreation of the experiment in the same laboratory by ICARUS found no discernible difference between the speed of a neutrino and the speed of light. The Standard Model of particle physics assumed that neutrinos are massless.

The experimentally established phenomenon of neutrino oscillation, which mixes neutrino flavor states with neutrino mass states (analogously to CKM mixing), requires neutrinos to have nonzero masses. Massive neutrinos were originally conceived by Bruno Pontecorvo in the 1950s. Enhancing the basic framework to accommodate their mass is straightforward by adding a right-handed Lagrangian.

Providing for neutrino mass can be done in two ways, and some proposals use both: If, like other fundamental Standard Model fermions, mass is generated by the Dirac mechanism, then the framework would require an additional right-chiral component which is an SU(2) singlet. This component would have the conventional Yukawa interactions with the neutral component of the Higgs doublet; but, otherwise, would have no interactions with Standard Model particles.

John Ellis, theoretical physicist at CERN, believed it difficult to reconcile the OPERA results with the SN 1987A observations. Observations of this supernova restricted 10 MeV anti-neutrino speed to less than 20 parts per billion (ppb) over lightspeed. This was one of the reasons most physicists suspected the OPERA team had made an error.

Physicists affiliated with the experiment had refrained from interpreting the result, stating in their paper: Despite the large significance of the measurement reported here and the stability of the analysis, the potentially great impact of the result motivates the continuation of our studies in order to investigate possible still unknown systematic effects that could explain the observed anomaly. We deliberately do not attempt any theoretical or phenomenological interpretation of the results.

Theoretical physicists Gian Giudice, Sergey Sibiryakov, and Alessandro Strumia showed that superluminal neutrinos would imply some anomalies in the velocities of electrons and muons, as a result of quantum-mechanical effects. Such anomalies could be already ruled out from existing data on cosmic rays, thus contradicting the OPERA results. Andrew Cohen and Sheldon Glashow predicted that superluminal neutrinos would radiate electrons and positrons and lose energy through vacuum Cherenkov effects, where a particle traveling faster than light decays continuously into other slower particles.

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.