Neutrino: The Particle that Shouldn't Exist

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In 1930, the great physicist Wolfgang Pauli did something that "no theorist should ever do": he invented a new particle that he thought nobody could ever detect in order to save the principle of energy conservation in certain radioactive decays he was studying. Pauli's impossible particle turned out to be real: the neutrino, a particle that one of its discoverers called "the most tiny quantity of reality ever imagined by a human being".

This lecture will chart the fascinating history and science of neutrinos, from their discovery in 1956 to the role they played in understanding solar physics. We will see that neutrinos are today hunted for in the depths of the Antarctic ice cap, shot through the crust of the Earth and observed in huge water tanks under miles of rock. They are revealing the physics of distant supernovae, helping understand dark matter and might hold the key to the Big Bang itself.

Pauli's Evil Spell

On September 23rd, 2011, the physics world was shocked when Prof. Antonio Ereditato presented at CERN, the European centre of particle physics research in Geneva, new results from a particle physics experiment called OPERA. The experiment consisted of timing the flight time of a beam of particles between CERN in Geneva and the OPERA detector, located 730 km away in Italy, in a cavern inside the Gran Sasso mountain near L'Aquila. The particles, travelling at the speed of light, were supposed to traverse the Earth's crust in 2.4 microseconds, but Prof. Ereditato reported that after three years of data taking their experiment had found that the particles arrived 60 nanoseconds earlier than that: they were travelling 7 km/s faster than the speed of light!

The implication was immense: the speed of light limit, the cornerstone of Einstein's theories of special and general relativity, could be broken. This would have revolutionized our understanding of physics. The world media picked up the story, with headlines such as "Does it mean time travel is possible?". Other experiments rushed to verify the claim, while theoretical physicists came up with a flurry of possible explanations. The report of the findings, posted before peer review so that the community could scrutinize it and help find any flaws, generated over 100 blog posts by scientists and over 200 scientific papers in the three months following its appearance.

Perhaps the physics community would have been better served had they recalled the tongue-in-cheek "Pauli effect" (not to be confused with the *Pauli exclusion principle*, a scientific fact). The purportedly faster-than-light particles were neutrinos, whose introduction into particle physics was due, as we shall see, to Wolfgang Pauli, one of the fathers of quantum theory and a giant of 20th century physics (Einstein considered Pauli as his "intellectual heir"). Strange yet believable reports started circulated in the 1930s and beyond about uncanny failures of laboratory equipment when Pauli was present, so much so that the Nobel Prize-winning physicist Otto Stern banned him from his lab in Hamburg for fear of his destructive influence (in 1950, the cyclotron at Princeton university burnt down when Pauli was visiting). Maybe the physicist who first dreamt up neutrinos was haunting the experiment that found them to violate Einstein's speed limit?

In June 2012, nine months after the shock announcement, the scientists responsible for the experiment discovered that a faulty cable was to blame for the faster-than-light measurement. Neutrinos slowed down to the speed of light. Prof. Ereditato resigned his post.

From "Desperate Remedy" To New Physics

Once "a desperate remedy" adopted by Pauli to save the principle of conservation of energy, neutrinos have today become one of the most helpful and fascinating probes into fundamental particle physics, high energy astrophysics and cosmology. The very property that makes them incredibly difficult to measure is also their most useful characteristic, in that they carry information about processes and corners of the universe otherwise impossible to see.

The fascinating history of neutrinos begins in 1930, when Pauli was greatly puzzled by the mystery of beta decay: certain unstable atoms had been observed to spontaneously transform into a different element, emitting an electron in the process. The electron had been measured to have a range of kinetic energies, which seemed to contradict the fundamental principle of conservation of energy. Whatever process was at work inside the atom, if a certain amount of energy was available as a result and some electrons only carried away a fraction of it, where did the rest of the energy go? Niels Bohr (he of the quantum theory of the atom) proposed to abandon conservation of energy altogether; Pauli hit on a different idea. Conscious that his proposal was bound to be controversial, he first tested the waters by advancing it in a letter to his circle of "radioactive friends" in Tübingen, a university town in South Germany 200 km North of Zurich, where he worked at the Swiss Federal Institute of Technology (ETHZ).

In his letter, Pauli proposed a "desperate way to escape from the problems of […] the continuous beta spectrum in order to save […] the law of energy conservation". He postulated that inside the atom lurked a new, electrically neutral and light particle, which he called "the neutron" (*not* the neutron we know today!), and that such a "neutron" would be emitted together with the electron during beta decay. The missing energy was being carried away by the unseen "neutron". At that time, the only known sub-atomic particles were the proton (positively charged) and the electron (negatively charged), so to introduce a third, charge-neutral entity was a bold step indeed. Two years later, James Chadwick announced in a Nature paper the discovery of a heavy, neutral particle inside the nucleus – the neutron we know today. Pauli's still hypothetical particle was in need of a new name. Italian physicist Enrico Fermi dubbed it "neutrino", by adding the Italian suffix -ino (meaning "small") to the root of "neutral" (as opposed to "-one", meaning "big", as in the Italian "neutrone"). Fermi then showed in 1934 that if the electron and the neutrino are created together during beta decay in virtue of an interaction much weaker than the force holding in the nucleus together, the observed distribution of electron energies could be explained quantitatively. We now know that this is indeed the case, and that an electron-antineutrino pair is formed when a neutron decays into a proton inside the nucleus, thus changing the element into the one to its right in the periodic table. A new branch of physics dedicated to the study of this novel "weak interaction" was born. To this day, no fewer than 10 Nobel prizes for physics have been awarded for discoveries in the field[1], sadly none of them to a woman (thus far).

Catch Me If You Can

As the theory of weak interactions was worked out, it became clear why neutrinos had not been seen before: the weak interaction, the only force to which they are subject[2], only reaches a distance

[1] Fermi (1938), Yang and Lee (1957), Gell-Mann (1969), Glashow, Salam and Weinberg (1979), Rubbia and van der Meer (1984), Lederman, Schwartz and Steinberger (1988), Reines (1995), 't Hooft and Veltman (1999), Davis and Koshiba (2002), Kajita and McDonald (2015).

[2] This is not strictly correct, as neutrinos are also subject to gravity (regardless of whether they possess mass; photons are massless, yet they interact gravitationally).

100 times smaller than the size of a nucleus, where it's about 100,000 times weaker than the electromagnetic force. As a consequence, neutrinos can effortlessly penetrate the densest material, with only a minuscule chance of being stopped (and hence, detected). On average, a neutrino could traverse a light year of lead (that's *a thousand million km of lead!*) before being stopped. A 1934 paper by theoretical physicists Rudolf Peierls and Hans Bethe had concluded that observing the neutrino was practically impossible.

It would take another two decades before the ghostly neutrinos would be observed experimentally, although theorists were by then convinced beyond doubt of their existence. In 1951, Fred Reines, who had worked with Richard Feynman on the Manhattan project, decided that he was going to achieve the impossible feat of detecting the neutrino, "because" – he would later say – "everybody said you couldn't do it". Having been directly involved in nuclear testing in Los Alamos during the war, he first imagined placing a detector near an atomic explosion to catch some of the copious flux of neutrinos produced. Upon hearing of his plan, Fermi wrote to express his interest and confidence that it would succeed: "I shall be very interested in seeing how your 10 cubic feet scintillator counter [a particle detector] is going to work, but I do not know of any reason why it should not[3]".

Upon meeting fellow physicist Clyde Cowan at Los Alamos, Reines decided to switch to a less extreme source of neutrinos: the nuclear plant of Hanford, Washington. Their new idea was to exploit the intense flux of 10,000 billion antineutrinos per square cm per second produced by the nuclear reactor, and to detect the high energy photons produced by the interaction of antineutrinos and protons in the water of a 400-litre tank. The first experiment produced only tentative results, so they moved it near another nuclear plant, this time in South Carolina, with more favourable conditions. In July 1956 they announced the detection of the neutrino, after reliably seeing an average of 3 events per hour. They had managed to catch what Reines would describe as "...the most tiny quantity of reality ever imagined by a human being".

This was just the beginning of a journey of discoveries that over the years would see the neutrino at the heart of many mysteries in physics, some of which remain unsolved to this day. The antineutrino seen by Reines and Cowan was the "electronic" type, associated with the electron; a second type of neutrino, the muon neutrino -associated with a heavier version of the electron called the muon- was discovered in 1962; the final member of the neutrino family, the tau neutrino, was observed in 2000. Today, advanced neutrino detectors technology inspired by Reines and Cowan pioneering efforts could be deployed to monitor the production of weapon-grade material in nuclear reactors in sensitive countries (see Huber, 2020).

Neutrinos' Disappearing Trick

Neutrinos started cropping up everywhere nuclear reactions were present. Nuclear fusion in the Sun's core transforms hydrogen into helium, and in the process, it produces a flux of 10 billion neutrinos per second at the location of the Earth. Starting in the 70s, Raymond Davis built an underground neutrino detector in the Homestake gold mine in South Dakota and filled it with 450,000 litres of a chlorine-based dry cleaning fluid. Upon hitting the chlorine atoms, solar neutrinos would produce about 20 radioactive argon atoms per month. After over 25 years of efforts, Davis and collaborators announced in 1998 that they could only see a third of the expected number of electron neutrinos. A lot of head scratching followed among physicists: either the theoretical calculation of what goes on inside the Sun was wrong, or Davis' experiment wasn't working correctly… or the the neutrinos themselves were up to some more mischief.

An even bigger detector was built 2 km underground near Sudbury, Canada: with its 1000 tons of ultra pure heavy water (i.e., water containing a high fraction of molecules with a deuterium nucleus

[3] Enrico Fermi to Fred Reines, letter dated Oct 8th, 1952.

–one proton and one neutron– replacing the usual hydrogen atom), the Sudbury Neutrino Observatory was able to measure simultaneously the number of electron neutrinos and the total number of neutrinos across the three families (which physicists call the three “flavours”). The results confirmed that Davis’ experiment and the theoretical calculations of the solar electron neutrino production were *both* right: the *total* amount of neutrinos reaching the Earth was as expected from theory, but only a third of them were of the electronic family. The remainder was made up of muon and tau neutrinos. Neutrinos had changed flavour as they emerged from the electron-rich environment of the Sun[4].

This disappearing trick of electron neutrinos had profound implications for the Standard Model of particle physics. According to the standard theory, neutrinos ought to be massless, just like the photon, in which case each neutrino family keeps strictly by itself and electron neutrinos cannot change into other flavours. But the experimental evidence of “neutrino mixing” (i.e., that neutrinos from different families could change into each other) meant that the Standard Model of particle physics is incomplete. It also implied that neutrinos must have mass, against the expectation of the otherwise very successful Standard Model. That neutrinos could transmutate from one family to the other was first established in 1998, when the Super-Kamiokande detector in Japan (a behemoth tank holding 50,000 tons of ultra-pure water) observed both electronic and muon neutrinos produced in the Earth’s atmosphere by incoming cosmic rays (mostly protons). They found that the ratio of muon to electron neutrinos was smaller than the theoretical expectations, and that muon neutrinos going upwards (i.e., produced in the atmosphere on the other side of the Earth) were only half the number of neutrinos travelling downwards (i.e., produced in the atmosphere just above the detector). This meant that some of the muon neutrinos transformed into unobserved tau neutrinos as they traversed the Earth.

The Almost Invisible Messenger

As our understanding of neutrinos rapidly increased, it became clear that these ghostly particles carry invaluable information about the universe, if only we can decrypt it. Neutrinos being neutral and so feebly interacting, they are not deflected along their path by magnetic fields, like cosmic rays are; they are not stopped by dense plasma in the early Universe or within stars, nor do they lose energy when traversing dust clouds, like photons do. Astrophysicists started hunting for them, for they could tell us about processes deep inside stars, test physical conditions right after the Big Bang, or even reveal the nature of dark matter in ways that other, more ordinary particles never could.

The birth of neutrino astronomy can be pinpointed to February 23rd, 1987, at precisely 16:35:35 Tokyo local time – although it would take another four days before anyone, including the Nobel-prize winner discoverer, would realize it. On February 23rd, the light from the supernova explosion of a giant blue star 168,000 light years away, in the Large Magellanic Cloud, reached the Earth. At the time of the explosion, Homo Sapiens still shared the Earth with the Neanderthals. This was the first chance since the invention of the telescope to see a supernova event relatively close by; the last supernova in the vicinity of the Earth had been Kepler’s supernova in 1604 (much closer and much brighter than the one in 1987). Theoretical models of supernova explosions predicted that much of the huge energy released would be carried away in the form of almost-invisible neutrinos, and that 10,000 billion billion of them would pass through the Earth. Two days after the light from the supernova was detected, astronomer Sidney Bludman at the University of Pennsylvania sent a fax (yes, that was before the world wide web was invented!) to the University of Tokyo, alerting his colleagues in charge of the Kamioka neutrino detector, a precursor to the bigger Super-Kamiokande. Bludman’s fax was nothing short of frantic with excitement: “SENSATIONAL NEWS! SUPERNOVA

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[4] This was *not* evidence for neutrino oscillations, as it is often wrongly stated (a mistake made even by the Nobel committee in 2015), see Adrian Cho, “Did the Nobel committee get the physics wrong?”, Science, Dec 14th 2016, online: https://www.sciencemag.org/news/2016/12/did-nobel-committee-get-physics-wrong

WENT OFF 4-7 DAYS AGO IN LARGE MAGELLANIC CLOUD […] CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!"

The magnetic tapes recording the data from the detector were sent for (yes, that was before the world wide web was invented!) and fetched from Kamioka. Two days later, as researchers poured over hundreds of pages of printouts, Ms Keiko Hirata, a master's student, found a clear spike in the number of events, lasting about 13 seconds: her heart must have skipped a beat as she realized she was the first person to see neutrinos from a supernova explosion. Fifteen years later, Masatoshi Koshiba, the scientist who directed the group, received a quarter of the share of a Nobel prize. Two further detectors found a signal, and all in all about two dozen neutrinos were observed. The fact that they had a range of energies and arrival times differing by a few seconds can be used to put a constraint on the neutrino mass: if neutrinos were massless, all the neutrinos would have arrived at exactly the same time as they all travelled at exactly the same speed, namely the speed of light. The range of their arrival times told us that their mass was at most 50 millionths of that of an electron. The fact that they were discovered at all enabled astronomers to probe the finer details of their supernova explosion models. The era of neutrino astronomy had begun.

Our Helpful Friend the Neutrino

Today, neutrinos have become a powerful instrument in the astrophysicist's toolbox: they are helping our searches for dark matter, revealing unexpected phenomena in the high-energy universe and probing the earliest moments after the Big Bang, all the while keeping some of their physics secrets close to their chest.

Dark matter has long been the *bête noire* of cosmologists. Since the first evidence of its existence in the 1930s, data have accumulated showing that there is about 5 times more dark matter in the universe than normal matter. Yet nobody knows what dark matter is made of. A prime possibility is that dark matter is a massive, neutral particle that does not interact with light – just like the neutrino! Neutrinos were thus the obvious first port of call as an explanation for dark matter: a sea of neutrinos was produced in the aftermath of the Big Bang, and those particles are still around us, their energy reduced by the cosmic expansion to a temperature a mere two degrees Kelvin above absolute zero, and their density in space diluted to 336 neutrinos per cubic centimetre. Could these relic neutrinos from the Big Bang be the mysterious dark matter? Unfortunately, it was quickly realized that neutrinos could only account for at most 10% of the dark matter in the universe, as particle physics experiments were able to put an increasingly stringent upper limit to their mass. Furthermore, if neutrinos were the bulk of dark matter, they would change the way galaxies grow in the universe, by "washing out" gravitational potentials due to their high speed (close to the speed of light). This effect has not been observed in large galaxy surveys that map out the position and distance of millions of galaxies in the cosmos, thus ruling out neutrinos as the main component of dark matter.

Even though it is today accepted that neutrinos cannot be the long looked-for dark matter, they can still help us in our quest to find this mysterious particle. An extension of the Standard Model called supersymmetry predicts that dark matter is a massive, neutral particle, thousands of times heavier than a proton. Over time, the dark matter in our solar system is captured by the Sun (and, to a much smaller extent, by the Earth), and it sinks to the core of our star (and of our planet). When two dark matter particles collide, they annihilate and in the process are expected to emit, among other particles, neutrinos, which escape at close to the speed of light (by contrast, a photon created in the core of the Sun by fusion takes tens of thousands of years to reach the surface, as it keeps being scattered by the dense stellar plasma). So by detecting such high-energy neutrinos generated by the collision of dark matter particles either in the core of the Sun or the Earth, we hope to be able to learn about dark matter itself.

The prime instrument for this and other astrophysical neutrino searches today is the IceCube detector, a feat of ingenuity and technical prowess. The detector consists of 86 strings of photosensors, set at a depth of between 1.5 and 2.5 km into the crystal-clear ice of Antarctica near the Amundsen-Scott South Pole Station. The photosensors observe a volume of a billion tons of ice (20,000 times bigger than Super-Kamiokande), which acts as a detecting medium to incoming neutrinos – thus replacing the heavy water, ultra-pure water or chlorine of other experiments. When a neutrino interacts with the polar cap ice, it produces a shower of charged particle that travel faster than the speed of light in ice. This creates the light equivalent of a sonic boom, namely a cone of blue light that is picked up by the photosensors.

The IceCube search to date hasn't turned up any evidence for dark matter, but in keeping with tradition it did reveal something new about the universe. After sifting through hundreds of thousands of atmospheric neutrinos (produced "locally" by incoming protons from space hitting the atmosphere of the Earth), IceCube identified 28 neutrinos which had a much larger energy than anything previously detected, and definitely originated from outside our galaxy. There is no known mechanism for accelerating neutrinos to such high-energy (over 1000 times larger than what the Large Hadron Collider at CERN can achieve), except perhaps the gargantuan particle jets emitted by black holes in distant galaxies as they swallow stars all around them. The continuing study of such events will hopefully shed light on some of the most mysterious and highly energetic events in the cosmos.

Neutrinos are also being used to test the physics of the very early universe. The oldest light in the cosmos was released 380,000 years after the Big Bang, when the cosmic microwave background radiation was formed. While this is a short amount of time compared to the time elapsed since (13.8 billion years), it is substantially later than "time zero", when the Big Bang itself happened. Cosmic neutrinos, on the other hand, were produced when the universe was just one second old and have been travelling through the cosmos since. While detecting such cosmic neutrinos in the lab was once considered hopeless, new technologies involving 2D graphene layers make the prospect potentially viable. This would require about 100g of tritium, a radioactive isotope of hydrogen that is used as a luminescent agent and in nuclear weapons, a relatively large amount but not technologically unfeasible (total tritium production in the United States since 1955 runs into the hundreds of kg). In the meantime, the signature of the existence of a cosmic neutrino background has been unambiguously seen in the details of the temperature distribution of cosmic microwave background photons. Various analyses have demonstrated that the cosmic microwave data are in agreement with the prediction of three families of neutrinos we see today having existed as early as 1 second after the Big Bang.

Almost a century after Pauli dreamt it up, the neutrino hasn't revealed all of its secrets. Despite enormous progress and amazingly ingenious experiments, many questions remain: what is the neutrino mass? Are neutrino and anti-neutrino the same particle, as very recent results from the CUORE experiment appear to show and like the Italian physicist Ettore Majorana predicted in 1937, before mysteriously vanishing himself in 1938? Where do the ultra-high energy neutrinos seen by IceCube come from? What can neutrinos tell us about the nature of dark matter? Will relic neutrinos eventually confess the secret of the Big Bang? The particle that shouldn't exist patiently awaits; its knowledge of the universe revealed one quantum at the time.

Further reading

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