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Ghost busters

Neutrino physics is largely an art of
learning a great deal
by observing nothing.
HAIM HARARI[1]

I have done a terrible thing: I have postulated a
particle that cannot be detected.
WOLFGANG PAULI

Savannah River, South Carolina, 14 June 1956

Frederick Reines was singing as he drove to the bomb plant. He loved to sing almost as much as he loved to do physics. Back in college in New Jersey, he had even taken lessons from a voice coach at the Metropolitan Opera and sung solos in Handel's *Messiah*.[2] When he was working on a particularly tough theoretical problem, he had been known to sing for hours on end while locked away in his office. But on this June morning there was a very specific reason why his fine baritone boomed out through the wound-down car window, turning the heads of pedestrians walking by on the sidewalk. After almost a year of exhausting work – five years, if you counted the total effort that had led up to this day – he was in celebration mode. He and his team were about to achieve the impossible.

It was eight miles from Aiken, the pretty beach-side community where they had been domiciled since November, to the

Savannah River Plant. As he drove out of town, the sweet smell of camellias and magnolias came in through the window on the hot damp air, reminding him of how exotic South Carolina had seemed when they had arrived from the high desert of Los Alamos. On their first drive out from Aiken through the swampy Savannah River Valley, their car lurched over something in the road and they were tossed about like rag dolls. Looking back, they saw that what they had assumed was a speed bump was actually a giant rattlesnake.[3]

At the gates to the Savannah River Plant, Reines pulled up behind a long double-line of cars. The site, with its five nuclear reactors, separation facilities and waste dumps, covered an area larger than New York City and employed almost forty thousand people. When the US government had announced its plan to build the facility, it had said it was not for the 'manufacture of atomic weapons', but that was splitting hairs. Everyone knew the truth: it made the fuel for nuclear weapons – which is why, even in the shops and beach bars of Aiken, Savannah River was referred to as the 'bomb plant'.[4]

In early September 1949, a US Air Force B-29 bomber had sniffed the air high above the Pacific coast of the Soviet Union and caught the unmistakable aroma of an atomic bomb blast. Like most of his colleagues at Los Alamos, Reines had worked on the Manhattan Project to build the first atomic bomb, and he still remembered his shock at the announcement, a mere four years after Hiroshima, that the Russians had caught up and the US no longer had an atomic monopoly.

To counter the Soviet threat, President Harry Truman embarked on a drive to build a 'superbomb' whose destructive power would dwarf an atomic bomb. It involved the construction of vast facilities across the country, not only to make the fuel for such 'hydrogen bombs' but to assemble them. As part of the programme, on 28 November 1950 the US government announced the seizure of almost 500 square kilometres of land by the Savannah River to make two key components of nuclear bombs: tritium and plutonium. Four towns were bulldozed and six thousand people moved, and, by early 1952, the plant was in full production mode.[5]

On 1 November 1952, the US exploded a hydrogen bomb on Elugelab, part of Enewetak Atoll, a Pacific island liberated from the Japanese in the Second World War. With 700 times the destructive power of the bomb dropped on Hiroshima, it vaporised the island, creating a radioactive mushroom cloud 150 kilometres across and gouging a hole in the ocean floor more than two kilometres wide and as deep as a sixteen-storey building. But a mere nine months later, in August 1953, came the scarcely believable news that the Russians had detonated their own hydrogen bomb. Their design could not be scaled up to make bigger explosions, but everyone knew it was only a matter of time. Sure enough, on 22 November 1955, at the Soviet test site at Semipalatinsk in Kazakhstan, the Russians exploded their first true hydrogen bomb.

Reines reached the head of the line of cars, flashed his ID card through the open window and accelerated towards the hulking shape of P Reactor. The Savannah River facility boasted five reactors – R, P, K, L and C – whose letter designations had been chosen entirely at random. They were built at two-and-a-half mile intervals, so they could not be wiped out by a single Soviet nuclear strike, and were spread along a horseshoe-shaped curve to make them immune to a straight-line bombing run. Each reactor rose sixty metres into the air and was sunk twelve metres into the ground, for even more protection. It was this last feature that was of key importance to Reines and his team. It was what had brought them from New Mexico in search of their impossible quarry: a ghostly subatomic particle that had been predicted a quarter of a century earlier and whose existence would almost certainly be confirmed that day.

Zurich, December 1930

The elusive particle had been predicted by the Austrian physicist Wolfgang Pauli. A one-time infant prodigy, Pauli had at twenty-one written such a masterful survey of the theory of relativity that it had astonished even the theory's creator, Albert Einstein. In fact, Pauli – his confidence bordering on arrogance – had famously stood up at the end of a lecture given by Einstein, turned to the audience and reassured them that 'What Professor Einstein said is not entirely stupid.'[6]

In the mid-1920s, Pauli was one of the principal architects of 'quantum theory', the revolutionary description of the submicroscopic world of the atom and its constituents. His name is immortalised in the 'Pauli exclusion principle', which, by preventing electrons from piling on top of each other, makes atoms and the everyday world possible.

By the late 1920s, a new puzzle began to worry Pauli and his peers. It concerned radioactive 'beta decay'. A beta particle was one of the three distinct types of radiation spat out by the nucleus of an unstable atom as it 'decayed', rearranging its constituents to attain a more stable state. In 1899, three years after the discovery of radioactivity by Frenchman Henri Becquerel, New Zealand physicist Ernest Rutherford had shown that beta particles were 'electrons' – not the common-or-garden variety that orbited the nucleus of an atom, but electrons from inside the nucleus.

In the world of the atomic nucleus, greater stability is synonymous with lower energy. Consequently, when a nucleus decays, it drops from a higher to a lower energy 'state'. The excess energy is spat out as an alpha particle, beta particle or gamma ray. Experimenters observed that alpha particles and gamma rays were emitted at precise energies, which made perfect sense if those energies were equal to the difference in energy between the initial and final states of the nucleus. However, the English physicist James Chadwick discovered something peculiar about beta particles in 1914: unlike their cousins, they were emitted not with a precise energy but with a continuous range of energies.

Think of a gun, which uses a fixed amount of energy to fire a bullet. Every bullet exits the gun at the same speed. It is never the case that one leaves at moderate speed, the next at high speed and the one after that so slowly that it dribbles out the end of the gun barrel. But this is precisely what the tiny electron bullets spat out in beta decay do. Not surprisingly, physicists were shocked at what Chadwick's experiment was telling them.

This behaviour of beta particles might, of course, have a perfectly mundane explanation. Perhaps before escaping they bounced around inside an atom like a ball bearing in a pinball machine, striking multiple electrons and losing a portion of their energy to each one. However, by 1927, this possibility had been ruled out by an experiment by Charles Ellis and William Wooster at Cambridge University.[7] The beta particle puzzle remained, and was so serious that it caused Niels Bohr, one of the founding fathers of quantum theory and the greatest physicist of the twentieth century after Einstein, to question one of the foundation stones of physics – that energy can neither be created nor destroyed but only transformed from one type to another. Perhaps in the world of the atom, Bohr suggested, processes do not obey the 'law of conservation of energy'.

Enter Pauli, a physicist at the Swiss Federal Institute of Technology in Zurich. To him, the conservation of energy was like a life raft in a violent, storm-tossed sea, and abandoning it was absolutely unthinkable. 'Bohr is on entirely the wrong track,' he said. But what, then, was the solution to the beta particle puzzle?

Pauli was having the worst year of his life. Two years earlier, in November 1927, his mother, having been abandoned by her husband, committed suicide. The event had such a profound effect on Pauli that he left the Catholic Church, no doubt feeling abandoned by God. Then, on 23 December 1929, he married Käthe Deppner, a twenty-three-year-old cabaret dancer from Berlin six years his junior. When she met Pauli she was seeing a chemist called Paul Goldfinger, and she continued the affair during their marriage. An anguished Pauli, who was not even living with his wife, told a friend that he was only 'loosely married'.[8]

Losing his wife to another man hurt, but Pauli felt the humiliation even more keenly because it affected his pride. 'Had she taken a bullfighter I would have understood,' he complained to friends. 'With such a man I could not compete – but a chemist – such an average chemist!'[9]

Pauli's troubled marriage to Deppner resulted in him developing a drink problem and a smoking habit.[10] 'With women and me things don't work out at all,' he wrote despairingly. 'This, I am afraid, I have to live with, but it is not always easy.

I am somewhat afraid that, in getting older, I will feel increasingly lonely.'[11, 12]

In the darkest times, occupying his mind with the problems thrown up by quantum theory may have served as an escape from his troubles, but this may have further strained his relationship with Deppner. She reported that Pauli received many letters from physicists, especially quantum pioneer Werner Heisenberg, and would walk around in their apartment 'like a caged lion . . . formulating his answers in the most biting and witty manner'.[13] It was during the eleven anguished months that he was loosely married to Deppner that Pauli came up with the idea for solving the puzzle of beta decay.

Pauli set out his solution to the problem on 4 December 1930, in an open letter to fellow scientists at a meeting in Germany.[14] 'Dear Radioactive Ladies and Gentlemen,' it began. 'Unfortunately, I cannot appear personally in Tübingen, since I am indispensable here in Zurich because of a ball on the night of 6 to 7 December.' The dance was at the 'Baur au Lac', the most distinguished hotel in the centre of Zurich, and it was a mere ten days since his divorce. Emotionally bruised though he was, Pauli intended to get straight back on the horse and find himself another woman.

The letter was read out aloud to attendees at the Tübingen meeting, including Lise Meitner, who would later play a crucial role in the discovery of 'nuclear fission'. Pauli pointed out that even if a fixed amount of energy was available in beta decay, the fact that the electron emitted from the nucleus did not have a fixed amount could be explained if it shared it with a hitherto unknown particle.

Think of the gun again. If a bullet emerged from the barrel with a second projectile, the two would share the available energy. If the second projectile took very little of the energy and the bullet took the lion's share, it would be expelled at high speed. If the second projectile took most of the energy and the bullet had very little energy, it might emerge at such a low speed that it dribbled out the end of the gun. Depending on how much of the available energy was used by the second projectile, the bullet could have any of a range of possible energies.

However, no second particle had been identified accompanying the electron emitted in beta decay. Pauli's new particle must therefore interact very rarely with the atoms of normal matter, and he estimated that it would take a ten-centimetre-thick lead wall to stop it in its tracks.

On the hypothetical particle's other properties, Pauli was also quite specific. In order for it to not noticeably affect the mass of a nucleus, it must weigh very little, if anything at all. He did not realise that it might not actually exist in the nucleus but instead be created at the moment of emission, just as a photon of light is created at the moment of emission and is in no sense taken from a pre-existing 'bag of photons' within an atom. Pauli was also specific about the electric charge of the hypothetical particle, which, like energy, cannot be created or destroyed. In beta decay, for instance, there is no net change in the total charge – though the nucleus increases its positive charge, this is compensated for by the negative charge carried by the emitted electron.* In order for the new particle not to upset this delicate balance, it must therefore carry no charge.

* We now know that in beta decay, a 'neutron' in a nucleus changes into a proton. Since both protons and neutrons are composite particles made of triplets of 'quarks', we can be more specific: a down-quark in a neutron changes into an up-quark, turning the neutron into a proton.

In recognition of its electrical neutrality, Pauli christened it a 'neutron', a name that would later be changed to 'neutrino'.

'I don't feel secure enough to publish anything about this idea,' Pauli wrote in his letter to the Tübingen meeting. The neutrino was a 'desperate remedy'. The reason was that, in 1930, only three subatomic building blocks of matter were known: the 'proton' in the nucleus of the atom; the electron, which orbited the nucleus; and the photon, the particle of light. By adding another particle, Pauli was increasing the number of nature's fundamental building blocks by a third.

The first time Pauli announced the neutrino in public was on 16 June 1931 at the inaugural summer meeting of the American Physical Society in Pasadena, but it gained more traction among physicists four months later, at a meeting in Rome organised by Enrico Fermi. Fermi, who would turn out to be the greatest Italian scientist since Galileo, had, like Pauli, made key contributions to quantum theory. He was instantly captivated by the Austrian physicist's idea, not simply because it solved the problem of the spread of energy of beta particles, but because it also fixed another problem: that of spin.

Physicists had discovered that subatomic particles behave as if they are spinning, even though they are not. Like everything else in the submicroscopic quantum realm, spin comes in indivisible chunks, or 'quanta'. Since a spinning charge acts like a tiny magnet, it is possible to deduce the spin of a particle from the way in which it is deflected by a magnetic field. The proton, neutron and electron all turn out to have a spin of ½. (For historic reasons, the smallest chunk is half of a particular value.)[15] In recognition of the behaviour of particles with 'half-integer spin', an idea that was elucidated principally by Fermi, they are known as 'fermions'.

Spin, like electric charge and momentum, is one of those quantities that never changes, or is conserved.* However, if a neutron (spin ½) changes into a proton (spin ½) and an electron (spin ½), the final spins add up to either 1 – if the proton and electron spin the same way – or 0 if they spin in opposite directions and their spins cancel each other out. Neither of these is the spin ½ of the initial neutron. However, Pauli, in his letter to the Tübingen meeting, had not only proposed that the neutrino has no electric charge, very little mass and that it interacts with normal matter very rarely – he had postulated that it has a spin of ½. This made it possible for the spins of the proton, electron and neutrino (½ + ½ – ½ = ½) to equal the spin of the initial neutron (½).

Never before in the history of physics had anyone predicted the existence of a new entity that solved so many problems simultaneously and whose characteristics – spin, electric charge, mass and ability to penetrate matter – were so precisely pinned down by experimental observations. It caught Fermi's imagination to such an extent that, after the October 1931 meeting in Rome, he was spurred to develop a revolutionary theory of beta decay.[16]

In the couple of years it took for Fermi to incubate his ideas, two new subatomic particles came to light, as mentioned earlier. In August 1932, Carl Anderson, studying 'cosmic rays' at the California Institute of Technology, found the first particle of 'antimatter' – a positively charged twin of the electron, which he christened the 'positron'.† And in January 1932, James Chadwick

* This is not strictly true. It is 'angular momentum' that is conserved. Spin is simply intrinsic angular momentum.

† Cosmic rays are high-speed atomic nuclei, mostly protons, from space. Low-energy ones come from the Sun, while high-energy ones

at Cambridge University discovered a second constituent of the nucleus, identical in mass to the positively charged proton but with no electric charge. It was the discovery of the 'neutron' that caused Fermi to suggest a new name for Pauli's hypothetical particle, neutrino being Italian for 'little neutral one'.

Fermi's theory of beta decay, when it was published in 1934, was a triumph. It required the existence of a third fundamental force of nature, in addition to the well-known gravitational and electromagnetic forces. The new 'interaction', which Fermi christened 'the weak force', operated only over a very short range within the atomic nucleus, which was why nobody had noticed it before. It acted to change a neutron in a nucleus into a proton and simultaneously create an electron and an antineutrino.

Fermi's theory also permitted the reverse process, in which a proton captured a neutrino, causing it to change into a neutron and emit a positron. (In fact, this is the process that creates a neutrino; beta decay creates an antineutrino, which was what Pauli was actually describing.) The physicists Hans Bethe and Rudolf Peierls immediately pointed out that such 'inverse beta decay' would, in theory, permit a neutrino flying through space to be stopped by matter and to therefore be detected, though this would happen extremely rarely.

Fermi did not call the new interaction the weak force for nothing. It was about ten trillion times weaker than the electromagnetic force that holds together the atoms in our bodies. It was so weak, in fact, that the chance of a neutrino being stopped by a proton in an atomic nucleus was calculated to be close to

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probably come from supernovae. The origin of ultra-high-energy cosmic rays, particles millions of times more energetic than anything we can currently produce on Earth, is one of the great unsolved puzzles of astronomy.

zero.[17] Whereas Pauli had thought a neutrino might be halted by a piece of lead about ten centimetres thick, according to Fermi's theory it would require a layer of lead many light years thick.*†[18] As the American novelist Michael Chabon would later observe, 'Eight solid light years of lead . . . is the thickness of that metal in which you would need to encase yourself if you wanted to keep from being touched by neutrinos. I guess the little fuckers are everywhere.'[19]

Despite Fermi's theory of beta decay bolstering the case for the neutrino, many remained sceptical of its existence. And who could honestly blame them? As Nobel Prize-winning American physicist Leon Lederman would one day observe, 'Neutrinos . . . win the minimalist contest: zero charge, zero radius, and very possibly zero mass.'[20]

One of the sceptics was the English astronomer Arthur Eddington. 'Just now nuclear physicists are writing a great deal about hypothetical particles called neutrinos supposed to account for certain peculiar facts observed in beta-ray disintegration,' he said. 'We can perhaps best describe the neutrinos as little bits of spin-energy that have got detached. I am not much impressed by the neutrino theory.'

Eddington stopped short of saying that he did not believe in neutrinos. 'I have to reflect that a physicist may be an artist, and you never know where you are with artists.' If neutrinos did

* In quantum theory, fundamental forces are caused by the exchange of force-carrying particles. A weak force is therefore one in which force-carrying particles are exchanged rarely, and a strong force is one in which they are exchanged frequently. This is why neutrinos, which are subject to weak force, interact with other particles so rarely.
† A light year is the distance light travels in a vacuum in a year. It is roughly equal to ten trillion kilometres.

exist, Eddington recognised the problem of proving it, but even here he was cautious. 'Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos? Whatever I may think, I am not going to be lured into a wager against the skill of experimenters,' he said. 'If they succeed in making neutrinos, perhaps even in developing industrial applications of them, I suppose I shall have to believe – though I may feel that they have not been playing quite fair.'[21]

The undetectability of neutrinos was a major concern even to those who believed in their existence. The irony is that Pauli, a man who so feared loneliness, had postulated the existence of the loneliest entity in creation – a particle so mind-bogglingly antisocial that it interacts with hardly anything in the universe. 'I have done a terrible thing,' he said. 'I have postulated a particle that cannot be detected.' Leading physicists were in agreement that finding the neutrino would be impossible, and Pauli himself bet a case of champagne that nobody would ever catch one.

Los Alamos, New Mexico, November 1955

Frederick Reines had been doing the impossible for more than a decade. When he joined the Manhattan Project in 1944, it had seemed impossible that they would be able to create a runaway nuclear chain reaction, releasing a million times more energy, pound for pound, than dynamite. But they achieved that feat at Alamagordo on 16 July 1945. 'I have become Death, the destroyer of worlds,' Robert Oppenheimer, director of the Manhattan Project, had quoted from the Bhagavadgita, as they watched a mushroom cloud rise into the dawn sky above the New Mexico desert.

Later, it had seemed impossible that they could create the 'super', a device that used an atomic bomb as a trigger and unleashed the energy of the Sun itself. But they achieved that feat too, with the detonation of the hydrogen bomb in Enewetak Atoll on 1 November 1952.

They had always been faced with impossible challenges, but they had met them head-on, and triumphed. For the test of a boosted atomic bomb in 1951, for instance, they had known that their electronics would be fried when the intense flash of gamma rays from the explosion generated a huge surge of electricity in the signal cables running from the bomb tower to the instrumentation bunker. The only thing providing shielding on the scale they required was the island on which they were testing the bomb, so they simply dug up one side of the island and piled it on top of the other.[22]

The impossible challenges of the bomb tests had instilled in all of them a 'can-do' spirit and a tendency to 'think big'. It was exactly this mindset that had led Reines to seriously consider the impossible challenge of detecting the neutrinos from the explosion of a nuclear bomb.

In 1951, he had returned to the US from a series of successful bomb tests on Enewetak Atoll. Tired and jaded after six gruelling years with the weapons programme, he was in desperate need of a break. He asked the leader of the theoretical division at Los Alamos for time off from his duties to think about fundamental physics, and Carson Mark, who was an enlightened man, granted him his request. Reines was given a bare office, where he sat staring at a blank pad of paper for several months. He asked himself what he wanted to do with his life, and for a long time he did not know. But then he thought of the neutrino.

At Los Alamos, Reines had served on the 'Bomb-Test Steering and Liaison Group'. On occasion, it had tossed around the wild idea of piggy-backing physics experiments on nuclear tests and using the intense burst of heat radiation, gamma rays and neutrons to study fundamental phenomena. Reines knew that a nuclear fireball generated one additional type of radiation. When a nucleus of uranium or plutonium 'fissions', it creates two unstable 'daughter' nuclei. Each nucleus, in its desperate quest for stability, undergoes on average six beta decays, every time spitting out an antineutrino. As a result, a nuclear explosion creates an intense burst of antineutrinos.

The chance of detecting one antineutrino was impossibly low, but if there were vast numbers of them, Reines reasoned, the odds of ensnaring one would be hugely improved.

One day, in the summer of 1951, Reines heard that Enrico Fermi himself was visiting Los Alamos and was installed in an office just down the corridor. Since creating the theory of beta decay in Rome in the early 1930s, Fermi had won the 1938 Nobel Prize in Physics and fled Mussolini's fascist dictatorship for America. On 2 December 1942, he had changed the course of history: in a crude 'pile' of uranium and graphite on a squash court under the West Stands of the University of Chicago's Stagg Field, he had unleashed the stupendous energy of the atomic nucleus in the world's first sustained nuclear chain reaction.

Reines knocked nervously on Fermi's door. When he told him of his plan to detect neutrinos in the blast of a nuclear explosion, Fermi, to his surprise, did not dismiss the idea out of hand and agreed that a nuclear explosion offered the best chance of detecting the elusive particles.

A neutrino had very little chance of being stopped by a proton in an atom; the way to boost the chance was to put together lots of atoms. Reines estimated that, with a detector mass of about a tonne, it would be possible to detect a handful of neutrinos, but neither he nor Fermi had any idea of how to go about it.

The fact that Fermi had not ridiculed his idea gave Reines confidence that detecting the neutrino was possible, but the problem was that he was just one man with an obsession. That changed when he flew to a meeting in Princeton, New Jersey. The plane had engine trouble and was forced to land in Kansas City. Travelling with him from New Mexico was a physicist called Clyde Cowan, who had worked with the British on radar in the Second World War and had arrived at Los Alamos in 1949. Although Reines and Cowan had been part of the same American bomb teams, they had never had a chance to talk properly. Now, as they strolled through the streets of Kansas City while waiting for their plane to be fixed, they hit it off.

Their conversation quickly turned to fundamental physics and the question: What was the hardest experiment in the world? Both men agreed it was the detection of the neutrino. The fact that everyone thought it was impossible made it appealing to them, and they imagined the buzz of achieving something that everyone said could never be done. There and then, the two men decided to work together on detecting neutrinos. Reines had found his partner in crime.

Back at Los Alamos, there was much enthusiasm for the venture, which resulted in the creation of a neutrino group in late 1951. Since the neutrino was a fleeting ghost that barely haunted the world of physical reality, the quest to detect it was christened 'Project Poltergeist'.

The way to snare a neutrino, as Bethe and Peierls had already realised, was via inverse beta decay. On rare occasions, an antineutrino interacted with a proton, creating a neutron and a positron in the process. The positron would quickly run into an electron, since electrons are ubiquitous in matter, and 'annihilate' with it. There would emerge two high-energy photons, or gamma rays, flying away in opposite directions. It was these gammas – proxies for the antineutrino – that Reines and Cowan intended to detect; proving the existence of the antiparticle would automatically prove the existence of the particle, in this case the neutrino.

A year earlier, in 1950, several teams had discovered transparent liquids that emit flashes of light when a charged subatomic particle or gamma ray flies through them. The light flashes from such 'liquid scintillators' were weak, but could be boosted by placing 'photomultipliers' all around the scintillator, which converted the light into a measurable electrical signal.

The neutrino detector envisioned by Reines and Cowan would incorporate tanks of liquid scintillator and a bath of water. The protons in the water would provide a large number of targets for the antineutrinos. The pair of gamma rays created in the interaction of an antineutrino and a proton would fly out through tanks of liquid scintillator on either side of the water bath, and photomultipliers arranged around each tank would detect them.

The experiment was little more than a dull piece of plumbing, but the place where Reines and Cowan intended to locate it was anything but dull. And it was here that the fearless thinking and sheer chutzpah of the two physicists came to the fore. An atomic bomb creates a blisteringly hot fireball capable of erasing a city, and Reines and Cowan planned to place their detector a mere fifty metres from the centre of such an inferno.

Nothing in the open could survive such a blast, but Reines and Cowan envisaged placing the neutrino detector in a vertical shaft ten feet in diameter and 150 feet deep. They would pump the air out of the shaft and, at the very instant the bomb went off, would let the detector drop. During its two-second fall, not only would it be shielded from the ferocity of the fireball by the surrounding ground, but because it was in free fall, it would be protected from the potentially catastrophic shockwave thundering through the earth. At the bottom of the shaft, the fall of the apparatus would be cushioned by a thick bed of foam rubber and feathers. Reines and Cowan intended to retrieve the detector several days later, when radiation levels would be low enough to risk a quick in-and-out foray.

The extraordinary plan was granted approval by Norris Bradbury, director of Los Alamos, and work even started on digging the 150-foot-deep shaft to house the detector at the bomb test site in Nevada. But then, in the autumn of 1952, Jerome Kellogg, leader of the Los Alamos Physics Division, asked Reines and Cowan whether it might be possible to carry out the experiment with a nuclear reactor rather than a nuclear bomb. At first sight, it did not look promising – a nuclear reactor was a weaker source of neutrinos than a nuclear explosion by a factor of a thousand. However, when Reines and Cowan investigated it in detail, they were surprised to find that such a neutrino experiment was indeed possible.

When an antineutrino hit a proton, it created not only a positron, which could be detected by the two gamma rays created by its annihilation, but a neutron. The key thing, Reines and Cowan realised, was to detect the neutron as well as the positron. The neutron could be detected by taking a substance like cadmium that acted like a neutron-sponge and adding it to the liquid scintillator. Each neutron would ricochet from nucleus to nucleus, before burying itself in a cadmium nucleus after about five millionths of a second and shedding its surplus energy as a gamma ray.

The electronics connected to the photomultipliers could be arranged to register a response only to a signal consisting of two gamma rays (from the annihilation of the positron) followed by a single gamma ray (from the capture of the neutron). This 'delayed coincidence' signal was so distinctive that it was unlikely to be mimicked by any other particle process going on in the detector. The ability to reject other confusing signals would make the detection of neutrinos at a nuclear reactor possible, even though it was a far weaker source of the particles than a nuclear explosion.

A nuclear reactor had other advantages over a nuclear explosion. Rather than providing an ultra-brief window of a second or two in which to detect neutrinos, it could be monitored continuously for weeks, months or even years. Furthermore, there was no risk of the experiment being incinerated or of harm to anyone who retrieved it from a radiation-scarred landscape.[23]

In the early spring of 1953, Reines and Cowan's team loaded their vehicles with a 300-litre neutrino detector, barrels of liquid scintillator and racks of electronics, and headed for the plutonium-producing reactor at the Hanford Engineer Works in Washington state. America's newest and largest reactor was expected to generate the largest flux of antineutrinos. If it had been possible to see neutrinos with the naked eye, the reactor would have glowed like a second sun.

But at Hanford, Project Poltergeist hit a show-stopper. The neutrons the team was looking for turned out to be not the only neutrons in town; it became clear that there were others coming from fissioning nuclei in the reactor core. To absorb them and stop them reaching the detector, the team built a thick wall of paraffin, borax and lead around their experiment. It worked, but then they encountered another problem: the neutrons from the reactor core were not the only source of a signal that mimicked the signal they were looking for. There was another source, and it came from space.

Cosmic rays are high-energy nuclei created by exploding stars and other violent cosmic events. At the top of the Earth's atmosphere, they slam into nuclei of atoms and create 'secondary' particles, which shower down through the atmosphere like a fine rain. The most penetrating of all the particles are 'muons', a form of heavy electron. Cosmic ray muons slammed into nuclei in the shield that Reines' team had built around their experiment, creating sprays of neutrons. Unfortunately, these neutrons were ten times more abundant than those expected from the neutrons produced by neutrinos. 'The lesson of our work was clear: it is easy to shield out the noise men make, but impossible to shut out the cosmos,' said Cowan. 'We felt we had the neutrino by the coattails, but our evidence would not stand up in court.'

Reines and Cowan were disappointed, but not defeated. They at least knew that the technology they were using worked; all they needed was a nuclear reactor that was better shielded from the confusing signals from cosmic rays. Finally, they found one in P Reactor at the Savannah River Plant. By virtue of the fact that it was buried twelve metres deep in the ground, it was perfectly shielded from the menace from space. In November 1955, Project Poltergeist moved to South Carolina.

Savannah River, South Carolina, 14 June 1956

Reines drove past the sign a joker on the team had put up – 'DANGER, DO NOT STAND CLOSE TO FENCE – HIGH NEUTRINO FLUX' – and parked next to the empty truck that had brought a load of wet sawdust to the site.[24] The control room, with its humming generator, was in a trailer dwarfed by the concrete hulk of the reactor. Cables snaked across the ground, carrying the electrical signals up from the scintillator tanks twelve metres below and creating a trip-hazard that Reines had to be careful to avoid. Inside, Cowan was sitting in front of a wall of oscilloscopes, switches and racks of glowing vacuum tubes, monitoring the output from the detector.

With its team of almost a dozen and a mountain of accompanying equipment, the ten-tonne detector was the biggest physics experiment on the planet. Nobody before had dared carry out anything as complex, but nobody else had learnt their craft while testing the weapons of Armageddon or had at their disposal the financial resources, machine shops and technology of Los Alamos. This was big science. It was a vision of the future: one day much of physics would be done like this, in laboratories that spanned national borders, employed thousands of researchers and cost tens of billions of dollars.

The final design for the Project Poltergeist apparatus was a kind of double-decker sandwich. Two layers of water with cadmium chloride added to it acted as the neutrino target, and these were interleaved with three layers of liquid scintillator. Positrons produced by neutrinos interacting with protons in the water would be detected almost immediately via back-to-back gamma rays in the adjacent scintillator tanks, and neutrons produced by the same neutrinos would reveal themselves five microseconds later via another burst of gamma rays in the same tanks.

Project Poltergeist had been running for 1,371 hours. Not only was the gamma ray signal it had measured four times bigger than the background level, it was five times bigger when the reactor was switched on than when it was switched off. Every hour they detected three neutrinos.

The possibility remained, however, that neutrons from nuclear fissions in the reactor were penetrating the eleven metres of concrete shielding around the reactor and creating spurious gamma rays in their experiment. So overnight, while Reines had slept, the rest of the team had piled bags of wet sawdust against the wall of the reactor. Their material of choice – a tribute to the cuisine of South Carolina – had actually been black-eyed peas, but wet sawdust was easier and cheaper to obtain in the required quantities.[25]

If some of the gamma rays they were detecting were coming from neutrons produced by the reactor, the extra shielding of the wet sawdust should have stopped them, reducing the signal by a factor of ten. 'Any change in the signal?' asked Reines. Cowan, looking up from an oscilloscope, grinned. 'No change.' It was exactly what Reines had wanted to hear.

Outside the trailer, the whole team had assembled: Richard Jones and Forrest Rice, who had installed the detectors and lead shielding; F. B. Harrison, the expert in large liquid scintillators; Austin McGuire, who had designed the tank farm containing the scintillator; Herald Kruse, who had been responsible for interpreting the oscilloscope traces; and Martin Warren, the gopher. All of them looked exhausted, but they were euphoric and pumped each other's hands, slapping each other on the back. They had overcome the final hurdle and achieved the impossible. After five years of sweat and struggle, they had detected the elusive neutrino.[26]

There remained only two things to do: send a telegram and then pack up their equipment and drive back to Los Alamos.

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Pauli received the telegram on 14 June 1956: 'We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing the inverse beta decay of protons . . . Frederick Reines, Clyde Cowan.'

The next day, Pauli replied from the Swiss Federal Institute of Technology in Zurich: 'Frederick REINES, and Clyde COWAN, Box 1663, LOS ALAMOS, New Mexico. Thanks for message. Everything comes to him who knows how to wait. Pauli.'

With the proof of the neutrino that he had predicted a quarter of a century earlier, Pauli well and truly joined the ranks of the magicians. Who in their most extravagantly wild dreams would have imagined something as insubstantial, ghostlike and downright weird as the neutrino? Pauli had predicted it for the sole reason that it was what the mathematical logic was telling him. The neutrino simply had to exist because, without it, radioactive beta decay made no sense at all.

Pauli announced the discovery of the neutrino at a symposium at CERN, the European laboratory for particle physics near Geneva, the week after he received Reines' telegram. Reines, in his Nobel Prize acceptance speech in 1995, would recount that Pauli celebrated with a case of champagne.[27] That certainly made a good story since Pauli had, of course, bet a case of champagne that the neutrino would never be detected, though sadly it was not true.[28]

Reines and Cowan, for their part, were rather more sober. Standing outside P Reactor in the South Carolina sunshine, they and their team celebrated their success not with flutes of champagne but with paper cups of Coca-Cola.[29]

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For the neutrino, it was only the beginning of the story. Hold up your hand. About one hundred billion neutrinos pass through your thumbnail every second. Eight and a half minutes ago they were in the heart of the Sun. Solar neutrinos are produced in prodigious quantities by sunlight-generating nuclear reactions.

Remarkably, Reines and Cowan's team was not the only one with the temerity to attempt the impossible feat of detecting the neutrino; it was not even the only one to do it at the Savannah River Plant. In 1954, a team led by Raymond Davis, the American chemist and physicist, had installed a detector filled with 3,800 litres of cleaning fluid – carbon tetrachloride – in the basement of one of the nuclear reactors. The idea behind the detector had been suggested by Bruno Pontecorvo, a one-time colleague of Enrico Fermi's who had defected to the Soviet Union. Occasionally, a neutrino would interact with a chlorine nucleus in the cleaning fluid, turning it into a nucleus of argon, a gas which could be easily separated. The amount collected would correspond to the number of neutrinos detected.

Unfortunately, Davis had suffered similar problems to Reines and Cowan at Hanford. His detector was not sufficiently shielded from the confusing effect of cosmic rays and so he lost out in the race to detect the neutrino. But he was nothing if not persistent. In the mid-1960s, he located a detector of 400,000 litres of cleaning fluid 1.5 kilometres underground in the Homestake gold mine in Lead, South Dakota. His aim was to detect neutrinos from the core of the Sun, and incredibly, he succeeded, becoming the first person to see into the heart of a star.

But there was a problem. Unexpectedly, Davis registered only between one third and a half of the neutrinos which were predicted by the theory of energy generation in the Sun. Was there something wrong with our understanding of the Sun, or with our understanding of neutrinos?

Davis's conundrum triggered a wave of other experiments to check his anomalous result, and he is credited with giving birth to the field of 'neutrino astronomy'. The belief of pretty much everyone was that Davis was wrong. Contrary to expectations, however, the new experiments confirmed that there was indeed a shortfall in the number of neutrinos coming from the Sun.[30]

The 'solar neutrino puzzle' had an extraordinary solution, which was eventually confirmed by the Sudbury Neutrino Observatory in Ontario, Canada: there are three types of neutrino. These are the electron neutrino; the muon neutrino, discovered in 1962 at Brookhaven, New York; and the tau neutrino, discovered in 2000 at Fermilab near Chicago. Nobody knows why nature has chosen to triplicate its neutrinos – along with all its other basic building blocks, the quarks – but crucially, the observatory could detect all three types. What it showed, in 2006, was that there was no shortfall in neutrinos, as long as the numbers of the three types were added together.

As early as 1957, Pontecorvo had suggested neutrinos might come in different types, or 'flavours', and that, flying through space on their way from the Sun to the Earth, they might morph from one type to another. Imagine a dog walking along a street and changing into a cat after one hundred metres, a rabbit after another one hundred metres and back into a dog after a further one hundred metres. Say, for some weird reason, your eyes can only spot dogs: you would see them only a third of the time. So it was with neutrinos. Davis's experiment was sensitive only to electron neutrinos, but the neutrinos arriving at his detector in the Homestake mine were in the guise of electron neutrinos only a third of the time.[31]

Such neutrino 'oscillations' have implications for the mass of the neutrino, which many had assumed was zero. According to Einstein's special theory of relativity, only a massless particle like the photon can travel at the ultimate cosmic speed limit – the speed of light – and, for such a particle, relativity predicts that time slows to a standstill. The photon cannot therefore change since change is something that can only happen in time. However, the neutrino emphatically does change, oscillating between its three flavours. The implication is that it must travel slower than the speed of light and therefore have a mass.[32]

The mass of the neutrino is, not surprisingly, hard to measure. It appears to be at least 100,000 times smaller than that of the electron, which was formerly the lightest known subatomic particle. This suggests that neutrinos acquire their mass in a different way to all the other fundamental particles, which get theirs by interacting with the 'Higgs field' (see chapter 'The god of small things'). The Higgs is a key component of the Standard Model of particle physics, a quantum description of nature's three non-gravitational forces. Although very successful, the Standard Model fails to predict the masses of the fundamental particles or the relative strengths of the fundamental forces and is widely believed to be an approximation of a deeper, more satisfactory theory. The hope among physicists is that if they can understand how the neutrino gets its mass, they might gain important clues about this elusive 'theory of everything'.

Despite the fact that the mass of the neutrino is extremely small, neutrinos could still have important consequences for the universe. Prodigious quantities of them flood out of the Sun, not to mention every other star in the galaxy, and they were also created in uncountable numbers by processes in the Big Bang that created the universe 13.82 billion years ago.[33] Neutrinos are the most elusive entities in nature, as close to nothing as anything we know of and apparently spectators rather than participants in the life of the cosmos. However, they turn out to be the second most common particles in nature, after photons. In terms of sheer numbers, we live in a neutrino-and-photon universe.

So even though neutrinos have ultra-tiny masses, they could still make up a significant fraction of the mass of the universe. In fact, if there exists an as-yet-undiscovered massive neutrino, neutrinos could be a component of the universe's mysterious dark matter, which is known to outweigh the visible stars and galaxies by a factor of about six.[34]

But this is not the only way in which neutrinos could be the key to the universe. Experiments showing differences between the rates of creation and destruction of neutrinos and antineutrinos hint at a fundamental asymmetry between matter and antimatter. It may one day explain one of the biggest mysteries of the universe: why we live in a universe of matter that contains virtually no antimatter.[35]

Once Reines' team detected the neutrino in 1956, he was far from finished. In 1987, he was a member of one of two teams that detected a total of nineteen neutrinos coming from another star. Supernova 1987A marked the detonation of a massive star in the Large Magellanic Cloud, a satellite galaxy of the Milky Way. It was the first supernova seen in our galaxy for four hundred years.

When a massive star reaches the end of its life, it runs out of fuel to generate the internal heat necessary to oppose the gravity trying to crush it. As the core shrinks catastrophically, heating up to ferocious temperatures, the elements built up by nuclear reactions over the star's lifetime come apart into protons, neutrons and electrons. Electrons are squeezed into protons to create a superdense ball known as a 'neutron core', in the process unleashing a tsunami of neutrinos. In the case of Supernova 1987A, this amounted to 10^{58} – or ten billion trillion trillion trillion trillion – neutrinos. Although a supernova can shine as bright as a galaxy of 100 billion stars, it turns out that a mere 1 per cent of its energy is emitted in the form of light; 99 per cent consists of neutrinos.

It is the neutrinos flooding out of the star that turn the implosion of the core into a supernova explosion, blowing the exterior envelope of the star into space. This contains elements which enrich interstellar gas clouds, destined to become stellar nurseries when they fragment into the new generations of stars. Without neutrinos, the elements essential for life would remain locked up inside stars. 'Why does nature need them? What use are they?' asks the English physicist Frank Close.[36] The remarkable truth of Pauli's 'impossible particle' is that it is more critical to the universe than anyone could possibly have imagined. Without it, you would not be reading these words; in fact, you would not even have been born.