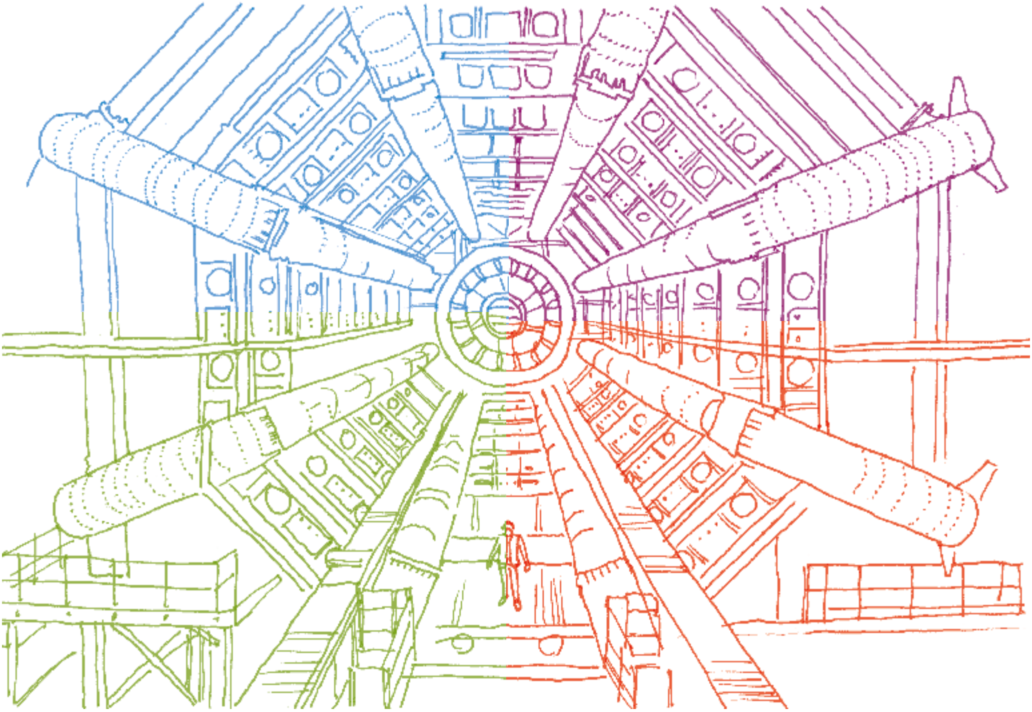
IOP Education | Stories from physics booklet 8

Quantum, Nuclear and Particle Physics

By Richard Brock



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Introduction

The 20th century was the quantum century, from the discovery of radioactivity and the structure of the atom, through the mathematical descriptions of quantum mechanics, and reaching the gigantic experiments of particle physics. Our views and understanding of the universe have been fundamentally changed by this revolution.

This quantum revolution has been more than a revolution in ideas - it has been a revolution in the physics community. This period has seen a change in the way that physics is done, from individuals and small groups working in isolation in university laboratories, through to the giant collaborations seen in international laboratories such as CERN. Over the last 125 years or so, physics has expanded to include physicists from every part of the planet and from every background.

This is an important message to share with your students, the physicists of the future. Physics is no longer a lone endeavour - international collaboration is vital to make the next set of breakthroughs.

But whilst there are now thousands of physicists active in particle, nuclear and quantum physics, we can still look at the history of our subject and enjoy the stories of the revolutionaries who made the quantum leaps, as well as some of the rather unexpected outputs of their labours.

In this final instalment of Richard Brock's marvellous Stories from Physics booklets, we get to see some of those characters behind the equations and particles. Our thanks go to Richard for all his hard work and creativity in producing this - and the other seven - superb booklets.

Mark Whalley
IOP education manager

Message from the author

This booklet covers three topics, quantum, nuclear and particle physics, that are rich in absorbing stories. In the quantum section, you will find out which playground game Max Planck excelled at (and indeed why he was not really 'Max' Planck). Learn about what de Broglie did on the Eiffel Tower, the truth about Schrödinger's pet and what hornets have to do with the photoelectric effect.

In the nuclear section, you will read about Lise Meitner's dramatic escape, why Rutherford was compared to a crocodile and what happened to the mouse that drank a heavy water cocktail. There are stories about what Winnie the Pooh had to do with the first nuclear reactor and the simpler times when children found 'nuclear' toys in cereal boxes.

The particle physics section includes stories about how Chadwick's illustrious career began with a queuing mistake, the physicist who cured his mother's cancer and the mystery of the two beer bottles found in a CERN particle accelerator. You will also encounter the strange case of Majorana, the eccentric physicist who vanished without a trace.

The publication of this final booklet in the series is an appropriate time to thank all of those who have contributed to the project. First, to the Institute of Physics for enabling me to share these stories widely with teachers. Caroline Davis has been instrumental - I am grateful for her support, encouragement and for her wrangling of my prose. Thank you also to Mark Whalley and Joe Rowing for their physics insights. The stories have been brought to life and enriched by Stuart Redfern's beautiful and creative illustrations. Finally, without Charles Tracy's enthusiasm, the stories project would never have gone beyond my hard drive – I am indebted to him for his belief.

So, for the final time, let me tell you some stories about physics...

Richard Brock

Quantum physics

Planck

Early Planck

Max Planck was a German theoretical physicist and a leading figure in the early development of quantum theory around the start of the twentieth century. Contrary to what many believe, Planck's first name was not Max – he was baptised Karl Ernst Ludwig Marx Planck and Marx (an old variant on Markus) was indicated as his primary name, but he soon became known as Max and that name stuck for the rest of his life. Planck was a gifted musician, playing both the piano and the organ, and he performed duets with Einstein on violin. When Planck chose to study physics, Munich University physics professor Philipp von Jolly discouraged him arguing that "in this field, almost everything is already discovered, and all that remains is to fill a few holes".

Women: lecture theatre or at home?

In some respects, Planck was ahead of his time - he argued that enthusiastic female students of physics should be admitted to lectures, and he advocated on Lise Meitner's behalf, creating her first paid position. However, he also held views that were more in keeping with the sexist stance of the culture at the time. He wrote: "Nature itself has designated for woman her vocation as mother and housewife, and that under no circumstances can natural laws be ignored without grave damage."

Planck's tag

Meitner reported that Max Planck was skilled at the game of tag: "The more advanced students… were regularly invited to [his home on] Wangenheimstrasse… we played tag in the garden… Planck participated with almost childish ambition and great agility. It was almost impossible not to be caught by him."

Meeting Hitler

In 1933, Planck wrote to Hitler to request a meeting and the two men met on the 16 May. Planck used the meeting to advocate for Jewish colleagues, including the chemist Fritz Haber. During the meeting, Hitler became angry and Planck reported he "hit himself hard on the knee, spoke faster and faster, and flew into such a rage that I could only remain silent and withdraw".

Parental pain

Planck suffered a string of family tragedies: his first wife died from tuberculosis, his oldest son was killed in the First World War and both his daughters died in childbirth. Planck's youngest son, Erwin, was part of an underground anti-Nazi group in wartime Germany and was arrested for his involvement in an unsuccessful assassination attempt on Hitler in 1944. Erwin was tortured and executed by the Gestapo. Planck was devastated by the loss of his son and wrote to a friend: "You give me credit for too much if you think I have the strength to withstand this pain." Planck died a few years after his son in 1947.

Betting on Planck's constant

In 2013, a group of physicists from the US National Institute of Standards and Technology (NIST) met at a local bar to celebrate their determination of Planck's constant to an unprecedented degree of accuracy using a Watt balance. During happy hour, each member of the group wrote, on a paper napkin, a prediction to ten decimal places for the future measured value of Planck's constant. They placed the napkin in a plastic bottle and buried it in a cavity in the foundation of an NIST building that was then under construction. Four years later, a new measurement of Planck's constant allowed the winner to be declared: Shisong Li from China's National Institute of Metrology. He was awarded the prize of an Italian rum cake with the newly measured value for Planck's constant written in icing on top.

On the 20 May 2019, as part of a redefinition of SI units, an exact value of Planck's constant was finalised as 6.62607015 × 10^{-34} J s.

Schrödinger

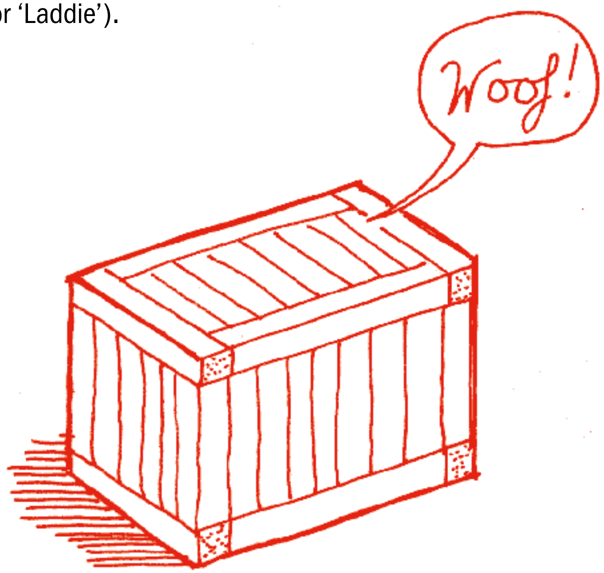
Erwin Schrödinger was an Austrian physicist who made several significant contributions to the development of quantum theory.

A parallel career

In an interview with *The Observer* in 1931, Schrödinger revealed that he had always wanted to be a poet and turned to physics because it offered the opportunity of a stable career. Schrödinger's personal poetic output is notable for its focus on love, but in addition, he translated poems into German, including one by W.B. Yeats.

Schrödinger's dog

Contrary to expectations about his choice of pet, Schrödinger's daughter reports that, whilst the family lived in Dublin, the family had a pet dog, a collie named Burschie (German for 'Laddie').



Dressing like a physicist

As his academic standing grew, Schrödinger switched from the formal dress normally expected at conferences to more relaxed fashion choices. At the Fifth Solvay Conference in Brussels in 1927, his selection of a sports jacket and bow tie contrasted with the dark suits and starched collars of other attendees. Indeed, he is said to have shocked the conservative Dirac by arriving at the conference hotel dressed in a traditional Tirolean costume, complete with a knapsack on his back.

Ungracious accommodation

Whilst a Fellow of Oxford's Magdalen College between 1933-1938, Schrödinger rented a house from Imperial Chemical Industries (ICI), the large British chemical manufacturing company. He had paid a deposit of £31 at the start of his tenancy with the understanding that the money would be refunded when his rental period finished, less some money for depreciation of fixtures. However, at the end of his tenancy, ICI encountered greater costs than they had expected, including the expense of restoring a neglected garden, and kept the profit they had made in selling the fixtures (£20) to the next tenant, rather than returning the deposit to Schrödinger. This decision irritated the physicist who wrote to ICI, the tax authorities and others complaining of the behaviour. Eventually, the chairman of ICI sent Schrödinger a cheque for £20 but his behaviour was seen as ungracious.

Hertz's photoelectric effect

Heinrich Hertz made perhaps the earliest recorded observation of the photoelectric effect in 1887, during his experiments on radio waves. Hertz had set up a receiver for radio waves consisting of a spark gap in a curved piece of brass capped with small metal spheres. Current induced by radio waves in the u-shaped conductor would produce a spark between the spheres. Hertz observed that when he placed a piece of glass in front of the loop, the size of the spark decreased. And when he replaced the glass with a quartz plate, which allows ultraviolet light to pass through, the spark returned to its original size. Hertz was mystified by the results commenting:

> ...the effect is striking and yet totally puzzling. Naturally it would be nicer if it were less puzzling; however, there is some hope that, when this puzzle is solved, more new facts will be clarified than if it were easy to solve.

A Nobel winner's descent

Philipp Lenard had been an assistant of Hertz and built on his work on the photoelectric effect. He discovered that the total charge of electrons emitted, but not their velocity, depended on the intensity of light shone on to the metallic surface. He went on to be awarded the Nobel Prize in 1905 for his work on cathode rays.

Lenard's 1903 paper on the photoelectric effect was an important source for Einstein and the two physicists corresponded. Early in their communication, Einstein addressed Lenard as "Esteemed Professor!" and wrote "I thank you very much for the work you have sent me, which I have studied with the same feeling of admiration as your earlier works". Lenard responded by addressing Einstein as his "highly esteemed colleague" and commented: "What could be more exciting for me than when a profound comprehensive thinker finds favour with some points from my work". However, just a few years later, in a letter to a friend Einstein commented that Lenard's ideas were "infantile" and bordered on the absurd.

In 1920, Einstein and Lenard had a public confrontation about general relativity at a meeting of the Association of German Scientists and Physicians. Lenard felt slighted by the awarding of the 1921 physics Nobel Prize for the photoelectric effect to Einstein alone, as he felt he had made a significant contribution to the research.

It is reported that Lenard had a tendency to jealousy and insecurity - he kept his laboratory locked out of fear of colleagues stealing his ideas and he required students to make obsequious comments about him in seminars.

He became caught up in the rising wave of German nationalism and anti-Semitism and was appointed 'chief of Aryan science' in the Nazi regime. He referred to relativity as "the Jewish fraud" and made other claims about the inferiority of "Jewish science". When the US army occupied Heidelberg, the 83-year-old physicist attempted to flee but was captured. Though it was proposed that he be put on trial at Nuremberg, it was felt a greater punishment would be to ignore him and Lenard died two years later.

Accepting Einstein's photons...

Many colleagues in the physics community expressed scepticism towards Einstein's notion of the photon when he first proposed the idea. This prompted Planck to defend his colleague in a somewhat lukewarm manner. In his nomination letter for Einstein's membership of the Prussian Academy of Science in 1913, Planck wrote "that [Einstein] sometimes, as for instance in his hypothesis on light quanta, ... may have gone overboard in his speculations should not be held too much against him".

... and Millikan's manipulations

It is often reported that Robert Millikan's 1915 photoelectric experiment verified Einstein's hypothesis about light quanta. Indeed, this is what Millikan himself claimed in his 1950 autobiography. However, his support for Einstein was less effusive at the time than this later claim would suggest. He maintained a semi-classical interpretation of the results, rather than accepting a fully quantum interpretation, writing in a 1916 paper of Einstein's photon as a "bold, not to say reckless, hypothesis of an electro-magnetic light corpuscle of energy $h\nu$, which flies in the face of thoroughly established facts of interference" and reported that the notion of the photon "now has been pretty generally abandoned". Millikan's tendency to rewrite history did not end here. In his elementary physics textbook, Millikan etched out a cigarette from a photograph of J. J. Thompson, perhaps, it is speculated, to avoid corrupting young physicists.

Compton's competence

Millikan's experiment did not lead to the rapid acceptance of Einstein's ideas. His light quantum model was widely treated with suspicion until Arthur Compton's explanation of the effect in 1925. Curiously, Compton's paper, which encouraged the acceptance of Einstein's hypothesis, does not cite Einstein's now famous 1905 article: *On a heuristic point of view concerning the production and transformation of light.*

Compton himself was far from infallible. He concluded from some experimental data that the electron had a diameter of 1×10^{-11} m which was ten million times larger than the accepted value. The mistake led Rutherford to give him this less than flattering introduction before a lecture in Cambridge: "This is Dr Compton who is here to talk to us about the size of the electron. Please listen to him attentively, but you don't have to believe him." A member of the audience reported that, at one point, Rutherford burst out: "I will not have an electron as big as a balloon in my laboratory."

Bohr

Niels Bohr was a Danish physicist who contributed to foundational research into atomic structure and the development of quantum theory. It may have been for the best that Bohr chose to study theoretical physics as his chemistry teacher reported that he was second to none in breaking glassware. When the laboratory was rocked by an explosion, he is said to have commented: "Oh, that must be Bohr!"

Beer myth

The Royal Danish Academy of Science was financially supported by the Carlsberg Brewery whose founder had specified in his will that his palatial mansion was to be used as the residence of Denmark's most famous living scientist. Hence, in the 1930s, Bohr came to live in the Carlsberg mansion. A story, reported by *The Guardian* newspaper and *Forbes*, claims that a beer pipe connecting the mansion with the Carlsberg Brewery allowed Bohr a ready supply of alcohol. The director of the National Bohr Archive has dismissed the story as a myth but reports that Bohr was entitled to free bottles and kegs of beer between 1932 and 1962.

Rescue mission

Bohr's mother was Jewish and the physicist played a significant role in saving Jews during the Nazi occupation of Denmark. The story is told that, in order to help those fleeing, Bohr attempted to get an audience with King Gustav of Sweden. Friends of Bohr knew Greta Garbo, who called the king and begged him to meet Bohr, and the physicist was able to convince King Gustav to accept thousands of Jewish refugees.

Hiding from the Nazis

During the Nazi occupation of Denmark, in order to prevent their confiscation, Bohr was entrusted with the gold Nobel Prize medals of German physicists James Franck (who investigated fluorescence, in collaboration with Hertz) and Max von Laue (who discovered crystal X-ray diffraction). With the Hungarian physicist Georg von Hevsey, Bohr devised the idea of dissolving the medals in *aqua regia*, a mixture of hydrochloric and nitric acid. The resulting solution was left on a laboratory shelf, safe from confiscation. In 1945, the metal was recovered from the solution and the medals recast.

A breathless escape

In 1943, Bohr fled occupied Denmark, travelling first by boat to Stockholm. Bohr made the journey carrying a green beer bottle that he believed contained heavy water, a key ingredient for the Nazi atomic bomb project. On reaching Sweden, he realised he had taken the wrong bottle – the one he carried contained only beer. The Danish resistance were contacted and agents entered Bohr's home which had already been ransacked. The resistance fighters questioned Bohr's housekeeper who led them to a bottle, stored amongst others in the larder and containing a quarter of a litre of heavy water. The bottle was sent on to Bohr in Stockholm, where he was met by a British Mosquito (a combat aircraft) to escape to England. When the plane arrived, he was given a flight helmet with built-in headphones but it was too small for his head. Bohr, therefore, did not hear the pilot's instruction to begin using his oxygen mask and passed out. The Mosquito pilot was forced to drop the plane to a lower altitude to revive the oxygen-starved scientist.

Bohr *continued*

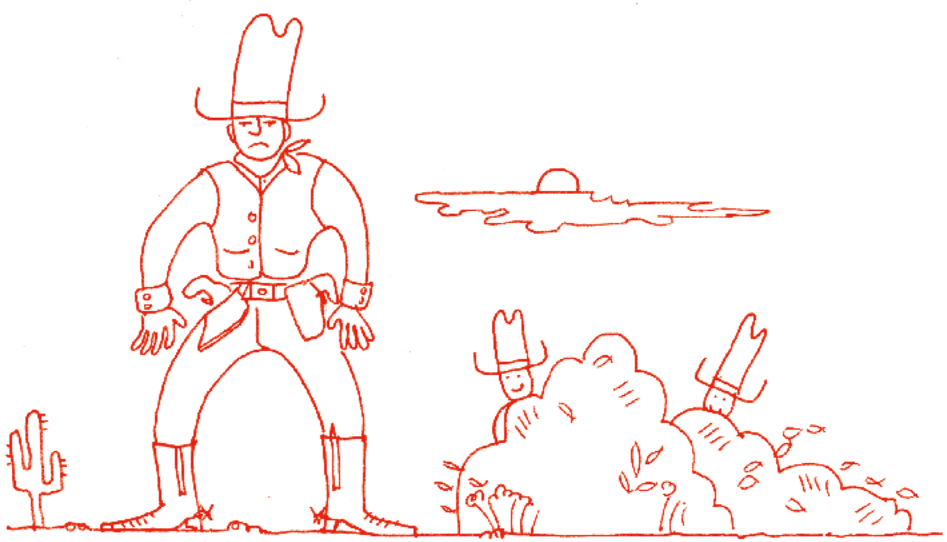
Family ties and football

Niels Bohr's younger brother Harald was, like his sibling, numerically talented and received his PhD in mathematics at just 21. Harald had at least one skill in which he outshone his older sibling - football. Harald played as a midfielder for the Danish club Akademisk Boldklub (AB) and was selected to represent his country at the London Olympics in 1908. In what might be considered the Danish team's first international game, the Danes beat the French 'B' team 9-0 with Harald contributing two goals. In the semi-finals, Denmark beat France 17-1, before losing 2-0 to the British team in the gold medal match. Like his brother, Niels had signed to play for AB, but in contrast to Harald, Niels played as the goalkeeper. However, it is reported that, during a game against a German side, as a long ball was hit towards the goal, Niels was looking at a goalpost where he had previously scratched an equation. Two versions of the story differ at this point – in one, a shout roused Bohr and he managed to make a save; in the other the physicist's inattention resulted in a goal being conceded.

Bohr and Gamow's duel

Bohr enjoyed watching cowboy films. Despite his delight in the genre, Bohr often failed to follow the plots and is reported to have pestered his colleagues with questions during screenings such as: "Is that the sister of that cowboy who shot the Indian who tried to steal a herd of cattle belonging to her brother-in-law?"

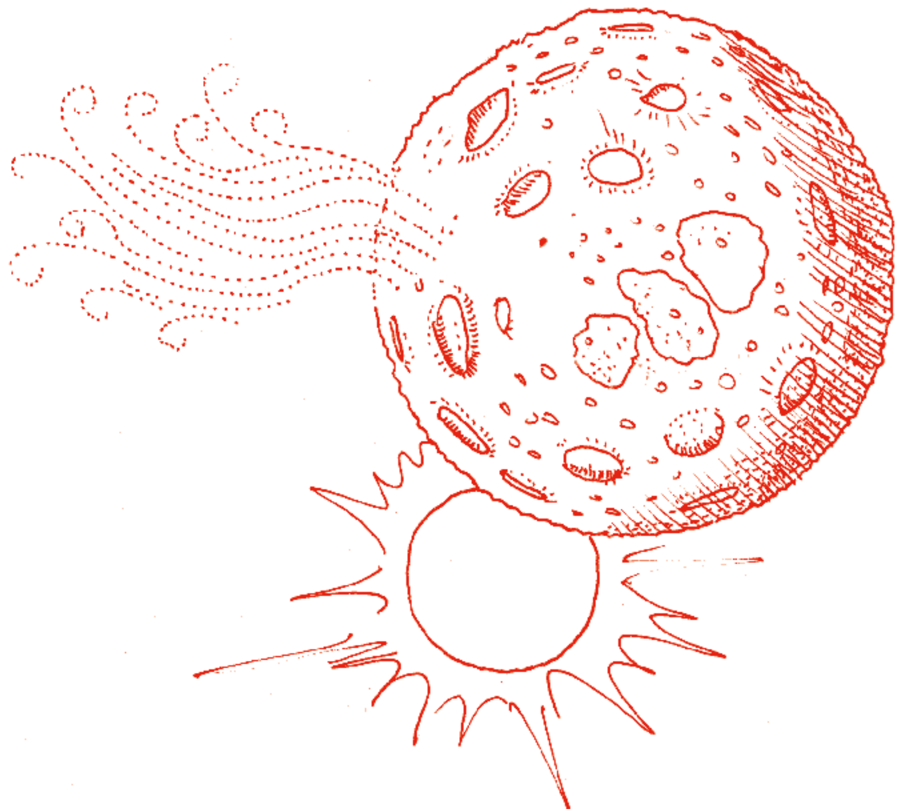
On one occasion, he had been to see a cowboy film with George Gamow, the Russian-American theoretical physicist and cosmologist. Gamow observed that it was strange that, in gunfights shown in the films, the hero was quicker at drawing their gun than the villain. The villain, Gamow argued, should be better prepared than the hero and so react faster. Bohr disagreed arguing rather innocently that, as the hero did not intend to kill, their clear conscience would lead to a faster reaction time. The following day, Gamow and Bohr armed themselves with toy pistols and, at an unexpected moment, Gamow and some colleagues ambushed Bohr. Victory in the 'duel' went to Bohr and his theory of the effect of innocence on reaction time gained at least some empirical support.



In contrast to his speed with a pistol, Gamow claimed that Bohr was often the last person to understand arguments presented in seminars. Gamow said that even after the whole audience had understood the thesis, Bohr would claim not to and would insist colleagues re-explain it to him. After considerable discussion, Bohr would begin to understand but often in a way that showed the physicist presenting was mistaken.

Photoelectric fountains of the Moon

In 1972, Apollo 17 astronauts in orbit around the Moon observed an unexpected phenomenon – what they described as *bands, streamers* or *twilight rays* rising from the lunar surface. NASA scientists believe the dust fountain effect arises from the photoelectric effect. On the daylit side of the Moon, X-ray and UV radiation can cause electrons to be emitted from Moon dust, forming positively charged particles. These particles repel each other, throwing the dust up to several kilometres from the Moon's surface before they fall back. The dust on the dark side of the Moon acquires a negative charge from electrons carried by the solar wind that can exert even larger forces, potentially causing larger fountains.

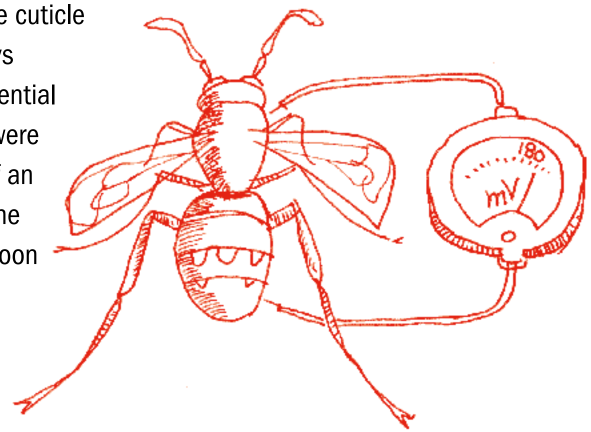


Photoelectric facts

- In his 1905 photoelectric paper, Einstein did not use the term *photon*, but referred to a 'light quantum'. The word *photon* was first used in 1926 by the chemist Gilbert Lewis who is best known for the discovery of the covalent bond.

- The way that the photoelectric equation ($eV=hv\text{-}\Phi$) is presented in textbooks is "at best, misleading, and at worst, simply incorrect", according to physicist Stephen Klassen. He argues that when the photoelectric effect is investigated at room temperature, the electrons in the metal surface have a distribution of energies and hence there is no single value of the stopping potential. It is therefore impossible to calculate the stopping potential at room temperature using the linear equation.

- It has been observed that the cuticle of the Oriental hornet displays photoelectric properties. Potential differences of 60 - 180 mV were detected between the tips of an Oriental hornet's body with the highest values occurring at noon due to peak irradiation with ultraviolet radiation. The evolutionary purpose of the effect is not known.



- William Henry Bragg, who won the Nobel Prize for his work with his son Lawrence on X-ray crystallography, nicely described the incredulity of scientists when they first made sense of the dual nature of light:

  On Mondays, Wednesdays and Fridays light behaves like waves, on Tuesdays, Thursdays and Saturdays like particles, and like nothing on Sundays.

Heisenberg

Mothers vs Nazis

Werner Heisenberg was a German physicist who proposed an important novel conceptualisation of quantum theory. Born in 1905, he went to school with Heinrich Himmler who went on to become the commander of the SS in Nazi Germany. During the Nazi era, Heisenberg was attacked in the SS publication, Das Schwarze Korps. Though Heisenberg was a member of the German Evangelical Church, the newspaper called him a "white Jew" and ominously argued that he should "disappear". Heisenberg's mother visited Himmler's mother and told her: "We have to care for our boys." Whilst Himmler was slow to respond to his mother, he wrote to SS Gruppenfuhrer Reinhard Heydrich that Germany could not afford to lose Heisenberg. In response, Heydrich wrote to Heisenberg warning him not to mix his personal and professional lives. Following the war, Heisenberg settled in Göttingen, in north-west Germany. He had five children and when his wife gave birth to twins, his colleague Pauli (see below) congratulated him on his 'pair creation' - an allusion to the process of pair production in particle physics.

Heisenberg's horrific viva

Heisenberg nearly failed his doctorate because one of his examiners in practical physics, Wilhelm Wien (noted for his contributions to thermodynamics and electromagnetism), had set him some experimental tasks to carry out before his final examination, which Heisenberg failed to complete. In the examination, Wein asked Heisenberg about an interferometer he was meant to have studied, but Heisenberg had not used the device and tried to come up with an answer on the spot. This response angered Wein who then questioned Heisenberg about the resolving power of telescopes. Again, the young scientist was found lacking. It was only because of the intervention of Heisenberg's theoretical supervisor, Arnold Sommerfeld, who believed that his student was a genius, that Heisenberg was allowed to gain his doctorate.

Sommerfeld is notable for his work in atomic and quantum theory. He was nominated for the Nobel Prize 84 times but never won the award himself. However, his teaching achievements are attested by the fact that four of his doctoral students (Heisenberg, Pauli, Debye and Bethe), and three of his postdoctoral researchers (Pauling, Rabi and von Laue) won the prize.

Hay fever in Helgoland

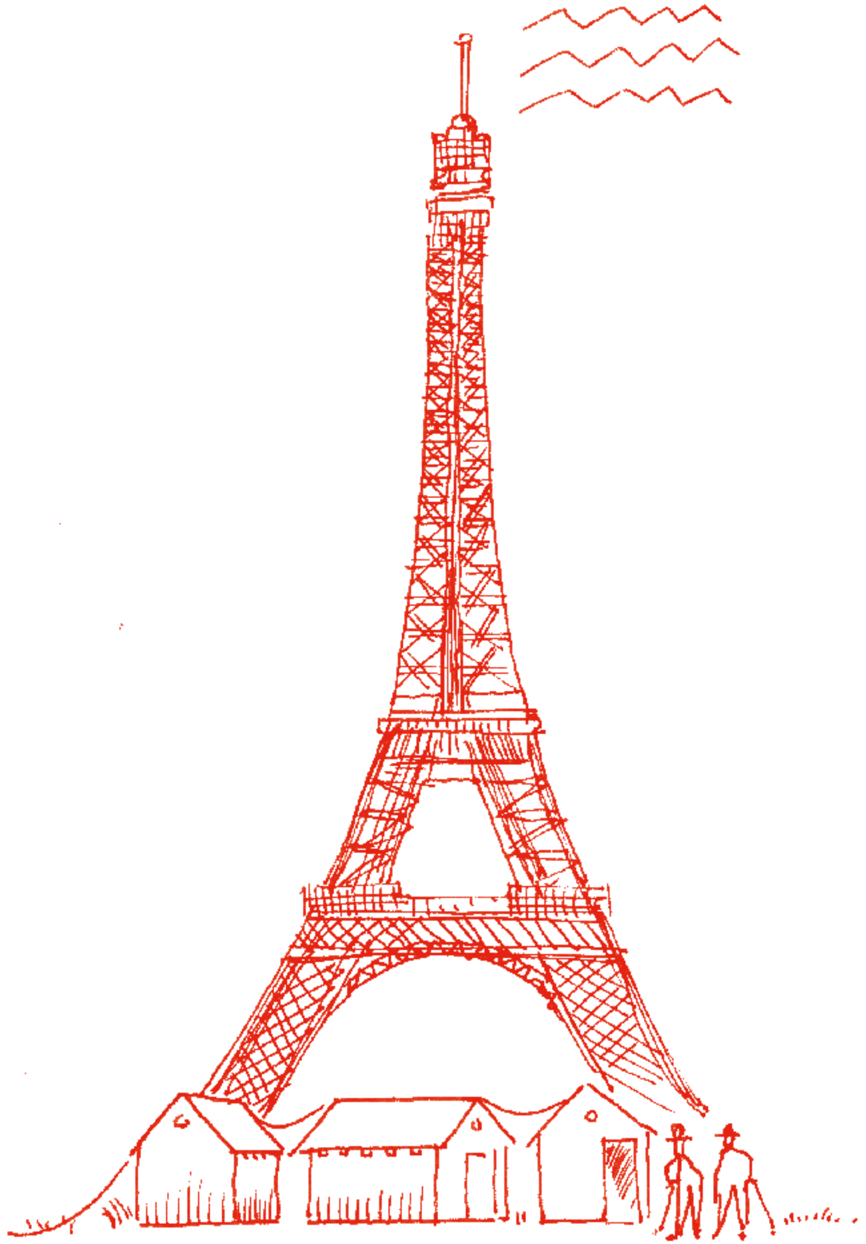
Whilst allergies are typically not conducive to scientific thinking, in one case at least, they may have led to a breakthrough. In June 1925, Heisenberg suffered a severe bout of hay fever that made him spend time in Helgoland, a small archipelago in the North Sea. Whilst on the islands, Heisenberg developed a novel strategy for calculating the energy levels of atomic oscillators. The approach was radical but produced excellent results and Heisenberg wrote that he was unsure whether to publish the method or "throw it into the flames". Fortunately, after sending his work to his colleague Pauli, he chose the first option.

Uncertainty of an assassin

Heisenberg was a central figure in the Nazi regime's efforts to construct an atomic weapon. The US intelligence agency, the Office of Strategic Services, initially planned to disrupt the nuclear programme by kidnapping Heisenberg but decided that assassination would be more feasible. Bizarrely, their chosen assassin was Moe Berg, a major league baseball catcher, who had become an agent during the war. Towards the end of 1944, Berg was ordered to attend a lecture by Heisenberg in Switzerland. Armed with a gun, Berg was instructed to kill the physicist during the lecture if it became clear that Heisenberg was involved in the bomb project. Berg decided that the assassination was not necessary and, a few days after the lecture, managed to secure an invitation to a dinner party Heisenberg was attending. Berg used the opportunity to talk to Heisenberg and accompany him back to his hotel. The American concluded that Nazi atomic research was at an early stage and further covert action unnecessary.

De Broglie's towering achievement

The French physicist Louis de Broglie was descended from a noble family - his great-great-grandfather was guillotined in the French Revolution and the physicist held the courtesy title of 'prince' for most of his life until he succeeded his elder brother as the 7th duc de Broglie in 1960. De Broglie's first degree was in history, but he developed an interest in science whilst serving in the French Army. During the First World War, he served as a combat engineer and spent some time working at a radio communication post established in the Eiffel Tower. Remarkably for someone without a background in physics, he proposed the ground-breaking idea that particles have a wave-like nature. He derived the formula for what came to be known as the *de Broglie wavelength* in his PhD thesis. Whilst, in retrospect the value of his research is clear, his examiner Paul Langevin (who worked on magnetism and proposed the twin paradox), was not sure whether the young physicist's work was sufficiently significant to be awarded a doctorate. Langevin sent de Broglie's thesis to Einstein for another opinion. Einstein responded that de Broglie's work should certainly pass. Despite his distaste for quantum theory, Einstein described de Broglie's idea as "a first feeble light on this worst of physics enigmas".



Nuclear Physics

Pre-empting Einstein

Though the equation $E=mc^2$ is inextricably linked with Einstein, he was not the first person to propose the possibility of the equivalence of mass and energy:

- In 1704, Newton posed the question: “Are not gross Bodies and Light convertible into one another, and may not Bodies receive much of their Activity from the Particles of Light which enter their Composition?”
- J. J. Thomson, in 1881, noted that a moving charged sphere must produce a magnetic field, which modifies its own motion, effectively increasing its mass. He drew an analogy to a sphere moving through water. His analysis led to the conclusion the $E=\frac{3}{4}mc^2$ for an electron in motion.
- In 1900, Henri Poincaré linked energy with a ‘fictitious fluid’ with mass, $m=c^2/E$.
- In a lecture at Yale in 1903, Thompson mentioned the equation in the form $E=mc^2$.
- In 1904, just a few months before Einstein’s paper, Friedrich Hasenöhrl presented a paper that argued $E=3/8mc^2$. He subsequently published a correction, claiming $E=\frac{3}{4}mc^2$.

Meitner’s escape

Physicist Lisa Meitner, who many people believe should have been awarded a Nobel Prize for her work on nuclear fission, was involved in a dramatic escape from Nazi Germany. During Hitler’s rise to power, Meitner was working in Berlin. Unlike other Jewish scientists, such as Otto Frisch and Leo Szilard, who were forced to resign their academic posts, Meitner had Austrian citizenship and so was able to carry on working till 1938. As she began to feel increasingly threatened, her academic colleagues rallied to help her escape. Bohr invited her to lecture in Copenhagen, all expenses paid, but Meitner was refused travel documents. With the help of colleagues Otto Hahn and Dirk Coster, with whom she communicated in coded telegrams, Meitner managed to flee to the Netherlands. After her successful escape, Wolfgang Pauli sent Coster a telegram: “You have made yourself as famous for the abduction of Lise Meitner as for [the discovery of] hafnium!”

Meitner travelled from the Netherlands to Sweden, but she was treated as an outsider at the University of Stockholm and had to carry out technical work that was normally done by assistants. After moving to the Royal Institute of Technology in Stockholm in 1947, her research was better funded, but she was denied the title of professor. On her retirement in 1960, she moved to Cambridge where she continued to lecture and contribute to research.

Over her career, Meitner made significant contributions to fission research, including the discovery of protactinium, and became the first female full professor of physics in Germany. She was nominated for the Nobel Prize in physics 29 times and in chemistry 19 times but she never won. In 1997, element 192 was named Meitnerium in her honour (the only element named solely after a non-mythological woman).

Rutherford

Ernest Rutherford was a pioneering nuclear physicist who proposed the concept of half-life and categorised alpha and beta radiation.

Farming's loss is physics' gain

Ernest Rutherford grew up on a farm in rural New Zealand and spent his early life chopping wood and hunting pigeons. He received the news that he had been awarded a scholarship for postgraduate study at the Cavendish Laboratory in Cambridge whilst working on the farm and is reported to have said to his mother: "That's the last potato I'll ever dig."

Kapitsa's chutzpah

When the young Russian scientist Pytor Kapitsa sought a job in Rutherford's laboratory, Rutherford was initially uninterested. Kapitsa asked Rutherford how many students were in his laboratory and the usual degree of accuracy of experiments. Rutherford replied that there were 30 students and experimental accuracy was around 2-3%. Kapitsa is said to have responded: "Well then, one more student would not even be noticed within that margin of accuracy!" Kapitsa got the job and soon became one of Rutherford's favourite students.

Reptilian alter-ego

Kapitsa gave Rutherford the nickname 'the crocodile' because in Russia the crocodile is a symbol of the father and, because of its stiff neck, "it just goes straight forward with gaping jaws – like science, like Rutherford".

The sculptor Eric Gill was commissioned to add a carving of a crocodile to a wall of the Mond Laboratory in Cambridge.

More significant than submarines

Whilst Rutherford was carrying out experiments on the bombardment of nuclei with alpha particles during the First World War, he was called to a meeting of the Anti-Submarine Division. He didn't attend, sending a telegraph that read: "If, as I have reason to believe, I have disintegrated the nucleus of the atom, this is of greater significance than the war."

Golfing physicists

Rutherford became a keen golfer, after having been introduced to the sport by his supervisor J. J. Thomson. Thomson's interest in the sport had led him to publish a paper on the dynamics of the golf ball in the journal *Nature*.

Nobility and an untimely end

When Rutherford fell ill towards the end of his life, medical assistance was tragically delayed. Rutherford had received a peerage, becoming Lord Rutherford of Nelson. At the time, it was still the custom that only doctors who were members of the nobility could treat noble patients. It has been suggested that the delay which resulted from an appropriately ranked doctor, Sir Thomas Dunhill, travelling from Harley Street in London to Cambridge, cost Rutherford his life. Rutherford died in 1937 aged 66 of complications arising from surgery to remove a hernia.

Szilard's eureka moment

Leo Szilard, a Hungarian physicist, worked in Berlin during the 1920s. Because he was a Jew, Hitler's rise to power led him to flee to London. On the 13 September 1933, Szilard was walking on Southampton Row in Bloomsbury having just read Ernest Rutherford's pronouncement in *The Times* the day before that: "Anyone who looked for a source of power in the transformation of the atoms was talking moonshine." Szilard recalled that:

> ...as I was waiting for the light to change and as the light changed to green and I crossed the street, it suddenly occurred to me that if we could find an element which is split by neutrons and which would emit two neutrons when it absorbed one neutron, such an element, if assembled in sufficiently large mass, could sustain a nuclear chain reaction.

During his time in London, Szilard rented a small room at the Strand Palace Hotel which used to be a maid's cupboard. The room gave access to a communal bathroom and Szilard used his bath time to daydream about nuclear fission. He usually went to bathe at 9am but one day, a concerned maid knocked on the door at noon to ask: "Are you alright, sir?" The abstracted physicist had been in the bath for three hours, thinking about beryllium's role in fission.

Radioactive coal

Old coal-fired power stations may have released more radiation into the environment than current nuclear power stations. This effect occurred because of naturally occurring radionuclides in coal ash released from some coal-fired powerplants. Coal can contain radioactive isotopes including polonium-210, lead-210, radium-226 and uranium-238. One estimate, made in 1988, concluded that whilst the absolute radiation dose from coal-fired plants was small (0.001-0.0001 mSv a year), emissions of radionuclides from some plants were ten times higher than from nuclear equivalents. Conversely, the release of carbon dioxide from the combustion of the relatively old, and hence relatively low-activity carbon in fossil fuels into the atmosphere, causes a decrease in the naturally occurring radiation dose (the Suess effect).

Where helium comes from

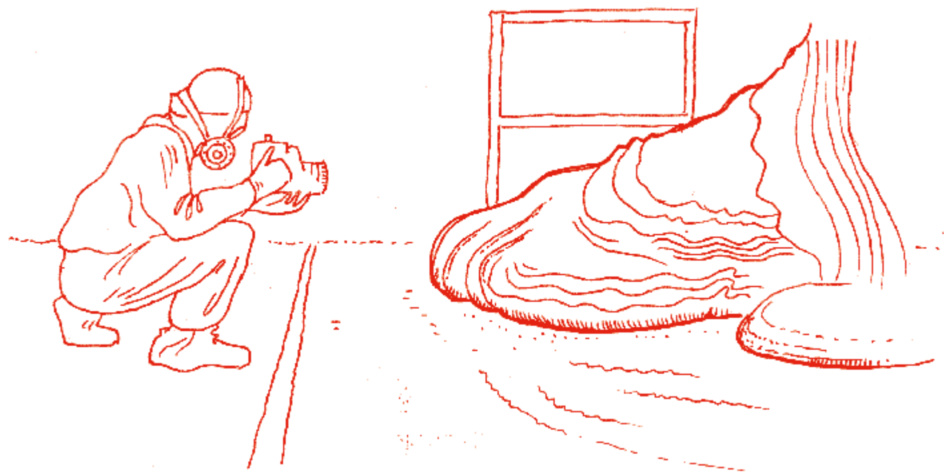
Global helium supplies are under threat - if demand continues to increase at the projected rate, world helium reserves could run out within 62 years. Atmospheric helium provides an interesting context for highlighting the impact of fission and fusion processes on our environment. Around 7% of the helium-4 (the most common isotope of helium) in the Earth's atmosphere is thought to have been produced from nuclear fusion in the Big Bang; the remainder is formed from the radioactive decay of uranium into thorium within the Earth. Around 190 grams of helium-4 are outgassed from the Earth's surface every second.

The radioactive elephant's foot

During the Chernobyl nuclear accident in 1986, the reactor core melted, mixing with steel and other materials to form lava-like flows which cooled and solidified beneath Reactor No. 4. A scientist who entered the power station after the meltdown described the material:

> It is very black, like glittering coal… It's awfully beautiful, it shines like silver. You feel like you're on the Moon but rationally you know the radiation is extremely high. It is an unforgettable experience.

The frozen flows have formed shapes reminiscent of stalactites and stalagmites with one particularly noticeable feature named the elephant's foot because of its shape. Even eight months after the disaster the elephant's foot gave off so much ionising radiation that a visitor had a 50% chance of death if they spent five minutes close to the foot. The activity of the waste has since decreased.



The mouse and the expensive nuclear cocktail

The first pure sample of heavy water (D_2O - water containing only deuterium, an isotope of hydrogen and oxygen) was produced in 1933 by Gilbert Lewis, an American chemist, using electrolysis. To determine if it was harmful to living things, Lewis fed his entire supply of heavy water, a total of 1 cm^3, to a mouse. Though the mouse survived, it was reported to have shown “marked signs of intoxication”. Lewis’ American colleague Ernest Lawrence, who was waiting to use the heavy water in his cyclotron, commented: “This was the most expensive cocktail that I think mouse or man ever had.”

The demon core

A 6.2 kg mass of plutonium at Los Alamos Laboratory acquired the nickname ‘the demon core’ due to its involvement in two fatal accidents. In the first, physicist Harry Daghlian dropped a 4.4 kg tungsten carbide brick onto the core whilst doing neutron reflection experiments, initiating an uncontrolled chain reaction in the plutonium which produced a burst of ionising radiation. Though he quickly removed the brick, Daghlian had received a fatal dose - he experienced blisters and burns to his hand and died 25 days after the incident. In the second accident, Louis Slotin was fixing two halves of a reflective beryllium sphere around the core when his screwdriver slipped, causing a rapidly accelerating chain reaction and releasing a burst of ionising radiation. Slotin managed to quickly pull the two halves of the core apart, saving others in the laboratory from further exposure to radiation. He described experiencing a sour taste and his colleagues reported a blue glow of air ionisation and a wave of heat. Slotin’s condition deteriorated rapidly and he died nine days after the event.

The radioactive Boy Scout

In August 1994, police in Detroit, responding to an unrelated call about the theft of tyres, found teenager David Hahn waiting in a parked car. Suspicious of the boy’s story, the police searched Hahn’s car and found a grey powdered substance inside a locked toolbox in the boot. Hahn told the police that the substance was radioactive and an emergency response team was called. Hahn had developed an interest in radioactivity after getting a chemistry set and, as a Boy Scout, had received a badge for atomic energy. He wrote to the director of the National Regulatory Commission asking about the presence of radioactive elements in everyday objects and the director replied, reporting that the quantities of radioactive materials were too small to pose a significant risk. Hahn set about collecting isotopes from objects he could buy from shops: thorium-232 from gas lanterns, americium-241 from smoke detectors and radium-226 from an old vial of luminous paint. He mixed the isotopes he had collected and wrapped them in aluminium foil as part of his own fission reactor constructed from a block of lead. During the building process, Hahn became concerned when his measurements of radiation levels showed elevated readings five blocks away from his home. He decided to divide up his cache of radioactive isotopes, splitting the material between his home, the boot of his car and a shed. The chance encounter with the police ended his nuclear experimentation and triggered a response from the FBI and a Federal Radiological Emergency Response. Commenting after the event, he said: “I wanted to make a scratch in life… I don’t believe I took more than five years off my life.” It has been reported that Hahn died in 2016 at the age of 39, possibly as a result of radiation exposure.

Fermi's fission

Italian physicist Enrico Fermi is often cited as one of the most significant contributors to the development of nuclear physics and technology. He led the construction of the first artificial nuclear reactor, Chicago Pile-1, and also carried out research in statistical and particle physics.

Early fission without imagination

The achievement of induced fission of uranium, whilst often credited to Otto Hahn and Fritz Strassmann in 1938, may have been unwittingly achieved by Fermi as early as 1934. Fermi had been attempting to produce elements heavier than uranium by irradiating the metal with neutrons. He noted that the bombardment led to the production of several isotopes with a range of different half-lives but did not, at the time, link the products with fission of the uranium nucleus. Fermi later reported:

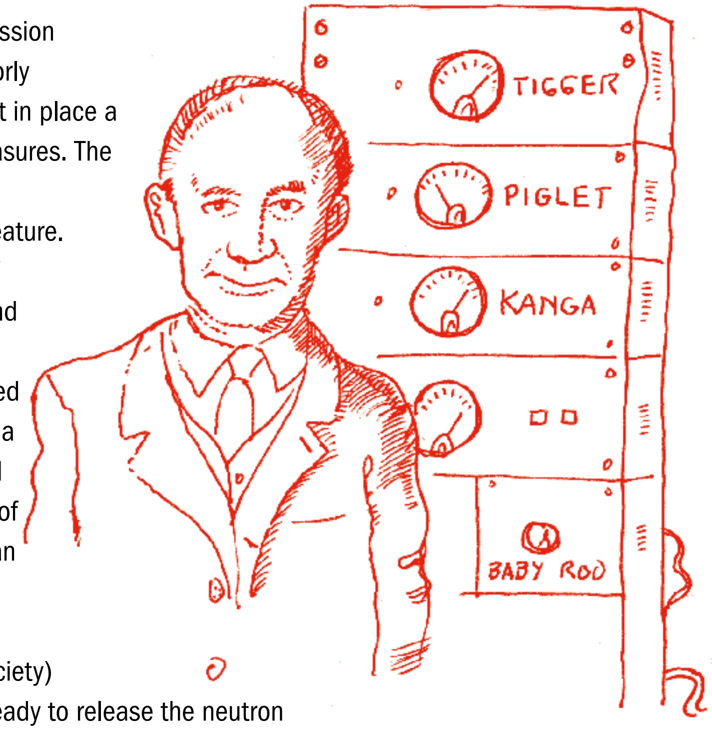
> We did not have enough imagination to think that a different process of disintegration might occur in uranium from that in any other element, and we tried to identify the radioactive products with elements close to uranium in the periodic table of elements. Moreover, we did not know enough chemistry to separate the products of uranium disintegration from one another.

A nuclear reactor in a balloon

The first self-sustaining nuclear reactor was built by Fermi and his team at the University of Chicago. It was contained within a bag made of balloon cloth (a fabric used in hot air balloons and, historically, aircraft skins) so the scientists could remove neutron-absorbing air, if necessary, to increase the rate of reaction. Engineers at the Goodyear Tire and Rubber Company were reportedly bemused when they received a request for a rectangular balloon with no information on the use of the material.

Tigger, Piglet, Kanga and the nuclear reactor

Whilst he was constructing the reactor, Fermi was learning English by reading A. A. Milne's *Winnie the Pooh*. He nicknamed several of the instruments used to observe the reactor after characters from the book: Tigger, Piglet, Kanga and Baby Roo.



As the risks of early fission experiments were poorly understood, Fermi put in place a number of safety measures. The reactor had a rather idiosyncratic safety feature. In addition to a set of control rods raised and lowered by a motor, a second rod, nicknamed 'zip', was attached to a heavy weight and tied to a rail. In the event of an emergency, Norman Hilberry (who went on to be president of the American Nuclear Society) waited with an axe, ready to release the neutron absorbing rod by cutting the rope. The third control rod was under Fermi's direction and used to regulate the rate of reaction during experiments. The control rods consisted of sheets of neutron-absorbing cadmium, nailed to wooden strips. A final safety measure was the so-called 'suicide squad', a team of three men who stood on a platform above the reactor and could flood the reactor with calcium sulphate in the event of an emergency.

One theory suggests that the name of a technique for rapidly shutting down nuclear reactors, the SCRAM procedure, derives from Hilberry's role (Safety Control Rod Axe Man). Another is simply that it is short for 'scramble' – ie run away very quickly.

Chernobyl's SCRAM and 'neutron poison'

The failure of a SCRAM procedure (see above) contributed to the Chernobyl disaster. When a technician pressed the emergency shutdown button, the control rods started moving at 0.4 m/s into the 7 m-high core. The rods had graphite tips below a neutron-absorbing boron carbide section. As the non-neutron-absorbing graphite tips entered the reactor, they displaced neutron-absorbing water and caused a power surge in the reactor, overheating the core. The pressure of the heated fuel and fission product gases caused the fuel rods to rupture and to mix with the cooling water leading to a steam explosion. During this incident, the power of the reactor jumped to ten times its normal operating output, reaching over 30,000 MW. The pressure of steam was sufficient to lift the 2,000 tonne upper biological shield and a refuelling machine from the top of the reactor.

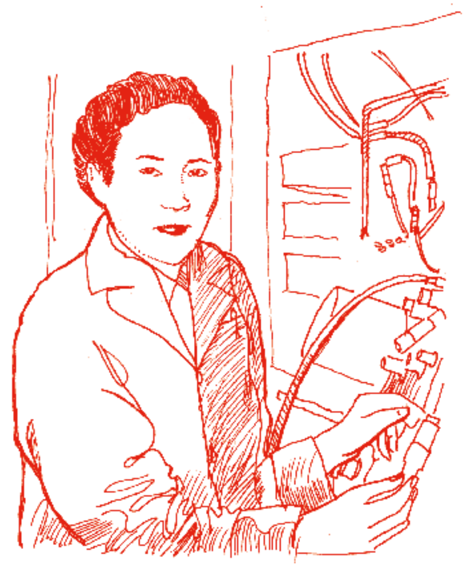
In addition to control rods, some reactors may have an emergency 'neutron poison fuse'. This is a thin metal wire which melts if the reactor gets too hot, releasing a spring-powered injector that injects a neutron-absorbing material (a 'neutron poison') into the reactor.

Uranium glass

Following his discovery of uranium in 1789, Martin Klaproth suggested that uranium calx (uranium oxide) could be used as a dye for colouring glass and porcelain. The pigment became known as *uranium yellow*. After uranium ore is mined, it is crushed and chemically treated to produce a yellow powder of uranium oxide (U_3O_8) known as yellow cake. Uranium oxide was used as a pigment in glassware to produce a range of yellow and green colours which fluoresce under ultraviolet light and were popular in the 1880s-1920s - and it is reported that Queen Victoria was gifted a pair of uranium glass candlesticks. The perceived similarity of the colour of the glassware to petroleum jelly led to its nickname 'Vaseline glass'. Manufacture of uranium glass products has continued to this day, though depleted uranium from spent nuclear fuel is typically used an alternative to mined yellow cake to preserve uranium reserves. The dose of radiation from uranium glass is typically too low to be harmful to humans.

Wu's wisdom

An historically overlooked contribution to particle physics was made by the Chinese scientist Chien-Shiung Wu. Wu was born in 1912 near Shanghai and encouraged to pursue her education by her father, a high-school principal. After studying at Nanjing and Berkeley, she worked on the Manhattan Project researching the enrichment of uranium. Subsequently, she researched beta-decay and showed that Fermi's prediction that electrons would leave the nucleus at high speeds was correct. Perhaps her most significant contribution was the development of an experiment proposed by Tsung-Dao Lee of Columbia University and Chen-Ning Yang of the Brookhaven National Laboratory.



Wu should be considered as one of a select group of scientists whose work revealed that a law of physics is not as universal as was once believed. Her data showed that the weak nuclear force, responsible for radioactive decay, broke the *law of parity conservation*. This law requires that mirror image versions of reactions should behave in identical ways and that the universe does not distinguish between left- and right-hand rotations.

Lee and Yang won the 1957 Nobel Prize for their work and many feel that Wu should also have been recognised for her contribution. Wu was committed to encouraging more women into STEM careers and commented at a meeting at MIT: "I wonder whether the tiny atoms and nuclei, or the mathematical symbols, or the DNA molecules have any preference for either masculine or feminine treatment."

The Nth Country Experiment

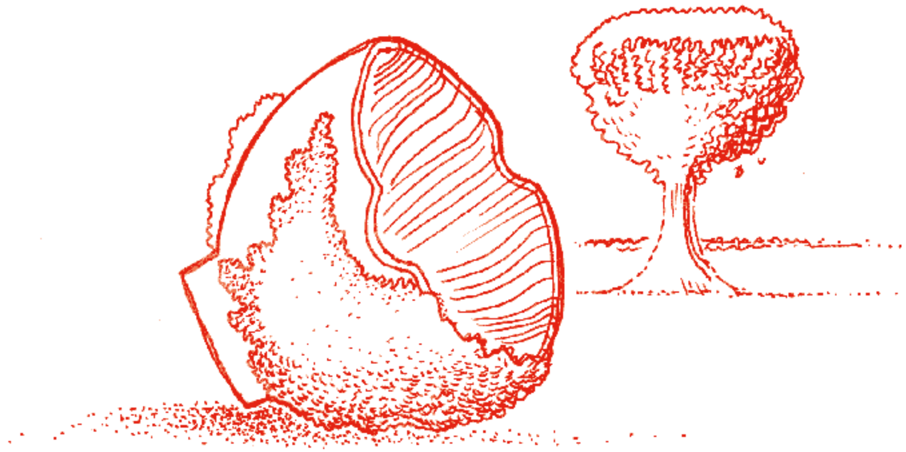
In the 1960s, during the Cold War, the United States government wanted to find out how easy it would be for other countries to develop nuclear weapons and started the secret Nth Country Experiment. Two recent physics PhD graduates were recruited, supplied with a laboratory and tasked with developing plans for a nuclear weapon. The two physicists produced plans for a bomb that, if it had been built, would have had as much explosive energy as the weapon dropped on Hiroshima.

Nuclear yen

Following the Fukushima nuclear disaster in Japan in 2011, researchers developed an unusual method for monitoring radiation levels using coins. They estimated the exposure of areas surrounding the nuclear plant to neutron radiation by collecting 5-yen coins from homes 100-500 m from the facility. The coins are composed of 37% zinc by weight and, when exposed to neutrons, the zinc-65 isotope is produced which decays with a half-life of 244 days with the emission of gamma rays. The researchers could calculate the intensity of neutron radiation at different distances from the plant by analysing the proportion of zinc isotopes in the coins.

The nuclear bowl

London's Science Museum houses a porcelain bowl retrieved from the aftermath of the nuclear blast at Hiroshima. The bowl has sand fused into its outer edges by the heat of the explosion.



Nuclear sandwiches

The Subway sandwich restaurant chain was co-founded by the nuclear physicist Dr Peter Buck. The idea for the store arose from a conversation between a 17-year-old working in a hardware store, Fred DeLuca, and Buck at a barbecue. The business was started in 1965 with the help of a $1,000 loan from the physicist. Today there are more than 44,000 Subway restaurants around the world.

Where the streets are radioactive

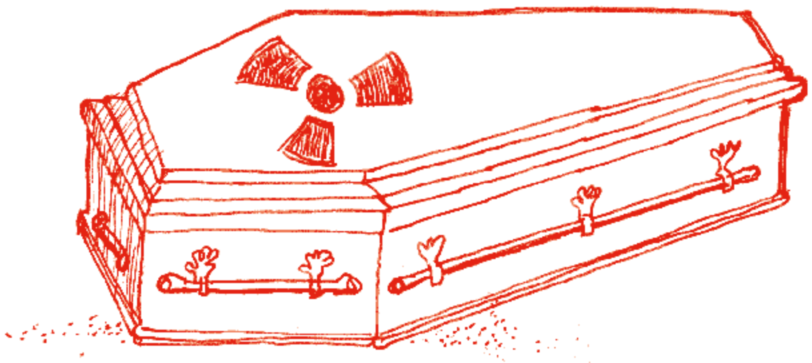
In the 1910s and 1920s, Denver was home to a plant that processed radium, largely for medical applications. Due to lax safety standards, radioactive residues ended up in waste that was used to bulk up foundation materials as well as in concrete and asphalt mixes. A subsequent review found that nine streets in Denver had been laid with asphalt contaminated with radioactive residues and peak gamma radiation levels were measured at 57 micro-roentgens per hour - far in excess of the 7 micro-roentgens per hour average US background radiation dose. The investigation concluded that the levels of radiation posed only a minimal threat to public health - even if someone stood at the location of the highest measured level of radiation for 16 hours, they would receive less than the recommended maximum annual safe radiation dose standard. Nonetheless, in the early 2000s, the city spent $20 million to cut out and safely dispose of sections of contaminated asphalt.

The radioactive reinforcing rods

In northern Taiwan, in 1982, a batch of steel used to make reinforcing rods was contaminated with cobalt-60, a beta and gamma emitting radioisotope. The rods were used in the construction of over 200 buildings, some including schools. A team of researchers followed up the effects of exposure to low levels of gamma radiation due to the rods over a period of 12 years and found an increased number of cases of leukaemia and breast cancer in those exposed to the radiation emitted by the contaminated steel.

Byers' lead coffin

The death, in 1932, of Eben McBurney Byers prompted a reconsideration of the dangers of radiation. Byers, a rich industrialist, socialite and athlete drank more than a thousand bottles of Radithor, a radium-treated water, perhaps lured by the manufacturer's claims of the healing effects of radiation. The drink had quite the opposite effect, leading to the loss of his jaw and the formation of holes in his skull. The high levels of radiation in his body meant Byers was buried in a lead-lined coffin.



Is a little radiation good for you?

An ongoing debate considers whether low levels of exposure to radiation may have beneficial effects. It had been assumed that there is a linear relationship between radiation risk and dose – the more radiation a person is exposed to, the greater the harm. This assumption arises from a probabilistic model of the risks of radiation: the greater the probability of a collision of a gamma ray photon with a DNA molecule, the greater the risk of harm. However, some researchers have suggested that the reality of the risk-to-dose relationship is more complex. Data from British nuclear industry workers suggest modest doses of radiation (10-50 mSv per year) may lead to lower incidences of leukaemia and cancer than found in the general population. In addition, an analysis of cases of cancer has found that the incidence of the disease was lower in areas with higher radon concentrations (over 10 mSv per year) in comparison to areas with lower levels of radon (less than 2 mSv per year). Studies of survivors of the nuclear bombs dropped on Hiroshima and Nagasaki revealed that victims of the blasts who received modest doses of radiation lived, on average, four years longer than the general population. One suggested mechanism to explain this unexpected effect is that exposure to low levels of radiation may induce changes in the immune system. For example, a study found that the number of antibodies produced by mice rose by a factor of five when exposed to doses of radiation up to 200 mSv per day. Such claims are controversial and more recent studies of radiation workers report that even small increments in dose led to increased incidences of cancer.

Nuclear cigarettes

In addition to its many other hazards, cigarette smoke can contain polonium-210. Levels of polonium vary between different brands of tobacco but the presence of this isotope occurs through the decay of two isotopes – radium present in the soil and lead in phosphate fertilisers.

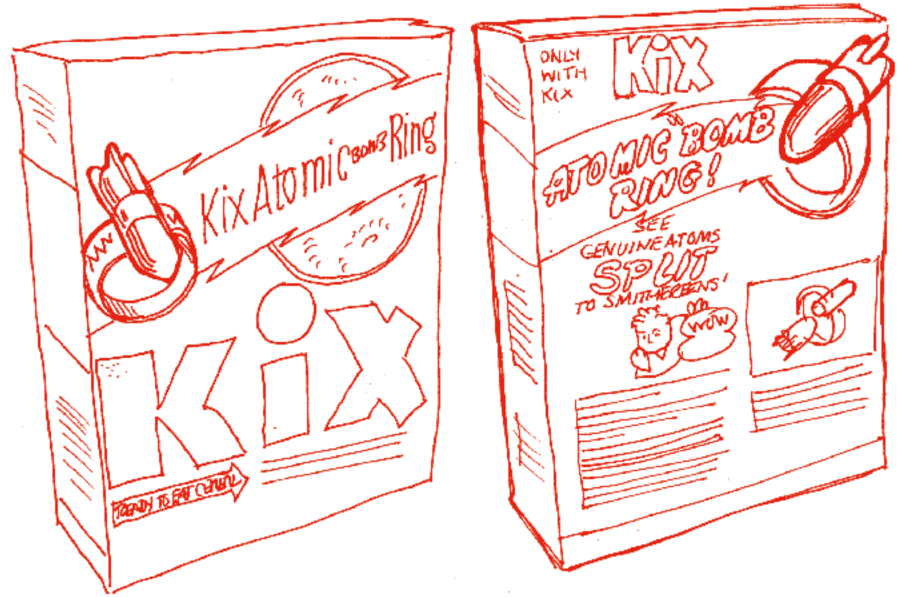
In addition to radioactive contaminants, smoking can cause irradiative harm in another way. In smoke-free environments, the naturally occurring radioactive gas radon, and the daughter nuclei produced by its decay, adhere to walls and furniture through the action of electrostatic forces. When an aerosol such as cigarette smoke is present in a radon-rich environment, radon's decay products can attach to smoke particles and are more likely to be inhaled than in smoke-free conditions. Radon decay product concentration has been found to double in indoor environments when cigarette smoke is present.

The radioactive nuclear plant worker

The need for monitoring of radon gas in homes in some areas was highlighted by a chance discovery. In 1984, Stanley Watras, a worker at Limerick nuclear power plant in Pottstown, Pennsylvania triggered an alarm in a routine radiation screening process at the facility. As fission had not yet been initiated at the plant, the alarm was not seen as significant. Curious, Watras decided to go through the radiation monitoring station on his way in to work and found that his higher-than-expected level of radiation persisted. The result triggered an investigation which discovered high levels of alpha radiation in his home. The radiation levels in the Watras' house exceeded the permitted dose for uranium miners by a factor of a hundred and the source of the radiation was traced to radon gas released from uranium-rich granite rocks in the area. The level of radiation was the highest ever recorded for a domestic building and is equivalent to the harmful effects of smoking 135 packs of cigarettes a day.

Radioactive toys

The physicist George Zweig, who went on to develop a model of quarks, recalled how his interest in nuclear physics was sparked by a free toy in a box of breakfast cereal. In the 1940s, after hearing about an 'atomic bomb ring' on the Lone Ranger radio show, he sent off 15 cents and a cereal box top to receive the toy. When the ring arrived, Zweig recalled taking the toy into a dark wardrobe, removing the cap and observing brilliant flashes of light. The ring was a spinthariscope, an instrument for observing nuclear disintergration (invented by William Crookes, the inventor of the eponymous tube used to discover X-rays) powered by a small piece of polonium.



In the early 1950s, Gilbert Toys, an American manufacturer of specialised science toys and chemistry sets, brought out Gilbert's U-238 Atomic Energy Lab. Costing $49.50 (approximately $500 in today's money), the set contained a Geiger-Müller counter, a cloud chamber, an electroscope and alpha, beta and gamma radiation sources. Radar Magazine dubbed the Atomic Energy Lab one of "the 10 most dangerous toys of all time" in 2006.

Geiger and Marsden

Experimental evidence for the nucleus was first collected by Ernest Marsden and Hans Geiger in 1909. Their experiment famously required an observer to notice tiny points of light, called scintillations, produced by the impact of an alpha particle. The delicate observation needed for this work required sharp eyesight – Marsden recalls being instructed by Geiger not to put his head out of the window when travelling by train, not due to safety concerns, but in case a smoke particle damaged his vision and reduced his ability to act as a human alpha particle detector.

Geiger and Marsden served on opposite sides of the Western Front during the First World War, Geiger as an artillery officer and Marsden in the sound-ranging section of the Signal's Corps. During the fighting, Geiger managed to communicate with Marsden by sending a letter using Niels Bohr in Copenhagen as an intermediary.

The exposed X-ray plates

After the detonation of the atomic bomb over Hiroshima in 1945, people on the ground struggled to understand how so much destruction had been caused by a single bomber. Rumours spread that the widespread fires were the result of petrol sprayed by aircraft and the bright flash was due to the ignition of magnesium powder. One piece of evidence that was mysterious at the time hinted at the radioactive nature of the blast – at a local Red Cross hospital, X-ray plates stored in the basement had become exposed.

Radioactive swimming

In the early days of the American nuclear industry, during the 1940s, the rules for the handling of radioactive materials were laxer. Galen Winsor was a safety officer at the Hanford Nuclear Site, the location of the first full-size plutonium-producing reactor. When Hanford's reactors were decommissioned at the end of the Cold War, the site housed 177 storage tanks, containing 200,000 m^3 of high-level radioactive waste. Winsor swam in the pool where spent fuel rods were kept and the water was heated to 38°C. He further claimed to have drunk a glass of water from the pool every day without ill effects. By contrast, since the 1980s, former workers have been attempting to gain compensation for symptoms caused by alleged exposure to radiation due to lax safety measures at the plant.

The Roman neutrino detector

Scientists at a facility at Gran Sasso, Italy, have found themselves at odds with archaeologists. Although lead is used as a radiation shield, mined samples contain the beta-emitting isotope lead-210 which has a half-life of 22 years. Lead produced in Roman times has a lower proportion of lead-210 than more recently processed metal and hence is an ideal material to shield sensitive neutrino detectors. The Gran Sasso researchers acquired 120 lead ingots recovered from a Roman shipwreck that occurred between 80 and 50 BCE off the coast of Sardinia. The physicists' use of the Roman lead sparked anger from archaeologists. The archaeologists claimed that the lead had been salvaged without consultation with archaeological experts and the use of ancient artefacts for research purposes raised questions about balancing the usefulness of physical research against heritage preservation.

Particle Physics

The priest, the Eiffel Tower and the cosmic rays

Experimental evidence for the non-terrestrial origin of some of the radiation detected on Earth (cosmic rays) was discovered in 1910 by a Jesuit priest, Father Theodor Wulf. Wulf had taken readings with an electroscope in a range of places including at high altitude in Zermat, Switzerland, and underground in chalk mines and caves. When he took his detector to the top of the Eiffel Tower, he noted that on four days between 11 am and 5 pm the device discharged less than he had expected, an indication that ionising radiation was striking the device. It had been hypothesised that the Earth was the source of all background radiation and hence it was expected that radiation readings should fall to a few percent of their value at ground level at an altitude of 300 m above the Earth. To account for his surprising result, Wulf first checked that the tower itself was not radioactive and then tentatively suggested a source of gamma rays in the atmosphere.

His data received little attention at the time. Two years after Wulf's experiments, Victor Hess reported elevated levels of radiation in the atmosphere from high-altitude balloon observations. Hess noted that the readings remained constant during a solar eclipse, eliminating the Sun as the source of the radiation. Hess, with Carl Anderson, would win the 1936 Nobel Prize for the discovery of cosmic radiation.

The physicist who cured his mother

Only two years after Roentgen's discovery of X-rays, Leopold Freund of the Medical University of Vienna, reported the successful treatment of a five-year-old girl's moles using X-rays. The use of radiotherapy advanced rapidly. John H. Lawrence was a medical doctor, researcher and the brother of Ernest O. Lawrence, the American nuclear physicist and inventor of the *cyclotron,* an early particle accelerator. In 1935, John joined the California Radiation Laboratory (now the Lawrence Berley National Laboratory) and developed treatments for leukaemia by injecting mice with radioisotopes of phosphorous produced from his brother's accelerator. When the Lawrence brothers' mother was diagnosed with terminal cancer in 1939, they used a laboratory X-ray tube to treat her. She went into remission and lived for 18 additional years. John Lawrence was awarded the Fermi award in 1983 for his "pioneering work and continuing leadership in nuclear medicine" and is considered a founder of the field.

Chadwick's queuing mistake

James Chadwick, the discoverer of the neutron, had meant to study mathematics at Victoria University, Manchester but a quirk of fate led him to a physics degree. In the crowded hall of prospective students, Chadwick joined the wrong line and was too shy to speak up when he found he was being interviewed for a place on the physics course.

After obtaining his master's degree working with Rutherford, Chadwick won a studentship and elected to work with Geiger in Berlin. Geiger introduced Chadwick to the physicists working in Berlin including Einstein, Hahn and Meitner.

When war was declared in 1914, Chadwick was arrested and interned for the duration of the hostilities in a camp for civilian prisoners in a former stable for racehorses, near Spandau to the west of Berlin. Determined not to let imprisonment interrupt his studies, Chadwick asked his German colleagues to send him equipment. He managed to obtain quantities of a new radioactive toothpaste from the camp guards and constructed an electroscope to investigate its emissions. His research inspired one of his fellow prisoners, Charles Drummond Ellis, to change his career aspirations from solider to physicist. After the war, Ellis studied at Cambridge and worked with Rutherford and Chadwick on beta and gamma decay, making a significant contribution to the discovery of the neutrino.

Desperate remedies for beta-decay

In a desperate attempt to explain the unexpected energy distribution of electrons in beta-decay, Niels Bohr suggested rejecting one of the most fundamental physical laws describing the decay as “a departure from the law of energy conservation in nuclear disintegrations”.

In 1930, Wolfgang Pauli proposed an alternative solution via an open letter to colleagues, including Geiger and Meitner. He began, “Dear Radioactive Ladies and Gentlemen...” and told them he had hit upon a “desperate remedy”. He proposed a new particle which was neutral and had spin-½ - what we now know as the *neutrino*, though he originally named the hypothetical entity the *neutron*.

His letter went on report that his predecessor, Peter Debye, had counselled him not to focus his energy on the beta-decay spectrum problem arguing: “Oh, it’s best not to think about it at all – like the new taxes.”

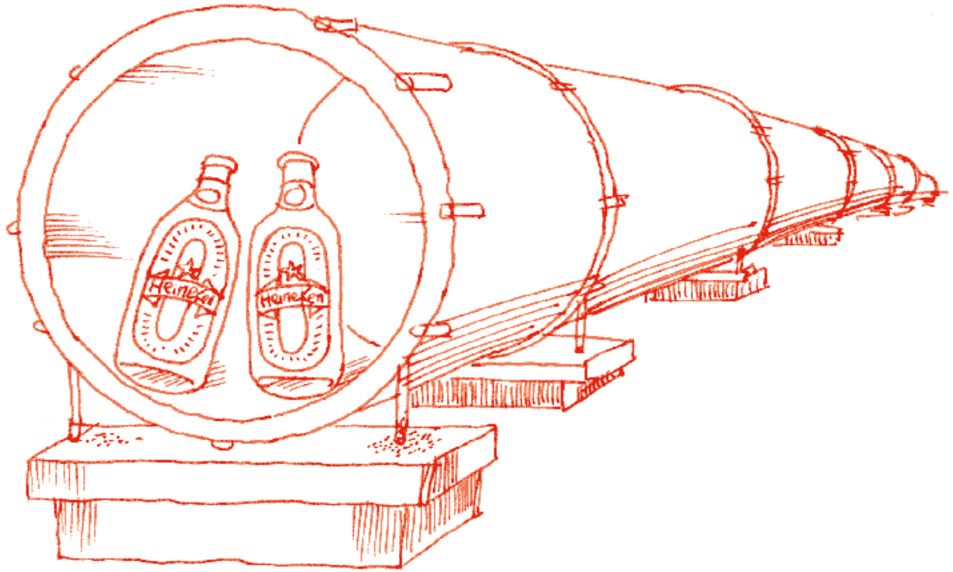
A year later, Chadwick discovered the particle now referred to as the neutron. Pauli’s particle was subsequently renamed the neutrino which means ‘little neutral one’ in Italian, after a joke in a conversation between Enrico Fermi and Edoardo Amaldi.

The Pauli effect

Wolfgang Pauli’s relationship with practical apparatus led to a phenomenon that became known as the *Pauli effect*. It is claimed that whenever Pauli entered a laboratory, equipment would suddenly break down. There are a number of documented cases of the effect. Pauli’s visit to an observatory coincided with damage to a refractor telescope. When he was travelling on a train, the cars behind his carriage decoupled whilst he carried on to his destination and on Pauli’s arrival at Princeton, an expensive new cyclotron caught fire. As a result of such reports, a university colleague banned Pauli from entering his laboratory. The legend of the *Pauli effect* led colleagues at a physics conference to set up a practical joke. They rigged a chandelier to come crashing down when Pauli entered the room. However, the apparatus became stuck and the chandelier remained suspended, which some have interpreted as further confirmation of the *Pauli effect.*

The beer bottles and the particle accelerator

At CERN, in 1996, the Large Electron Positron (LEP) particle accelerator occupied the 27 km circumference tunnel now occupied by the large hadron collider (LHC). In the summer of that year, scientists found that, after an upgrade to the collider, the beams of particles were no longer passing completely round the ring. An investigation uncovered two Heineken bottles blocking the beam line. The police were called in to investigate but the perpetrators were never found.



Becquerel’s serendipity

Serendipity sometimes plays a role in the development of physics, for instance in the case of Henri Becquerel’s discovery of radiation. The French physicist had assumed that sunlight was involved in uranium-enriched crystals’ ability to expose photographic plates. A period of inclement weather forced Becquerel to pause his experiments so he placed his crystal and plate in a closed drawer. On removing them, he was surprised to find the fogging effect continued in the absence of light, leading him to hypothesise a novel explanation for the phenomenon: radioactive decay.

Anderson's accident

The first detection of the positron, at least according to Carl Anderson who is credited with its discovery, is another example of experimental good fortune. In 1928, in an attempt to reconcile quantum theory and relativity, Paul Dirac noted that an equation could have both positive and negative solutions, suggesting a positively charged partner for the electron. In 1932, Anderson was examining the tracks made by cosmic rays in a cloud chamber and noted that some tracks curved in the opposite direction from those made by negative electrons. He noted that the tracks couldn't have been made by protons and, unaware of Dirac's theoretical work, proposed the existence of positive electrons or 'positrons'.

Anderson reported that his discovery was "wholly accidental". He acknowledged that Chung-Yao Chao, a graduate student at Caltech, had collected inconclusive data three years earlier which hinted at the positron's existence. Indeed, Frédéric and Irène Joliot-Curie, the daughter and son-in-law of Marie and Pierre Curie, and both future Nobel Prize winners, had evidence of positrons on photographic plates a few months before Anderson, but assumed the particles were protons. Anderson suggested that a wise physicist "had he [sic] been working in a well-equipped laboratory and had he taken the Dirac theory at face value he could have discovered the positron in a single afternoon".

A 'defective' physicist

One of Fermi's assistants disappeared in mysterious circumstances. Bruno Pontecorvo was born in Pisa and went on to work with Fermi on slow-neutron experiments. He moved to Paris to work with the Curies and then contributed to the Manhattan Project. After the war, Pontecorvo joined the Atomic Energy Research Establishment in the UK and was awarded a chair at the University of Liverpool. However, prior to taking up his post, he disappeared whilst holidaying in Italy. Five years later, Pontecorvo resurfaced in the Soviet Union, having defected to the Communist state via Sweden and Finland. It is speculated that he may have acted as a Soviet spy prior to his defection.

The Majorana mystery

Strangely, another of Fermi's assistants also disappeared. Italian physicist Ettore Majorana contributed to particle physics the proposition that spin-½ particles could be their own anti-particles, but the end of his life remains shrouded in mystery.

Whilst studying at university, Majorana had shown up at Fermi's lab and asked if he could switch his focus from engineering to physics. Fermi explained his current research and allowed Majorana to briefly look over some data. Majorana spent the night recalculating Fermi's results and returned the next day to explain to the surprised Fermi that his results were indeed correct. After being accepted into Fermi's institute, Majorana would scribble calculations on cigarette packets on his way to work on the tram but throw the packet away when he had finished smoking. Fermi later commented: "There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these."

In 1932, Irène Joliot-Curie and Frédéric Joliot-Curie observed that beryllium atoms that had been bombarded with alpha particles emitted a kind of radiation that led to the emission of protons from a wax target. They assumed that they had observed gamma radiation, but their calculations seemed to imply a violation of conservation of energy. Hearing of the result, Majorana rudely commented: "Oh, look at the idiots; they have discovered the neutral proton, and they don't even recognise it."

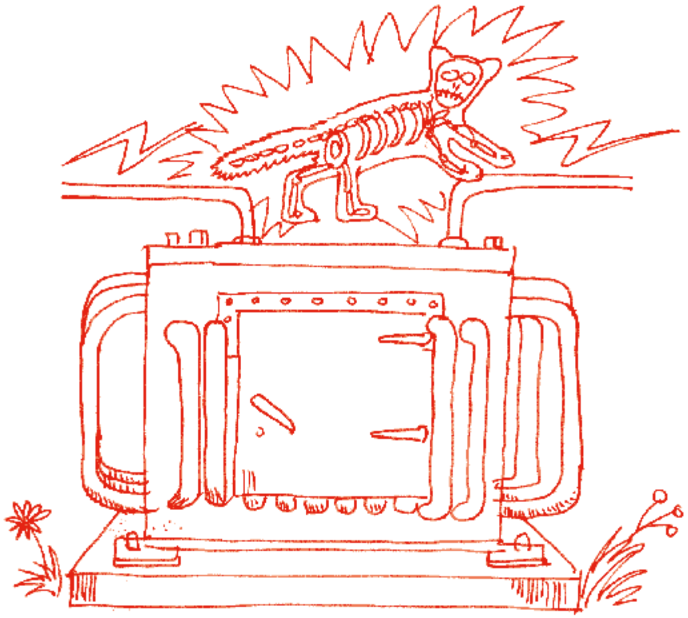
Always a shy man, he became increasingly withdrawn over time and stopped cutting his hair. In 1938, he disappeared, most probably on or after taking the Naples-Palermo ferry, and his fate remains a mystery.

The clumsy Nobel Laureate

British physicist J. J. Thomson's personal contributions to physics were substantial but he had a lasting legacy of discovery: seven of his research students went on to get Nobel Prizes, including his son, George. According to George, his father was "surprisingly clumsy . . . and though he could diagnose the faults of an apparatus with uncanny accuracy it was just as well not to let him handle it".

Collateral collider damage

The Natural History Museum in Rotterdam has a display of animals which met unfortunate ends. It includes the stuffed body of a stone marten (also known as a beech marten) that leapt over a substation fence and was electrocuted by an 18,000 V transformer at the Large Hadron Collider. The incident burned the poor animal and temporarily halted the work of the accelerator.



The mountaineering physicist

The *pion*, a kind of subatomic particle consisting of a quark and anti-quark, was first observed by Giuseppe Occhialini, César Lattes and Cecil Powell of the University of Bristol in 1947. The team used sensitive photographic plates, known as *nuclear emulsions*, to collect evidence of the pion. The pion is more likely to be observable at high altitudes as it has a short lifespan and many pions that enter the Earth's atmosphere decay before reaching sea level. Fortunately, Occhialini had worked as a rock-climbing guide and was skilled in both physics and rope work. The team exposed their nuclear emulsions at an altitude of 2,877 m on the Pic du Midi in the French Pyrenees, capturing the first traces of the pion.

Gell-Mann's greatness

Murray Gell-Mann received the Nobel Prize for his contributions to the classification of elementary particles and their interactions. He was a prodigy, skipping three years at school, starting Yale at 15 and completing his PhD at MIT by the age of 21.

Quirky quarks

Gell-Mann explained that he thought of the sound of the word 'quark' before deciding on the spelling. Whilst reading through James Joyce's *Finnegans Wake*, he came across the phrase: "Three quarks for Muster Mark" and reported that, though Joyce had perhaps intended 'quark' to rhyme with 'Mark', he wanted to find a reason for the particle to be pronounced 'kwork'. Gell-Mann argued Joyce's phrase might arise from a call for drinks: "Three quarts for Muster Mark" and therefore the particle should rhyme with the word 'quart'.

Simultaneous discovery

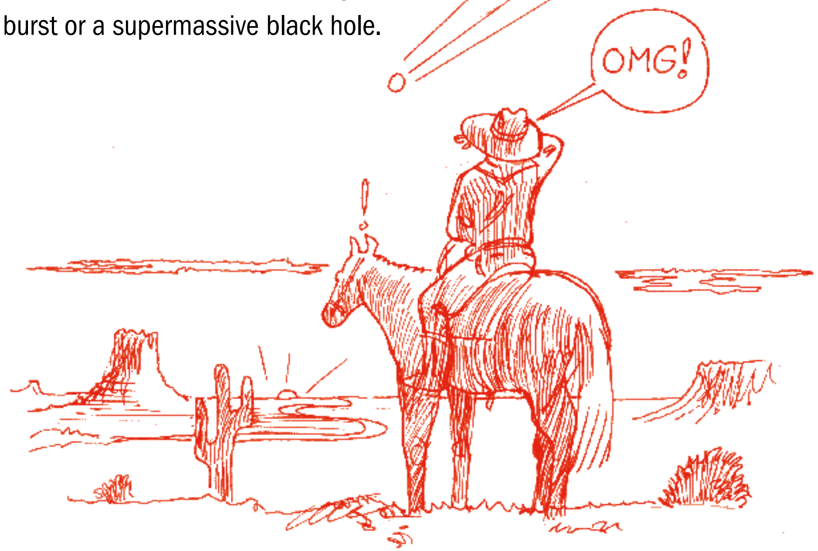
In 1969, at the same time as Murray Gell-Mann's quark model was published, George Zweig independently developed a model involving triplets of fundamental particles. He called the particles in his model aces and suggested baryons could be made of *treys* (triplets of aces) and mesons from deuces (pairs of aces and anti-aces). Zweig reported that the negative reaction of the physics community to his model left an "unpleasant aftertaste" and he went on to become a biologist.

Feynman fall-out

Gell-Mann's offices were close to Richard Feynman's at Caltech and at first they had a collaborative relationship. However, aspects of their personalities could clash: Gell-Mann referred to Feynman's best-selling books as "Dick's joke books"; Feynman finished a conversation with his peer by concluding, "Murray, in a hundred years nobody will know whether your name is hyphenated or not." Gell-Mann later reported that he was initially a great admirer of Feynman, but that his view changed over time: "We worked together for a number of years, but I found that he had difficulty thinking in terms of 'us'. He acted as if the only thing that mattered was his understanding of what was going on. It was all 'I, I, I,' and eventually it got on my nerves."

The *Oh My God* particle

On the 15 October 1991, a cosmic ray with an energy of 300 million TeV was detected in Utah. It is thought to have been a proton travelling at very close to the speed of light and its unprecedented energy has led to it being referred to as the *Oh My God* particle. The single particle would have had about as much energy as a baseball travelling at 100 km/h. The exact source of such a highly energetic particle is not known, but researchers speculate that it may have originated from either a hot spot in a radio galaxy, a gamma ray burst or a supermassive black hole.



Cosmic vision

In 1969, Buzz Aldrin reported seeing flashes of light in his vision whilst on the Apollo 11 mission. Subsequently, other astronauts have reported unusual visual phenomena whilst in space, such as faint spots or streaks of light seen when their eyes were closed and adapted to the dark. The cause of these flashes is thought to be an interaction between a charged particle - a cosmic ray - and the visual system. Experiments with particle accelerators on the ground have shown the phenomenon is reproducible and a variety of different particles (including muons, neutrons and pions) have been found to produce effects including stars, flashes and bright points of light in participants' visual fields.

Stories from physics

The Higgs Boson and Comic Sans

The presentation that announced the discovery of the Higgs Boson in 2012 used the Comic Sans font. The decision caused a Twitterstorm and was described by *The Guardian* newspaper as a "misuse" and "inappropriate". Good humouredly, on 1 April 2014, CERN announced on its website:

> From today, all of CERN's official communication channels are switching to exclusive use of the font Comic Sans... According to our calculations, 80% of the success of the presentation came not from the discovery of a fundamental particle that explains the Brout-Englert-Higgs mechanism for how particles get mass, but from the choice of font.

Unwanted and non-existent particles

Isidor Rabi won the 1944 Nobel Prize for his work on the magnetic properties of atomic nuclei. However, the apparently anomalous nature of the muon, a heavier but otherwise indistinguishable version of the electron, caused Rabi to remark: "Who ordered that?"

Leon Lederman is an American physicist who contributed to the discovery of the muon neutrino and the bottom quark. In 1975, Lederman's team at Fermilab noted an apparent peak in data produced from collisions between protons and a stationary beryllium target. The peak was taken to indicate the existence of a new 6 GeV particle (possibly a proposed bottom-anti-bottom quark bound state). The particle was given the label upsilon. After subsequent analysis it turned out the particle did not exist, and it was renamed the 'Oops-Leon' particle as a gesture to its original symbol and its discoverer.

A full set of references for this booklet is available at
talkphysics.org/groups/stories-from-physics

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The Institute of Physics (IOP)

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