

# Particle & Nuclear Briefing

The background features several glowing blue and white particle tracks against a dark blue background. One track starts from the bottom left, curves upwards and to the right, ending in a bright white point. Another track starts from the top left, curves upwards and to the right, ending in a bright white point. A third track starts from the top right, curves downwards and to the left, ending in a bright white point. A fourth track starts from the bottom right, curves upwards and to the left, ending in a bright white point. The tracks are composed of multiple overlapping lines, creating a sense of depth and movement.

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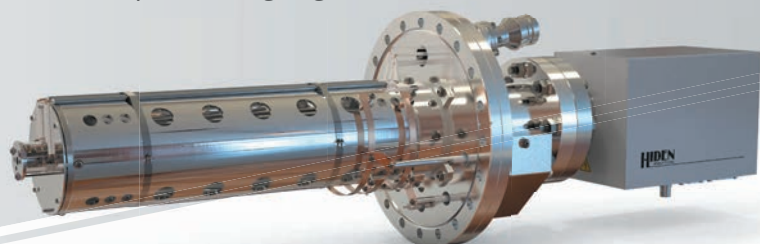
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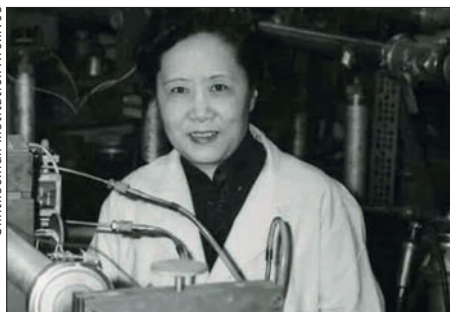
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BASE/Julia Jäger



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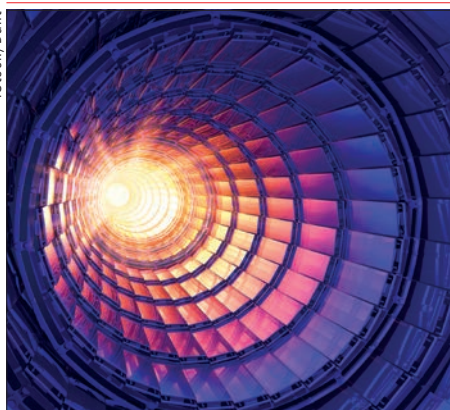
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**Particle physics desperately needs a Higgs factory** [p22](#)

**Michael Riordan** *author of The Hunting of the Quark*



Listen to *Physics World's* Hamish Johnston in conversation with particle physicist Tim Gershon, from the University of Warwick, UK. Gershon is

spokesperson-elect for the LHCb collaboration and is playing a leading role in the upgrade.

Gershon cautions that the future of the experiment and the future of UK particle physics have been imperilled by the announced funding cut.

They also chat about recent discoveries made by LHCb and look forward to what new physics the experiment could find after the upgrade.

## Planning ahead in uncertain times

Welcome to this *Physics World Particle and Nuclear Briefing*, which includes news, features and opinion on the latest developments in particle and nuclear physics.

Mark Thomson, who took the reins as CERN director-general in January, will have a lot to deal with over the coming years. He has already had to contemplate the consequences of the UK not committing any further contributions towards a major £150m upgrade to the LHCb detector – one of the four large experiments at the Large Hadron Collider that continues to do pioneering science (p5). Unless the decision is overturned or other avenues of funding are found, the experiment will now finish operations in 2033 and not take advantage of the High-Luminosity LHC that is currently being installed at CERN.

Another item in Thomson's in-tray will be setting the course for the next flagship collider at CERN after the HL-LHC finishes operations in the early 2040s. In the ongoing process to update the European Strategy for Particle Physics, the Future Circular Collider (FCC) is the preferred option. Earmarked to be built near the LHC, this huge 91 km circumference electron-positron collider will come with a significant cost of \$18bn. Thomson could find it a hard sell with some of the funding needing to come from outside CERN's 24 member states.

Yet there was some good news for the FCC on that front with CERN recently receiving \$1bn from private donors towards its construction (p7). A further boost for the FCC arrived when the Circular Electron-Positron Collider – a similar collider design to the FCC – was not considered for inclusion in China's next five-year plan, which runs from 2026 to 2030.

Despite these developments, there are still many questions over building the FCC, some of which will be discussed at the 17th International Particle Accelerator Conference in Deauville, France from 17–22 May. As physicist and historian Michael Riordan points out, the eye-watering cost of the FCC together with the worsening geopolitics of a fragmenting world order could make funding and building such colliders risky (p22).

Those sentiments are echoed by philosopher and science historian Robert P Crease who writes in this briefing that particle physics is using ever more interdisciplinary means to seek ever more exotic phenomena. Those ambitions could be threatened by the increasing isolation, fragmentation and polarization of the modern world (p26).

We hope you enjoy the briefing and let us know your feedback on the issue by e-mailing [physics.world@iopublishing.org](mailto:physics.world@iopublishing.org).



Michael Banks  
News editor, *Physics World*



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# UK cuts put LHCb upgrade at risk

Funding changes within the UK's research councils could derail a major upgrade to the LHCb detector at CERN, as **Michael Banks** reports



Maximilien Brice/CERN

A major upgrade to the LHCb experiment at CERN is under threat after the UK did not commit any further contributions towards the project. The decision by UK Research and Innovation (UKRI) to defund the plan means that unless the decision is overturned, the experiment will now likely finish operations in 2033.

LHCb is one of the four large experiments based at the Large Hadron Collider (LHC) at CERN. It specializes in the measurements of the parameters of charge-parity (CP) violation in the interactions of b- and c-hadrons, studies of which help to explain the matter-antimatter asymmetry in the universe. LHCb began recording its first data in 2009 when the LHC began operations and started its main research programme in 2010. At the end of 2018 it was shut down for upgrades, which were completed in 2022. That led to a vast increase in the amount of data the experiment could collect, allowing significant improvements in precision for many measurements. The detector is expected to operate until 2033, by which time it would have reached the end of its lifetime after years of intense

## Troubling times

A major upgrade to the LHCb experiment at CERN is unlikely to go ahead if cuts are not reversed.

radiation damage.

LHCb is operated by the LHCb collaboration, which involves about 1700 scientists and technicians from over 100 institutions in 22 countries around the world, with work on the machine having already resulted in over 800 publications. The UK is one of the leading countries working on LHCb – four of the eight spokespeople for the experiment have come from the UK – and over the past decade physicists from the UK have been planning an upgrade to the experiment dubbed LHCb upgrade II. This would take advantage of the upgrade to the LHC – the High-Luminosity LHC (HL-LHC) – and offer an order-of-magnitude increase in luminosity over upgrade I.

The second upgrade would provide another boost in capability to answer questions such as whether all CP-violation phenomena are consistent with the Standard Model of particle physics or require an extended theory, as well as how the strong interaction binds together the exotic tetraquark and pentaquark states that have been discovered by LHCb. At a cost of about

£150m, with the construction phase beginning in 2027, the upgrade components would be installed by 2035 before collecting data for five to six years until the HL-LHC is shut down in 2040.

UK researchers submitted a proposal to the UKRI infrastructure fund in 2021 to begin work on the upgrade and were awarded £49.4m in 2022. Some £5m has been spent on the pre-construction phase, in which agreements have been made with international partners on the scope and design of the improved detector. But in December 2025 researchers working on the project were sent a letter telling them that the remaining funding has “not been prioritized” and will now be cancelled. “It was a complete shock,” says Tim Gershon from the University of Warwick, who is principal investigator for the project in the UK and is set to become spokesperson for the international collaboration in July.

## ‘Out in the cold’

The core budget of the Science and Technology Facilities Council (STFC) has been held relatively flat from £835m to £842m from 2026 to 2030.

# News

The council says that projects would need to be cut given inflation, rising energy costs and “unfavourable movements in foreign exchange rates”, which have increased the STFC’s annual costs by over £50m a year. The STFC has already said that it needs to reduce spending from the core budget by at least 30% over 2024/2025 levels. At the same time it also announced that it will need to reduce the number of projects that are funded by its infrastructure fund.

Four projects will now not be prioritized. They include two UK national facilities: the Relativistic Ultrafast Electron Diffraction and Imaging facility and a mass spectrometry centre dubbed CMASS. The other two are international particle-physics projects: the upgrade to LHCb as well as a contribution to the Electron-Ion Collider at the Brookhaven National Laboratory in the US, which is currently being built by a collaboration of 40 countries.

“This is more terrible news for physics, for the UK and for global sci-

**We urge the government to step back and consider how its new funding strategy will impact UK science**

Paul Howarth,  
president of the  
Institute of Physics

entific progress,” says Paul Howarth, president of the Institute of Physics. “The withdrawal of funding in this abrupt way is incredibly damaging to our international reputation as a science superpower and could cause long-term damage to the UK economy. But even more important is the harm this cut will cause to human understanding of the universe and human progress.”

Gershon adds that the LHCb collaboration was not asked for any input before the decision was made and since then has been trying to work out what it means. “The UK pays the CERN subscription, which pays for the accelerator, but needs to also invest in experiments to obtain scientific return from this,” says Gershon. “It’s like paying to heat your house but then sitting outside in the cold.”

It might be possible for LHCb to get funding from elsewhere in the short term to cover the initial work on the upgrade, but Gershon says that without investment from UKRI/STFC, the project will be dead as it would

not be possible for international partners to go ahead without UK involvement on the timescale dictated by the LHC schedule. That would mean that LHCb stops operating from 2033 and does not take advantage of the HL-LHC. “The move also goes against the European Strategy for Particle Physics roadmap, of which the top priority is fully exploiting the HL-LHC,” says Gershon. “Without the LHCb upgrade, it won’t be possible to do that.”

Howarth adds there are “demonstrable impacts on UK growth and prosperity” for such research. “An earlier upgrade to the LHCb experiment generated about £15m in contracts for more than 80 UK companies,” he adds. “This funding cut means the upgrade is unlikely to go ahead, so all this business for UK innovators is lost. We urge the government to step back and consider how its new funding strategy will impact UK science.”

**Michael Banks** is news editor of *Physics World*

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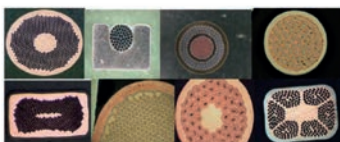
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# CERN accepts \$1bn in private cash

The CERN particle-physics lab has received \$1bn in private donations towards the Future Circular Collider, as **Michael Banks** explains



The CERN particle-physics lab near Geneva has received \$1bn from private donors towards the construction of the Future Circular Collider (FCC). The cash marks the first time in the lab's 72-year history that individuals and philanthropic foundations have agreed to support a major CERN project. If built, the FCC would be the successor to the Large Hadron Collider (LHC), where the Higgs boson was discovered.

CERN originally released a four-volume conceptual design report for the FCC in early 2019, with more detail included in a three-volume feasibility study that came out last year. It calls for a giant tunnel some 90.7 km in circumference – roughly three times as long as the LHC – that would be built about 200 m underground on average.

The FCC has been recommended as the preferred option for the next flagship collider at CERN in the ongoing process to update the European Strategy for Particle Physics, which will be passed over to the CERN Council in May 2026. If the plans are given the green light by CERN Council in 2028, construction on the FCC electron-positron machine, dubbed FCC-ee, would begin in 2030. It would start operations in 2047, a few years after

## Bigger and better

The Large Hadron Collider at CERN will shut down later this year to make way for a major upgrade – the High-Luminosity LHC.

the High Luminosity LHC (HL-LHC) closes down, and run for about 15 years until the early 2060s.

The FCC-ee would focus on creating a million Higgs particles in total to allow physicists to study its properties with an accuracy an order of magnitude better than is possible with the LHC. The FCC feasibility study then calls for a hadron machine, dubbed FCC-hh, to replace the FCC-ee in the existing 91 km tunnel. It would be a “discovery machine”, smashing together protons at high energy – about 85 TeV – with the aim of creating new particles. If built, the FCC-hh will begin operation in 2073 and run to the end of the century.

The funding model for the FCC-ee, which is expected to have a price tag of about \$18bn, is still a work in progress. But it is estimated that at least two-thirds of the construction costs will come from CERN's 24 member states, with the rest needing to be found elsewhere. One option to plug that gap is private donations and in December 2025 CERN received a significant boost from several organizations including the Breakthrough Prize Foundation, the Eric and Wendy Schmidt Fund for Strategic Innovation, and the entrepreneurs John

Elkann and Xavier Niel. Together, they pledged a total of \$1bn towards the FCC-ee.

Costas Fountas, president of the CERN Council, says CERN is “extremely grateful” for the interest. “This once again demonstrates CERN's relevance and positive impact on society, and the strong interest in CERN's future that exists well beyond our own particle physics community,” he notes.

Eric Schmidt, who co-founded Google, claims that he and Wendy Schmidt were “inspired by the ambition of this project”. The FCC, he believes, is an instrument that “could push the boundaries of human knowledge and deepen our understanding of the fundamental laws of the universe” and could lead to technologies that benefit society “in profound ways” from medicine to computing to sustainable energy.

The cash promised has been welcomed by former CERN director-general Fabiola Gianotti. “It's the first time in history that private donors wish to partner with CERN to build an extraordinary research instrument that will allow humanity to take major steps forward in our understanding of fundamental physics and the universe,” she said. “I am profoundly

## News

grateful to them for their generosity, vision, and unwavering commitment to knowledge and exploration.”

### Further boost

The cash comes after the Circular Electron–Positron Collider (CEPC) – a rival collider to the FCC-ee that would involve building a 100 km underground tunnel to study the Higgs – was not considered for inclusion in China’s next five-year plan, which runs from 2026 to 2030. There has been much discussion in China about whether the CEPC is the right project for the country, with the collider facing criticism from particle physicist and Nobel laureate Chen-Ning Yang, before he died last year.

Wang Yifang of the Institute of High Energy Physics in Beijing says the organization will submit the CEPC for consideration again in 2030 unless the FCC is officially approved before then. But for particle theorist John Ellis from Kings College London, China’s decision to effectively put the CEPC on the back burner “certainly simplifies the FCC discussion”. “However, an oppor-

**This once again demonstrates CERN’s relevance and positive impact on society**

Costas Fountas,  
president of the  
CERN Council

tunity for growing the world particle-physics community has been lost, or at least deferred [by the decision],” Ellis told *Physics World*.

Ellis adds that he would welcome China’s participation in the FCC. “Their accelerator and detector [technical design reviews] show that they could bring a lot to the table, if the political obstacles can be overcome,” he says.

If the FCC-ee goes ahead, China could perhaps make significant “in-kind” contributions like those that occur with the ITER experimental fusion reactor, which is currently being built in France. In this kind of agreement, instead of cash payments, the countries provide components, equipment and other materials.

Those considerations and more will now fall to Mark Thomson, who took over from Gianotti as CERN director-general on 1 January for a five-year term. As well as working on funding requirements for the FCC-ee, top of his in-tray will be shutting down the LHC in June to make way

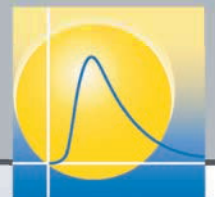
for further work on the HL-LHC, which involves installing powerful new superconducting magnets and improving the detection.

About 90% of the 27 km LHC accelerator will be affected by the upgrade with a major part being to replace the magnets in the final focus systems of the two large experiments, ATLAS and CMS. These magnets will take the incoming beams and then focus them down to less than 10 µm in cross section. The upgrade includes the installation of new state-of-the-art niobium-tin superconducting focusing magnets.

The HL-LHC will probably not turn on until 2030, which is when Thomson’s term will nearly be over but that doesn’t deter him from leading the world’s foremost particle-physics lab. “It’s an incredibly exciting project,” Thomson told the *Guardian*. “It’s more interesting than just sitting here with the machine hammering away.”

**Michael Banks** is news editor of *Physics World*

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# JUNO neutrino observatory complete

Scientists are celebrating the first results from China's huge JUNO underground facility, which will aim to probe the relationship between the three types of known neutrino, as **Michael Banks** reports

The \$330m Jiangmen Underground Neutrino Observatory (JUNO) has released its first results following the completion of the huge underground facility. On 18 November 2025 a paper was submitted to the arXiv preprint server concluding that the detector's key performance indicators fully meet or surpass design expectations (arXiv:2511.14590).

JUNO is located in Kaiping City, Guangdong Province, in the south of the country around 150 km west of Hong Kong. Construction of the facility began in 2015 and was set to be complete some five years later. But the project suffered from serious flooding, which delayed construction.

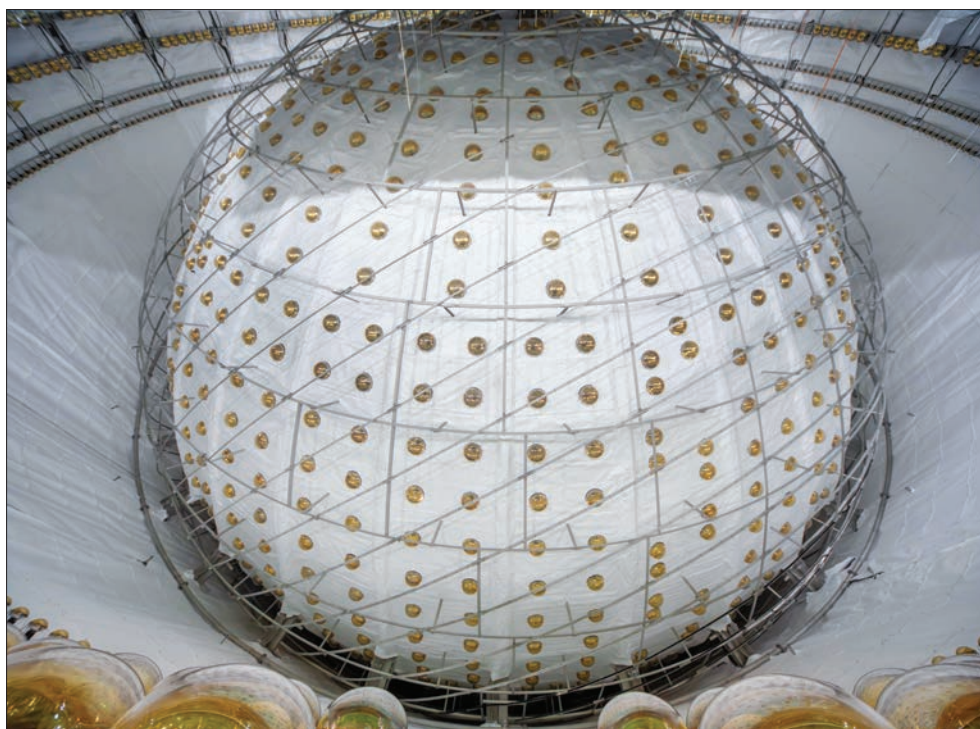
JUNO, which is expected to run for more than 30 years, aims to study the relationship between the three types of neutrino: electron, muon and tau. Although JUNO will be able to detect neutrinos produced by supernovae as well as those from Earth, the observatory will mainly measure the energy spectrum of electron antineutrinos released by the Yangjiang and Taishan nuclear power plants, which both lie about 50 km away.

To do this, the facility has an 80 m high and 50 m diameter experimental hall located 700 m underground. Its main feature is a 35 m radius spherical neutrino detector, containing 20 000 tonnes of liquid scintillator. When an electron antineutrino occasionally bumps into a proton in the liquid, it triggers a reaction that results in two flashes of light. They are detected by the 43 000 photomultiplier tubes that observe the scintillator.

## New measurement

Neutrinos oscillate from one flavour to another as they travel near the speed of light, rarely interacting with matter. This oscillation is a result of each flavour being a combination of three neutrino mass states.

Scientists do not know the absolute masses of the three neutrinos but can



JUNO Collaboration

## Next-generation success

The Jiangmen Underground Neutrino Observatory features a 35 m radius spherical neutrino detector, containing 20 000 tonnes of liquid scintillator.

measure neutrino oscillation parameters, known as  $\theta_{12}$ ,  $\theta_{23}$  and  $\theta_{13}$ , as well as the square of the mass differences ( $\Delta m^2$ ) between two different types of neutrinos.

A second JUNO paper submitted on 18 November 2025 used data collected between 26 August and 2 November to measure the solar neutrino oscillation parameter  $\theta_{12}$  and  $\Delta m^2_{21}$  with a factor of 1.6 better precision than previous experiments (arXiv: 2511.14593). Those earlier results, which used solar neutrinos instead of reactor antineutrinos, showed a 1.5 “sigma” discrepancy with the Standard Model of particle physics. The new JUNO measurements confirmed this difference, dubbed the solar neutrino tension, but further data will be needed to prove or disprove the finding.

“Achieving such precision within only two months of operation shows that JUNO is performing exactly as designed,” says Yifang Wang from the Institute of High Energy Physics of the Chinese Academy of Sciences, who is

JUNO project manager and spokesperson. “With this level of accuracy, JUNO will soon determine the neutrino mass ordering, test the three-flavour oscillation framework, and search for new physics beyond it.”

JUNO, which is an international collaboration of more than 700 scientists from 75 institutions across 17 countries including China, France, Germany, Italy, Russia, Thailand and the US, is the second neutrino experiment in China, after the Daya Bay Reactor Neutrino Experiment. It successfully measured the key neutrino oscillation parameter  $\theta_{13}$  in 2012 before being closed down in 2020.

JUNO is also one of three next-generation neutrino experiments, the other two being the Hyper-Kamiokande in Japan and the Deep Underground Neutrino Experiment in the US. Both are expected to become operational later this decade.

**Michael Banks** is news editor of *Physics World*

# News

## Facilities

# New Fermilab building honours Tevatron pioneer Helen Edwards

Officials at Fermilab and the US Department of Energy (DOE) officially opened the Helen Edwards Engineering Research Center at a ceremony held on 5 December 2025. The new building is Fermilab's largest purpose-built lab and office space since its iconic Wilson Hall was completed in 1974.

Construction of the Helen Edwards Engineering Research Center began in 2019 and was completed three years later. The centre is a 7500 m<sup>2</sup> multi-storey lab and office building that is adjacent and connected to Wilson Hall. The new centre is intended to let engineers, scientists and technicians design, build and test technologies across several areas of research such as neutrino science, particle detectors, quantum science and electronics. The centre also features clean rooms,



Ryan Postel, Fermilab

vibration-sensitive labs and cryogenic facilities.

With a PhD in experimental particle physics from Cornell University, Edwards was heavily involved with commissioning the university's 10 GeV electron synchrotron. In 1970 Fermilab's director Robert Wilson appointed Edwards as associate head of the lab's booster section and she later became

### Solid foundation

The Helen Edwards Engineering Research Center is designed to act as a collaborative space for scientists and engineers.

head of the accelerator division. While at Fermilab, Edwards' primary responsibility was designing, constructing, commissioning and operating the Tevatron, which led to the discoveries of the top quark in 1995 and the tau neutrino in 2000. Edwards retired in the early 1990s but continued to work as guest scientists at Fermilab and officially switched the Tevatron off during a ceremony held on 30 September 2011. Edwards died in 2016.

Darío Gil, the undersecretary for science at the DOE, says that Edwards' scientific work "is a symbol of the pioneering spirit of US research". "Her contributions to the Tevatron and the lab helped the US become a world leader in the study of elementary particles," notes Gil.

**Michael Banks**

## People

# Norbert Holtkamp starts life as boss of Fermilab

Particle physicist Norbert Holtkamp has taken over as the new director of Fermi National Accelerator Laboratory. He took up the position on 12 January, replacing Young-Kee Kim from the University of Chicago, who held the job on an interim basis following the resignation of Lia Merminga last year.

With a PhD in physics from the Technical University in Darmstadt, Germany, Holtkamp has managed large scientific projects throughout his career. Holtkamp is the former deputy director of the SLAC National Accelerator Laboratory at Stanford University where he managed the construction of the Linac Coherent Light Source upgrade, the world's most powerful X-ray laser, along with more than \$2bn of on-site construction projects. He has also worked at the ITER fusion experiment, which is currently under construction in Cadarache, France.

Holtkamp is not new to Fermilab, having been there between 1998 and 2001. As lab boss, one of his main aims will be to oversee the completion of the \$5bn Long-Baseline Neutrino

Ji Starr, Fermilab



### Lab figurehead

As new director of Fermilab, one of Norbert Holtkamp's main aims will be to oversee the completion of the \$1.5bn Long-Baseline Neutrino Facility-Deep Underground Neutrino Experiment.

Facility-Deep Underground Neutrino Experiment (LBNF-DUNE) at Fermilab, which is expected to come online towards the end of the decade.

LBNF-DUNE will study the properties of neutrinos in unprecedented detail, as well as the differences in behaviour between neutrinos and antineutrinos. The DUNE detector, which lies about 1300 km from Fermilab, will measure the neutrinos that are generated by Fermilab's accelerator complex, which is just outside Chicago.

In a statement, Holtkamp said he is "deeply honoured" to lead the lab. "Fermilab has done so much to advance our collective understanding of the fundamentals of our universe," he says. "I am committed to ensuring the laboratory remains the neutrino capital of the world, and the safe and successful completion of LBNF-DUNE is key to that goal. I'm excited to rejoin Fermilab at this pivotal moment to guide this project and our other important modernization efforts to prepare the lab for a bright future."

Fermilab has experienced a difficult few years, with questions raised

about its internal management and external oversight. In August 2024 a group of anonymous self-styled whistleblowers published a 113-page "white paper" on the arXiv preprint server, asserting that the lab was "doomed without a management overhaul" (arXiv:2407.13924). Then in October that year, a new organization – Fermi Forward Discovery Group – was announced to manage the lab for the US Department of Energy.

That move came under scrutiny given it is dominated by the University of Chicago and Universities Research Association (URA), a consortium of research universities, which had already been part of the management since 2007. Then a month later, almost 2.5% of Fermilab's employees were laid off.

"We're excited to welcome Norbert, who brings of a wealth of scientific and managerial experience to Fermilab," noted University of Chicago president Paul Alivisatos, who is also chair of the board of directors of Fermi Forward Discovery Group.

**Michael Banks**

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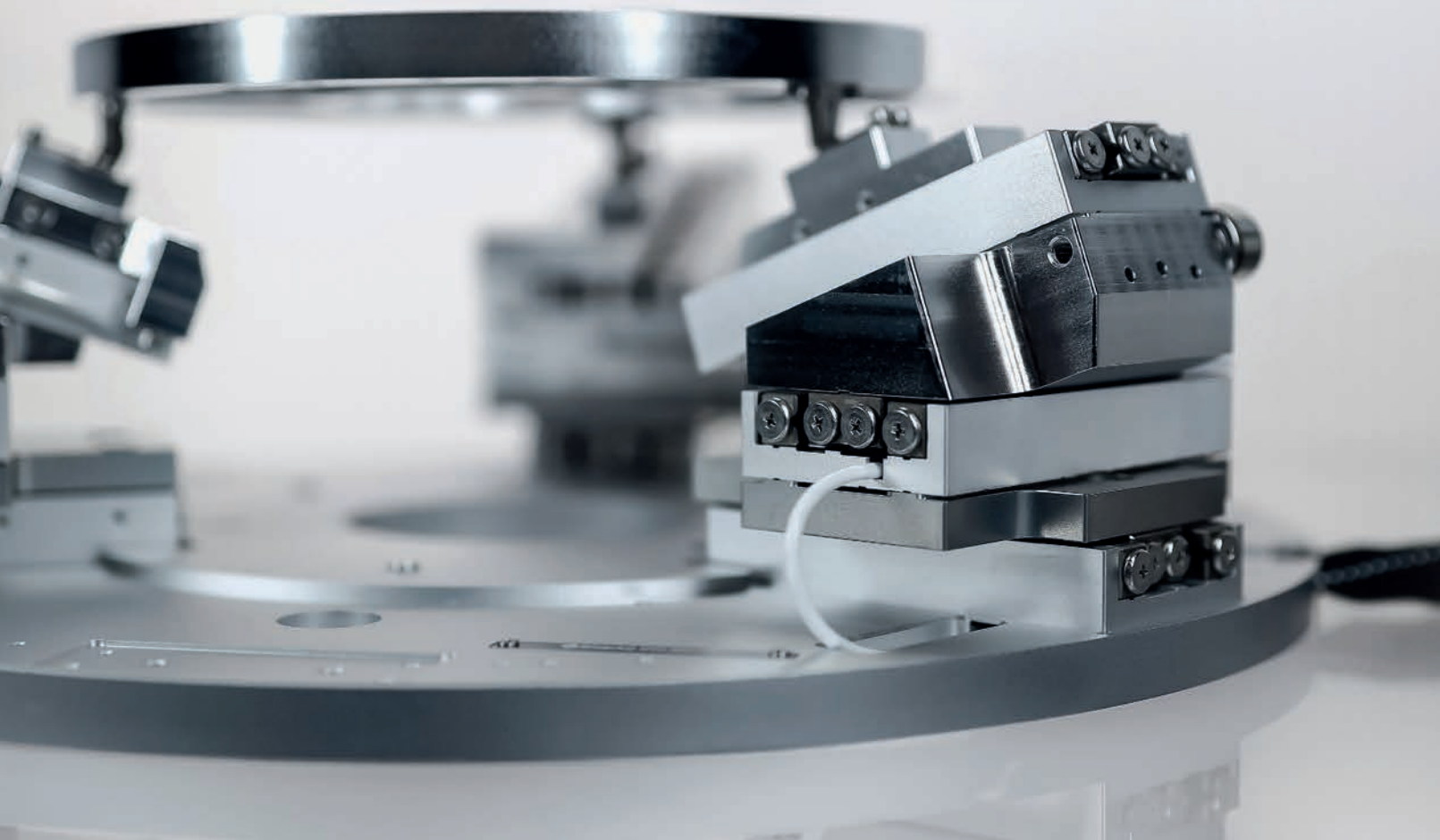
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# News

## Particle physics

# Russia to revive abandoned Soviet-era particle accelerator

Russia plans to restart a Soviet-era particle accelerator that has been abandoned since the 1990s. The Kurchatov Institute for High Energy Physics has allocated 176 million rubles (\$25m) to assess the current condition of the unfinished 600 GeV Proton Accelerator and Storage Complex (UNK) in Protvino near Moscow. The move is part of a strategy to strengthen Russia's technological sovereignty and its activity in high-energy physics.

Although work on the UNK was officially halted in the 1990s, construction only ceased in 2013. At that time, a 21 km tunnel had been built at a depth of 60 m along with underground experimental hall lighting and ventilation systems.

According to physicist Mikhail Kovalchuk, president of the Kurchatov Institute National Research Center, Western sanctions provided an additional impetus to restore the project, as scientists who had previously worked in CERN projects could no longer do so. "By participating in [CERN] pro-



Russia. "If this project is realized, then there is hope that it will be possible to at least somewhat slow down the scientific lag of Russian physics with global science," says Romaniouk.

While official plans for the accelerator have not been disclosed, it is thought that the proton beam energy could be upgraded to reach 3 TeV. Romaniouk says it is also unclear what kind of science will be done with the accelerator, which will depend on what ideas come forward.

Some Russian scientists say that it could be used to produce neutrinos. This would involve putting a neutrino detector nearby to characterize the beam before it is sent some 4000 km towards Lake Baikal where a neutrino detector – the Baikal Deep Underwater Neutrino Telescope – is already installed 1 km underground. "I think it's possible to find an area of high-energy physics where the research with the help of this collider could be beneficial," adds Romaniouk.

**Eugene Gerden**

jects, we not only preserved our scientific potential and survived a difficult period, but also enriched ourselves intellectually and technologically," added Kovalchuk. "Today we are self-sufficient."

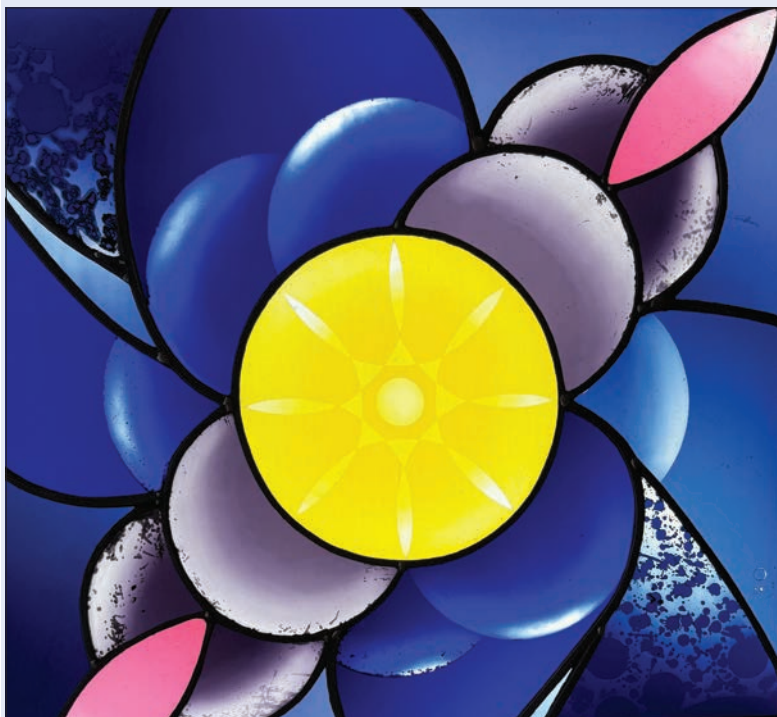
Anatoli Romaniouk, a Russian particle physicist who has worked at CERN since 1990, told *Physics World* that a revival of the UNK will at least maintain fundamental physics research in

### Ambitious plans

The revived Proton Accelerator and Storage Complex could be used to send a beam of neutrinos to the Baikal Deep Underwater Neutrino Telescope.

## Discovery of the Higgs boson at CERN inspires new stained-glass artwork

Oksana Kondratyeva



London-based artist Oksana Kondratyeva has created a new stained-glass artwork – entitled *Discovery* – that is inspired by the detection of the Higgs boson at CERN's Large Hadron Collider (LHC) in 2012. Born in Ukraine, Kondratyeva has a PhD in the theory of architecture and has an artist residency at the Romont Glass Museum (Vitromusée Romont) in Switzerland, where *Discovery* went on display. In 2023 Kondratyeva travelled to visit the LHC at CERN, which she says is "more than a laboratory [but] a gateway to the unknown". Kondratyeva says that the focal point of the artwork – a circle structured with geometric precision – represents the collision of two high-energy protons. The surrounding lead lines in the panel trace the trajectories of particle decays as they move through a magnetic field: right-curved lines represent positively charged particles, left-curved lines indicate negatively charged ones, while straight lines signify neutral particles unaffected by the magnetic field. The geometric composition within the central circle reflects the hidden symmetries of physical laws – patterns that only emerge when studying the behaviour of particle interactions. "Through glass, light and colour I sought to express the invisible forces and delicate symmetries that define our universe – ideas born in the realm of physics, yet deeply resonant in artistic expression," notes Kondratyeva.

**Michael Banks**

# India turns to small modular reactors

India's nuclear industry is looking to small modular nuclear reactors to help meet climate targets, but as **TV Padma** reports, there are concerns over their commercial viability

India has been involved in nuclear energy and power for decades, but now the country is turning to small modular nuclear reactors (SMRs) as part of a new, long-term push towards nuclear and renewable energy. In December 2025 the country's parliament passed a bill that for the first time allows private companies to participate in India's nuclear programme, which could see them involved in generating power, operating plants and making equipment.

Some commentators are unconvinced that the move will be enough to help meet India's climate pledge to achieve 500 GW of non-fossil-fuel based energy generation by 2030. Interestingly, however, India has now joined other nations, such as Russia, the UK and China, in taking an interest in SMRs. The technology could help stem the overall decline in nuclear power, which now accounts for just 9% of electricity generated around the world – down from 17.5% in 1996.

Last year India's finance minister Nirmala Sitharaman announced a nuclear-energy mission funded with 200 billion Indian rupees (\$2.2bn) to develop at least five indigenously designed and operational SMRs by 2033. Unlike huge, conventional nuclear plants, such as pressurized heavy-water reactors (PHWRs), most or all components of an SMR are manufactured in factories before being assembled at the reactor site. SMRs typically generate less than 300 MW of electrical power but – being modular – additional capacity can be brought online quickly and easily given their lower capital costs, shorter construction times, ability to work with lower-capacity grids and lower carbon emissions.

Despite their promise, there are only two fully operating SMRs in the world – both in Russia – with two further high-temperature gas-cooled SMRs currently being built in China. In June 2025 Rolls-Royce SMR was selected as the preferred bidder by Great British Nuclear to build the UK's first fleet of



## Better by design?

Unlike huge, conventional nuclear plants, most or all components of a small modular nuclear reactor are manufactured in factories before being assembled at the reactor site.

SMRs, with plans to provide 470 MW of low-carbon electricity.

## Cost benefit analysis

An official at India's Department of Atomic Energy told *Physics World* that part of that mix of five new SMRs in India could be a 200 MW Bharat small modular reactor, which are based on pressurized water reactor technology and use slightly enriched uranium as a fuel. Other options include 55 MW small modular reactors, and the Indian government also plans to partner with the private sector to deploy 220 MW Bharat small reactors.

Despite such moves, some are unconvinced that small nuclear reactors could help India scale its nuclear ambitions. "SMRs are still to demonstrate that they can supply electricity at scale," says Karthik Ganesan, a fellow and director of partnerships at the Council on Energy, Environment and Water, a non-profit policy research think-tank based in New Delhi. "SMRs are a great option for captive consumption, where large investment that will take time to start generating is at a premium."

Ganesan, however, says it is too early to comment on the commercial viability of SMRs because cost reductions from SMRs depend on how much of the technology is produced in a factory and in what quantities. "We are yet to get to that point and any test reactors deployed would certainly not be the ones to benchmark their long-term competitiveness," he says. "[But] even at a higher tariff, SMRs will still have a use case for industrial consumers who want certainty in long-term tariffs and

reliable continuous supply in a world where carbon-dioxide emissions will be much smaller than what we see from the power sector today."

M V Ramana from the University of British Columbia, Vancouver, who works in international security and energy supply, is concerned about the cost efficiency of SMRs compared with their traditional counterparts. "Larger reactors are cheaper on a per-megawatt basis because their material and work requirements do not scale linearly with power capacity," says Ramana. This, according to Ramana, means that the electricity SMRs produce will be more expensive than nuclear energy from large reactors, which are already far more expensive than renewables such as solar and wind energy.

## Clean or unclean?

Even if SMRs take over from PHWRs, there is still the question of what do with their nuclear waste. In Ramana's view, all activities linked to the nuclear fuel chain have significant health and environmental impacts. Ramana adds that those pollutants remain hazardous for hundreds of thousands of years. "There is no demonstrated solution to managing these radioactive wastes – nor can there be, given the challenge of trying to ensure that these materials do not come into contact with living beings," says Ramana.

Ganesan, however, thinks that nuclear energy is still clean as it produces electricity with a much lower environmental footprint, especially when it comes to so-called "criteria pollutants": ozone; particulate matter; carbon monoxide; lead; sulphur dioxide; and nitrogen dioxide. While nuclear waste still needs to be managed, Ganesan says the associated costs are already included in the price of setting up a reactor. "In due course, with technological development, the burn-up will be significantly higher and waste generated a lot less."

**TV Padma** is a freelance science writer based in India

## Research updates

# CERN takes protons on lorry ride

Researchers at CERN show that trapped protons can be transported by truck, which could pave the way for antimatter particles to go on the move, as **Isabelle Dumé** reports

Physicists at the CERN particle-physics lab have transported protons in a lorry across the lab's campus – a feat that allowed them in 2026 to complete a test run of transporting antiprotons in a similar manner. The goal is to study antimatter in places other than the labs that create it, enabling more precise measurements of the differences between matter and antimatter (*Nature* **641** 871).

According to the Standard Model of particle physics, particles such as protons and electrons should have a corresponding antiparticle that is identical in every way apart from its charge and magnetic properties (which are reversed). Yet the Big Bang that formed our universe nearly 14 billion years ago should have generated equal amounts of antimatter and matter. If that were the case, however, there shouldn't be any matter left, because whenever pairs of antimatter and matter particles collide, they annihilate each other in a burst of energy.

Physicists therefore suspect that there are other, more subtle differences between matter particles and their antimatter counterparts – differences that could explain why the former prevailed while the latter all but disappeared. By searching for these differences, they hope to shed more light on antimatter–matter asymmetry – and perhaps even reveal physics beyond the Standard Model.

### Spot the difference

At CERN's Baryon-Antibaryon Symmetry Experiment (BASE) experiment, the search for matter–antimatter differences focuses on measuring the magnetic moment (or charge-to-mass ratio) of protons and antiprotons. These measurements need to be extremely precise, but that is difficult at CERN's "Antimatter Factory" (AMF), which manufactures the necessary low-energy antiprotons in profusion. This is because essential



BASE/Julia Jäger

### Road trip

A Penning-trap system containing protons has been successfully transported by lorry across CERN's Meyrin campus.

nearby equipment – including the Antiproton Decelerator and ELENA, which reduce the energy of incoming antiprotons from GeV to MeV – produces magnetic field fluctuations that blur the signal.

To carry out more precise measurements, the team therefore needs a way of transporting the antiprotons to other, better-shielded, laboratories. This is easier said than done, however, given that antimatter needs to be carefully isolated from its environment to prevent it from annihilating with the walls of its container or with ambient gas molecules. The BASE team's solution was to develop a device that can transport trapped antiprotons on a truck for substantial distances. This device, known as BASE-STEP (for Symmetry Tests in Experiments with Portable Antiprotons), has now been field-tested for the first time.

### Protons on the go

During the test, the team successfully transported a cloud of about  $10^5$  trapped protons out of the AMF and across CERN's Meyrin campus over four hours. Although protons are not the same as antiprotons,

BASE-STEP team leader Christian Smorra says they are just as sensitive to disturbances in their environment caused by, say, driving them around. "They are therefore ideal stand-ins for initial tests, because if we can transport protons, we should also be able to transport antiprotons," he says.

The BASE-STEP device is mounted on an aluminium frame and measures  $1.95 \times 0.85 \times 1.65$  m. At 850–900 kg, it is light enough to be transported using standard forklifts and cranes. Like BASE, it traps particles in a Penning trap composed of gold-plated cylindrical electrode stacks made from oxygen-free copper. To further confine the protons and prevent them from colliding with the trap's walls, this trap is surrounded by a superconducting magnet bore operated at cryogenic temperatures. The second electrode stack is also kept at ultralow pressures of  $10^{-19}$  bar, which Smorra says is low enough to keep antiparticles from annihilating with residual gas molecules. To transport antiprotons instead of protons, Smorra adds, they would just need to switch the polarity of the electrodes.

The transportable trap system is designed to remain operational on the road. It uses a carbon-steel vacuum chamber to shield the particles from stray magnetic fields, and its frame can handle accelerations of up to  $1g$  ( $9.81 \text{ m/s}^2$ ) in all directions over and above the usual (vertical) force of gravity. This means it can travel up and down slopes with a gradient of up to 10%, or approximately  $6^\circ$ . Now that the BASE-STEP device has been reconfigured to transport antiprotons, the first destination on the team's list is a new Penning-trap system currently being constructed at the Heinrich Heine University in Düsseldorf, Germany. Here, physicists hope to search for charge-parity-time violations in protons and antiprotons with a precision at least 100 times higher than is possible at CERN's AMF.

If we can transport protons, we should also be able to transport antiprotons

## Particle physics

## KATRIN experiment sets tighter limit on neutrino mass

Researchers from the Karlsruhe Tritium Neutrino experiment (KATRIN) have announced the most precise upper limit yet on the neutrino's mass. The new limit – 0.45 electron volts (eV) at 90% confidence – is half that of the previous tightest constraint, and marks a step toward answering one of particle physics' longest-standing questions (*Science* 388 146).

KATRIN measures a process called tritium beta decay, where a tritium nucleus (a proton and two neutrons) decays into a helium-3 nucleus (two protons and one neutron) by releasing an electron and an electron antineutrino. Due to energy conservation, the total energy from the decay is shared between the electron and the antineutrino, with the neutrino's mass determining the balance of the split. As the subtle effects of neutrino mass are most visible in decays where the antineutrino carries away very little energy (most



Markus Bregler, KIT

of it bound up in mass), KATRIN concentrates on measuring electrons that have taken the lion's share. From these measurements, physicists can calculate neutrino mass without having to detect these notoriously weakly-interacting particles directly.

The new neutrino mass limit is based on data taken between 2019 and 2021, with 259 days of operations yielding over 36 million electron measurements. "That's six times more than the previous result," explains KATRIN member Christoph Wiesinger, who is a physicist

**Weighty matters**

The Karlsruhe Tritium Neutrino experiment has set a new upper limit on the neutrino mass.

at the Technical University of Munich, Germany. At 0.45 eV, the new limit means the neutrino is at least a million times lighter than the electron. "This is a fundamental number," Wiesinger adds. "It tells us that neutrinos are the lightest known massive particles in the universe, and maybe that their mass has origins beyond the Standard Model."

Despite the new tighter limit, however, definitive answers about the neutrino's mass are still some way off. "Neutrino oscillation experiments tell us that the lower bound on the neutrino mass is about 0.05 eV," says Patrick Huber, a theoretical physicist at Virginia Tech, US, who was not involved in the experiment. "That's still about 10 times smaller than the new KATRIN limit." KATRIN researchers are now aiming for 1000 days of operations by the end of 2025 and a final sensitivity approaching 0.3 eV.

Ananya Palivela

## High-quality muon beam holds promise for proposed collider

Researchers in Japan have accelerated muons into the most precise, high-intensity beam to date, reaching energies as high as 100 keV. The achievement could enable next-generation experiments such as better measurements of the muon's anomalous magnetic moment, which could in turn potentially point to physics beyond the Standard Model (*Phys. Rev. Lett.* 134 245001).

Muons are around 200 times heavier than electrons and so radiate less energy as they travel in circles – meaning that a muon accelerator could, in principle, produce more energetic collisions than a conventional electron machine for a given energy input. However, working with muons comes with challenges. Although scientists can produce high-intensity muon beams from the decay of other sub-atomic particles known as pions, these beams must then be cooled to make the velocities of their constituent particles more uniform before they can be accelerated to collider speeds. And while this cooling process is rela-



The authors

**One for the future**

A muon accelerator could, in principle, produce more energetic collisions than a conventional electron machine for a given energy input.

tively straightforward for electrons, for muons it is complicated by the particles' short lifetime of just 2 ms. Traditional cooling techniques (such as synchrotron radiation cooling or laser cooling) do not work.

To overcome this problem, researchers at the MUon Science Facility (MUSE) in the Japan Proton Accelerator Research Complex have been developing a method that involves cooling positively-charged muons, or antimuons, down to thermal energies of 25 meV and then accelerating them using radio-frequency cavities.

In the new work, a team led by particle and nuclear physicist Shusei Kamioka directed antimuons ( $\mu^+$ ) into a target made from a silica aerogel. This material has a unique

property: a muon that stops inside gets re-emitted as a muonium atom (an exotic atom consisting of an antimuon and an electron) with very low thermal energy. The researchers then fired a laser beam at these muonium atoms to remove their electrons, thereby producing antimuons with much lower – and, crucially, far more uniform – velocities than was the case for the starting beam. Finally, they guided the slowed particles into a rf cavity, where an electric field accelerated them to an energy of 100 keV.

The final beam has an intensity of  $2 \times 10^{-3} \mu^+$  per pulse, and a measured emittance that is much lower (by a factor of 200 in the horizontal direction and about 400 vertically) than the starting beam. This represents a two-orders-of-magnitude reduction in the spread of positions and momenta in the beam and makes accelerating the muons more efficient, says Kamioka. According to the researchers, these improvements are important steps on the road to a muon collider.

Isabelle Dumé

## Research updates

# CERN delves into the strong force

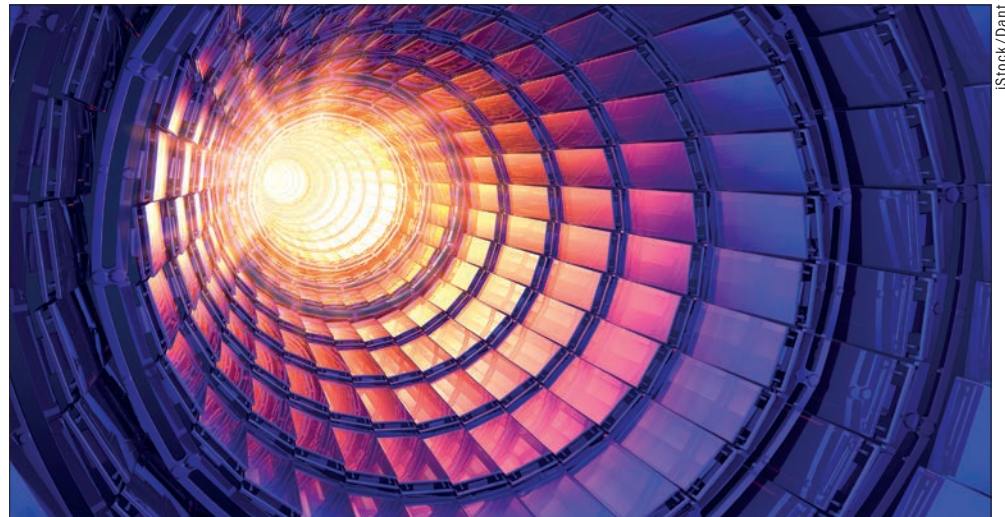
Measurements at the Compact Muon Solenoid suggests that tetraquarks are tightly bound, but more work is needed, as **Isabelle Dumé** explains

Researchers at CERN have made the first measurements of the quantum properties of a family of three “all-charm” tetraquarks that was recently discovered at the lab’s Large Hadron Collider (LHC). The findings could help shed more light on the properties of the strong nuclear force as well as improve our understanding of how ordinary matter forms (*Nature* **648** 58).

The LHC has in recent years discovered tens of massive particles called hadrons, which are made of quarks bound together by the strong force. Quarks come in six types: up, down, charm, strange, top and bottom and most observed hadrons comprise two or three quarks (called mesons and baryons, respectively). Physicists have also observed exotic hadrons that comprise four or five quarks – tetraquarks and pentaquarks respectively. Those seen so far usually contain a charm quark and its antimatter counterpart (a charm antiquark), with the remaining two or three quarks being up, down or strange quarks, or their antiquarks.

Identifying and studying tetraquarks and pentaquarks helps physicists better understand how the strong force, which also binds protons and neutrons in atomic nuclei, binds quarks together. Physicists are still divided, however, as to the nature of these exotic hadrons. Some models suggest that their quarks are tightly bound via the strong force, so making these hadrons compact objects. Others say that the quarks are only loosely bound. To confuse things further, there is evidence that in some exotic hadrons, the quarks might be both tightly and loosely bound at the same time.

The latest results from the Compact Muon Solenoid (CMS) Collaboration suggests that tetraquarks are indeed tightly bound. In their work, CMS physicists studied all-charm tetraquarks, which comprise two charm quarks and two charm antiquarks,



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that were produced by colliding protons at high energies at the LHC. Three states of this tetraquark have been identified at the LHC: X(6900); X(6600); and X(7100), where the numbers denote their approximate mass in millions of electron volts.

The team measured the fundamental properties of these tetraquarks, including their quantum numbers: parity (P); charge conjugation (C); angular momentum, and spin (J). P determines whether a particle has the same properties as its spatial mirror image; C whether it has the same properties as its antiparticle; and J, the total angular momentum of the hadron. These numbers provide information on the internal structure of a tetraquark.

The researchers used a version of a well-known technique called angular analysis, which is similar to the technique used to characterize the Higgs boson. This approach focuses on the angles at which the decay products of the all-charm tetraquarks are scattered. “We call this technique quantum state tomography,” CMS team member Chiara Mariotti of the INFN Torino in Italy told *Physics World*. “Here, we deduce the quantum state of an exotic state X from the analysis of its decay products. In particular,

### Charming measurement

Physicists have studied all-charm tetraquarks that were produced by colliding protons at CERN’s Large Hadron Collider.

the angular distributions in the decay  $X \rightarrow J/\psi J/\psi$ , followed by  $J/\psi$  decays into two muons, serve as analysers of polarization of two  $J/\psi$  particles.”

The researchers analysed all-charm tetraquarks produced at the CMS experiment between 2016 and 2018. They calculated that J is likely to be 2 and that P and C are both +1, with this combination of properties being expressed as  $2^{++}$ . “This result favours models in which all four quarks are tightly bound,” says particle physicist Timothy Gershon of the UK’s University of Warwick, who was not involved in this study. “However, the question is not completely put to bed. The sample size in the CMS analysis is not sufficient to exclude fully other possibilities, and additionally certain assumptions are made that will require further testing in future.”

Indeed, the findings do not completely rule out other models and further studies with larger data samples will be needed. The CMS Collaboration is now gathering more data and exploring additional decay modes of these exotic tetraquarks. “This will ultimately improve our understanding how this matter forms, which, in turn, could help refine our theories of how ordinary matter comes into being,” says Mariotti.



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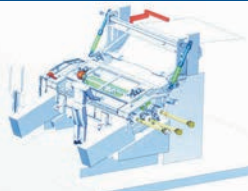


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## Research updates

# Baryon CP violation measured

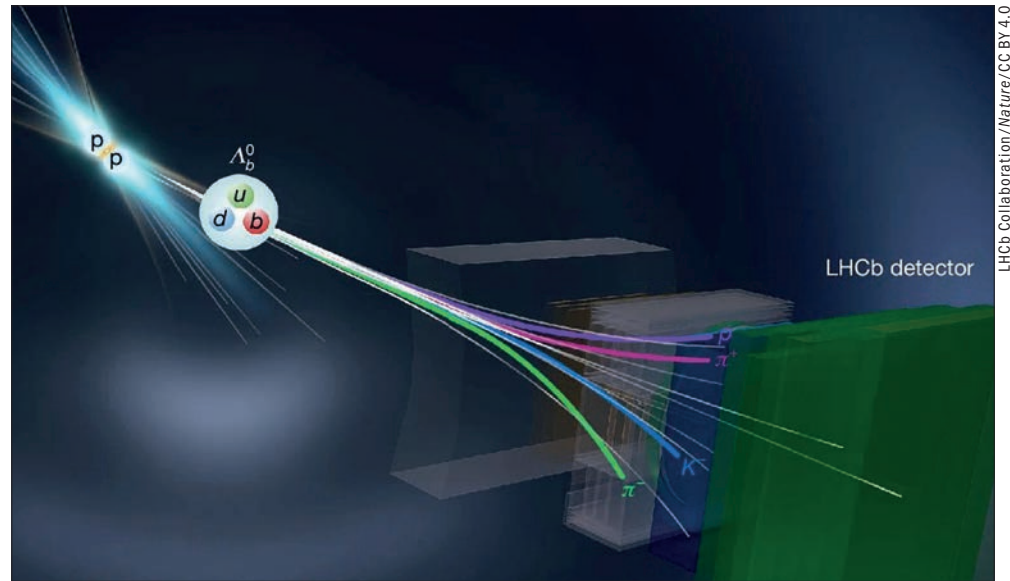
Result at CERN's LHCb experiment is consistent with the Standard Model, but could provide a path to new physics, as **Tim Wogan** reports

The first experimental evidence of charge–parity (CP) symmetry violation in baryons has been obtained by CERN's LHCb Collaboration. The result is consistent with the Standard Model of particle physics but could lead to constraints on theoretical attempts to extend the Standard Model to explain the excess of matter over antimatter in the universe (*Nature* **643** 1223).

Current models of cosmology say that the Big Bang produced a giant burst of matter and antimatter, the vast majority of which recombined and annihilated shortly afterwards. Today however, the universe appears to be made almost exclusively of matter with very little antimatter in evidence. This excess of matter is not explained by the Standard Model and its existence is an important mystery in physics.

In 1964, physicists in the US showed that the weak interaction violated CP symmetry, indicating that matter and antimatter could behave differently and it was suggested that, if amplified at very high mass scales in the early universe, CP violation could have induced the matter–antimatter asymmetry shortly after the Big Bang. Numerous observations of CP violation have subsequently been made in other mesonic systems and the phenomenon is now an accepted part of the Standard Model parametrized by the Cabibbo–Kobayashi–Maskawa (CKM) matrix. This describes the various probabilities of quarks of different generations changing into each other through the weak interaction – a process called mixing.

However, the CP violation produced through the CKM mechanism is a much smaller effect than would have been required to create the matter left over by the Big Bang. What is more, CP violation had never been observed in baryons (mostly protons and neutrons). “Theoretically the pre-



## Smashing result

Researchers at CERN's LHCb looked at the decays of beauty (or bottom) baryons and antibaryons that were produced in proton–proton collisions at the Large Hadron Collider during 2011–2018.

diction for baryon decay is very imprecise,” says Xueting Yang of China's Peking University, who is a member of the LHCb collaboration. “It's much more difficult to calculate than the meson decays because there's some interaction with the strong force.”

Given that baryons make up almost all the hadronic matter in the universe, it leaves open the slight possibility that the explanation might lie in some inconsistency between baryonic CP violation and the Standard Model prediction. In the new work, Yang and colleagues at LHCb looked at the decays of beauty (or bottom) baryons and antibaryons. These heavy cousins of neutrons contain an up quark, a down quark and a beauty quark and were produced in proton–proton collisions at the Large Hadron Collider in 2011–2018. The baryons and antibaryons can decay via multiple channels. In one, a baryon decays to a proton, a positive K-meson and a pair of pions – or, conversely, an antibaryon decays to an antiproton, a negative K-meson and a pair of pions.

CP violation should create an asymmetry between these processes, and the researchers looked for evidence of this asymmetry in the num-

bers of particles detected at different energies from all the collisions. The team found that the CP violation seen was consistent with the Standard Model and inconsistent with zero by  $5.2\sigma$ . “The experimental result is more precise than what we can get from theory,” says Yang. Other LHCb researchers scrutinized alternative decay channels of the beauty baryon: “Their measurement results are still consistent with CP symmetry... There should be CP violation also in their decay channels, but we don't have enough statistics to claim that the deviation is more than  $5\sigma$ .”

The current data do not rule out any extensions to the current Standard Model, adds Yang, simply because none of those extensions make precise predictions about the overall degree of CP violation expected in baryons. However, the LHC is now in its third run, and the researchers hope to acquire information on, for example, the intermediate particles involved in the decay: “We may be able to provide some measurements that are more comparable for theories and which can provide some constraints on the Standard Model predictions for CP violation,” says Yang.

## Nuclear physics

# Photon collisions provide a glimpse of gluons inside nuclei

A new experiment has offered the clearest view yet of how gluons behave inside atomic nuclei. Conducted at the Thomas Jefferson National Accelerator Facility in the US, the research sheds light on how gluons are distributed in nuclear matter and is a crucial step toward understanding the nature of protons within nuclei (*Phys. Rev. Lett.* **134** 201903).

Gluons, which are massless, generate most of the visible mass in the universe, but their role inside nuclei remains poorly understood. Mediating the strong nuclear force, which binds quarks as well as protons and neutrons in nuclei, gluons carry no electric charge and cannot be directly detected. The theory that describes gluons – quantum chromodynamics (QCD) – is difficult to test, especially in the dense, strongly interacting environment of a nucleus. Precision experiments are therefore essential for revealing how matter is held together at the deepest level.

The Jefferson Lab experiment focused on photoproduction, in which



Jefferson Lab/Aileen Devlin

a high-energy photon strikes a particle and creates something new, in this case, a  $J/\Psi$  meson. The  $J/\Psi$  comprises a charm quark and its antiquark and is especially useful for studying gluons. Charm quarks are much heavier than those found in ordinary matter and are not present in protons or neutrons. Therefore, they must be created entirely during the interaction, making the  $J/\Psi$  a particularly clean and sensitive probe of gluon behaviour inside nuclei.

Earlier studies had observed photoproduction using free protons. This new experiment extends the approach to protons confined in nuclei to see how that environment affects gluon behaviour. The researchers used Jeffer-

### Holding it together

Researchers used the Thomas Jefferson National Accelerator Facility in the US to study the behaviour of gluons within nuclei.

son Lab's Experimental Hall D, which delivers an intense beam of high-energy photons and the GlueX spectrometer.

As well as being the first to measure  $J/\Psi$  photoproduction from nuclei in the “threshold” region – where the photon has just enough energy to produce a  $J/\Psi$  meson – particularly striking were observations in the so-called “sub-threshold”. This is where the incoming photon does not carry enough energy to produce the  $J/\Psi$  on its own, so it must draw additional energy from the internal motion of protons or from the nuclear medium itself.

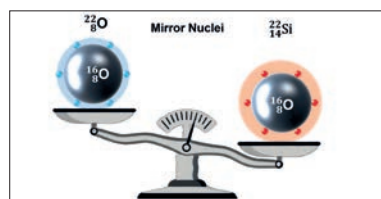
“The number of subthreshold  $J/\Psi$  exceeded expectations,” notes Jackson Pybus, who is now a postdoc at Los Alamos National Laboratory and one of the experiment's collaborators. “That raises questions about how the photon is able to pick up so much energy from the nucleus.” The results suggest that gluons may be modified inside nuclei in ways that are not described by existing models – suggesting a new frontier in nuclear physics.

Andrey Feldman

# Physicists discover a new proton magic number

The first precise mass measurements of an extremely short-lived and proton-rich nucleus, silicon-22, have revealed the “magic” nature of nuclei containing 14 protons. As well as shedding light on nuclear structure, the discovery could improve our understanding of the strong nuclear force and the mechanisms by which elements form (*Phys. Rev. Lett.* **135** 012501).

At the lighter end of the periodic table, stable nuclei tend to contain similar numbers of neutrons and protons. As the number of protons increases, additional neutrons are needed to balance out the mutual repulsion of the positively-charged protons. As a rule, therefore, an isotope of a given element will be unstable if it contains either too few neutrons or too many. According to the nuclear shell model, nuclei that contain certain “magic” numbers of nucleons (neutrons and/or protons) are more bound



because they have just the right number of nucleons to fully fill their shells.

Nuclei that contain magic numbers of both protons and neutrons are even more bound and are said to be “doubly magic”. Subsequent studies showed that for neutrons, these magic numbers are 2, 8, 20, 28, 50, 82 and 126.

While the magic numbers for stable and long-lived nuclei are now well-established, those for exotic, short-lived ones with unusual proton-neutron ratios are comparatively little understood. After measurements on oxygen-22 (14 neutrons, 8 protons) showed that 14 is a magic number of neutrons for this neutron-rich

### IMP Weighty matters

Mass measurements of silicon-22 reveal that it possesses a double-magic structure similar to that of its mirror nucleus, oxygen-22.

isotope, the hunt was on for a proton-rich counterpart. “Of all the new neutron-rich doubly-magic nuclei discovered, only one loosely bound mirror nucleus for oxygen-22 exists,” says Yuhu Zhang, a physicist at the Institute for Modern Physics (IMP) of the Chinese Academy of Sciences. “This is silicon-22.”

The problem is that silicon-22 (14 protons, 8 neutrons) has a short half-life and is hard to produce in large quantities. Working at the Cooler-Storage Ring of the Heavy Ion Research Facility in Lanzhou, China, the researchers accelerated a beam of stable  $^{36}\text{Ar}^{15+}$  ions onto a target, causing them to fragment into silicon-22 nuclei. After injecting these nuclei into the storage ring, the researchers confirmed that the proton number 14 is indeed magic in silicon-22.

Isabelle Dumé

# Research updates

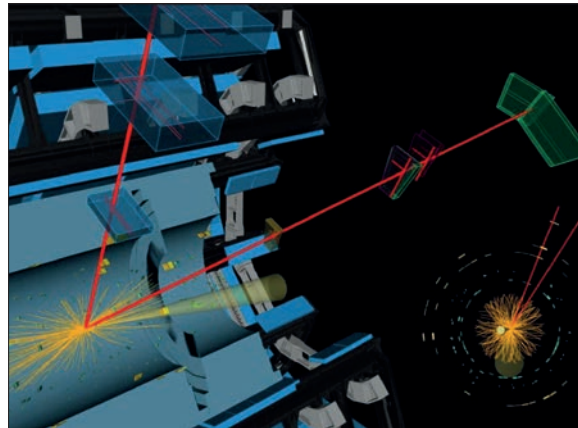
## Particle physics

### Higgs decay to muon–antimuon pairs sheds light on the origin of mass

A new measurement by CERN's ATLAS Collaboration has strengthened evidence that the masses of fundamental particles originate through their interaction with the Higgs field. Building on earlier results from CERN's CMS Collaboration, the observations suggest that muon–antimuon pairs (dimuons) can be created by the decay of Higgs bosons (*Phys. Rev. Lett.* **135** 231802).

In the Standard Model of particle physics, fermions are organized into three different generations. The first generation comprises the two lightest quarks (up and down), the lightest lepton (the electron) and the electron neutrino. The second includes the strange and charm quarks, the muon and its neutrino; and the third generation the bottom and top quarks, the tau and its neutrino.

All of the quarks and leptons have both right- and left-handed components, which relate to the direction of a particle's spin relative to its direction of motion (right-handed if both directions are aligned; left-handed if they are anti-aligned).



#### Smashing result

Work on the ATLAS detector at CERN has found that muon–antimuon pairs can be created by the decay of Higgs bosons – agreeing with previous results.

In the 1960s it was proposed that the Higgs field acts as a bridge between each particle's left- and right-handed components in a way that respects the Standard Model's underlying symmetry. This interaction causes the particle to constantly flip between its two components, creating a resistance to motion that can be perceived as mass. However, higher-mass particles must interact more strongly with this Higgs field – but the strong and electromagnetic forces can only differentiate between these particles according to

their charges (colour and electrical).

So how does the Higgs field distinguish between particles in different generations if their charges are identical? Key to solving this mystery is observing the decay products of Higgs bosons with different interaction strengths. In 2022, proton–proton collision experiments at CERN's Large Hadron Collider independently observed Higgs bosons decaying to tau–antitau pairs at the same rate as predicted by theory.

A year earlier, similar experiments by the CMS Collaboration probed the second generation by observing muon–antimuon pairs from the decays of Higgs bosons. This rarer event occurs in just 1 in 5000 Higgs decays. In their latest study, the ATLAS Collaboration have now reproduced this CMS result independently. They collided protons at about 13 TeV and observed muon–antimuon pairs in the same range of energies predicted by theory. These new results bring dimuon observations to a statistical significance of  $3.4\sigma$  – up from  $3.0\sigma$  in 2021.

**Sam Jarman**

### KATRIN and MicroBooNE fail to spot sterile neutrinos

Two major experiments have found no evidence for sterile neutrinos – hypothetical particles that could help explain some puzzling observations in particle physics. The KATRIN experiment searched for sterile neutrinos that could be produced during the radioactive decay of tritium; whereas the MicroBooNE experiment looked for the effect of sterile neutrinos on the transformation of muon neutrinos into electron neutrinos (*Nature* **648** 64 and 648 70).

There is some experimental evidence that the current Standard-Model description of neutrino oscillation is not quite right. This includes lower-than-expected neutrino fluxes from some beta-decaying nuclei and some anomalous oscillations in neutrino beams. One possible explanation for these oscillation anomalies is the existence of a fourth type of neutrino. Because we have yet to detect this

Markus Breig/KIT



particle, the assumption is that it does not interact via the weak interaction – which is why these hypothetical particles are called sterile neutrinos.

Now, two neutrino experiments have both reported no evidence of sterile neutrinos. One is KATRIN, which is located at the Karlsruhe Institute of Technology in Germany. Its aim is to make a very precise measurement of the mass of the electron antineutrino. If sterile neutrinos exist, then they could sometimes be emitted in place

#### Back to the drawing board

Work on the KATRIN experiment in Germany has found no evidence for sterile neutrinos.

of electron antineutrinos during beta decay. This would change the electron energy spectrum – but this was not observed at KATRIN.

Meanwhile, physicists on the MicroBooNE experiment at Fermilab in the US looked for evidence for sterile neutrinos in how muon neutrinos oscillate into electron neutrinos. If sterile neutrinos exist, they would be involved in the oscillation process and would therefore affect the number of electron neutrinos detected by MicroBooNE. Neutrino beams from two different sources were used in the experiments, but no evidence for sterile neutrinos was found.

“Any time you rule out one place where physics beyond the Standard Model could be, that makes you look in other places,” says Justin Evans at the UK's University of Manchester, who is co-spokesperson for MicroBooNE.

**Hamish Johnston**

## Particle physics

## Sympathetic cooling gives antihydrogen experiment a boost

Physicists working on the Antihydrogen Laser Physics Apparatus (ALPHA) experiment at CERN have trapped and accumulated 15 000 antihydrogen atoms in less than seven hours – an accumulation rate more than 20 times the previous record. Large ensembles of anti-hydrogen could be used to search for physics beyond the Standard Model (*Nature Comms* **16** 10106).

Why there is much more matter than antimatter in the visible universe, and the reason for this “baryon asymmetry” is a big mystery. If physicists could find discrepancies between the measured and predicted properties of antimatter it could point to new physics.

An antihydrogen antiatom comprises an antiproton bound to an antielectron (positron). Antihydrogen offers physicists several powerful ways to probe antimatter at a fundamental level. Trapped antiatoms can be

released in freefall to determine if they respond to gravity in the same way as atoms. Spectroscopy can be used to make precise measurements of how the electromagnetic force binds the antiproton and positron in antihydrogen with the aim of finding differences compared to hydrogen.

So far, antihydrogen’s gravitational and electromagnetic properties appear to be identical to hydrogen. However, these experiments were done using small numbers of antiatoms, and having access to much larger ensembles would improve the precision of such measurements. Today, antihydrogen can only be made in significant quantities at CERN, where a beam of protons is fired at a solid target, creating antiprotons that are then cooled and stored using electromagnetic fields. Positrons, meanwhile, are gathered from the decay of radioactive nuclei and cooled and stored using electro-



2023-2025 CERN/Brice, Maximilien

### Precision probe

Creating larger ensembles of antihydrogen atoms could provide a better probe of its gravitational and electromagnetic properties.

magnetic fields. These antiprotons and positrons are then combined in a special electromagnetic trap to create antihydrogen.

This process works best when the antiprotons and positrons have very low kinetic energies. If the energy is too high, the antiatoms will escape. So, it is crucial that the positrons and antiprotons are as cold as possible. ALPHA physicists have now used a technique called sympathetic cooling on positrons. Using beryllium ions, they cooled the positrons to 10 K, which is five degrees colder than previously achieved. These cold positrons boosted the efficiency of the creation and trapping of antihydrogen, allowing the team to accumulate 15 000 antihydrogen atoms in less than 7 h. “These numbers would have been considered science fiction 10 years ago,” says ALPHA spokesperson Jeffrey Hangst.

**Hamish Johnston**

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## Opinion

# CERN needs a 'Plan B'

The fragmenting world order makes plans to build the Future Circular Collider questionable, warns

**Michael Riordan**

In November 2025 I visited the CERN particle-physics lab near Geneva to attend the 4th International Symposium on the History of Particle Physics, which focused on advances in particle physics during the 1980s and 1990s. As usual, it was a refreshing, intellectually invigorating visit. I'm always inspired by the great diversity of scientists at CERN – complemented this time by historians, philosophers and other scholars of science.

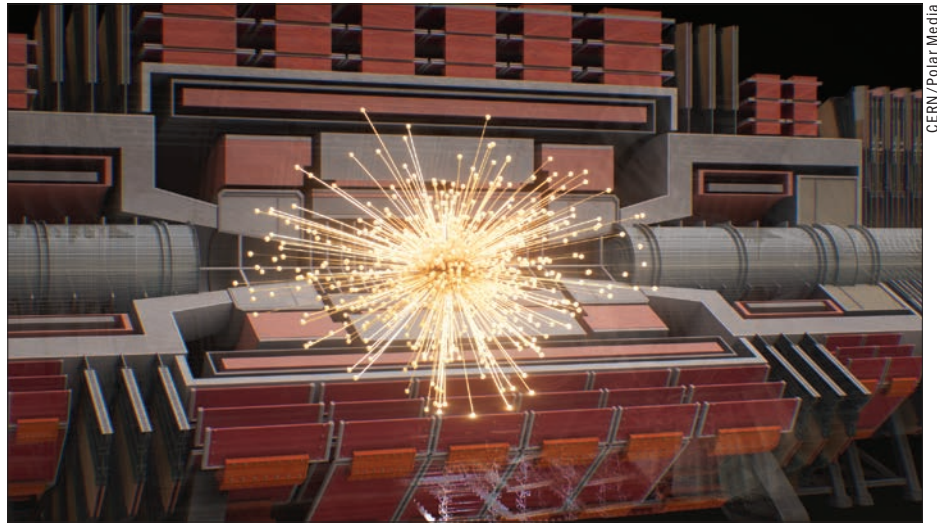
As noted by historian John Krige in his opening keynote address, "CERN is a European laboratory with a global footprint. Yet for all its success it now faces a turning point." During the period under examination at the symposium, CERN essentially achieved the "world laboratory" status that various leaders of particle physics had dreamt of for decades.

By building the Large Electron Positron (LEP) collider and then the Large Hadron Collider (LHC), the latter with contributions from Canada, China, India, Japan, Russia, the US and other non-European nations, CERN has attracted researchers from six continents. And as the Cold War ended in 1989–1991, two prescient CERN staff members developed the World Wide Web, helping knit this sprawling international scientific community together and enable extensive global collaboration.

The LHC was funded and built during a unique period of growing globalization and democratization that emerged in the wake of the Cold War's end. After the US terminated the Superconducting Super Collider in 1993, CERN was the only game in town if one wanted to pursue particle physics at the multi-TeV energy frontier. And many particle physicists wanted to be involved in the search for the Higgs boson, which by the mid-1990s looked as if it should show up at accessible LHC energies.

Having discovered this long-sought particle at the LHC in 2012, CERN is now contemplating an ambitious construction project, the Future Circular Collider (FCC). Over three times larger than the LHC, it would study this all-important, mass-generating boson in greater detail using an electron-positron collider dubbed FCC-ee, estimated to cost \$18bn and start operations by 2050.

Later in the century, the FCC-hh, a proton-proton collider, would go in the same tunnel to see what, if anything, may lie at



CERN/Polar Media

**Cost measures** CERN is proposing the Future Circular Collider to study the Higgs boson in great detail, but can it afford the \$18bn price tag?

much higher energies. That collider, the cost of which is currently educated guesswork, would not come online until the mid 2070s.

But the steadily worsening geopolitics of a fragmenting world order could make funding and building these colliders dicey affairs. After Russia's expulsion from CERN, little in the way of its contributions can be expected. Chinese physicists had hoped to build an equivalent collider, but those plans seem to have been put on the backburner for now.

And the "America First" political stance of the current US administration is hardly conducive to the multibillion-dollar contribution likely required from what is today the world's richest (albeit debt-laden) nation. The ongoing collapse of the rules-based world order was recently put into stark relief by the US invasion of Venezuela and abduction of its president Nicolás Maduro, followed by the war in Iran.

**Recent events suggest how difficult it may become to fund gargantuan international scientific projects such as the FCC**

While these shocking events have immediate significance for international relations, they also suggest how difficult it may become to fund gargantuan international scientific projects such as the FCC. Under such circumstances, it is very difficult to imagine non-European nations being able to contribute a hoped-for third of the FCC's total costs.

But the mounting European populist right-wing parties are no great friends of physics either, nor of international scientific endeavours. And Europeans face the not-insignificant costs of military rearmament in the face of Russian aggression and likely US withdrawal from Europe.

So the other two thirds of the FCC's many billions in costs cannot be taken for granted – especially not during the decades needed to construct its 91 km tunnel, 350 GeV electron-positron collider, the subsequent 100 TeV proton collider, and the massive detectors both machines require.

According to former CERN director-general Chris Llewellyn Smith in his symposium lecture, "The political history of the LHC", just under 12% of the material project costs of the LHC eventually came from non-member nations. It therefore warps the imagination to believe that a third of the much greater costs of the FCC can come from non-member nations in the current "Wild West" geopolitical climate.

But particle physics desperately needs a Higgs factory. After the 1983 Z boson discovery at the CERN SPS Collider, it took just six years before we had not one but two Z factories – LEP and the Stanford Linear Collider – which proved very productive machines. It’s now been more than 13 years since the Higgs boson discovery. Must we wait another 20 years?

**Other options**

CERN therefore needs a more modest, realistic, productive new scientific facility – a “Plan B” – to cope with the geopolitical uncertainties of an imperfect, unpredictable world. And I was encouraged to learn that several possible ideas are under consideration, according to outgoing CERN director-general Fabiola Gianotti in her symposium lecture, “CERN today and tomorrow”.

Three of these ideas reflect the European Strategy for Particle Physics, which states that “an electron-positron Higgs factory is the highest-priority next CERN collider”. Two linear electron-positron colliders would require just 11–34 km of tunnelling and could begin construction in the mid-2030s, but would involve a fair amount of technical risk and cost roughly €10bn.

The least costly and risky option, dubbed

LEP3, involves installing superconducting radio-frequency cavities in the existing LHC tunnel once the high-luminosity proton run ends. Essentially an upgrade of the 200 GeV LEP2, this approach is based on well-understood technologies and would cost less than €5bn but can reach at most 240 GeV. The linear colliders could attain over twice that energy, enabling research on Higgs-boson decays into top quarks and the triple-Higgs self-interaction.

Other proposed projects involving the LHC tunnel can produce large numbers of Higgs bosons with relatively minor backgrounds, but they can hardly be called “Higgs factories”. One of these, dubbed the LHeC, could only produce a few thousand Higgs bosons annually and would allow other important research on proton structure functions. Another idea is the proposed Gamma Factory, in which laser beams would be backscattered from LHC beams of partially stripped ions. If sufficient photon energies and intensity can be achieved, it will allow research on the  $\gamma\gamma \rightarrow H$  interaction. These alternatives would cost at most a few billion euros.

As Krige stressed in his keynote address, CERN was meant to be more than a scientific laboratory at which European physi-

cists could compete with their US and Soviet counterparts. As many of its founders intended, he said, it was “a cultural weapon against all forms of bigoted nationalism and anti-science populism that defied Enlightenment values of critical reasoning”. The same logic holds true today.

In planning the next phase in CERN’s estimable history, it is crucial to preserve this cultural vitality, while of course providing unparalleled opportunities to do world-class science – lacking which, the best scientists will turn elsewhere.

I therefore urge CERN planners to be daring but cognizant of financial and political reality in the fracturing world order. Don’t for a nanosecond assume that the future will be a smooth extrapolation from the past. Be fairly certain that whatever new facility you decide to build, there is a solid financial pathway to achieving it in a reasonable time frame.

The future of CERN – and the bracing spirit of CERN – rests in your hands.



**Michael Riordan** is author of *The Hunting of the Quark* and lead author of *Tunnel Visions: the Rise and Fall of the Superconducting Super Collider*

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# The impact of the Straton model



Sakata Memorial Archival Library

**Meeting of minds** Mao Zedong (left) at the 1964 Peking Symposium congratulating Japanese theorist Shoichi Sakata (right) on his achievements in particle physics, as distinguished Chinese physicist Peiyuan Zhou looks on.

An obscure theory of elementary particles proved to be key to China's re-emergence as a scientific nation after the Cultural Revolution had stalled its development. **Robert P Crease** finds out more from the Chinese historian of physics Jinyan Liu

“The Straton Model of elementary particles had very limited influence in the West,” said Jinyan Liu as she sat with me in a quiet corner of the CERN cafeteria. Liu, who I caught up with during a break in a recent conference on the history of particle physics, was referring to a particular model of elementary particle physics first put together in China in the mid-1960s. The Straton Model was, and still largely is, unknown outside that country. “But it was an essential step forward,” Liu added, “for Chinese physicists in joining the international community.”

Liu was at CERN to give a talk on how Chinese theorists redirected their research efforts in the years after the Cultural Revolution, which ended in 1976. They switched from the Straton Model, which was a politically infused theory of matter favoured by Mao Zedong, the founder of the People's Republic of China, to mainstream particle physics as practised by the rest of the world. It's easy to portray the move as the long-overdue moment when Chinese scientists resumed their “real” physics research. But,

Liu told me, “actually it was much more complicated”.

A physicist by training, Liu received her PhD on contemporary theories of spontaneous charge-parity (CP) violation from the Institute of Theoretical Physics at the Chinese Academy of Sciences (CAS) in 2013. She then switched to the CAS Institute for the History of Natural Sciences, where she was its first member with a physics PhD. Her initial research topic was the history and development of the Straton Model.

The model is essentially a theory of the structure of hadrons – either baryons (such as protons and neutrons) or mesons (such as pions and kaons). But the model's origins are as improbable as they are labyrinthine. Mao, who had a keen interest in natural science, was convinced that matter was infinitely divisible, and in 1963 he came across an article by the Marxist-inspired Japanese physicist Shoichi Sakata (1911–1970).

First published in Japanese in 1961 and later translated into Russian, Sakata's paper was entitled “Dialogues concerning a new view

of elementary particles”. It restated Sakata's belief, which he had been working on since the 1950s, that hadrons are made of smaller constituents – “elementary particles are not the ultimate elements of matter” as he put it. With some Chinese scholars back then still paying close attention to publications from the Soviet Union, their former political and ideological ally, that paper was then translated into Chinese.

This version appeared in the *Bulletin of the Studies of Dialectics of Nature* in 1963. Mao, who received an issue of that bulletin from his son-in-law, was engrossed in Sakata's paper, for it seemed to offer scientific support for his own views. Sakata's article – both in the original Japanese and now in Chinese – cited Friedrich Engels' view that matter has numerous stages of discrete but qualitatively different parts. In addition, it quoted Lenin's remark that “even the electron is inexhaustible”.

## A wider dimension

“International politics now also entered,” Liu told me, as we discussed the issue further

Jinyan Liu



**Major attraction** The high-water mark for the Straton model occurred at a physics colloquium organized by the China Association for Science and Technology in Tiananmen Square, Beijing, in July 1966, the opening ceremony of which is shown here.

at CERN. A split between China and the Soviet Union had begun to open up in the late 1950s, with Mao breaking off relations with the Soviet Union and starting to establish non-governmental science and technology exchanges between China and Japan. Indeed, when China hosted the Peking Symposium of foreign scientists in 1964, Japan brought the biggest delegation, with Sakata as its leader.

At the event, Mao personally congratulated Sakata on his theory. It was, Sakata later recalled, “the most unforgettable moment of my journey to China”. In 1965, Sakata’s paper was retranslated from the Japanese original, with an annotated version published in *Red Flag* and the newspaper *Renmin ribao*, or “People’s Daily”, both official organs of the Chinese Communist Party.

Chinese physicists, who had been assigned to work on the atomic bomb and other research deemed important by the Communist Party, now started to take note. Uninterested in philosophy, they realized that they could capitalize on Mao’s enthusiasm to make elementary particle physics a legitimate research direction.

As a result, 39 members of CAS, Peking University and the University of Science and Technology of China formed the Beijing Elementary Particle Group. Between 1965 and 1966, they wrote dozens of papers on a model of hadrons inspired by both Sakata’s work and quark theory based on the available experimental data. It was dubbed the Straton Model because it involved layers or “strata” of particles nested in each other.

Liu has interviewed most surviving members of the group and studied details of the model. It differed from the model being

developed at the time by the US theorist Murray Gell-Mann, which saw quarks as not physical but mathematical elements. As Liu discovered, Chinese particle physicists were now given resources they’d never had before. In particular, they could use computers, which until then had been devoted to urgent national defence work. “To be honest,” Liu chuckled, “the elementary particle physicists didn’t use computers much, but at least they were made available.”

The high-water mark for the Straton Model occurred in July 1966 when members of the Beijing Elementary Particle Group presented it at a summer physics colloquium organized by the China Association for Science and Technology. The opening ceremony was held in Tiananmen Square, in what was then China’s biggest conference centre, with attendees including Abdus Salam from Imperial College London. The only high-profile figure to be invited from the West, Salam was deemed acceptable because he was science advisor to the president of Pakistan, a country considered outside the western orbit.

The proceedings of the colloquium were later published as “Research on the theory of elementary particles carried out under the brilliant illumination of Mao Tse-Tung’s thought”. Its introduction was what Liu calls a “militant document” – designed to reinforce the idea that the authors were carrying Mao’s thought into scientific research to repudiate “decadent feudal, bourgeois and revisionist ideologies”.

Participants in Beijing had expected to make their advances known internationally by publishing the proceedings in English. But the Cultural Revolution had just begun two months before, and publications in English

were forbidden. “As a result,” Liu told me, “the model had very limited influence outside China.” Sakata, however, had an important influence on Japanese theorists having co-authored the key paper on neutrino flavour oscillation (*Prog. Theoretical. Physics* **28** 870).

### A resurfaced effort

In recent years, Liu has shed new light on the Straton Model, writing a paper in the journal *Chinese Annals of History of Science and Technology* (2 85). In 2022, she also published a Chinese-language book entitled *Constructing a Theory of Hadron Structure: Chinese Physicists’ Straton Model*, which describes the downfall of the model after 1966. None of its predicted material particles appeared, though a candidate event once occurred in a cosmic ray observatory in the south of China.

By 1976, quantum chromodynamics (QCD) had convincingly emerged as the established model of hadrons. The effective end of the Straton Model took place at a conference in January 1980 in Conghua, near Hong Kong. Hung-Yuan Tzu, one of the key leaders of the Beijing Group, gave a paper entitled “Reminiscences of the Straton Model”, signalling that physics had moved on.

During our meeting at CERN, Liu showed me photos of the 1980 event. “It was a very important conference in the history of Chinese physics,” she said, “the first opening to Chinese physicists in the West”. Visits by Chinese expatriates were organized by Tsung-Dao Lee and Chen Ning Yang, who shared the 1957 Nobel Prize for Physics for their work on parity violation.

### The critical point

It is easy for westerners to mock the Straton Model; Sheldon Glashow once referred to it as about “Maons”. But Liu sees it as significant research that had many unexpected consequences, such as helping to advance physics research in China. “It gave physicists a way to pursue quantum field theory without having to do national defence work”.

The model also trained young researchers in particle physics and honed their research competence. After the post-Cultural Revolution reform and its opening to the West, these physicists could then integrate into the international community. “The story,” Liu said, “shows how ingeniously the Chinese physicists adapted to the political situation.”

**Robert P Crease** is a professor in the Department of Philosophy, Stony Brook University, US; e-mail robert.crease@stonybrook.edu; www.robertpcrease.com; his latest book is *The Leak* (2022 MIT Press)

## Opinion

# Lessons from the past



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Particle physics is using ever more interdisciplinary means to seek ever more exotic phenomena, **Robert P Crease** finds, but these ambitions might be threatened by the increasing isolation, fragmentation and polarization of the modern world

In his opening remarks to the 4th International Symposium on the History of Particle Physics, Chris Llewellyn Smith – who was a director-general of CERN in the 1990s – suggested participants should speak about “what’s not written in the journals”, including “mistakes, dead-ends and problems with getting funding”. Doing so, he said, would “provide insight into the way science really progresses”.

The symposium was not your usual science conference. Held in November 2025 at CERN, it took place inside the lab’s 400-seat main auditorium, which has been the venue for many historic announcements, including the discovery of the Higgs boson. Its brown-beige walls are covered with lively designs by the Finnish artist Ilona Rista, suggesting to me the aftermath of a collision of high-energy bar codes.

The focus of the meeting was the development of particle physics in the 1980s and 1990s – a period that saw the construction and operation of various important accelerators and detectors. At CERN, these included the UA1 and UA2 experiments at the Super Proton Synchrotron, where the W and Z bosons

were discovered. Later, there was the Large Electron-Positron Collider (LEP), which came online in 1989, and the Large Hadron Collider (LHC), approved five years later.

Delegates also heard about the opening of various accelerators in the US during those two decades, including two at the Stanford Linear Accelerator Center – the Positron-Electron Project in 1980 and the Stanford Linear Collider in 1989. Most famous of all was the start-up of the Tevatron at Fermilab in 1983. Over at Dubna in the former Soviet Union, meanwhile, scientists built the Nuclotron, a superconducting synchrotron, which opened in 1992.

Conference speakers covered unfinished machines of the era as well. The US cancelled two proton-proton facilities – ISABELLE in 1983 and the Superconducting Super Collider (SSC) a decade later. The Soviet Union, meanwhile, abandoned the multi-TeV proton-proton collider UNK a few years later, though news has recently emerged that Russia might revive the project.

Several speakers recounted the discovery of the W and Z particles at CERN in 1983 and

the discovery of the top quark at Fermilab in 1995. Others addressed the strange fact that fewer neutrinos from the Sun had been detected than theory suggested. The “solar-neutrino problem”, as it was known, was finally resolved by Takaaki Kajita’s discovery of neutrino oscillation in 1998, for which he shared the 2015 Nobel Prize for Physics with Art McDonald.

The conference also addressed unsuccessful searches for proton decay, axions, magnetic monopoles, the Higgs boson, supersymmetry particles and other targets. Other speakers described projects with highly positive outcomes, such as the advent of particle cosmology, or what some have jokingly dubbed “the heavenly lab”. The development of string theory, grand unified theories and perturbative quantum chromodynamics was tackled too.

In an exchange in the question-and-answer session after one talk, the Greek physicist Kostas Gavroglu referred to many of such quests as “failures”. That remark prompted the Australian-born US theoretical physicist Helen Quinn to say she

## As a result of the Superconducting Super Collider's controversial closure, the centre of gravity of high-energy physics shifted to Europe

preferred the term “falling forward”; such failures, she said, were instances of “I tried this, and it didn’t work so I tried that”.

In relating his work on detecting gravitational waves, the US Nobel-prize-winning physicist Barry Barish said he felt his charge was not to celebrate the importance of his discoveries nor the ingenuity of the route he took. Instead, Barish explained, his job was to answer the much more informal question: “What made me do what?”.

His point was illustrated by the US theorist Alan Guth, who described the very human and serendipitous path he took to working on cosmic inflation – the super-fast expansion of the universe just after the Big Bang. When he started, Guth said, “all the ingredients were already invented”. But the startling idea of inflation hinged on accidental meetings, chance conversations, unexpected visits, a restricted word count for *Physical Review Letters*, competitions, insecurities and “spectacular realizations” coalescing.

### Wider world

Another theme that arose in the conference was that science does not unfold inside its own bubble but can have extensive and immediate impacts on the world around it. Two speakers, for instance, recounted the invention of the World Wide Web at CERN in the late 1980s. It’s fair to say that no other discovery by a single individual – Tim Berners-Lee – has so radically and quickly transformed the world.

The growing role of international politics in promoting and protecting projects was mentioned too, with various speakers explaining how high-level political negotiations enabled physicists to work at institutions and experiments in other nations. The Polish physicist Agnieszka Zalewska, for example, described her country’s path to membership in CERN, while Russian-born US physicist Vladimir Shiltsev spoke about the “diaspora” of Russian particle physicists after the fall of the Soviet Union in 1991.

Sometimes politics created destructive interference. The US physicist, historian and author Michael Riordan described how the US’s determination to “go it alone” to out-compete Europe in high-energy physics was a major factor in bringing about the opposite: the termination of the SSC in 1993. As a result of that project’s controversial closure,



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**Joint effort** It was in the 1990s that CERN fully became the focus of international collaboration in high-energy physics – a role that is now becoming somewhat uncertain.

the centre of gravity of high-energy physics shifted to Europe.

Indeed, contemporary politics occasionally hit the conference itself in incongruous and ironic ways. Two US physicists, for example, were denied permission to attend because budgets had been cut and travel restrictions increased. In the end, one took personal time off and paid his own way, leaving his affiliation off the programme.

Before the conference, some people complained that conference organizers hadn’t paid enough attention to physicists who’d worked in the Soviet Union but were from occupied republics. Several speakers addressed this shortcoming by mentioning people like Gersh Budker (1918–1977). A Ukrainian-born physicist who worked and died in the Soviet Union, Budker was nominated for a Nobel Prize (1957) and even has had a street named after him at CERN. Unmentioned, though, was that Budker was Jewish and that his father was killed by Ukrainian nationalists in a pogrom.

On the final day of the conference, which just happened to be World Science Day for Peace and Development, CERN mounted a public screening of the 2025 documentary film *The Peace Particle*. Directed by Alex Kiehl, much of it was about CERN’s internationalism, with a poster for the film describing the lab as “Mankind’s biggest experiment... science for peace in a divided world”.

But in the Q&A afterwards some audience members criticized CERN for allegedly whitewashing Russia for its invasion of

the Ukraine and Israel for genocide. Those onstage defended CERN on the grounds of its desire to promote internationalism.

### The critical point

The keynote speaker of the conference was John Krige, a science historian from Georgia Tech who has worked on a three-volume history of CERN. Those who launched the lab, Krige reminded the audience, had radical “scientific, political and cultural aspirations” for the institution. Their dream was that CERN wouldn’t just revive European science and promote regional collaborative effects after the Second World War, but also potentially improve the global world order too.

Krige went on to quote one CERN founder, who’d said that international science facilities such as CERN would be “one of the best ways of saving Western civilization”. Recent events, however, have shown just how fragile those ambitions are. Alluding to CERN’s Future Circular Collider and other possible projects, Llewellyn Smith ended his closing remarks with a warning.

“The perennial hope that the next big high-energy project will be genuinely global,” he said, “seems to be receding over the horizon due to the polarization of world politics”.

**Robert P Crease** is a professor in the Department of Philosophy, Stony Brook University, US; e-mail robert.crease@stonybrook.edu; www.robertpcrease.com; his latest book is *The Leak* (2022 MIT Press)

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# Particle and nuclear physics

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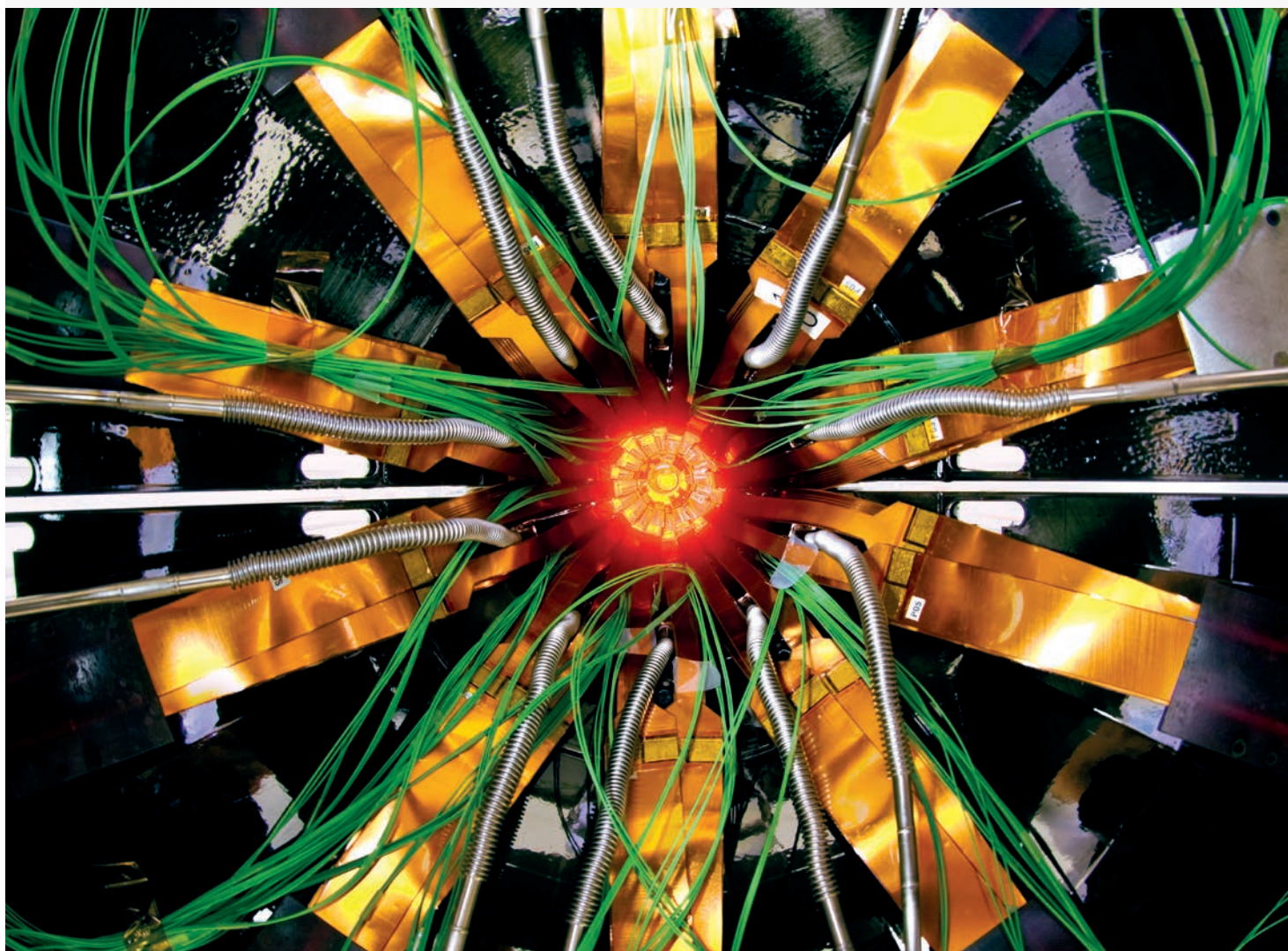
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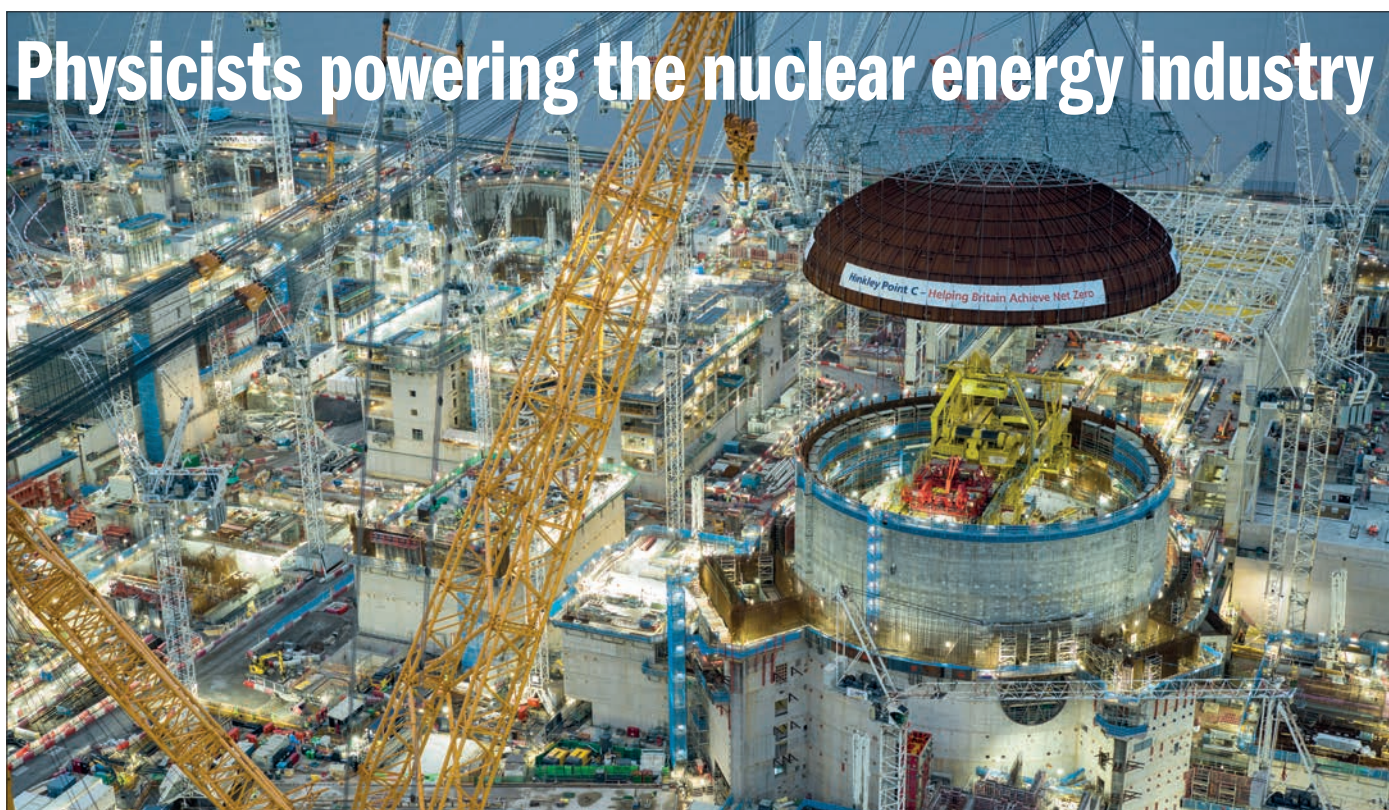
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EDF energy

**Big energy** The 245-tonne domed roof has been lowered onto the first of two new reactors being built at Hinkley Point C.

With the push to move away from fossil fuels, the UK is turning to nuclear power. New reactors are being built and new technology is being developed, but there is a skills shortage. **Sarah Tesh** talks to six physicists working across the nuclear energy industry, highlighting how a background in physics can open many doors in this expanding sector

Nuclear power in the UK is on the rise – and so too are the job opportunities for physicists. Whether it's planning and designing new reactors, operating existing plants safely and reliably, or dealing with waste management and decommissioning, physicists play a key role in the burgeoning nuclear industry.

The UK currently has nine operational reactors across five power stations, which together provided 12% of the country's electricity in 2024. But the government wants that figure to reach 25% by 2050 as part of its goal to move away from fossil fuels and reach net zero. Some also think that nuclear energy will be vital for powering data centres for AI in a clean and efficient way.

While many see fusion as the future of nuclear power, it is still in the research and development stages, so fission remains where most job opportunities lie. Although eight of the current fleet of nuclear reactors are to be retired by the end of this decade,

the first of the next generation are already in construction. At Hinkley Point C in Somerset, two new reactors are being built with costs estimated to reach £46bn; and in July 2025, Sizewell C in Suffolk got the final go-ahead. Rolls-Royce, meanwhile, has just won a government-funded bid to develop small modular reactors (SMR) in the UK. Although currently an unproven technology, the hope is that SMRs will be cheaper and quicker to build than traditional plants, with proponents saying that each reactor could produce enough affordable emission-free energy to power about 600,000 homes for at least 60 years.

The renaissance of the nuclear power industry has led to employment in the sector growing by 35% between 2021 and 2024, with the workforce reaching over 85 000. However – as highlighted in a 2025 members survey by the Nuclear Institute – there are concerns about a skills shortage. In fact, the Nuclear Skills Plan was detailed by the Nuclear Skills Delivery Group in 2024 with

the aim to address this problem.

Supported by an investment of £763m by 2030 from the UK government and industry, the plan's objectives include quadrupling the number of PhDs in nuclear fission, and doubling the number of graduates entering the workforce. It also aims to provide opportunities for people to “upskill” and join the sector mid-career. The overall hope is to fill 40 000 new jobs by the end of the decade.

Having a degree in physics can open the door to any part of the nuclear-energy industry, from designing, operating or decommissioning a reactor, to training staff, overseeing safety or working as a consultant. We talk to six nuclear experts who all studied physics at university but now work across the sector, for a range of companies – including EDF Energy and Great British Energy – Nuclear. They give a quick snapshot of their “nuclear journeys”, and offer advice to those thinking of following in their footsteps.

## Design and construction

### Michael Hodgson, lead engineer, Rolls-Royce SMR

My interest in nuclear power started when I did a project on energy at secondary school. I learnt that there were significant challenges around the world's future energy demands, resource security, and need for clean generation. Although at the time these were not topics commonly talked about, I could see they were vital to work on, and thought nuclear would play an important role.

I went on to study physics at the University of Surrey, with a year at Michigan State University in the US and another at CERN. After working for a couple of years, I returned to Surrey to do a part-time masters in radiation detection and instrumentation, followed a few years later by a PhD in radiation-hard semiconductor neutron detectors.

Up until recently, my professional work has mainly been in the supply chain for nuclear applications, working for Thermo Fisher Scientific, Centronic and Exosens. Nuclear power isn't made by one company, it's a combination of thousands of suppliers and sub-suppliers, the majority of which are small to medium-sized enterprises that need to operate across multiple industries. My job was primarily a technical design authority for manufacturers of radiation detectors and instruments, used in applications such as reactor power monitoring,

Michael Hodgson



health physics, industrial controls, and laboratory equipment, to name but a few. Now I work at Rolls-Royce SMR as a lead engineer for the control and instrumentation team. This role involves selecting and qualifying the thousands of different detectors and control instruments that will support the operation of small modular reactors.

Beyond the technical knowledge I've gained throughout my education, studying physics

**Logical, evidence-based problem solving is the cornerstone of science and a powerful tool in any work setting**

has also given me two important skills. Firstly, learning how to learn – this is critical in academia but it also helps you step into any professional role. The second skill is the logical, evidence-based problem solving that is the cornerstone of science, which is a powerful tool in any work setting.

A career in nuclear energy can take many forms. The industry is comprised of a range of sectors and thousands of organizations that altogether form a complex support structure. My advice for any role is that knowledge is important, but experience is critical. While studying, try to look for opportunities to gain professional experience – this may be industry placements, research projects, or even volunteering. And it doesn't have to be in your specific area of interest – cross-disciplinary experience breeds novel thinking. Utilizing these opportunities can guide your professional interests, set your CV apart from your peers, and bring pragmatism to your future roles.

## Skills initiatives

### Saralyn Thomas, skills lead, Great British Energy – Nuclear

During my physics degree at the University of Bristol, my interest in energy led me to write a dissertation on nuclear power. This inspired me to do a masters in nuclear science and technology at the University of Manchester under the Nuclear Technology Education Consortium. The course opened doors for me, such as a summer placement with the UK National Nuclear Laboratory, and my first role as a junior safety consultant with Orano.

I worked in nuclear safety for roughly 10 years, progressing to principal consultant with Abbott Risk Consulting, but decided that this wasn't where my strengths and passions lay. During my career, I volunteered for the Nuclear Institute (NI), and worked with the society's young members group – the Young Generation Network (YGN). I ended up becoming chair of the YGN and a trustee of the NI, which involved supporting skills initiatives including those feeding into the Nuclear Skills Plan. Having a strategic view of the sector and helping to solve its skills challenges energized me in a

Great British Energy – Nuclear



new way, so I chose to change career paths and moved to Great British Energy – Nuclear (GBE-N) as skills lead. In this role I plan for what skills the business and wider sector will need for a nuclear new build programme, as well as

**The UK's nuclear sector is seeing significant government commitment, but there is a major skills gap**

develop interventions to address skills gaps.

GBE-N's current remit is to deliver Europe's first fleet of small modular reactors, but there is relatively limited experience of building this technology. Problem-solving skills from my background in physics have been essential to understanding what assumptions we can put in place at this early stage, learning from other nuclear new builds and major infrastructure projects, to help set us up for the future.

To anyone interested in nuclear energy, my advice is to get involved now. The UK's nuclear sector is seeing significant government commitment, but there is a major skills gap. Nuclear offers a lifelong career with challenging, complex projects – ideal for physicists who enjoy solving problems and making a difference.

## Reactor operation

**Katie Barber**, nuclear reactor operator and simulator instructor, Sizewell B, EDF

I studied physics at the University of Leicester simply because it was a subject I enjoyed – at the time I had no idea what I wanted to do for a career. I first became interested in nuclear energy when I was looking for graduate jobs. The British Energy (now EDF) graduate scheme caught my eye because it offered a good balance of training and on-the-job experience. I was able to spend time in multiple different departments at different power stations before I decided which career path was right for me.

At the end of my graduate scheme, I worked in nuclear safety for several years. This involved reactor physics testing and advising on safety issues concerning the core and fuel. It was during that time I became interested in the operational response to faults. I therefore applied for the company's reactor operator training programme – a two-year course that was a mixture of classroom and simulator training. I really enjoyed being a reactor operator, particularly during outages when the plant would be shutdown, cooled, depressurised and disassembled for refuelling before reversing the process to start up again.

Katie Barber



But after almost 10 years in the control room, I wanted a new challenge.

Now I develop and deliver the training for the control-room teams. My job, which includes simulator and classroom training, covers everything from operator fundamentals (such as reactor physics and thermodynamics) and normal operations (e.g. start up and shutdown), through to accident scenarios.

My background in physics gives me a solid foundation for understanding the reactor

**A graduate training scheme is an excellent way to get an overview of the business, and gain experience across many different departments and disciplines**

physics and thermodynamics of the plant. However, there are also a lot of softer skills essential for my role. Teaching others requires the ability to present and explain technical material; to facilitate a constructive debrief after a simulator scenario; and to deliver effective coaching and feedback. The training focuses as much on human performance as it does technical knowledge, highlighting the importance of effective teamwork, error prevention and clear communications.

With Hinkley Point C construction progressing well and the recent final investment decision for Sizewell C, now is an exciting time to join the nuclear industry. A graduate training scheme is an excellent way to get an overview of the business, and gain experience across many different departments and disciplines, before making the decision about which area is right for you.

## Uranium enrichment

**Mark Savage**, nuclear licensing manager, Urenco UK

As a child, I remember going to the visitors' centre at the Sellafield nuclear site – a large nuclear facility in the north-west of England that's now the subject of a major clean-up and decommissioning operation. At the centre, there was a show about splitting the atom that really sparked my interest in physics and nuclear energy.

I went on to study physics at Durham University, and did two summer placements at Sellafield, working with radiometric instruments. I feel these placements helped me get a place on the Rolls-Royce nuclear engineering graduate scheme after university. From there I joined Urenco, an international supplier of uranium enrichment services and fuel cycle products for the civil nuclear industry.

While at Urenco, I have undertaken a range of interesting roles in nuclear safety and radiation physics, including criticality safety assessment and safety case management. Highlights have included being the licensing manager for a project looking to deploy a high-temperature gas-cooled reactor design,

Mark Savage



**I would always recommend anyone interested in working in nuclear energy to look for work experience**

and presenting a paper at a nuclear industry conference in Japan. These roles have allowed me to directly apply my physics background – such as using Monte Carlo radiation transport codes to model nuclear systems and radiation sources – as well as develop broader knowledge and skills in safety, engineering and project management.

My current role is nuclear licensing manager at the Capenhurst site in Cheshire, where we operate a number of nuclear facilities including three uranium enrichment plants, a uranium chemical deconversion facility, and waste management facilities. I lead a team who ensure the site complies with regulations, and achieves the required approvals for our programme of activities. Key skills for this role include building relationships with internal and external stakeholders; being able to understand and explain complex technical issues to a range of audiences; and planning programmes of work.

Some form of relevant experience is always advantageous, so I would always recommend anyone interested in working in nuclear energy to look for work experience visits, summer placements or degree schemes that include working with industry.

## Nuclear safety

**Jacob Plummer**, principal nuclear safety inspector, Office for Nuclear Regulation

I'd been generally interested in nuclear science throughout my undergraduate physics degree at the University of Manchester, but this really accelerated after studying modules in applied nuclear and reactor physics. The topic was engaging, and the nuclear industry offered a way to explore real-world implementation of physics concepts. This led me to do a masters in nuclear science and technology, also at Manchester (under the Nuclear Technology Education Consortium), to develop the skills the UK nuclear sector required.

My first job was as a graduate nuclear safety engineer at Atkins (now AtkinsRealis), an engineering consultancy. It opened my eyes to the breadth of physics-related opportunities in the industry. I worked on new and operational power station projects for Hitachi-GE and EDF, as well as a variety of defence new-build projects. I primarily worked in hazard analysis, using modelling and simulation tools to generate evidence on topics like fire, blast and flooding to support safety case claims and inform reactor designs. I was also able to gain

Jacob Plummer



experience in project management, business development, and other energy projects, such as offshore wind farms. The analytical and problem solving skills I had developed during my physics studies really helped me to adapt to all of these roles.

Currently I work as a principal nuclear safety inspector at the Office for Nuclear Regulation. My role is quite varied. Day to day

**Physics skills and experience are valued across the nuclear industry, from hazards and fault assessment to security, safeguards, project management and more**

I might be assessing safety case submissions from a prospective reactor vendor; planning and delivering inspections at fuel and waste sites; or managing fire research projects as part of an international programme. A physics background helps me to understand complex safety arguments and how they link to technical evidence; and to make reasoned and logical regulatory judgements as a result.

It's a great time to join the nuclear industry with a huge amount of activity and investment across the nuclear lifecycle. I'd advise early-career professionals to cast the net wide when looking for roles. There are some obvious physics-related areas such as health physics, fuel and core design, and criticality safety, but physics skills and experience are valued across the nuclear industry, from hazards and fault assessment to security, safeguards, project management and more. Don't be limited by the physicist label.

## Waste and decommissioning

**Becky Houghton**, principal consultant, Galson Sciences Ltd

My interest in a career in nuclear energy sparked mid-way through my degree in physics and mathematics at the University of Sheffield, when I was researching "safer nuclear power" for an essay. Several rabbit holes later, I had discovered a myriad of opportunities in the sector that would allow me to use the skills and knowledge I'd gained through my degree in an industrial setting.

My first job in the field was as a technical support advisor on a graduate training scheme, where I supported plant operations on a nuclear licensed site. Next, I did a stint working in strategy development and delivery across the back end of the fuel cycle, before moving into consultancy. I now work as a principal consultant for Galson Sciences Ltd, part of the Egis group. Egis is an international multi-disciplinary consulting and engineering firm, within which Galson Sciences provides specialist nuclear decommissioning and waste management consultancy services to nuclear sector clients worldwide.

Ultimately, my role boils down to providing strategic and technical support to help clients

Egis



**Whichever part of the nuclear fuel cycle you end up in, the work you do makes a difference**

make decisions. My focus these days tends to be around radioactive waste management, which can mean anything from analysing radioactive waste inventories to assessing the environmental safety of disposal facilities.

In terms of technical skills needed for the role, data analysis and the ability to provide high-quality reports on time and within budget are at the top of the list. Physics-wise, an understanding of radioactive decay, criticality mechanisms and the physico-chemical properties of different isotopes are fairly fundamental requirements. Meanwhile, as a consultant, some of the most important soft skills are being able to lead, teach and mentor less experienced colleagues; develop and maintain strong client relationships; and look after the well-being and deployment of my staff.

My advice to anyone looking to go into the nuclear energy is to go for it. There are lots of really interesting things happening right now across the industry, all the way from building new reactors and operating the current fleet, to decommissioning, site remediation and waste management activities. Whichever part of the nuclear fuel cycle you end up in, the work you do makes a difference, whether that's by cleaning up the legacy of years gone by or by helping to meet the UK's energy demands. Don't be afraid to say "yes" to opportunities even if they're outside your comfort zone, keep learning, and keep being curious about the world around you.



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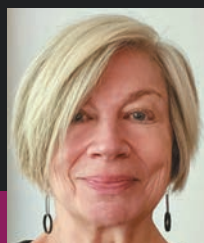
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## Feature

Smithsonian Institution Archives



# Chien-Shiung Wu: how she missed the 1957 Nobel prize

Many have wondered why the Chinese-American physicist Chien-Shiung Wu never won a share of the 1957 Nobel Prize for Physics for her experimental verification of parity violation. **Mats Larsson** and **Ramon Wyss** reveal the true story after becoming the first people to open that year's Nobel archives

**Mats Larsson** is in the Department of Physics at Stockholm University and **Ramon Wyss** is at KTH Royal Institute of Technology in Stockholm, Sweden

The facts seem simple enough. In 1957 Chen Ning Yang and Tsung-Dao Lee won the Nobel Prize for Physics “for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles”. The idea that parity is violated shocked physicists, who had previously assumed that every process in nature remains the same if you reverse all three spatial co-ordinates.

Thanks to the work of Lee and Yang, who were Chinese-American theoretical physicists, it now appeared that this fundamental physics concept wasn't true (see box “The Wu experiment”). As Yang once told *Physics World* columnist and historian of science Robert Crease, the discovery of parity violation was like having the lights switched off and being so confused that you weren't sure you'd be in the same room when they came back on.

But one controversy has always surrounded the prize.

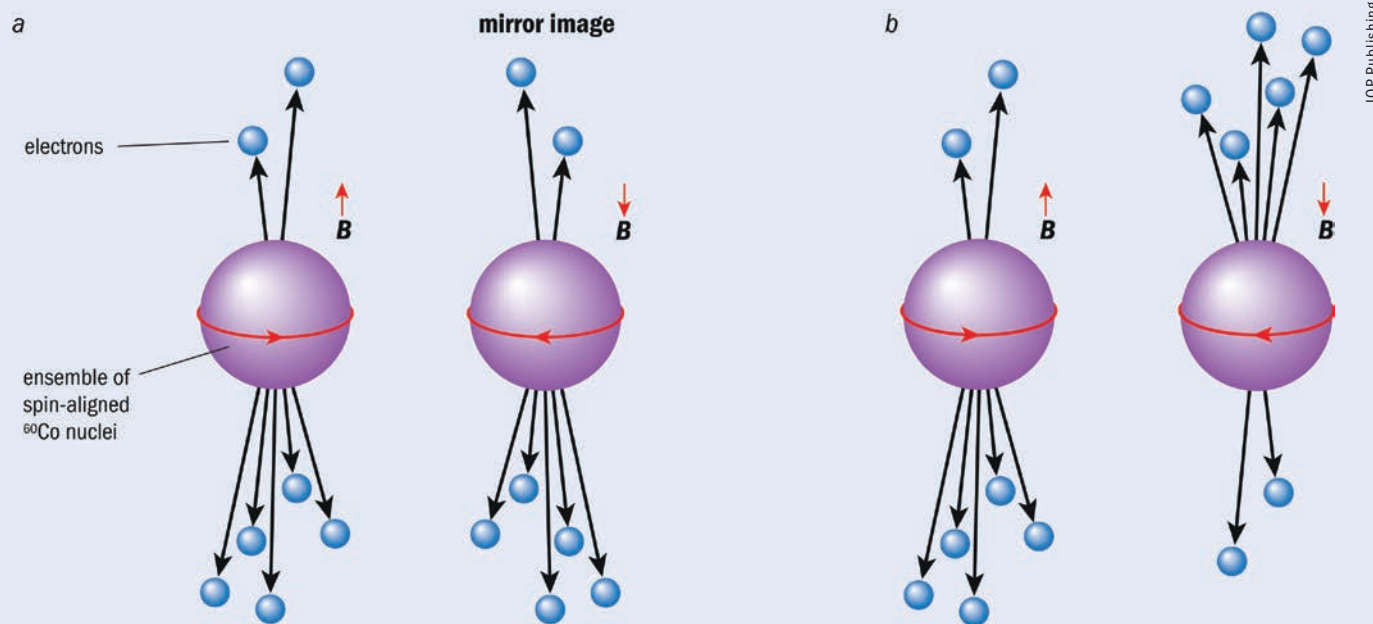
Lee and Yang published their findings in a paper in October 1956 (*Phys. Rev.* **1** 254), meaning that their Nobel prize was one of the rare occasions that satisfied Alfred Nobel's will, which says the award should go to

work done “during the preceding year”. However, the first verification of parity violation was published in February 1957 (*Phys. Rev.* **105** 1413) by a team of experimental physicists led by Chien-Shiung Wu at Columbia University, where Lee was also based. (Yang was at the Institute for Advanced Study in Princeton at the time.)

Surely Wu, an eminent experimentalist (see the box “Chien-Shiung Wu: a brief history” on p36), deserved a share of the prize for contributing to such a fundamental discovery? In her paper, entitled “Experimental Test of Parity Conservation in Beta Decay”, Wu says she had “inspiring discussions” with Lee and Yang. Was gender bias at play, did her paper miss the deadline, or was she simply never nominated?

Back then, the Nobel statutes stipulated that all details about who had been nominated for a Nobel prize – and why the winners were chosen by the Nobel committee – were to be kept secret forever. Later, in 1974, the rules were changed, allowing the archives to be opened 50 years after an award had been made. So why did the mystery not become clear in 2007, half a

## The Wu experiment



Parity is a property of elementary particles that says how they behave when reflected in a mirror. If the parity of a particle does not change during reflection, parity is said to be conserved. In 1956 Tsung-Dao Lee and Chen Ning Yang realized that while parity conservation had been confirmed in electromagnetic and strong interactions, there was no compelling evidence that it should also hold in weak interactions, such as radioactive decay. In fact, Lee and Yang thought parity violation could explain the peculiar decay

patterns of K mesons, which are governed by the weak interaction.

In 1957 Chien-Shiung Wu suggested an experiment to check this based on unstable cobalt-60 nuclei radioactively decaying into nickel-60 while emitting beta rays (electrons). Working at very low temperatures to ensure almost no random thermal motion – and thereby enabling a strong magnetic field to align the cobalt nuclei with their spins parallel – Wu found that far more electrons were emitted in a downward direction than upward.

In the figure, (a) shows how a mirror image of this experiment should also produce more electrons going down than up. But when the experiment was repeated, with the direction of the magnetic field reversed to change the direction of the spin as it would be in the mirror image, Wu and colleagues found that more electrons were produced going upwards (b). The fact that the real-life experiment with reversed spin direction behaved differently from the mirror image proved that parity is violated in the weak interaction of beta decay.

century after the 1957 prize?

The reason is that there is a secondary criterion for prizes awarded by the Royal Swedish Academy of Sciences – in physics and chemistry – which is that the archive must stay shut for as long as a laureate is still alive. Lee and Yang were in their early 30s when they were awarded the prize and both went on to live very long lives. Lee died on 24 August 2024 aged 97 and it was not until the death of Yang on 18 October 2025 at 103 that the chance to solve the mystery finally arose.

## Entering the archives

As two physicists based in Stockholm with a keen interest in the history of science, we had already examined the case of Lise Meitner, another female physicist who never won a Nobel prize – in her case for fission. We'd published our findings about Meitner in the December 2023 issue of *Fysikaktuellt* – the journal of the Swedish Physical Society. So after Yang died, we asked the Center for History of Science at the Royal Swedish Academy of Sciences if we could look at the 1957 archives.

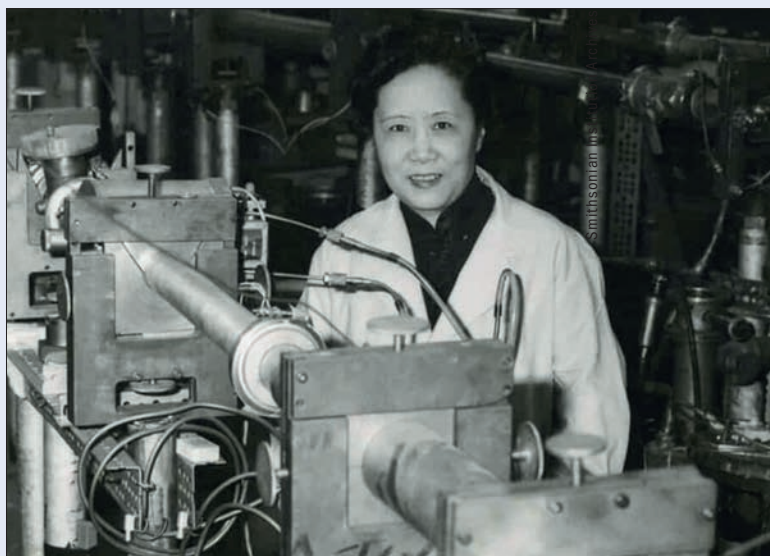
A previous article in *Physics World* from 2012 by Magdolna Hargittai, who had spoken to Anders Bárány,

former secretary of the Nobel Committee for Physics, seemed to suggest that Wu wasn't awarded the 1957 prize because her *Physical Review* paper had been published in February of that year. This was after the January cut-off and therefore too late to be considered on that occasion (although the trio could have been awarded a joint prize in a subsequent year).

After receiving permission to access the archives, we went to the centre on Thursday 13 November 2025, where – with great excitement – we finally got our hands on the thick, black, hard-bound book containing information about the 1957 Nobel prizes in physics and chemistry. About 500 pages long, the book revealed that there were a total of 58 nominations for the 1957 Nobel Prize for Physics – but none at all for Wu that year. As we shall go on to explain, she did, however, receive a total of 23 nominations over the next 16 years.

Lee and Yang, we discovered, received just a single nomination for the 1957 prize, submitted by John Simpson, an experimental physicist at the University of Chicago in the US. His nomination reached the Nobel Committee on 29 January 1957, just before the deadline of 31 January. Simpson clearly had a lot of clout with

## Chien-Shiung Wu: a brief history



Born on 31 May 1912 in Jiangsu province in eastern China, Chien-Shiung Wu graduated with a degree in physics from National Central University in Nanjing. After a few years of research in China, she moved to the US, gaining a PhD at the University of California at Berkeley in 1940. Three years later Wu took up a teaching job at Princeton University in New Jersey – a remarkable feat given that women were not then even allowed to study at Princeton.

During the Second World War, Wu joined the Manhattan atomic-bomb project, working on radiation detectors at Columbia University in New York. After the conflict was over, she started studying beta decay – one of the weak interactions associated with radioactive decay. Wu famously led a crucial experiment studying the beta decay of cobalt-60 nuclei, which confirmed a prediction made in October 1956 by her Columbia colleague Tsung-Dao Lee and Chen Ning Yang in Princeton that parity can be violated in the weak interaction.

Lee and Yang went on to win the 1957 Nobel Prize for Physics but the Nobel Committee was not aware that Lee had in fact consulted Wu in spring 1956 – several months before their paper came out – about potential experiments to prove their prediction. As she was to recall in 1973, studying the decay of cobalt-60 was “a golden opportunity” to test their ideas that she “could not let pass”.

The first woman in the Columbia physics department to get a tenured position and a professorship, Wu remained at Columbia for the rest of her career. Taking an active interest in physics well into retirement, she died on 16 February 1997 at the age of 84. Only now, with the publication of this *Physics World* article, has it become clear that despite receiving 23 nominations from 18 different physicists in 16 years between 1958 and 1974, she never won a Nobel prize.

the committee, which commissioned two reports from its members – both Swedish physicists – based on his recommendation. One was by Oskar Klein on the theoretical aspects of the prize and the other by Erik Hulthén on the experimental side of things.

### Report revelations

Klein devotes about half of his four-page report to the Hungarian-born theorist Eugene Wigner, who – we discovered – received seven separate nominations for the 1957 prize. In his opening remarks, Klein notes that Wigner’s work on symmetry principles in physics, first published in 1927, had gained renewed relevance in light of recent experiments by Wu, Leon Lederman and others. According to Klein, these experiments cast a new light on the fundamental symmetry principles of physics.

Klein then discusses three important papers by Wigner and concludes that he, more than any other physicist, established the conceptual background on symmetry principles that enabled Lee and Yang to clarify the possibilities of experimentally testing parity non-conservation. Klein also analyses Lee and Yang’s award-winning *Physical Review* paper in some detail and briefly mentions subsequent articles of theirs as well as papers by two future Nobel laureates – Lev Landau and Abdus Salam.

Klein does not end his report with an explicit recommendation, but identifies Lee, Yang and Wigner as having made the most important contributions. It is noteworthy that every physicist mentioned in Klein’s report – apart from Wu – eventually went on to receive a Nobel Prize for Physics. Wigner did not have to wait long, winning the 1963 prize together with Maria Goeppert Mayer and Hans Jensen, who had also been nominated in 1957.

As for Hulthén’s experimental report, it acknowledges that Wu’s experiment started after early discussions with Lee and Yang. In fact, Lee had consulted Wu at Columbia on the subject of parity conservation in beta-decay before Lee and Yang’s famous paper was published. According to Wu, she mentioned to Lee that the best way would be to use a polarized cobalt-60 source for testing the assumption of parity violation in beta-decay.

Many physicists were aware of Lee and Yang’s paper, which was certainly seen as highly speculative, whereas Wu realized the opportunity to test the far-reaching consequences of parity violation. Since she was not a specialist of low-temperature nuclear alignment, she contacted Ernest Ambler at the National Bureau of Standards in Washington DC, who was a co-author on her *Physics Review* paper of 15 February 1957.

Hulthén describes in detail the severe technical challenges that Wu’s team had to overcome to carry out the experiment. These included achieving an exceptionally low temperature of 0.001 K, placing the detector inside the cryostat, and mitigating perturbations from the crystalline field that weakened the magnetic field’s effectiveness.

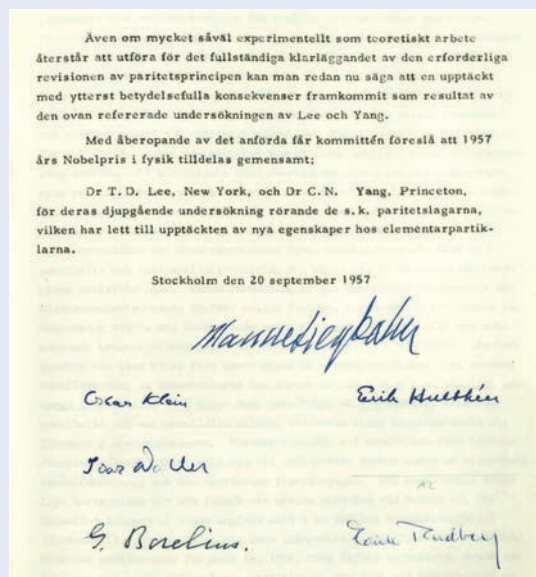
Despite these difficulties, the experimentalists managed to obtain a first indication of parity violations, which they presented on 4 January 1957 at a regular lunch that took place at Columbia every Friday. The news of these preliminary results spread like wildfire throughout the physics community, prompting other groups to immediately follow suit.

Hulthén mentions, for example, a measurement of the magnetic moment of the mu ( $\mu$ ) meson (now known as the muon) that Richard Garvin, Leon Lederman and Marcel Weinrich performed at Columbia’s cyclotron almost as soon as Lederman had obtained information of Wu’s work. He also cites work at the University of Leiden in the Netherlands led by C J Gorter that apparently had started to look into parity violation independently of Wu’s experiment (*Physica* 23 259).

### Wu’s nominations

It is clear from Hulthén’s report that the Nobel Physics Committee was well informed about the experimental work carried out in the wake of Lee and Yang’s paper of

### The Nobel Committee report of 1957



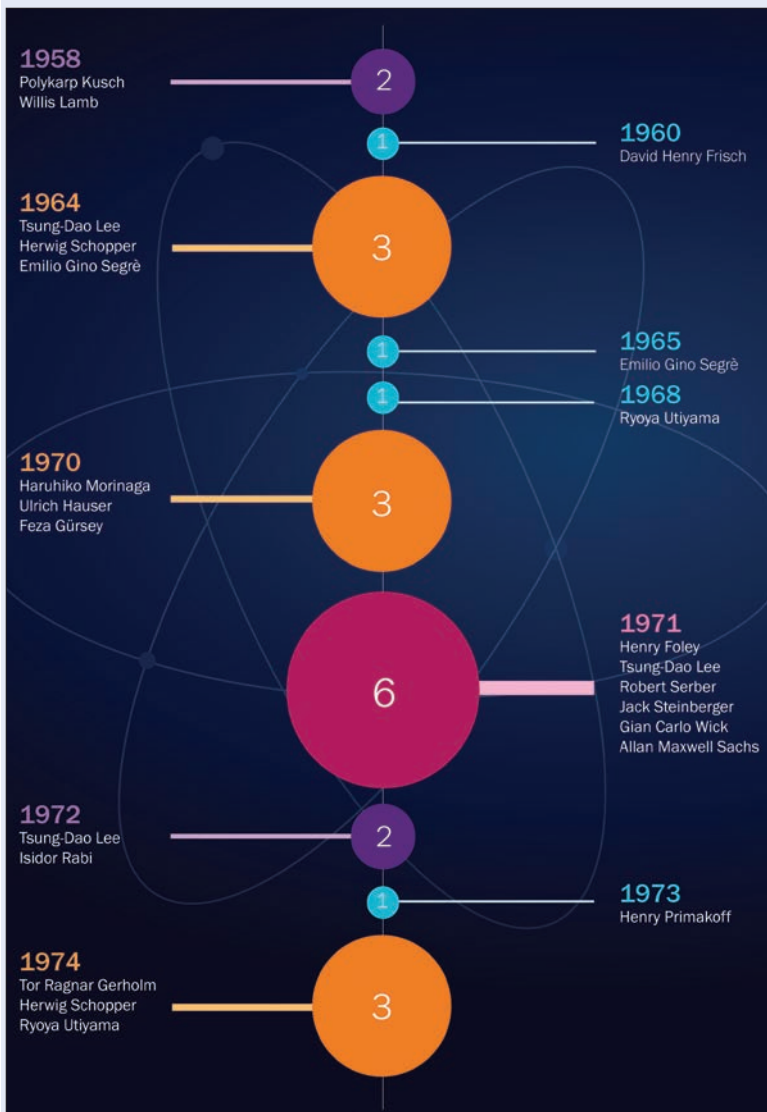
The Nobel Archive, The Royal Swedish Academy of Sciences, Stockholm

This image is the final page of a report written on 20 September 1957 by the Nobel Committee for Physics about who should win the 1957 Nobel Prize for Physics. Dated 20 September 1957 and published here for the first time since it was written, the English translation is as follows. “Although much experimental and theoretical work remains to be done to fully clarify the necessary revision of the parity principle, it can already be said that a discovery with extremely significant consequences has emerged as a result of the above-mentioned study by Lee and Yang. In light of the above, the committee proposes that the 1957 Nobel Prize in Physics be awarded jointly to: Dr T D Lee, New York, and Dr C N Yang, Princeton, for their profound investigation of the so-called parity laws, which has led to the discovery of new properties of elementary particles.” The report was signed by Manne Siegbahn (chair), Gudmund Borelius, Erik Hulthén, Oskar Klein, Erik Rudberg and Ivar Waller.

October 1956, in particular the groundbreaking results of Wu. However, it is not clear from a subsequent report dated 20 September 1957 (see box above: “The Nobel Committee report of 1957) from the Nobel Committee why Wigner was not awarded a share of the 1957 prize, despite his seven nominations. Nor is there any suggestion of postponing the prize a year in order to include Wu. The report was discussed on 23 October 1957 by members of the “Physics Class” – a group of physicists in the academy who always consider the committee’s recommendations – who unanimously endorsed it.

Most noteworthy with regard to this meeting of the Physics Class was that Meitner – who had also been overlooked for the Nobel prize – took part in the discussions. Meitner, who was Austrian by birth, had been elected a foreign member of the Royal Swedish Academy of Sciences in 1945, becoming a “Swedish member” after taking Swedish citizenship in 1951. In the wake of these discussions, the academy decided on 31 October 1957 to award the 1957 Nobel Prize for Physics to Lee and Yang. We do not know, though, if Meitner argued for Wu to be awarded a share of that year’s prize.

### Nominations for Wu from 1958 to 1974



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Our examination of the newly released Nobel archive from 1957 indicates that although Chien-Shiung Wu was not nominated for that year’s prize, which was won by Chen Ning Yang and Tsung-Dao Lee, she did receive a total of 23 nominations over the next 16 years (1974 being the last open archive at the time of writing). Those 23 nominations were made by 18 different physicists, with Lee nominating Wu three times and Herwig Schopper, Emilio Segrè and Ryoya Utiyama each doing so twice. The peak year for nominations for her was 1971 when she received six nominations. The archives also show that in October 1957 Werner Heisenberg submitted a nomination for Lee (but not Yang); it was registered as a nomination for 1958. The nomination is very short and it is not clear why Heisenberg did not nominate Yang.

Although Wu did not receive any nominations in 1957, she was nominated the following year by the 1955 Nobel laureates in physics, Willis Lamb and Polykarp Kusch. In fact, after Lee and Yang won the prize, nominations to give a Nobel prize to Wu reached the committee on 10 separate years out of the next 16 (see box “Nominations for Wu from 1958 to 1974”). She was nominated by a total of 18 leading physicists, including various Nobel-prize winners and Lee himself. In fact, Lee nominated Wu for a Nobel prize on three separate occasions – in 1964, 1971 and 1972.

Anne Miche de Mailleay



**History in the making** Above: Mats Larsson (centre) and Ramon Wyss (left) at the Center for History of Science at the Royal Swedish Academy of Sciences in Stockholm, Sweden, on 13 November 2025, where they become the first people to view the archive containing information about the nominations for the 1957 Nobel Prize for Physics. They are shown here in the company of centre director Karl Grandin (right). Right image: Larsson and Wyss with their hands on the archives, on which this *Physics World* article is based.



Anne Miche de Mailleay

However, it appears she was never nominated by Yang (at the time of writing, we only have archive information up to 1974). One reason for Lee's support and Yang's silence could be attributed to the early discussions that Lee had with Wu, influencing the famous Lee and Yang paper, which Yang may not have been aware of. It is also not clear why Lee and Yang never acknowledged their discussion with Wu about the cobalt-60 experiment that was proposed in their paper; further research may shed more light on this topic.

Following Wu's nomination in 1958, the Nobel Committee simply re-examined the investigations already carried out by Klein and Hulthén. The same procedure was repeated in subsequent years, but no new investigations into Wu's work were carried out until 1971 when she received six nominations – the highest number she got in any one year.

That year the committee decided to ask Bengt Nagel, a theorist at KTH Royal Institute of Technology, to investigate the theoretical importance of Wu's experiments. The nominations she received for the Nobel prize concerned three experiments. In addition to her 1957 paper on parity violation there was a 1949 article she'd written with her Columbia colleague R D Albert verifying Enrico Fermi's theory of beta decay (*Phys. Rev.* **75** 315) and another she wrote in 1963 with Y K Lee and L W Mo on the conserved vector current, which is a fundamental hypothesis of the Standard Model of particle physics (*Phys. Rev. Lett.* **10** 253).

After pointing out that four of the 1971 nominations came from Wu's colleagues at Columbia, which to us may have hinted at a kind of lobbying campaign for her, Nagel stated that the three experiments had "without doubt been of great importance for our understanding of the weak interaction". However, he added, "the experiments, at least the last two, have been conducted to certain aspects as commissioned or direct suggestions of theoreticians".

In Nagel's view, Wu's work therefore differed signifi-

cantly from, for example, James Cronin and Val Fritsch's famous discovery in 1964 of charge-parity (CP) violation in the decay of  $K^0$  mesons. They had made their discovery under their own steam, whereas (Nagel suggested) Wu's work had been carried out only after being suggested by theorists. "I feel somewhat hesitant whether their theoretical importance is a sufficient motivation to render Wu the Nobel prize," Nagel concluded.

### Missed opportunity

The Nobel archives are currently not open beyond 1974 so we don't know if Wu received any further nominations over the next 23 years until her death in 1997. Of course, had Wu not carried out her experimental test of parity violation, it is perfectly possible that another physicist or group of physicists would have something similar in due course.

Nevertheless, to us it was a missed opportunity not to include Wu as the third prize winner alongside Lee and Yang. Sure, she could not have won the prize in 1957 as she was not nominated for it and her key publication did not appear before the January deadline. But it would simply have been a case of waiting a year and giving Wu and her theoretical colleagues the prize jointly in 1958.

Another possible course of action would have been to single out the theoretical aspects of symmetry violation and award the prize to Lee, Wigner and Yang, as Klein had suggested in his report. Unfortunately, full details of the physics committee's discussions are not contained in the archives, which means we don't know if this was a genuine possibility being considered at the time.

But what is clear is that the Nobel committee knew full well the huge importance of Wu's experimental confirmation of parity violation following the bold theoretical insights of Lee and Yang. Together, their work opened a new chapter in the world of physics. Without Wu's interest in parity violation and her ingenious experimental knowledge, Lee and Yang would never have won the Nobel prize. ■

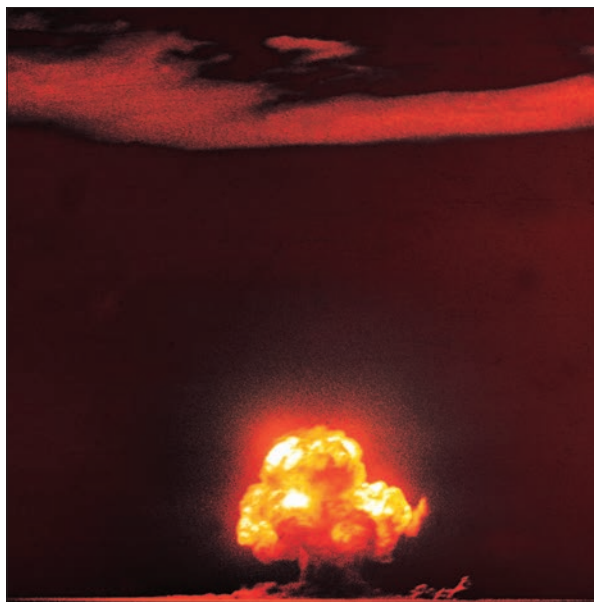
# Builders of the bomb

**Andrew Robinson** reviews *Destroyer of Worlds: the Deep History of the Nuclear Age 1895–1965* by Frank Close

**Destroyer of Worlds: the Deep History of the Nuclear Age 1895–1965**

Frank Close

2025 Allen Lane  
£25.00hb 321pp



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**Dark destroyers** This photo of the Trinity test was taken by Jack W Aeby, a Los Alamos employee, on 16 July 1945. Two months later many Manhattan Project participants returned to the Trinity test site for news crews, including Robert J Oppenheimer and General Leslie Groves, who are shown here examining the remains of a base of the steel test tower.

The title of particle physicist Frank Close's engaging new book, *Destroyer of Worlds*, refers to Robert Oppenheimer's famous comment after he witnessed the first detonation of an atomic bomb, known as the Trinity test, in July 1945. Quoting the Hindu scripture *Bhagavad Gita*, he said "Now I am become death, the destroyer of worlds." But although Close devotes much space to the Manhattan Project, which Oppenheimer directed between 1942 and 1945, his book has a much wider remit.

Aimed at non-physicist readers with a strong interest in science, though undoubtedly appealing to physicists too, the book seeks to explain the highly complex physics and chemistry that led to the atomic bomb – a term first coined by H G Wells in his 1914 science-fiction novel *The World Set Free*. It also describes the contributions of numerous gifted scientists to the development of those weapons.

Close draws mainly on numerous published sources from this deeply analysed period, including Richard Rhodes's seminal 1988 study *The*

*Making of the Atomic Bomb*. He starts with Wilhelm Röntgen's discovery of X-rays in 1895, before turning to the discovery of radioactivity by Henri Becquerel in 1896 – described by Close as "the first pointer to nuclear energy [that was] so insignificant that it was almost missed". Next, he highlights the work on radium by Marie and Pierre Curie in 1898.

After discussing the emergence of nuclear physics, Close goes on to talk about the Allies' development of the nuclear bomb. A key figure in this history was Enrico Fermi, who abandoned Fascist Italy in 1938 and emigrated to the US, where he worked on the Manhattan Project and built the first nuclear reactor, in Chicago, in 1942.

Within seconds of seeing Trinity's blast in the desert in 1945, Fermi showed his legendary ability to estimate a physical phenomenon's magnitude by shredding a sheet of paper into small pieces and throwing them into the air. The bomb's shock wave blew this "confetti" (Close's word) a few metres away. After measuring the

exact distance, Fermi immediately estimated that the blast was equivalent to about 10 000 tonnes of TNT. This figure was not far off the 18 000 tonnes determined a week later following a detailed analysis by the project team.

The day after the Trinity test, a group of 70 scientists, led by Leo Szilard, sent a petition to US President Harry Truman, requesting him not to use the bomb against Japan. Albert Einstein agreed with the petition but did not sign it, having been excluded from the Manhattan Project on security grounds (though in 1939 he famously backed the bomb's development, fearing that Nazi Germany might build its own device). Despite the protests, atomic bombs were dropped on Hiroshima and Nagasaki less than a month later – a decision that Close neither defends nor condemns.

Other key figures in the Manhattan Project were emigrants to the UK, who had fled Germany in the mid-1930s because of Nazi persecution of Jews, and later joined the secret British Tube Alloys bomb project. The best

## Review

# The Manhattan Project ... set an example for the future of science as a highly collaborative, increasingly international albeit sometimes dangerous adventure

known are probably the nuclear physicists Otto Frisch and Rudolf Peierls, who initially worked together at the University of Birmingham for Tube Alloys before joining the Manhattan Project. They both receive their due from Close.

Oddly, however, he neglects to mention their fellow émigré Franz (Francis) Simon by name, despite acknowledging the importance of his work in demonstrating a technique to separate fissionable uranium-235 from

the more stable uranium-238. In 1940 Simon, then working at the Clarendon Laboratory in wartime Oxford, showed that separation could be achieved by gaseous diffusion of uranium hexafluoride through a porous barrier, which he initially demonstrated by hammering his wife's kitchen sieve flat to make the barrier.

As Close ably documents and explains, numerous individuals and groups eventually ensured the success of the Manhattan Project. In addition to ending the Second World War and preserving freedom against Fascism, there is an argument that it also set an example for the future of science as a highly collaborative, increasingly international albeit sometimes dangerous adventure.

### A fusion of minds

Close finishes the book with a shorter discussion of the two decades of Cold War rivalry between scientists from the US and the Soviet Union to develop and test the hydrogen bomb. It features physicists such as Edward Teller and

Andrei Sakharov, who led the efforts to build the American "Super Bomb" and the Soviet "Tsar Bomba", respectively.

The book ends in around 1965, after the 1963 partial test-ban treaty signed by the US, Soviet Union and the UK, preventing further tests of the hydrogen bomb for fear of their likely devastating effects on Earth's atmosphere. As Close writes, the Tsar Bomba was more powerful than any recorded explosion other than the meteorite impact 65 million years ago that wreaked global change and killed the dinosaurs, which had ruled for 150 million years.

"Within just one per cent of that time, humans have produced nuclear arsenals capable of replicating such levels of destruction," Close warns. "The explosion of a gigaton weapon would signal the end of history. Its mushroom cloud ascending towards outer space would be humanity's final vision."

**Andrew Robinson** is the author of *Einstein on the Run* and *Einstein in Oxford*



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