WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the November/December 2020 issue of *CERN Courier*.

Superconducting radio-frequency (SRF) cavities drive accelerators around the world, transferring energy efficiently from high-power radio waves to beams of charged particles. Behind the march to higher SRF-cavity performance is the TESLA Technology Collaboration (p35), which was established in 1990 to advance technology for a linear electron–positron collider. Though the linear collider envisaged by TESLA is yet to be built (p9), its cavity technology is already established at the European X-Ray Free-Electron Laser at DESY (a cavity string for which graces the cover of this edition) and is being applied at similar broad-user-base facilities in the US and China.

Accelerator technology developed for fundamental physics also continues to impact the medical arena. Normal-conducting RF technology developed for the proposed Compact Linear Collider at CERN is now being applied to a first-of-a-kind “FLASH-therapy” facility that uses electrons to destroy deep-seated tumours (p7), while proton beams are being used for novel non-invasive treatments of cardiac arrhythmias (p49). Meanwhile, GANIL’s innovative new SPIRAL2 linac will advance a wide range of applications in nuclear physics (p39).

Detector technology also continues to offer unpredictable benefits – a powerful example being the potential for detectors developed to search for sterile neutrinos to replace increasingly outmoded traditional approaches to nuclear nonproliferation (p30).

Elsewhere in the issue: hints of low-frequency gravitational waves (p12), feebly interacting particles to the fore (p21), PCs and the future of computing (p43), the latest from the LHC experiments (p17), and more – not least the *Courier*’s inaugural end-of-year cryptic crossword (p58).

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CERNCOURIER
November/December 2020 cerncourier.com Reporting on international high-energy physics

ADVANCING CAVITY TECHNOLOGY

Neutrinos for peace
Feebly interacting particles
ALICE’s dark side

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NSF/Green Bank Observatory

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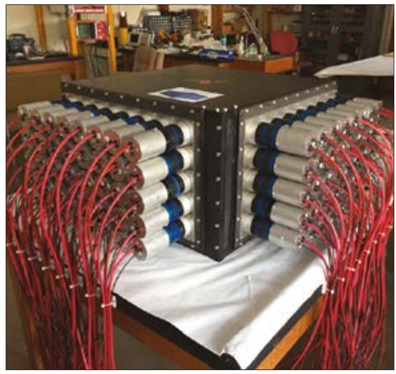
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FROM THE EDITOR

Accelerator applications shine

Matthew Chalmers
Editor

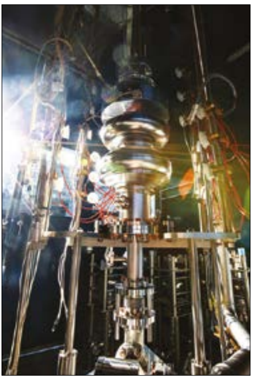
Tens of thousands of particle accelerators are in operation worldwide – almost all of them in industry and clinical settings, with only a few percent used in research. In recent decades, particle physicists have perfected the art of superconducting radio-frequency (SRF) acceleration (the cover theme of this issue), whereby metallic cavities provide a pristine, resonant space in which to transfer energy from high-power radio waves to a beam of charged particles. While both superconducting and normal-conducting cavities still vie for inclusion in the biggest projects, as evidenced by the designs of the proposed electron–positron Higgs factories ILC and CLIC, SRF cavities store energy with very low losses and offer a high conversion efficiency from "plug- to beam-" power.

SRF accelerator technology took hold in the mid-1980s with bulk-niobium cavities at Cornell's CESR facility. JLab's CEBAF followed suit, while CERN turned to niobium-coated copper cavities to extend the energy reach of LEP from the Z to the WW threshold. These days, niobium-copper cavities ramp the LHC's protons to 6.5 TeV and keep them tightly bunched, while SRF "crab cavities" built entirely from ultra-pure niobium are undergoing tests for the high-luminosity LHC, where they will tilt proton bunches to ensure maximum collision intensity. SRF underpins the ALPI and SPIRAL2 (p39) linacs at INFN and GANIL, and drives advanced X-ray and neutron sources.

Though to the untrained eye the RF cavity might look like a simple metal shell, subtle material effects, fabrication techniques, surface smoothness and, above all, surface cleanliness have a dramatic effect on its performance. In recent years, bulk-niobium SRF technology has seen big increases in attainable accelerating gradients and quality factors due to nitrogen-doping or nitrogen-infusion, while CERN has continued its R&D on coated cavities. Seamless niobium-copper cavities built using a sophisticated electrodeposition technique are the basis of the recent HIE-ISOLDE energy upgrade, extending ISOLDE's reach to heavier isotopes. The CERN team is also investigating SRF thin-film technology relevant for a possible future circular electron–positron collider.

Unforeseen benefits

Behind this march to higher SRF performance is the TESLA Technology Collaboration (p35), which was established in 1990 to advance technology for a linear electron–positron collider. Its remit later expanded to cover the full diversity of applications, enabling the sharing of ideas, planning and testing across associated projects, and all the major particle-physics labs are members. Though the linear collider envisaged by TESLA is yet to be built (p9), its cavity technology is already established at the European XFEL in Germany and for other X-ray free-electron lasers in the US and China. It will be deployed in neutron sources such as the ESS and in Fermilab's PIP-II linac, serving short- and long-baseline neutrino experiments.



D Noelle/DESY

High impact *SRF cavities drive accelerators for applied research.*

Advanced accelerator technology also continues to impact the medical arena. Normal-conducting X-band RF technology developed for CLIC is now being applied to a first-of-a-kind "FLASH-therapy" facility that uses electrons to destroy tumours (p7), while proton beams are being used for novel non-invasive treatments of cardiac arrhythmias (p49). A further powerful example of the unpredicted benefits of fundamental research is the role of state-of-the-art neutrino detectors in nuclear safeguarding (p30).

Elsewhere in the issue: hints of low-frequency gravitational waves (p12), feebly interacting particles to the fore (p21), PCs and the future of computing (p43), the latest from the LHC experiments (p17), and more – not least the *Courier*'s inaugural end-of-year cryptic crossword (p58).

Advanced accelerator technology continues to impact the medical arena

Reporting on international high-energy physics

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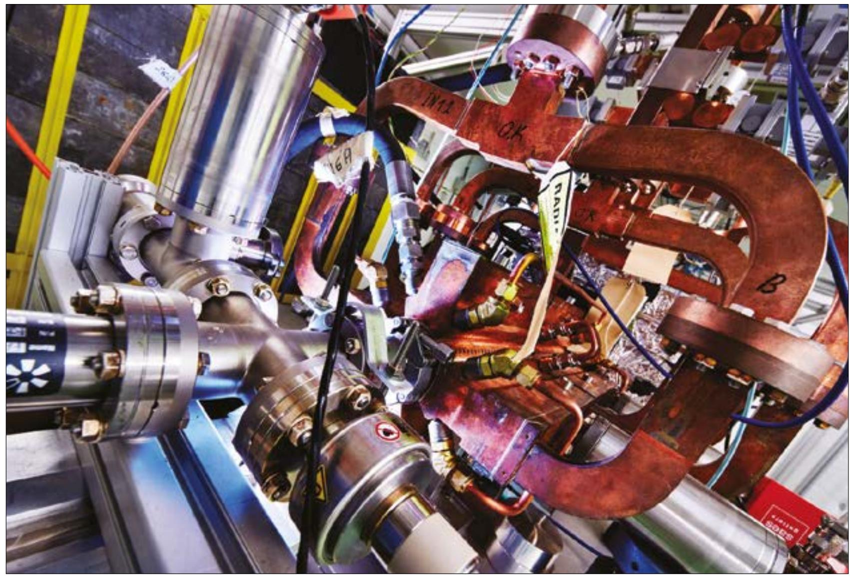
APPLICATIONS

CLIC lights the way for FLASH therapy

Technology developed for the proposed Compact Linear Collider (CLIC) at CERN is poised to make a novel cancer radio-therapy facility a reality. Building on recently revived research from the 1970s, oncologists believe that ultrafast bursts of electrons damage tumours more than healthy tissue. This "FLASH effect" could be realised by using high-gradient accelerator technology from CLIC to create a new facility at Switzerland's Lausanne University Hospital (CHUV).

Traditional radiotherapy scans photon beams from multiple angles to focus a radiation dose on tumours inside the body. More recently, hadron therapy has offered a further treatment modality: by tuning the energy of a beam of protons or ions so that they stop in the tumour, the particles deposit most of the radiation dose there (the so-called Bragg peak), while sparing the surrounding healthy tissue by comparison. Both of these treatments deliver small doses of radiation to a patient over an extended period, whereas FLASH radiotherapy is thought to require a maximum of three doses, all lasting less than 100 ms.



CERN-PHOTO-202008-108-10

X-band *A high-gradient accelerating structure at CERN's CLEAR test facility, showing the waveguides that feed RF power in and out.*

Look again

When the FLASH effect was first studied in the 1970s, it was assumed that all tissues suffer less damage when a dose is ultrafast, regardless of whether they are healthy or tumorous. In 2014, however, CHUV researchers published a study in which 200 mice were given a single dose of 4.5 MeV gamma rays at a conventional therapy dose-rate, while others were given an equivalent dose at the much faster FLASH-therapy rate. The results showed explicitly that while the normal tissue was damaged significantly less by the ultrafast bursts, the damage to the tumour stayed consistent for both therapies. In 2019, CHUV applied the first FLASH treatment to a cancer patient, finding similarly positive results: a 3.5 cm diameter skin tumour completely disappeared using electrons from a 5.6 MeV linear accelerator, "with nearly no side effects". The challenge was to reach deeper tumours.

Now, using high-gradient "X-band" radio-frequency cavity technology developed for CLIC, CHUV has teamed up with CERN to develop a facility that can produce electron beams with energies around 100 MeV, in order to reach tumour depths of up to 20 cm. The idea came about three years ago when it was realised that CLIC technology was almost a perfect match for what CHUV were looking for: a high-powered accelerator, which uses X-band technology to accelerate particles over a short distance, has a high luminosity, and utilises a high current that allows a higher volume of tumour to be targeted.

It really looks like it has the potential to be an important complement to existing radiation therapies

"CLIC has the ability to accelerate a large amount of charge to get enough luminosity for physics studies," explains Walter Wuensch of CERN, who heads the FLASH project at CERN. "People tend to focus on the accelerating gradient, but as important, or arguably more important, is the ability to control high-current, low-emittance beams."

The first phase of the collaboration is nearing completion, with a conceptual design report, funded by CHUV, being created together by CERN and CHUV. The development and construction of the first facility, which would be housed at CHUV, is predicted to cost around €25 million, and CHUV aims to complete the facility within three years.

"The intention of CERN and the team is to be heavily involved in the process of getting the facility built and operating," states Wuensch. "It really looks like it has the potential to be an important complement to existing radiation therapies."

Cancer therapies have taken advantage of particle accelerators for many decades, with proton radiotherapy entering the scene in the 1990s. The CERN-based Proton-Ion Medical Machine Study, spawned by the TERA Foundation, resulted in the National Centre for Cancer Hadron Therapy (CNAO) in Italy and MedAustron in Austria, which have made significant progress in the field of proton and ion therapy. FLASH radiotherapy would add electrons to the growing modality of particle therapy.

Environment

CERN publishes first environmental report

“It is our vision for CERN to be a role model for environmentally responsible research,” writes CERN Director-General Fabiola Gianotti in her introduction to a landmark environmental report released by the laboratory on 9 September. While CERN has a longstanding framework in place for environmental protection, and has documented its environmental impact for decades, this is its first public report. Two years in the making, and prepared according to the Global Reporting Initiative Sustainability Reporting Standards, it details the status of CERN’s environmental footprint, along with objectives for the coming years.

Given the energy consumption of large particle accelerators, environmental impact is a topic of increasing importance for high-energy physics research worldwide. Among the recommendations of the 2020 update of the European strategy for particle physics was a strong emphasis on the need to continue with efforts to minimise the environmental impact of accelerator facilities and maximise the energy efficiency of future projects.


CERN-PHOTO-201504-073-3

Greener pastures *Members of the CERN safety engineering and environment group at one of around 100 environment monitoring stations on and around the laboratory’s sites.*

When the Large Hadron Collider (LHC) is operating, CERN uses an average of 4300 TJ of electricity every year (30–50% less when not in operation) – enough energy to power just under half of the 200,000 homes in the canton of Geneva. “This is an inescapable fact, and one that CERN has always taken into consideration when designing new facilities,” states Frédérick Bordry, director for accelerators and technology.

Action plan

An energy-management panel established at CERN in 2015 has already led to actions, including free cooling and air-flow optimisation, better optimised LHC cryogenics, and the implementation of SPS magnetic cycles and stand-by modes, which significantly reduce energy consumption. The LHC delivered twice as much data per Joule in its second run (2015–2018) compared to its first (2010–2013), states the new report. With the High-Luminosity LHC due to deliver a tenfold increase in luminosity towards the end of the decade, CERN has made it a priority to limit the increase in energy consumption to 5% up to the end of 2024, with longer-term objectives to be set in future reports.

CERN procures its electricity mainly from France, whose production capacity is 87.9% carbon-free. In terms of direct greenhouse-gas emissions, the 192,000 tonnes of carbon-dioxide equivalent emitted by CERN in 2018 is mainly due to fluorinated gases used in the LHC detectors for cooling, particle detection, air conditioning and electrical insulation. CERN has set a formal objective that, by 2024, direct greenhouse emissions will be reduced by 28% by replacing fluorinated gases – which were designed in the 1990s to be ozone-friendly – with carbon dioxide, which has a global-warming potential several thousand times lower.

Other areas of environmental significance studied in the report include radiation exposure, noise and waste. CERN commits to limit the emission of ionising radiation to no more than 0.3 mSv per year – less than a third of the annual dose limit for public exposure set by the European Council. The report states that the actual dose to any member of the public living in the immediate vicinity of CERN due to the laboratory’s activities is below 0.02 mSv per year, which is less than the exposure received from cosmic radiation during a transatlantic flight.

A 2018 measurement campaign showed that noise levels at CERN have not changed since the early 1990s, and are low by urban standards. Nevertheless, CERN has have invested 0.7 million CHF to reduce noise at its perimeters to below 70 dB during the day and 60 dB at night (which corresponds to the level of conversational speech). The organisation has also introduced approaches to preserve the local landscape and protect flora, including 15 species of orchid growing on CERN’s sites.

CERN has set a formal objective that, by 2024, direct greenhouse emissions will be reduced by 28%

Waste not

Water consumption, mostly drawn from Lac Léman, has slowly decreased over the past 10 years, the report notes, and CERN commits to keeping the increase in water consumption below 5% to the end of 2024, despite a growing demand for cooling from upgraded facilities. CERN also eliminates 100% of its waste, states the report, and has a recycling rate of 56% for non-hazardous waste (which comprises 81% of the total). A major project under construction since last year will see waste hot water from the cooling system for LHC Point 8 (where the LHCb experiment is located) channeled to a heating network in the nearby town of Ferney-Voltaire from 2022, with LHC Points 2 and 5 being considered for similar projects.

CERN plans to release further environment reports every two years. “Today, more than ever, science’s flag-bearers need to demonstrate their relevance, their engagement, and their integration into society as a whole,” writes Gianotti. “This report underlines our strong commitment to environmental protection, both in terms of minimising our impact and applying CERN technologies for environmental protection.”

Accelerators

Preparatory ‘pre-lab’ proposed for ILC

On 10 September the International Committee for Future Accelerators (ICFA) announced the structure and members of a new organisational team to prepare a “pre-laboratory” for an International Linear Collider (ILC) in Japan. The ILC International Development Team (ILC-IDT), which consists of an executive board and three working groups governing the pre-lab setup, accelerator, and physics and detectors, aims to complete the preparatory phase for the pre-lab on a timescale of around 1.5 years.


R Hori/KEK

Down the line *How an accelerating module for the International Linear Collider (ILC) might look.*

The aim of the pre-lab is to prepare the ILC project, should it be approved, for construction. It is based on a memoranda of understanding among participating national and regional laboratories, rather than intergovernmental agreements, explains chair of the ILC-IDT executive board Tatsuya Nakada of École Polytechnique Fédérale de Lausanne. “The ILC-IDT is preparing a proposal for the organisational and operational framework of the pre-lab, which will have a central office in Japan hosted by the KEK laboratory,” says Nakada. “In parallel to our activities, we hope that the effort by our Japanese colleagues will result in a positive move by the Japanese government that is equally essential for establishing the pre-laboratory.”

In June the Linear Collider Board and Linear Collider Collaboration, which were established by ICFA in 2013 to promote the case for an electron–positron linear collider and its detectors as a worldwide collaborative project, reached the end of their terms in view of ICFA’s decision to set up the ILC-IDT.

The ILC has been on the table for almost two decades. Shortly after the discovery of the Higgs boson in 2012, the Japanese high-energy physics community proposed to host the estimated $7 billion project, with Japan’s prime minister at that time, Yoshihiko Noda, stressing the importance of establishing an international framework. In 2018 ICFA backed the ILC as a Higgs factory operating at a centre-of-mass energy of 250 GeV – half the energy set out five years earlier in the ILC’s technical design report.

An electron–positron Higgs factory is the highest-priority next collider, concluded the 2020 update of the European strategy for particle physics (ESPPU). The ESPPU recommended that Europe, together with its international partners, explore the feasibility of a future hadron collider at CERN at the energy frontier with an electron–positron Higgs factory as a possible first stage, noting that the timely realisation of the ILC in Japan “would be compatible with this strategy”. Two further proposals exist: the Compact Linear Collider at CERN and the Circular Electron–Positron Collider in China. While the ILC is the most technically ready Higgs-factory proposal (see p35), physicists are still awaiting a concrete decision about its future.

In March 2019 Japan’s Ministry of Education, Culture, Sports, Science and Technology (MEXT) expressed “continued interest” in the ILC, but announced that it had “not yet reached declaration” for hosting the project, arguing that it required further discussion in formal academic decision-making processes. In February KEK submitted an application for the ILC project to be considered in the MEXT 2020 roadmap for large-scale research projects. KEK withdrew the application the following month, announcing the move in September following the establishment of the ILC-IDT.

“The ministry will keep an eye on discussions by the international research community while exchanging opinions with government authorities in the US and Europe,” said Koichi Hagiuda, Japanese minister of education, culture, sports, science and technology, at a press conference on 11 September.

Steinar Stapnes of CERN, who is a member of the ILC-IDT executive board representing Europe, says that clear support from the Japanese government is needed for the ILC pre-lab. “The overall project size is much larger than the usual science projects being considered in these processes and it is difficult to see how it could be funded within the normal MEXT budget for large-scale science,” he says. “During the pre-lab phase, intergovernmental discussions and negotiation about the share of funding and responsibilities for the ILC construction need to take place and hopefully converge.”

Electron makeover studied for the SPS

CERN’s Super Proton Synchrotron (SPS) could be upgraded so that not only protons have the possibility to be accelerated, but also electrons. A 173-page conceptual design report for the “eSPS” posted on arXiv on 15 September describes the installation of a high-energy electron accelerator that could have the potential to be used for accelerator R&D, dark-sector physics, and for electro-nuclear measurements for future neutrino experiments. First proposed in 2018 by Torsten Åkesson of Lund University and colleagues at CERN, the facility would marry technology developed for the proposed Compact Linear Collider (CLIC) and the Future Circular Collider (FCC), and could also provide a step towards a potential electron–positron Higgs factory.

The SPS is one of CERN’s longest running accelerators

The SPS is one of CERN’s longest running accelerators, commissioned in June 1976 at an energy of 400 GeV and serving numerous fixed-target experiments ever since. It was later converted into a proton–antiproton collider that was used to discover the W and Z bosons ▷

CERN-PHOTO-201902-032-12

Workhorse *Engineers in the SPS tunnel during the current long shutdown of CERN's accelerator complex.*

in 1983. Then, in addition to its fixed-target programme, the SPS became part of the injection chain for LEP, and most recently, has been used to accelerate protons for the LHC.

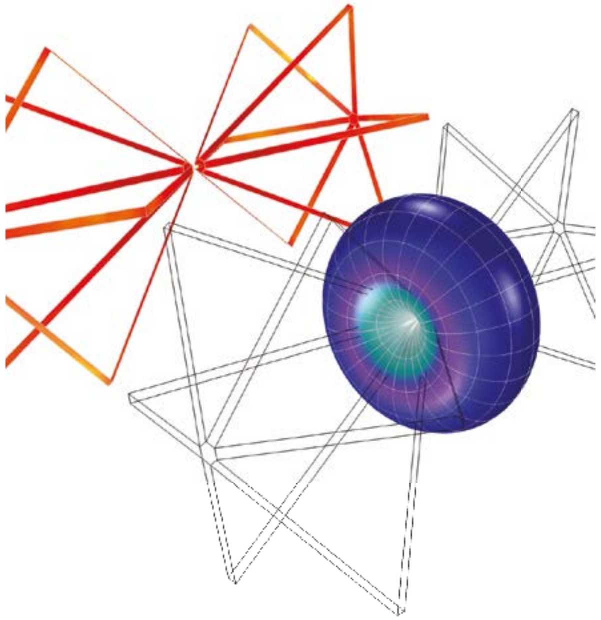
Electrons would be injected into the eSPS at an energy of 3.5 GeV by a new compact high-gradient linac based on CLIC's X-band radio-frequency (RF) cavity technology, which would fill the circular machine with 200 ns-duration pulses at a rate of 100 Hz. An additional 800 MHz superconducting RF system, similar to what is needed for FCC-ee, would then accelerate the electron beam from 3.5 GeV to an extraction energy of 18 GeV.

The requirements of the primary electron beam to be delivered by the eSPS were determined by the needs of the proposed Light Dark Matter eXperiment (LDMX), which would use missing-momentum techniques to explore potential couplings between hidden-sector particles and electrons. The facility could also provide multi-GeV drive beam bunches and electron witness bunches for plasma wakefield acceleration. Positron witness bunches could be delivered in a possible second phase, complementing the work done by the AWAKE collaboration. Positron production would be a crucial element for any future Higgs-factory and it would also allow studies of the Low Emittance Muon Accelerator (LEMMA) – a novel scheme for obtaining a low-emittance muon beam for a muon collider.

The eSPS proposal came about as a result of work in CERN's Physics Beyond Colliders study. Were it to go ahead, the facility could be made operational in about five years and would operate in parallel and without interference with Run 4 of the LHC, write the authors.

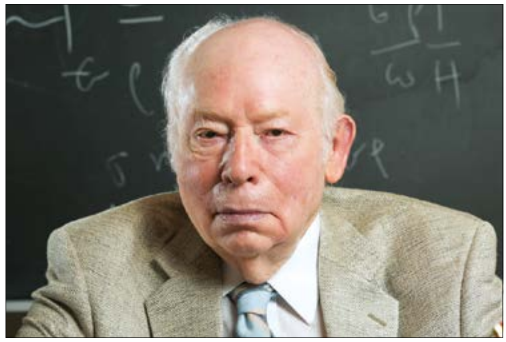
Further reading

M Aicheler *et al.* 2020 arXiv.org:2009.06938.



AWARDS

Weinberg wins Breakthrough Prize



M Valentine

Model physicist *Weinberg is currently the Jack S Josey–Welch Foundation Chair in Science at the University of Texas at Austin.*

Steven Weinberg's continuous leadership in particle physics, gravity and cosmology was on 10 September rewarded with a Special Breakthrough Prize in Fundamental Physics. While his contribution to the genesis of the Standard Model has undoubtedly been Weinberg's greatest single achievement, stated the selection committee for the $3 million prize, he would be recognised as a leader in the field even if he had not made this particular contribution.

Weinberg's 1967 paper "A Model of Leptons" is one of the most pivotal in theoretical physics. It applies the notion of spontaneous symmetry breaking to the weak interaction, revealing that it is unified with the electromagnetic interaction and predicts the existence of the W, Z and Higgs bosons (*CERN Courier* November 2017 p25). The electroweak theory won Weinberg, Abdus Salam and Sheldon Glashow the 1979 Nobel Prize in Physics.

"Of course, nothing compares with the Nobel Prize in prestige, if only because of the long history of great scientists to whom it has been awarded in the past," says Weinberg, when invited to compare the awards, "but for me there was a special pleasure in being awarded the Breakthrough Prize because the selection committee is composed of a younger generation of outstanding physicists who are today playing a leading role in research." The prize committee also cited Weinberg's achievements in communicating science and acknowledged his highly visible public role as a spokesman for science and rationality.

Also worth $3 million, the 2021 Breakthrough Prize in Fundamental Physics has been awarded to Eric Adelberger, Jens H Gundlach and Blayne Heckel, the leaders of the Eöt-Wash group at the University of Washington, "for precision fundamental measurements that test our understanding of gravity, probe the nature of dark energy and establish limits on couplings to dark matter". Three New Horizons in Physics Prizes, each worth $100,000 and designed to recognise early-career researchers, were awarded to: Tracy Slatyer (MIT) for major contributions to particle astrophysics; Rouven Essig (Stony Brook University), Javier Tiffenberg (Fermilab), Tomer Volansky (Tel Aviv University) and Tien-Tien Yu (University of Oregon) for advances in the detection of sub-GeV dark matter; and Ahmed Almheiri (IAS), Netta Engelhardt (MIT), Henry Maxfield (UC Santa Barbara) and Geoff Penington (UC Berkeley) for calculating the quantum information content of a black hole and its radiation.

The Breakthrough Prize in Fundamental Physics has been awarded annually for the past nine years, while the Special Breakthrough Prize in Fundamental Physics has only been handed out on six occasions. Last year, theorists Sergio Ferrara, Dan Freedman and Peter van Nieuwenhuizen received a Special Breakthrough Prize for their 1976 invention of supergravity. The 2021 prize ceremony is due to take place in March.

Black holes attract 2020 Nobel Prize

Creative Commons

Space-time pioneers *From left: Nobel winners Roger Penrose, Andrea Ghez and Reinhard Genzel.*

The 2020 Nobel Prize in Physics, announced on 6 October, has recognised seminal achievements in the theoretical and experimental understanding of black holes. One half of the SEK 10 million ($1.15 million) award went to Roger Penrose of the University of Oxford "for the discovery that black-hole formation is a robust prediction of the general theory of relativity". The other half was awarded jointly to Andrea Ghez of the University of California, Los Angeles and Reinhard Genzel of the Max Planck Institute for Extraterrestrial Physics "for the discovery of a supermassive compact object at the centre of our galaxy", after the pair led separate research teams during the 1990s to identify a black hole at the centre of the Milky Way.

As soon as Einstein had completed his theory of general relativity in 1915, it was clear that solutions in the vicinity of a spherically symmetric, non-rotating mass allow space-time to be "pinched" to a point, or singularity, where known physics ceases to apply. Few people, including Einstein himself, however, thought that black holes really exist. But 50 years later, Penrose invented a mathematical tool called a trapped surface to show that black holes are a natural consequence of general relativity, proving that they each hide a singularity. His groundbreaking article (*Phys. Rev. Lett.* **14** 57) is heralded as the first post-Einsteinian result in general relativity.

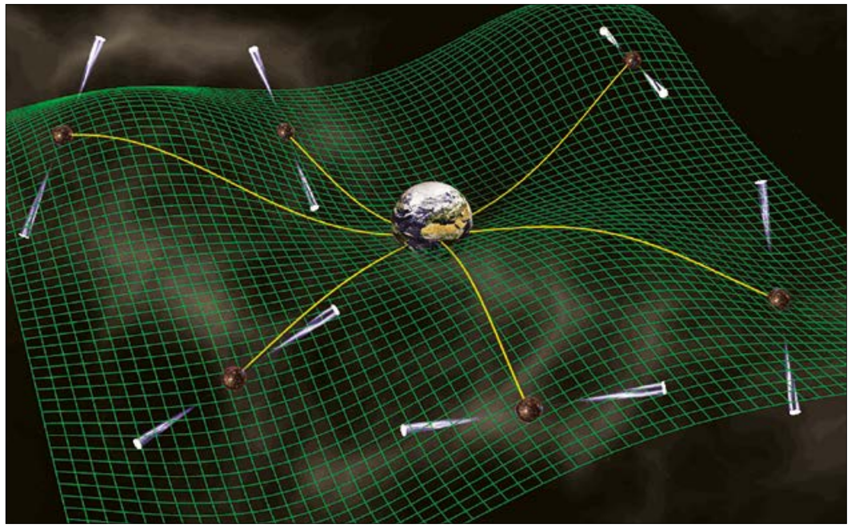
Penrose is also known for the "Penrose process", whereby a particle–antiparticle pair that forms close to the event horizon of a black hole can become separated, with one of the two particles falling into the black hole and the other one escaping and carrying away energy and angular momentum. He also proposed twistor theory, which has evolved into a rich branch of theoretical and mathematical physics with potential relevance to the unification of general relativity and quantum mechanics, among many other contributions.

"I really had to have a good idea of the space-time geometry. Not just 3D, you had to think of the whole 4D space-time… I do most of my thinking in visual terms, rather than writing down equations," said Penrose in an interview with the Nobel Foundation following the award. "Black holes have become more and more important, also in ways that people don't normally appreciate. They are the basis of the second law of thermodynamics… You might ask where the greatest entropy is in the universe – by an absolutely enormous factor it is in black holes."

Astrowatch

Pulsars hint at low-frequency gravitational waves

The direct detection of a gravitational wave (GW) in 2015 by the LIGO and Virgo collaborations confirmed the existence of these long-sought-after events. However, the kHz-regime GW events detected so far constitute only a small fraction of the vast GW spectrum. As a result, they only probe phenomena such as stellar mass black-hole and neutron-star mergers. On the opposite side of the spectrum to LIGO and Virgo are pulsar timing array (PTA) experiments, which search for nHz-frequency GWs. Such low-frequency signals can originate from supermassive black-hole binaries (SMBHBs), while in more exotic models they can be proof of cosmic strings, phase transitions or a primordial GW background. The NANOGrav (North American Nanohertz Observatory for Gravitational Waves) collaboration has now found possible first hints of low-frequency GWs.


D Champion

nHz waves *NANOGrav uses variations in the arrival time of the signals from an array of very stable, quickly rotating pulsars to detect potential distortions in space–time caused by low-frequency gravitational waves.*

Track and trace

To detect such rumblings of space–time, which also have tiny amplitudes, researchers need to track subtle movements of measurement points spread out over the galaxy. For this purpose, the NANOGrav collaboration uses light from millisecond pulsars, several tens of which have been detected in our galaxy. Pulsars are quickly rotating neutron stars that emit cones of electromagnetic emission from their poles. When a pole points towards Earth it is detected via a short pulse of electromagnetic radiation. Not only is the frequency of millisecond pulsars high, making it easier to detect small variations in arrival time, but it is very stable over periods of many years. Combined with their great distances from Earth, this makes millisecond-pulsar emissions sensitive to any small alterations in their travel path – for example, those introduced by distortions of space–time by low-frequency gravitational waves. Such waves would cause the pulses to arrive a few nanoseconds early during January and a few nanoseconds late in June, for instance. By observing the radio emission of these objects once a week throughout many years, researchers can search for such effects.

The problem is that GWs are not the only things that can cause a change in the arrival time of the pulses. Changes in the Earth's atmosphere in the position of the pulsar itself (which is usually part of a quickly rotating binary system), and the movement of Earth with respect to the source, all change the arrival time of the pulses. The complexity of the measurements lies mostly in correcting for all of these effects. The latest results from NANOGrav, for example, reduce systematics by incorporating unprecedented precision (of the order of tens of km) in the orbital parameters of Jupiter.

Researchers track measurement points spread out over the galaxy

Whereas previous results by NANOGrav and other PTA collaborations only allowed upper limits to be set on the amplitude of the GW background travelling through our galaxy, the new results show a clear sign of a common spectrum between the studied pulsars. Based on 12.5 years of data and a total of 47 pulsars studied using the ultra-sensitive Arecibo Observatory and Green Bank Telescope, the spectrum of variations in the pulsar signal arrival time was found to agree with theoretical predictions of the GW background produced by SMBHBs. The uncertainties remain large, however. This admits alternative interpretations such as cosmic strings – domain structures in the universe predicted to arise from a spontaneously broken gauge symmetry – that predict only a slightly different spectral shape. Furthermore, a key ingredient is still missing: a spatial correlation between the pulsar variations, which would confirm the quadrupole nature of GWs and provide clear proof of the nature of the signal. Finding this "smoking gun" will require longer observation times, more pulsars and smaller systematic errors – something the NANOGrav team is now working towards.

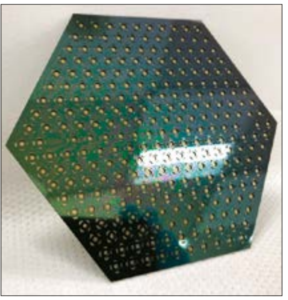
Bright and beautiful

Several exotic interpretations have also been proposed, though the NANOGrav collaboration remains cautious. The final sentences of their preprint summarise the status of the field well: "The LIGO–Virgo discovery of high-frequency, transient GWs from stellar black-hole binaries appeared meteorically, with incontrovertible statistical significance. By contrast, the PTA discovery of very-low-frequency GWs from SMBHBs will emerge from the gradual and not always monotonic accumulation of evidence and arguments. Still, our GW vista on the unseen universe continues to get brighter."

Further reading

NANOGrav Collaboration 2020 arXiv.org:2009.04496.

NEWS DIGEST


C Chang/Argonne

A prototype silicon wafer for the CMB-S4 telescopes.

Berkeley to lead CMB-S4
The US Department of Energy in September selected Lawrence Berkeley National Laboratory to lead the proposed Cosmic Microwave Background Stage 4 (CMB-S4) experiment. CMB-S4 aims to survey the temperature and polarisation of the CMB in unprecedented detail using a mix of large and small telescopes at the South Pole and in the high Chilean desert. Researchers will look for signs of inflation, seek to measure the mass of the neutrino, constrain dark-sector models and aid in the detection and study of gamma-ray bursts and jet-emitting blazars. If approved, CMB-S4 will follow in the footsteps of Penzias and Wilson's ground-based measurements of the CMB in 1964 and the COBE, WMAP and Planck satellites. The first telescopes may be deployed as early as 2027.

Sterile neutrinos to the rescue?
A University of California trio points to sterile neutrinos as a possible explanation for the ~5σ discrepancy in measurements of the Hubble constant at small and large scales. The presence of an additional neutrino-like particle that decayed just before Big-Bang nucleosynthesis could explain why the microwave sky appears to be expanding more slowly than suggested by observations of Cepheid variables and Type-Ia supernovae, say the authors. Unstable sterile neutrinos with a mass of 10 MeV could account for the needed 40% of an effective neutrino flavour, they claim. Though potentially oscillating far too fast to be seen by conventional sterile-neutrino searches, the authors suggest that simple models could be within the reach of Japan's Super-Kamiokande detector or the NA62 experiment at CERN (arXiv:1906.10136).

Snowmass limbers up
A virtual community planning meeting for the 2021 Snowmass exercise, which will plot a course for US particle physics over the coming decade, took place from 5 to 8 October. The meeting attracted some 3000 participants and more than 1500 letters of intent across 10 "Snowmass frontiers", from the energy frontier to community engagement. First convened in the eponymous Coloradoan mountain resort in 1982, Snowmass studies have been produced on numerous occasions throughout the years, most recently in 2013. A final report will be published in October 2021.

Magnet milestone
Engineers at Tokamak Energy have come within a whisker (0.2 T) of the world-record field for a magnet based on high-temperature superconductors (HTS). The UK company, which pursues "desktop" fusion reactors, teamed up with CERN's cryolab to cool a solenoid to 4 K and ramp it up to 26.2 T over the course of a few days in September. Similar technology could also be reconfigured for future particle accelerators, potentially offering fields up to 30 T, in excess of the 16 T Nb_3Sn magnets envisaged by the baseline FCC-hh design. CERN magnet engineers will shortly use HTS to boost the field of the experimental 14.6 T Nb_3Sn FRESCA2 magnet to just under 20 T – a record field for a dipole magnet.

Green light for Science Gateway
Local authorities in Geneva in September approved the construction of the Science Gateway – a new education and outreach facility at CERN designed by Renzo Piano's architecture firm to evoke the twin beam pipes of the LHC. Linked by a centrepiece bridge, the new spaces will house exhibitions, laboratories and educational activities, surrounded by 400 newly planted trees. 80% of the total budget, which will be entirely funded by donations, has been secured. The facility is due to be open at the end of 2022.


RPBW

An artist's impression of the Science Gateway facility.

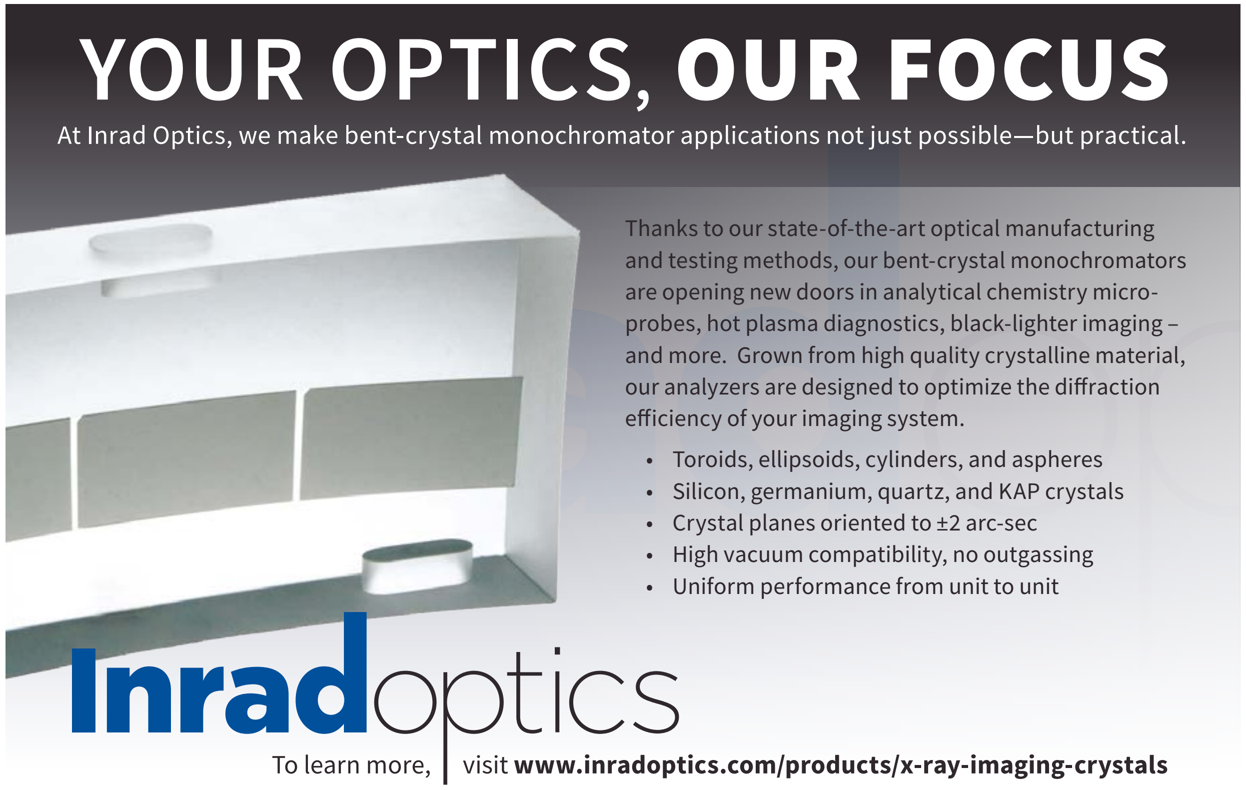
APS recognises black history
Baltimore's Morgan State University (MSU) and the Sanford Underground Research Facility (SURF) have been designated historic sites by the American Physical Society (APS). MSU was the birthplace in 1977 of the National Society of Black Physicists, and has worked to increase the representation of African Americans in physics and technology ever since. SURF was home to Ray Davis's Homestake experiment, which uncovered the solar-neutrino problem. The sites join 48 others on the APS list.

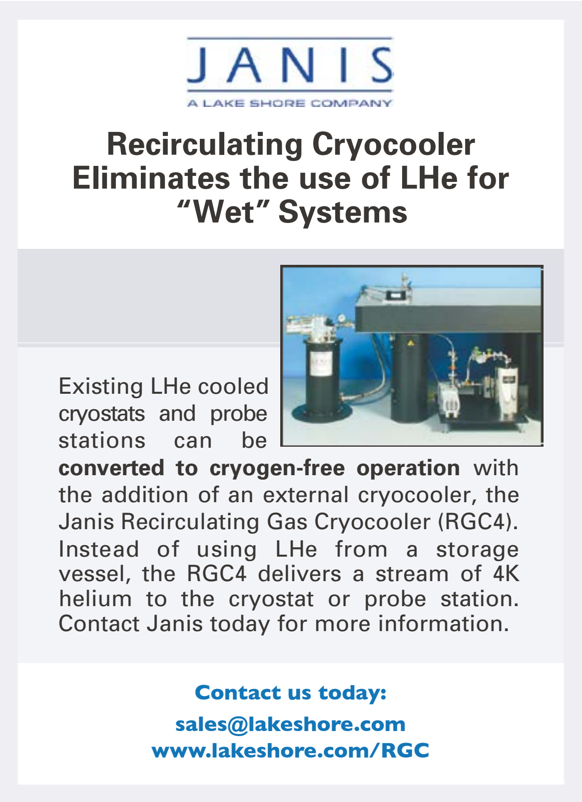
Time travel without paradoxes
University of Queensland theorist Fabio Costa and student Germain Tobar have delighted sci-fi fans worldwide with claims that free will can be maintained when travelling back in time and interacting with yourself (*Class. Quantum Grav.* **37** 205011). Einstein's general theory of relativity allows for closed time-like curves (CTCs) wherein a worldline returns to its starting point, provoking possible logical headaches such as the grandfather paradox. The pair serve up maths in support of the view that complex dynamics is possible in the presence of CTCs, compatible with the free choice of local operations without inconsistency.

Brushing up on Raphael
Czech start-up InsightArt has used photon detectors developed by CERN's Medipix project to dismiss a century of tittle-tattle impugning Raphael as the true artist behind the painting of the *Madonna and Child* commissioned by Leo X in 1517. Since the early 1990s, Medipix collaborators have developed the "colour X-ray" for a wide range of applications, in this case differentiating brushstrokes and pigments. A group of independent experts used eleven 50 μm-resolution scans at different wavelengths to establish that the work was painted by Raphael personally, without the help of apprentices. The painting was stolen from the Holy See by Napoleon's armies in 1798, before being sold into private property by Louis XVIII in 1813.


InsightArt

Raphael's Madonna and Child.





ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

LHCb

In pursuit of right-handed photons

On 17 January 1957, a few months after Chien-Shiung Wu's discovery of parity violation, Wolfgang Pauli wrote to Victor Weisskopf: "*Ich glaube aber nicht, daß der Herrgott ein schwacher Linkshänder ist*" (I cannot believe that God is a weak left-hander). But maximal parity violation is now well established within the Standard Model (SM). The weak interaction only couples to left-handed particles, as dramatically seen in the continuing absence of experimental evidence for right-handed neutrinos. In the same way, the polarisation of photons originating from transitions that involve the weak interaction is expected to be completely left-handed.

The LHCb collaboration recently tested the handedness of photons emitted in rare flavour-changing transitions from a b-quark to an s-quark. These are mediated by the bosons of the weak interaction according to the SM – but what if new virtual particles contribute too? Their presence could be clearly signalled by a right-handed contribution to the photon polarisation.

The $b \to s\gamma$ transition is rare. Fewer than one in a thousand b-quarks transform into an s-quark and a photon. This process has been studied for almost 30 years at particle colliders around the world. By precise measurements of its properties, physicists hope to detect hints of new heavy particles that current colliders are not powerful enough to produce.

The probability of this b-quark decay has been measured in previous experiments with a precision of about 5%, and found to agree with the SM prediction, which bears a similar theoretical uncertainty. A promising way to go further is to study the polarisation of the emitted photon. Measuring the $b \to s\gamma$ polarisation is not easy though. The emitted photons are too energetic to be analysed by a polarimeter and physicists must find innovative ways to probe them indirectly. For example, a right-handed polarisation contribution could induce a charge-parity asymmetry in the $B^0 \to K_S\pi^0\gamma$ or $B^0_s \to \phi\gamma$ decays. It could also contribute to the total rate of radiative $b \to s\gamma$ decays, containing any strange meson, $B \to X_s\gamma$.

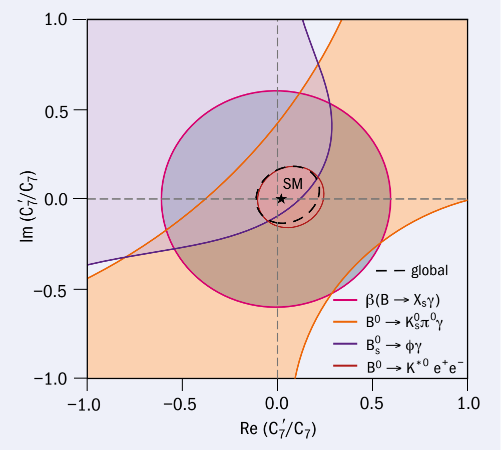


Fig. 1. *2σ constraints on the ratio of right- and left-handed Wilson coefficients, C_7'/C_7, using the* flavio *software package. C_7 quantifies the coupling strength to photons, and is fixed to its SM value. Any deviation in C_7'/C_7, from (0,0) would signify new physics. The new LHCb measurement is shown in red.*

The LHCb collaboration has pioneered a new method to perform this measurement using virtual photons and the largest sample of the very rare $B^0 \to K^{*0}e^+e^-$ decay ever collected. First, the sub-sample of decays that come from $B^0 \to K^{*0}\gamma$ with a virtual photon that materialises in an electron–positron pair is isolated. The angular distributions of the $B^0 \to K^{*0}e^+e^-$ decay products are then used as a polarimeter to measure the handedness of the photon. The number of decays with a virtual photon is small compared to the decays with a real photon, but these latter decays cannot be used as the information on the polarisation is lost.

The size of the right-handed contribution to $b \to s\gamma$ is encoded in the magnitude of the complex parameter C_7'/C_7. This is a ratio of the right- and left-handed Wilson coefficients that are used in the effective description of $b \to s$ transitions. The new $B^0 \to K^{*0}e^+e^-$ analysis by the LHCb collaboration constrains the value of C_7'/C_7, and thus the photon polarisation, with unprecedented precision (figure 1). The measurement is compatible with the SM prediction.

This result showcases the exceptional capability of the LHCb experiment to study $b \to s\gamma$ transitions. The uncertainty is currently dominated by the data sample size, and thus more accurate studies are foreseen with the large data sample expected in Run 3 of the LHC. More precise measurements may yet unravel a small right-handed polarisation.

Further reading

LHCb Collab. 2020 arXiv:2010.06011.

CMS

Leptoquarks and the third generation

The Standard Model (SM) groups quarks and leptons separately to account for their rather different observed properties, but might they be unified through a new particle that couples to both and turns one into the other? Such "leptoquarks" emerge quite naturally in several theories that extend the SM. Searches for leptoquarks have been an important part of the LHC's research programme since the beginning, and have received additional attention recently in the light of hints of deviations from the principle of lepton universality – the so-called flavour anomalies.

In a recent CMS analysis, where the events collected in pp collisions during Run 2 (137 fb^{-1}) are analysed, researchers have challenged the SM by investigating a previously unexplored leptoquark signature involving the third generation of fermions. The motivation for considering the third generation is to confront the principle of lepton universality, which asserts that the couplings of leptons with gauge bosons are flavour independent. This principle is built into the SM, but has recently been put under stress by a series of anomalies observed in precision measurements of certain B-meson decays by the LHCb, Belle and BaBar collaborations (*CERN Courier* May/June 2019 p33). A possible explanation for these anomalies, which are still under investigation and not yet confirmed, lies in the existence of leptoquarks that preferentially couple to the heaviest fermions.

The pursuit of this promising solution for the unification of quarks and leptons must continue

The new CMS search looks for both single and pair production of leptoquarks. It considers leptoquarks that decay to a ▷

quark (top or bottom) and a lepton (tau or neutrino), targeting the signature with a top quark, a tau lepton, missing transverse momentum due to a neutrino, and, in the case of double production, an additional bottom-quark jet. This is the first search to simultaneously consider both production mechanisms by categorising events with one or two jets originating from a bottom quark. The analysis also includes a dedicated selection for the case of a large mass splitting between the leptoquark and the top quark, which would boost the top quark and could cause its decay products to be inseparable given the spatial resolution of jets.

The observations are found to be in agreement with the SM prediction, and exclusion limits are derived in the plane of the leptoquark–lepton–quark vertex coupling λ and the leptoquark mass. The results are derived separately for hypothetical spin-0 and spin-1 (figure 1) leptoquarks, reflecting the two types allowed by theoretical models. The analysis assumes that the leptoquark decays half the time to each of the possible quark–lepton flavour pairs, for example, in the case of a spin-1 leptoquark, to a top quark and a neutrino, or to a bottom quark and a tau lepton. CMS finds a range of lower limits on the leptoquark mass between 0.98 and 1.73 TeV, at 95% confidence, depending on λ and the spin.

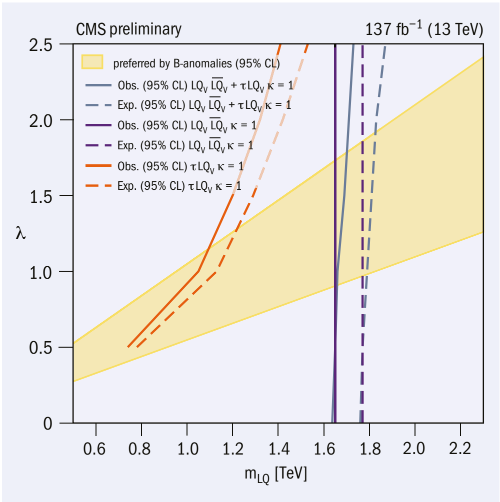


Fig. 1. *95% confidence limits on the mass and coupling of a spin-1 (vector) leptoquark (LQ_V), considering single (orange) and pair (purple) production mechanisms, and their combination (blue), compared to the region favoured by models seeking to explain the B-physics anomalies (yellow). The regions to the left are excluded.*

These results are the most stringent limits to date on the presence of leptoquarks that couple preferentially to the third generation of fermions. They also probe the parameter space preferred by the B-physics anomalies in several models, excluding relevant portions. As theories predict leptoquark masses as high as many tens of TeV, the pursuit of this promising solution for the unification of quarks and leptons must continue. The CMS collaboration has a broad programme for further investigations that will exploit the larger data samples from Run 3 and the high-luminosity LHC under different hypotheses. If leptoquarks exist, they may well be revealed in the coming data.

Further reading

CMS Collab. 2020 CMS-PAS-EXO-19-015.

ATLAS

Cornering WIMPs with ATLAS

Dark matter is estimated to account for an unseen 85% of matter in the universe, but its nature is unknown. One possible explanation is weakly-interacting massive particles, or WIMPs, which could interact with ordinary matter through the exchange of a Higgs boson ("Higgs-portal" models) or a new mediator field yet to be discovered. The ATLAS collaboration has recently released two new investigations of WIMPs based on the full Run-2 data set.

At the LHC, a mediator may be produced and decay into a pair of stable WIMPs, which then escape the detector unseen – an undetectable process, unless the mediator is produced, for example, in association with a high-p_T gluon radiated from one of the incoming protons. This would provide a clear signature: a high-p_T jet and significant missing transverse momentum (MET). A first "monojet" analysis sought events with MET in excess of 200 GeV, recoiling against a jet with $p_T > 150$ GeV, with up to three additional jets and no leptons or photons. The leading background arises from events wherein a Z boson decays to neutrinos – a process experimentally indistinguishable from WIMP production. The predictions of this and other backgrounds benefitted from state-of-the-art theoretical calculations, detailed groundwork on particle reconstruction in ATLAS, and the use of data-control regions rich in W and Z boson decays. No significant excess was observed with respect to the Standard Model (SM) (figure 1).

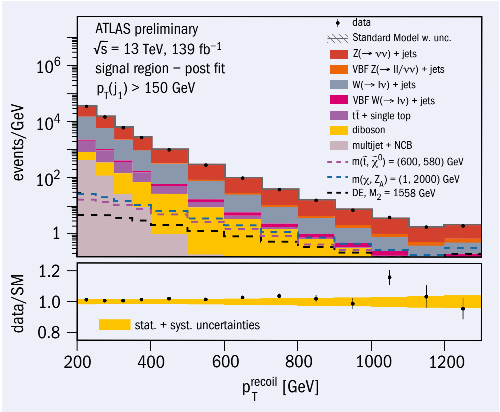


Fig. 1. *Monojet missing transverse momentum compared to SM predictions, and the distributions of illustrative supersymmetric (purple dashed line), WIMP (blue dashed line) and dark-energy (black dashed line) signals.*

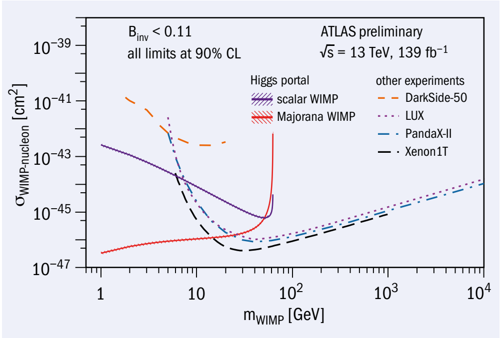


Fig. 2. *90% confidence upper limits on the elastic WIMP-neutron scattering cross section as a function of the mass of a scalar (purple) or spin-½ Majorana (red) WIMP.*

A second "dijet" WIMP analysis searches for invisible decays of Higgs bosons produced via vector-boson fusion. Though accounting for just 10% as many Higgs bosons as the dominant gluon-fusion process at the LHC, the topology's clear signature, with two widely separated jets in pseudorapidity, lends itself to searching for MET, as the jets tend to be close together in the transverse plane when recoiling against a Higgs boson with $p_T > 200$ GeV. The art of this analysis is again in the precise modelling of SM backgrounds – a feat accomplished here with extrapolations from control regions and the use of jet kinematics to separate signal events from Z-boson decays to neutrinos, and W decays with an undetected charged lepton. As invisible Higgs-boson decays in the SM (chiefly $H \rightarrow ZZ^* \rightarrow 4\nu$) have a branching fraction of just 10^{-3}, ▷

any significant signal would indicate new physics. No deviation from the SM was observed, allowing a 95% confidence upper limit to be placed on the branching fraction for invisible Higgs-boson decays of 13% – a factor two improvement in sensitivity compared to the previous analysis, despite the increase in pileup – or 9% when combining with other ATLAS Higgs-boson measurements. The results are complementary to direct-detection experiments looking for relic WIMPs with deep underground detectors, as they plumb lower WIMP masses than direct-detection experiments can currently access (figure 2).

These results also translate into limits on alternative dark-matter-related theories such as axion-like-particles (ALPs) and large extra-dimensions, and into model-independent limits on new phenomena. ATLAS will continue to explore the parameter space of dark-sector models such at ALPs, dark photons, dark scalars and heavy neutral leptons, complementing the results of dedicated smaller-scale experiments.

The art of this analysis is in the precise modelling of SM backgrounds

Further reading

ATLAS Collab. 2020 ATLAS-CONF-2020-048.
ATLAS Collab. 2020 ATLAS-CONF-2020-008.
ATLAS Collab. 2020 ATLAS-CONF-2020-027.

ALICE

Fragile light nuclei flow through freeze-out

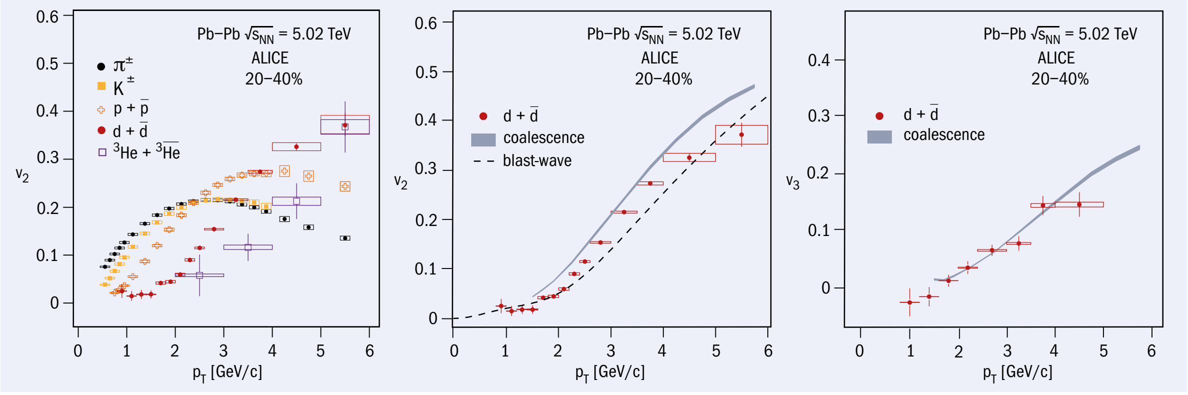


Fig. 1. *The elliptic flow of deuterons, compared with other species (left) and phenomenological models (middle), and their triangular flow (right), in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in the centrality class 20–40%.*

Ultra-relativistic heavy-ion collisions create a system of deconfined quarks and gluons known as the quark–gluon plasma (QGP). Among other particles, a large number of light nuclei such as the deuteron, triton, helium-3, helium-4 and their corresponding antinuclei are produced, and can be measured with very good precision by the ALICE experiment at the LHC thanks to its excellent tracking and particle-identification capabilities via specific energy loss and time-of-flight measurements. Considering that the binding energies of light (anti)nuclei do not exceed a few MeV, it is not clear how such fragile objects can survive the hadron gas phase created after the phase transition from the QGP to hadrons, where particles rescatter with a typical momentum transfer in excess of 100 MeV. The production mechanism of light (anti)nuclei in these collisions is still not understood and is under intense debate in the scientific community. Constraining models of light antinuclei production is also important for predicting the backgrounds to indirect dark-matter searches using cosmic rays, as performed by experiments in space and in hot-air balloons, for which light antinuclei are promising signals.

Azimuthal anisotropies of light (anti) nuclei production with respect to the symmetry plane of the collision are key observables to study interactions in the hadron-gas phase, and can shed light on the production mechanism of these fragile objects. The ALICE collaboration has recently reported the measurements of two harmonic coefficients (v_n) in a Fourier decomposition of the azimuthal distribution of deuterons in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV: their elliptic flow, v_2, and the first measurement of their triangular flow, v_3. A clear mass ordering is observed in the elliptic flow of non-central Pb–Pb collisions at low p_T when the deuteron results are compared with other particle species, as expected for an expanding hydrodynamic system (figure 1, left).

The results are often compared to three phenomenological models, namely the statistical hadronisation model, the coalescence model, and the blast-wave model. In the statistical hadronisation model, light (anti)nuclei are assumed to be emitted by a source of thermal and hydrochemical equilibrium, like other hadron species, and their abundances fixed at the chemical freeze-out – the time at which inelastic interactions cease. However, this model only describes their yields, and not their flow. On the other hand, the coalescence model predicts that light nuclei are formed by the coalescence of protons and neutrons that are close in phase space at the kinetic freeze-out – the time at which *elastic* interactions cease. The blast-wave model, which is based on a simplified version of relativistic hydrodynamics, describes their transverse momentum spectra with just a few parameters, such as the kinetic freeze-out temperatures and transverse velocity.

In the new ALICE results, the measured elliptic flow of light nuclei is bracketed by the simple coalescence approach and the blast-wave model, which describe the data in different multiplicity regimes (figure 1, middle). The deuteron triangular flow is consistent with the coalescence model predictions, but large uncertainties do not allow a conclusive statement (figure 1, right). This specific aspect will be addressed with the larger data sample that ALICE will record in Run 3, which will also allow measurement of the flow of heavier nuclei. These results will contribute to shed light on their production mechanism and to study the properties of the hadron gas phase.

Further reading

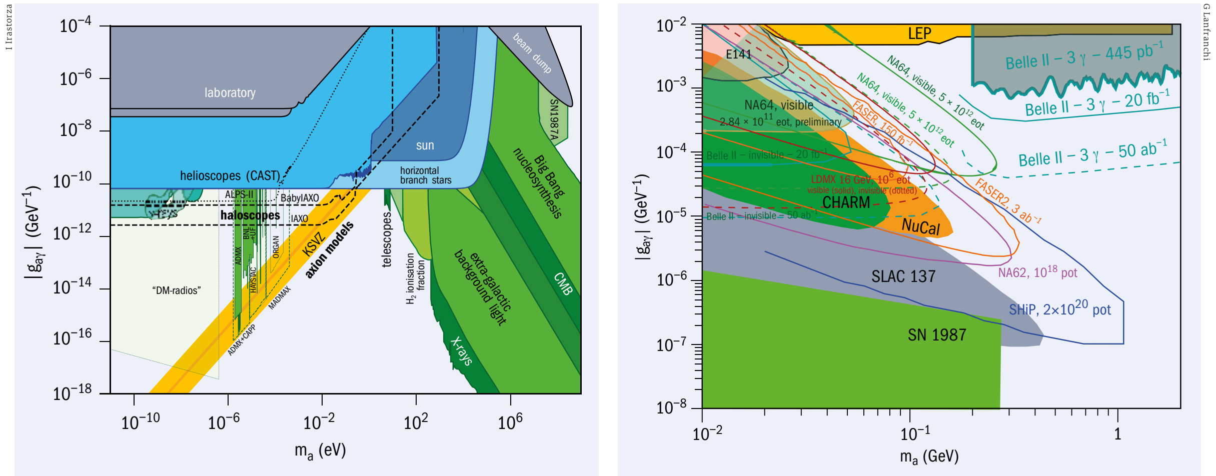
ALICE Collab. 2020 arXiv:2005.14639.

FIELD NOTES

Reports from events, conferences and meetings

FIPs 2020

Strong interest in feeble interactions



I Irastorza

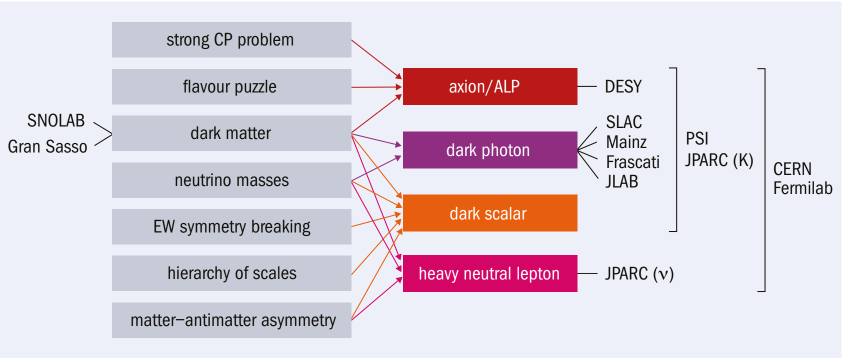
G Lanfranchi

Scaling the ALPs *Searches for axion-like particles (ALPs) at helioscopes, haloscopes and accelerators span more than 18 orders of magnitude in mass and 16 orders of magnitude in the coupling of axions to photons (left image), with the accelerator experiments investigating high masses and stronger couplings (see zoom image, right). The regions excluded at 90% confidence are plotted alongside a strip favoured by mainstream theoretical models (gold) and a range of potential astrophysical sources. The estimated future sensitivities are indicated by the dashed regions.*

Since the discovery of the Higgs boson in 2012, great progress has been made in our understanding of the Standard Model (SM) and the prospects for the discovery of new physics beyond it. Despite excellent advances in Higgs-sector measurements, searches for WIMP dark matter and exploration of very rare processes in the flavour realm, however, no unambiguous signals of new fundamental physics have been seen. This is the reason behind the explosion of interest in feebly interacting particles (FIPs) over the past decade or so.

The inaugural FIPs 2020 workshop, hosted online by CERN from 31 August to 4 September, convened almost 200 physicists from around the world. Structured around the four "portals" that may link SM particles and fields to a rich dark sector – axions, dark photons, dark scalars and heavy neutral leptons – the workshop highlighted the synergies and complementarities among a great variety of experimental facilities, and called for close collaboration across different physics communities.

Today, conventional experimental efforts are driven by arguments based on the naturalness of the electroweak scale. They result in searches for new particles with sizeable couplings to the SM, and masses near the electroweak scale. FIPs represent an alternative paradigm to the traditional beyond-the-SM physics explored at the LHC. With masses below the electroweak scale, FIPs could belong to a rich dark sector and answer many open questions in particle physics (see "Four portals" figure). Diverse searches using proton beams (CERN and Fermilab), kaon beams (CERN and JPARC), neutrino beams (JPARC and Fermilab) and muon beams (PSI) today join more idiosyncratic experiments across the globe in a worldwide search for FIPs. ▷



G Lanfranchi/M Rayner

Four portals *A selection of open questions in particle physics, their possible links to FIPs, and a broad-brush overview of the research avenues being pursued at laboratories worldwide.*

FIPs can arise from the presence of feeble couplings in the interactions of new physics with SM particles and fields. These may be due to a dimensionless coupling constant or to a "dimensionful" scale, larger than that of the process being studied, which is defined by a higher dimension operator that mediates the interaction. The smallness of these couplings can be due to the presence of an approximate symmetry that is only slightly broken, or to the presence of a large mass hierarchy between particles, as the absence of new-physics signals from direct and indirect searches seems to suggest.

Take the axion, for example. This is the particle that may be responsible for the conservation of charge-parity symmetry in strong interactions. It may also constitute a fraction or the entirety of dark matter, or explain the hierarchical masses and mixings of the SM fermions – the flavour puzzle.

Or take dark photons or dark Z' bosons, both examples of new vector gauge bosons. Such particles are associated with extensions of the SM gauge group, and, in addition to indicating new forces beyond the four we know, could lead to evidence of dark-matter candidates with thermal origins and masses in the MeV to GeV range.

Exotic Higgs bosons could also have been responsible for cosmological inflation

Then there are exotic Higgs bosons. Light dark scalar or pseudoscalar particles related to the SM Higgs may provide novel ways of addressing the hierarchy problem, in which the Higgs mass can be stabilised dynamically via the time evolution of a so-called "relaxion" field. They could also have been responsible for cosmological inflation.

Finally, consider right-handed neutrinos, often referred to as sterile neutrinos or heavy neutral leptons, which could account for the origin of the tiny, nearly-degenerate masses of the neutrinos of the SM and their oscillations, as well as providing a mechanism for our universe's matter-antimatter asymmetry.

Scientific diversity

No single experimental approach can cover the large parameter space of masses and couplings that FIPs models allow. The interconnections between open questions require that we construct a diverse research programme incorporating accelerator physics, dark-matter direct detection, cosmology, astrophysics, and precision atomic experiments, with a strong theoretical involvement. The breadth of searches for axions or axion-like particles (ALPs) is a good indication of the growing interest in FIPs (see "Scaling the ALPs" figure). Experimental efforts here span particle and astroparticle physics. In the coming years, helioscopes, which aim to detect solar axions by their conversion into photons (X-rays) in a strong magnetic field, will improve the sensitivity by more than 10 orders of magnitude in mass in the sub-eV range. Haloscopes, which work by converting axions into visible photons inside a resonant microwave cavity placed inside a strong magnetic field, will complement this quest by increasing the sensitivity for small couplings by six orders of magnitude (down to the theoretically motivated gold band in a mass region where the axions can be a dark-matter candidate). Accelerator-based experiments, meanwhile, can probe the strongly motivated QCD scale (MeV-GeV) and beyond for larger couplings. All these results will be complemented by a lively theoretical activity aimed at interpreting astrophysical signals within axion and ALP models.

FIPs 2020 triggered lively discussions that will continue in the coming months via topical meetings on different subjects. Topics that motivated particular interest between communities included possible ways of comparing results from direct-detection dark-matter experiments in the MeV-GeV range against those obtained at extracted beam line and collider experiments; the connection between right-handed neutrino properties and active neutrino parameters; and the interpretation of astrophysical and cosmological bounds, which often overwhelm the interpretation of each of the four portals.

The next FIPs workshop will take place at CERN next year.

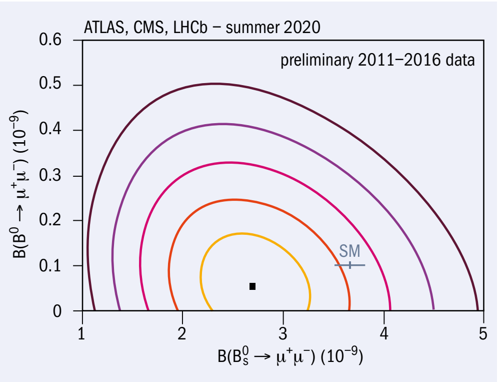
James Beacham *Duke University,*
Albert de Roeck *CERN and*
Gaia Lanfranchi *INFN.*

BEAUTY 2020

Heavy-flavour highlights from Beauty 2020

The international conference devoted to b-hadron physics at frontier machines, Beauty 2020, took place from 21 to 24 September, hosted virtually by Kavli IPMU, University of Tokyo. This year's edition, the 19th in the series, attracted around 350 registrants, significantly more than have attended physical Beauty conferences in the past. Two days were devoted to parallel sessions, a change in approach necessitated by the online format, stimulating lively discussion. There were 64 invited talks, of which 13 were overviews given by theorists.

Studies of beauty hadrons have great sensitivity to possible physics beyond the Standard Model (SM), as was stressed by Gino Isidori (University of Zurich) in the opening talk of the conference. Possible lepton-universality anomalies that have emerged from analyses of decays into pairs of leptons and accompanying hadrons are particularly tantalising, as they show significant deviations from the SM in a manner that could be explained by the existence of new particles such as leptoquarks or Z' bosons. We will know much more when LHCb releases measurements from the updated analysis of the full Run-2 data set. In the meantime, the combined results from ATLAS, CMS and LHCb for the branching ratio of the ultra-rare decay $B_s \to \mu^+\mu^-$ generated much discussion. This final state is produced only a few times every billion B_s decays, but is now measured to a remarkable precision of 13%. Intriguingly, the observed value of the branching ratio lies two standard deviations below the SM prediction (see "Ultra-rare" figure) – an effect that some commentators have noted could be driven by the same new particles invoked to explain the other flavour anomalies.



ATLAS/CMS/LHCb

Ultra-rare *A combination of results on $B^0 \to \mu\mu$ and $B^0_s \to \mu\mu$ from the ATLAS, CMS and LHCb experiments, showing the one through to five standard-deviation contours, and the prediction of the Standard Model.*

Recent impressive results were shown in the field of CP violation. LHCb presented the first ever observation of time-dependent CP violation in the B_s system – a phenomenon that has eluded previous experiments on account of the very fast (a rate of about 3×10^{12} Hz) B_s oscillations and inadequate sample sizes. In addition, new LHCb results were shown for the CP-violating phase γ. The most precise of these comes from an analysis that isolates $B \to DK$ decays which are followed by $D \to K_S\pi^+\pi^-$ decays, and the distributions of the final-state particles compared depending on whether they originate from B^- or B^+ mesons. This analysis is based on the full Run 1 and Run 2 data sets and constrains γ to a precision of five degrees, which from this single analysis alone represents around a four-fold improvement compared to when the LHC began operation. Further improvements are expected over the coming years.

Participants were eager to learn about the progress of the SuperKEKB accelerator and Belle II experiment. SuperKEKB is now operating at higher luminosity than any previous electron-positron machine, and the data set collected by Belle II (of the order 100 fb^{-1}) is already sufficient to demonstrate the capabilities of the detector and to allow for important early physics studies, which were shown during the week. Belle II has superior performance to the first-generation B-factory experiments, BaBar and Belle, in areas such as flavour tagging and proper-time resolution, and will collect around 50 times the integrated luminosity. By the end of the decade Belle II will have accumulated 50 ab^{-1} of data, from which many precise and exciting physics measurements are expected.

Studies of kaon decays provide important insights into flavour physics that are complementary to those obtained from b-hadrons. The NA62 collaboration presented its updated branching ratio for the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$, which is predicted to be around 10^{-10} in the SM. The data set is now sufficiently large to see a signal with a significance of more than three standard deviations. Future running is planned to allow a measurement to be made with a 10-20% precision, which will provide a powerful test of the SM prediction (*CERN Courier* September/October 2020 p9).

The concluding plenary session focused on the future of flavour physics. The LHCb experiment is currently being upgraded, and a further upgrade is foreseen at the end of the decade. In parallel, the upgrades of ATLAS and CMS will increase their capabilities for beauty studies. In the electron-positron domain, Belle II will continue to accumulate data, and there is the exciting possibility of a super-tau-charm factory, situated in either China or Russia, which will collect very large data sets at lower energies. These prospects were surveyed by Phillip Urquijo (University of Melbourne) in the summary talk of the conference, who stressed the importance of exploiting these ongoing and future facilities to the maximum. Flavour studies have a bright future, and they are sure to retain a central role in our search for physics beyond the SM.

Recent impressive results were shown in the field of CP violation

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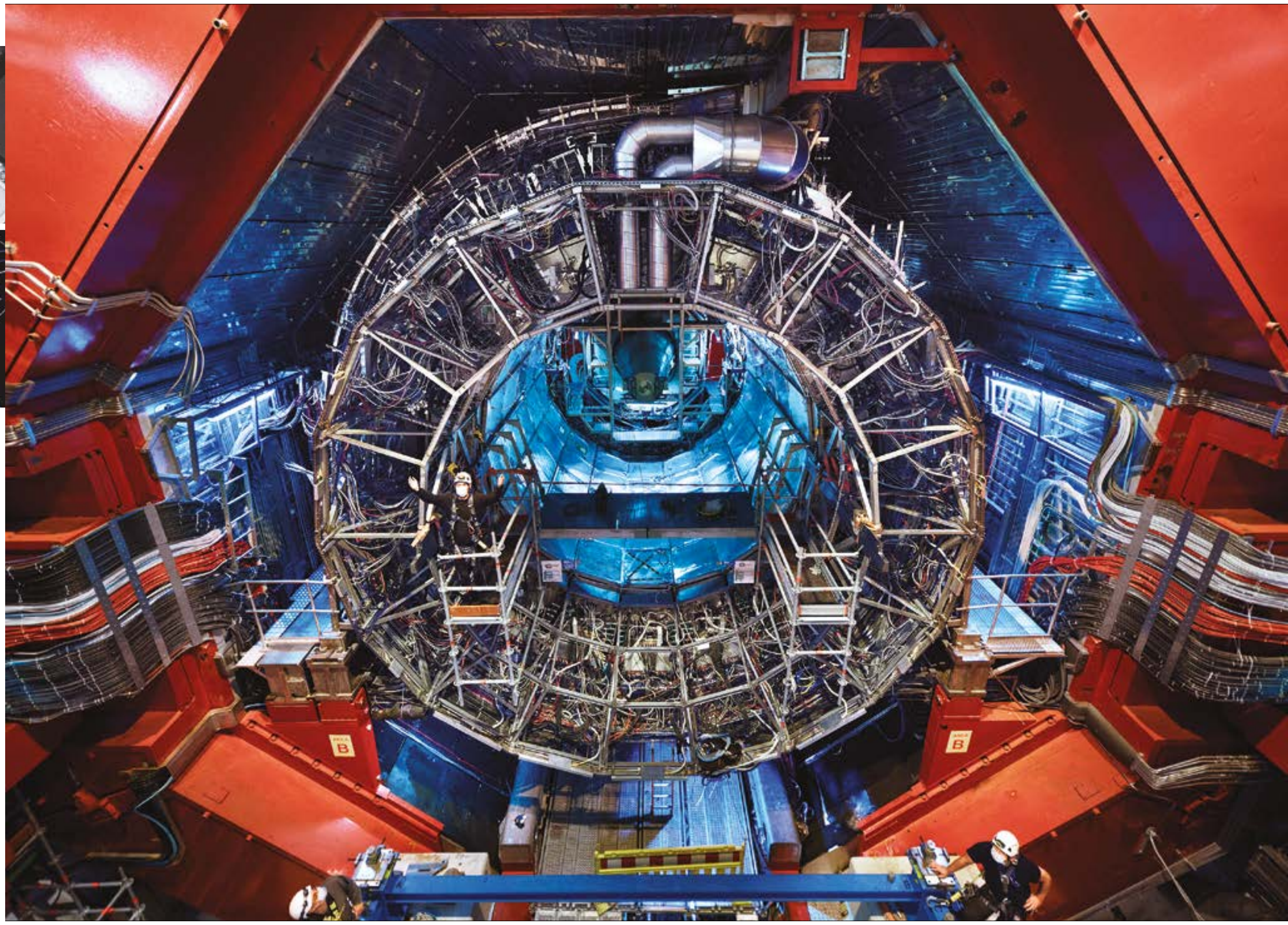


Opening doors *The ALICE experiment pictured in August, ready to welcome its upgraded TPC – a vital detector for studying the production and annihilation of antinuclei. (Credit: CERN-PHOTO-202008-104-63)*

ALICE'S DARK SIDE

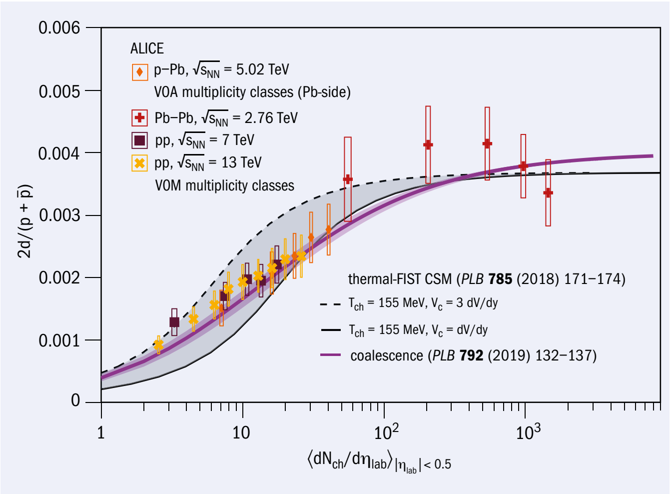
Precision measurements of the production and annihilation of light antinuclei at the LHC's ALICE experiment are sharpening the search for dark matter, explain Maximiliano Puccio and Ivan Vorobyev.

THE AUTHORS

Maximiliano Puccio *CERN* *and* **Ivan Vorobyev** *Technische Universität München.*

The nature of dark matter (DM) remains one of the most intriguing unsolved questions of modern physics. Astrophysical and cosmological observations suggest that DM accounts for roughly 27% of the mass-energy of the universe, with dark energy comprising 68% and ordinary baryonic matter as described by the Standard Model accounting for a paltry 5%. This massive hole in our understanding of the universe continues to drive multiple experimental searches for DM both in the laboratory and in space. No clear evidence for DM has yet been found, severely constraining the parameter space of the most popular "thermal" DM models.

Assuming DM is a material substance comprised of particles – not an illusion resulting from an imperfect



Source: *Eur. Phys. J. C* **80** 889

Competing models *The ratio of (anti)deuterons to protons in p–p, p–Pb and Pb–Pb collisions as a function of the average number of charged particles produced. The purple line shows the expectation of the coalescence model while the solid and dashed black lines represent extreme parameter configurations for the statistical hadronisation model.*

understanding of gravity – there are three independent ways to search for it. One is to directly measure the production of DM particles in a high-energy collider such as the LHC. Another is to infer the presence of DM particles via their scattering off nuclei, as investigated by large underground detectors such as XENON1T and LUX. A third, similarly indirect, strategy is to search for the annihilation or decay of DM particles into ordinary (anti) particles such as positrons or antinuclei – as employed by the AMS experiment on board the International Space Station and in balloon-borne experiments such as GAPS. Low-energy light antinuclei, such as antideuterons and antihelium, are particularly promising signals for such indirect DM searches, since the background stemming from ordinary collisions between cosmic rays and the interstellar medium is expected to be low with respect to the DM signal.

The ability to interpret any future observation of antinuclei in our galaxy – especially when trying to identify their creation in exotic processes like DM annihilations – requires a quantitative understanding of light antinuclei production and annihilation mechanisms within the interstellar medium. However, the production of light antinuclei in hadronic collisions between cosmic rays and the interstellar medium is still not fully understood: different models compete to explain how these loosely bound objects can be formed in such high-energy collisions. Furthermore, the inelastic annihilation cross section of light antinuclei with matter is completely unknown in the kinematic region relevant for indirect DM searches, forcing current estimates to rely on extrapolations and modelling.

Fortunately, both the antinuclei production mechanism and the interactions between antinuclei and ordinary matter can be studied on Earth using large accelerators. The main contributions so far have come from the LHC at CERN and from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Thanks to its unique low-material-budget tracker, which provides excellent tracking and particle-identification performance for low-momentum particles, ALICE is the only experiment at the LHC that is able to study the production and annihilation of low-energy antinuclei.

ALICE is the only experiment at the LHC that is able to study the production and annihilation of low-energy antinuclei

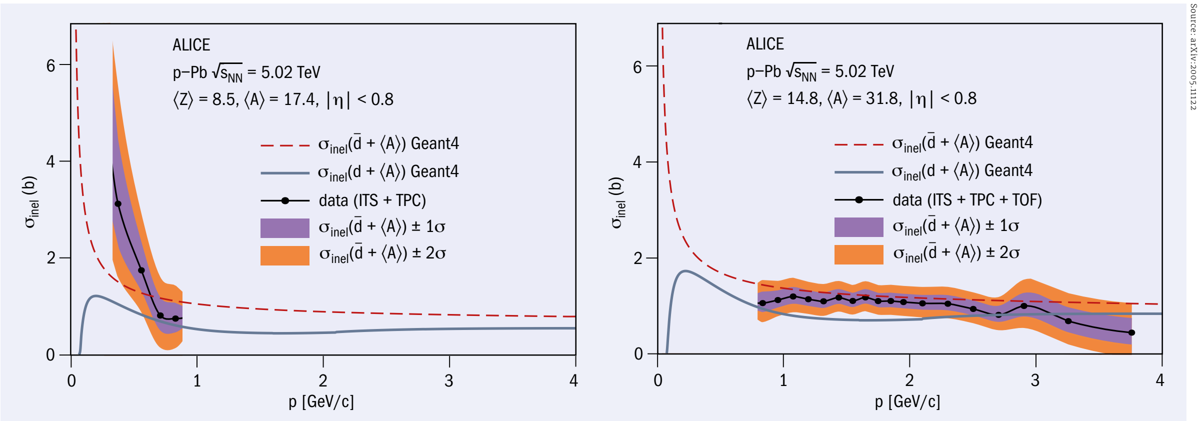
Antinucleosynthesis in the lab

While antinuclei can also be produced at lower collision energies, only at the LHC are matter and antimatter generated in equal abundances in the region transverse to the beam direction. The most abundant non-trivial antinucleus produced is the antideuteron, which consists of an antineutron and an antiproton. At low momentum, deuterons and antideuterons can be clearly identified thanks to their high energy loss in the ALICE detector's time-projection chamber. At larger momenta, a clean identification of antideuterons is possible using the ALICE time-of-flight detector. This information, combined with the measured track length and the particle momentum, provide a precise determination of the particle mass. Using these and other techniques, the ALICE collaboration has recently measured the production of (anti)deuterons in proton–proton collisions, as well as in other colliding systems, and set tight constraints on the production models of (anti)nuclei.

There are two main ways to model the production mechanism of (anti)nuclei. Coalescence models assume that primary (anti)neutrons and (anti)protons can bind if they are close enough in phase space. Statistical hadronisation models, on the other hand, assume that hadrons and (anti) nuclei emerge when the collision system reaches thermodynamical equilibrium, making the temperature and the volume of the system the key parameters. Measurements of nuclei-to-proton ratios in various colliding systems have recently enabled the ALICE collaboration to compare the two model approaches in detail (see "Competing models" figure). As can be seen, the two models give different predictions for the evolution of the nuclei-to-proton ratio versus particle multiplicity, with the latest ALICE measurements slightly favouring the coalescence approach.

Similar conclusions about the two models can be drawn using heavier antinuclei, like $^3\overline{\text{He}}$ and $^4\overline{\text{He}}$, which were already measured by ALICE in p–Pb and Pb–Pb collisions. The achievable precision of the measurement is limited by the available data: the antinuclei production rate in pp collisions goes down by a factor of about 1000 for every additional antinucleon in the antinucleus.

The precision of the measurements from proton–proton collisions places strong constraints on the production models, which can then be used to predict the antinuclei fluxes in space. Indeed, the ALICE measurements combined with different coalescence models have already been employed to estimate the antideuteron and antihelium flux from cosmic-ray interactions measurable by the AMS and GAPS experiments. These predictions will allow correct interpretations of the eventual antinuclei signal that might be observed in the future by the two collaborations.



Source: arXiv:2005.11122

Interaction probability *Antideuteron inelastic interaction cross section measured in different ALICE subdetectors. The dashed red line represents the parameterisations used for antideuterons in the Geant4 toolkit, and the full grey line shows the parameterisations for deuterons. The full points correspond to the experimental measurements, whereas the purple and orange bands are the one and two sigma uncertainty intervals, respectively.*

Further helping clarify the results of indirect DM searches, ALICE has recently performed the first measurement of the antideuteron inelastic cross section in the momentum range $0.3 < p < 4$ GeV/c – significantly extending our knowledge about this cross section from previous measurements at momenta of 13 and 25 GeV/c at the Serpukhov accelerator complex in Russia in the early 1970s. The collaboration took advantage of the ability of antideuterons produced at the LHC to interact inelastically with the detector material. To quantify this process, ALICE has employed a novel approach based on the antideuteron-to-deuteron ratio reconstructed in collisions of protons and heavy ions at a centre-of-mass energy per nucleon–nucleon pair of 5.02 TeV. Such a ratio depends on both of the inelastic cross sections of deuterons and antideuterons. The former has been measured in various previous experiments at different momenta; the latter can be constrained from the ALICE data by comparing the measured ratio with detailed Monte Carlo simulations.

The resulting antideuteron inelastic cross section is shown (see "Interaction probability" figure), where the two panels correspond to the different sub-detectors employed in the analysis and therefore to different average material crossed by (anti)deuterons – corresponding to a difference of about a factor two in average mass number. The inelastic cross sections include all possible inelastic antideuteron processes such as break-up, annihilation or charge exchange, and the analysis procedure was validated by demonstrating consistency with existing antiproton results from traditional scattering experiments.

The momentum range covered in this latest analysis is of particular importance to evaluate the signal predictions for indirect dark-matter searches. Additionally, these measurements can help researchers to understand the low-energy antideuteron inelastic processes and to model better the inelastic antideuteron cross sections in widely-used toolkits such as Geant4. Together with the proper modelling of antinuclei formation, the obtained results will impact the antideuteron flux expectations at low momentum for ongoing and future satellite- and balloon-borne experiments.

The heavier, the better

ALICE is studying the full range of antinuclei physics with unprecedented precision. These results, which have started to emerge only since 2015, are contributing significantly to our understanding of antinuclei formation and annihilation processes, with important ramifications for DM searches. Both the statistical hadronisation and coalescence models can describe antideuteron production at the LHC, while the detector material can be used as an absorber to study the antinuclei inelastic cross section at low energies relevant for the astrophysical applications.

For the foreseeable future, ALICE will continue to provide an essential reference for the interpretation of astrophysics measurements of antinuclei in space. With the increased integrated luminosity that will be acquired by ALICE during LHC Run 3 from early 2022, it will be possible to extend the current analyses to heavier (anti)nuclei, such as $^3\overline{\text{He}}$ and $^4\overline{\text{He}}$, with even better precision than the currently available measurements for (anti)deuterons. This will allow the collaboration to perform fundamental tests of the production and annihilation mechanisms with heavier, doubly-charged antinuclei, which are more easily identified by satellite-borne experiments and thus expected to provide an even clearer DM signature. ●

The momentum range covered is of particular importance to evaluate the signal predictions for indirect dark-matter searches

Further reading

ALICE Collab. 2020 *Eur. Phys. J. C* **80** 889.
ALICE Collab. 2020 *Phys. Rev. Lett.* **125** 162001.
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K Blum *et al.* 2017 *Phys. Rev. D* **96** 103021.
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A Shukla *et al.* 2020 *Phys. Rev. D* **102** 063004.

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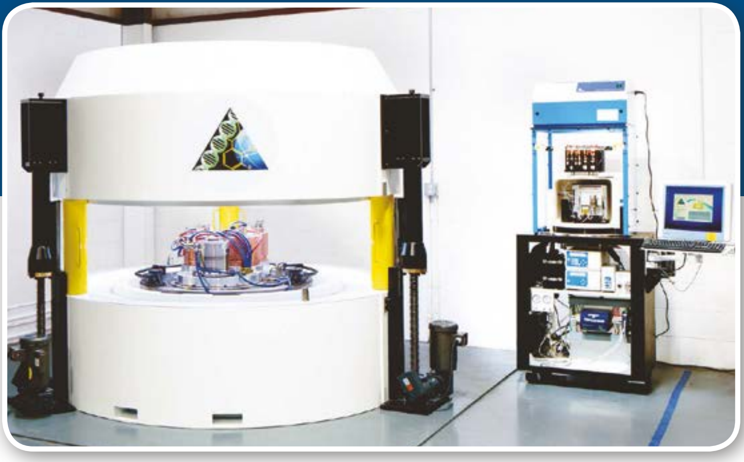

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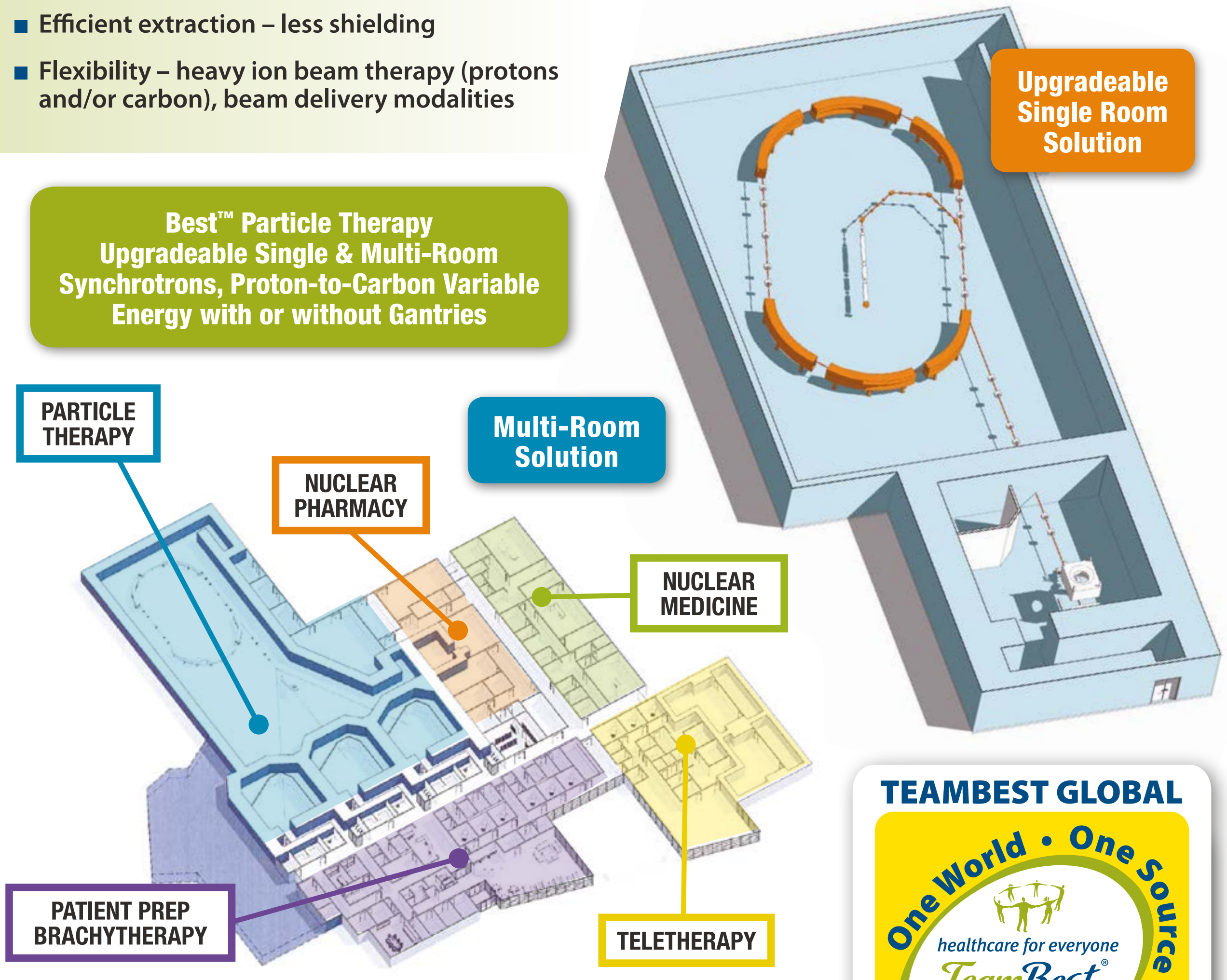

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NEUTRINOS FOR PEACE

Detectors similar to those used to hunt for sterile neutrinos could help guard against the extraction of plutonium-239 for nuclear weapons, writes Patrick Huber.

The first nuclear-weapons test shook the desert in New Mexico 75 years ago. Weeks later, Hiroshima and Nagasaki were obliterated. So far, these two Japanese cities have been the only ones to suffer such a fate. Neutrinos can help to ensure that no other city has to be added to this dreadful list.

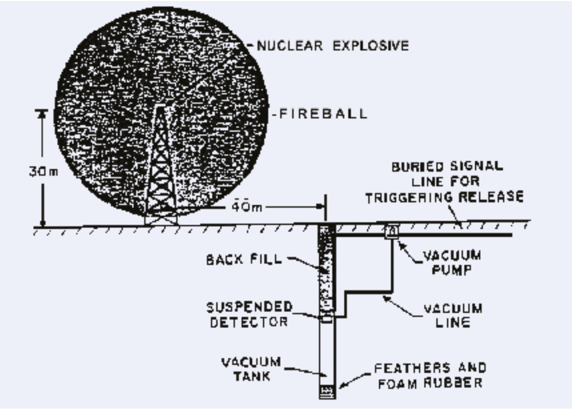
At the height of the arms race between the US and the USSR, stockpiles of nuclear weapons exceeded 50,000 warheads, with the majority being thermonuclear designs vastly more destructive than the fission bombs used in World War II. Significant reductions in global nuclear stockpiles followed the end of the Cold War, but the US and Russia still have about 12,500 nuclear weapons in total, and the other seven nuclear-armed nations have about 1500. Today, the politics of non-proliferation is once again tense and unpredictable. New nuclear security challenges have appeared, often from unexpected actors, as a result of leadership changes on both sides of the table. Nuclear arms races and the dissolution of arms-control treaties have yet again become a real possibility. A regional nuclear war involving just 1% of the global arsenal would cause a massive loss of life, trigger climate effects leading to crop failures and jeopardise the food supply of a billion people. Until we achieve global disarmament, nuclear non-proliferation efforts and arms control are still the most effective tools for nuclear security.

Technology demonstration *Technicians assemble the PROSPECT neutrino detector, which was installed a few metres from the High Flux Isotope Reactor at Oak Ridge National Laboratory in Tennessee. Similar technologies could be used to monitor nuclear reactors.*

PROSPECT collaboration/M Lavitt

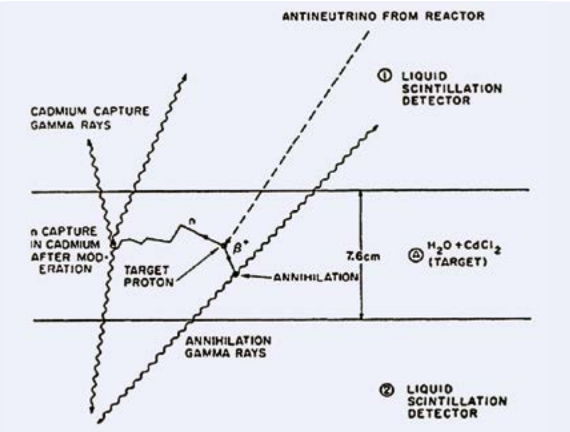
Not a bang but a whimper

The story of the neutrino is closely tied to nuclear weapons. The first serious proposal to detect the particle hypothesised by Pauli, put forward by Clyde Cowan and Frederick Reines in the early 1950s, was to use a nuclear explosion as the source (see "Daring experiment" figure). Inverse beta decay, whereby an electron-antineutrino strikes a free proton and transforms it into a neutron and a positron, was to be the detection reaction. The proposal was approved in 1952 as an addition to an already planned atmospheric nuclear-weapons test. However, while preparing for this experiment, Cowan and Reines realised that by capturing the neutron on a cadmium nucleus, and observing the delayed coincidence between the positron and this neutron, they could use the lower, but steady flux of neutrinos from a nuclear reactor instead (see "First detection" figure). This technique is still used today, but with gadolinium or lithium in place of cadmium.



F Reines

Daring experiment *Before observing neutrinos streaming from a nuclear reactor, Fred Reines and Clyde Cowan initially proposed to discover the particles using a nuclear explosion. A detector would be suspended in a vertical vacuum tank and allowed to free-fall until the shock wave had passed.*



F Reines

First detection *Reines and Cowan's "delayed coincidence" detection scheme. The neutron is captured on a cadmium nucleus about 10 microseconds after the prompt event caused by the positron annihilation, and the subsequent nuclear de-excitation tagged.*

The P reactor at the Savannah River site at Oak Ridge National Laboratory, which had been built and used to make plutonium and tritium for nuclear weapons, eventually hosted the successful experiment to first detect the neutrino in 1956. Neutrino experiments testing the properties of the neutrino including oscillation searches continued there until 1988, when the P reactor was shut down.

Neutrinos are not produced in nuclear fission itself, but by the beta decays of neutron-rich fission fragments – on average about six per fission. In a typical reactor fuelled by natural uranium or low-enriched uranium, the reactor starts out with only uranium-235 as its fuel. During operation a significant number of neutrons are absorbed on uranium-238, which is far more abundant, leading to the formation of uranium-239, which after two beta decays becomes plutonium-239. Plutonium-239 eventually contributes to about 40% of the fissions, and hence energy production, in a commercial reactor. It is also the isotope used in nuclear weapons.

The dual-use nature of reactors is at the crux of nuclear non-proliferation. What distinguishes a plutonium-production reactor from a regular reactor producing electricity is whether it is operated in such a way that the plutonium can be taken out of the reactor core before it deteriorates and becomes difficult to use in weapons applications. A reactor with a low content of plutonium-239 makes more and higher energy neutrinos than one rich in plutonium-239.

> The story of the neutrino is closely tied to nuclear weapons

Lev Mikaelyan and Alexander Borovoi, from the Kurchatov Institute in Moscow, realised that neutrino emissions can be used to infer the power and plutonium content of a reactor. In a series of trailblazing experiments at the Rovno nuclear power plant in the 1980s and early 1990s, their group demonstrated that a tonne-scale underground neutrino detector situated 10 to 20 metres from a reactor can indeed track its power and plutonium content.

The significant drawback of neutrino detectors in the 1980s was that they needed to be situated underground, beneath a substantial overburden of rock, to shield them from cosmic rays. This greatly limited potential deployment sites. There was a series of application-related experiments – notably the successful SONGS experiment conducted by researchers at Lawrence Livermore National Laboratory, which aimed to reduce cost and improve the robustness and remote operation of neutrino detectors – but all of these detectors still needed shielding.

From cadmium to gadolinium

Synergies with fundamental physics grew in the 1990s, when the evidence for neutrino oscillations was becoming impossible to ignore. With the range of potential oscillations frequencies narrowing, the Palo Verde and Chooz

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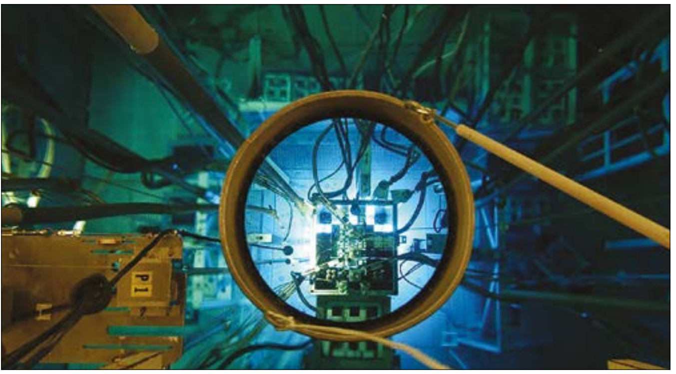


CEA Saclay

Purpose driven *A spin off from Double Chooz, the Nucifer detector was small and efficient at detecting neutrinos, but required a significant overburden of rock.*

reactor experiments placed multi-tonne detectors about 1km from nuclear reactors, and sought to measure the relatively small θ_{13} parameter of the neutrino mixing matrix, which expresses the mixing between electron neutrinos and the third neutrino mass eigenstate. Both experiments used large amounts of liquid organic scintillator doped with gadolinium. The goal was to tag antineutrino events by capturing the neutrons on gadolinium, rather than the cadmium used by Reines and Cowan. Gadolinium produces 8 MeV of gamma rays upon de-excitation after a neutron capture. As it has an enormous neutron-capture cross section, even small amounts greatly enhance an experiment's ability to identify neutrons.

Eventually, neutrino oscillations became an accepted fact, redoubling the interest in measuring θ_{13}. This resulted in three new experiments: Double Chooz in France, RENO in South Korea, and Daya Bay in China. Learning lessons from Palo Verde and Chooz, the experiments successfully measured θ_{13} more precisely than any other neutrino mixing parameter. A spin-off from the Double Chooz experiment was the Nucifer detector (see "Purpose driven" figure), which demonstrated the operation of a robust sub-tonne-scale detector designed with missions to monitor reactors in mind, in alignment with requirements formulated at a 2008 workshop held by the International Atomic Energy Agency (IAEA). However, Nucifer still needed a significant overburden.

In 2011, however, shortly before the experiments established that θ_{13} is not zero, fundamental research once again galvanised the development of detector technology for reactor monitoring. In the run-up to the Double Chooz experiment, a group at Saclay started to re-evaluate the predictions for reactor neutrino fluxes – then and now based on measurements at the Institut Laue-Langevin in the 1980s – and found to their surprise that the reactor flux prediction came out 6% higher than before. Given that all prior experiments were in agreement with the old flux predictions, neutrinos were missing. This "reactor-antineutrino anomaly" persists to this day. A sterile neutrino with a mass of about 1 eV would be a simple explanation. This mass range has been suggested by experiments with accelerator neutrinos, most notably LSND and MiniBooNE, though it conflicts with predictions that muon neutrinos should oscillate into such a sterile neutrino, which experiments such as MINOS+ have failed to confirm.

To directly observe the high-frequency oscillations of an eV-scale sterile neutrino you need to get within about 10 m of the reactor. At this distance, backgrounds from the operation of the reactor are often non-negligible, and no overburden is possible – the same conditions a detector on a safeguards mission would encounter.

From gadolinium to lithium

Around half a dozen experimental groups are chasing sterile neutrinos using small detectors close to reactors. Some of the most advanced designs use fine spatial segmentation to reject backgrounds, and replace gadolinium with lithium-6 as the nucleus to capture and tag neutrons. Lithium has the advantage that upon neutron capture it produces an alpha particle and a triton rather than a handful of photons, resulting in a very well localised tag. In a small detector this improves event containment and thus efficiency, and also helps constrain event topology.

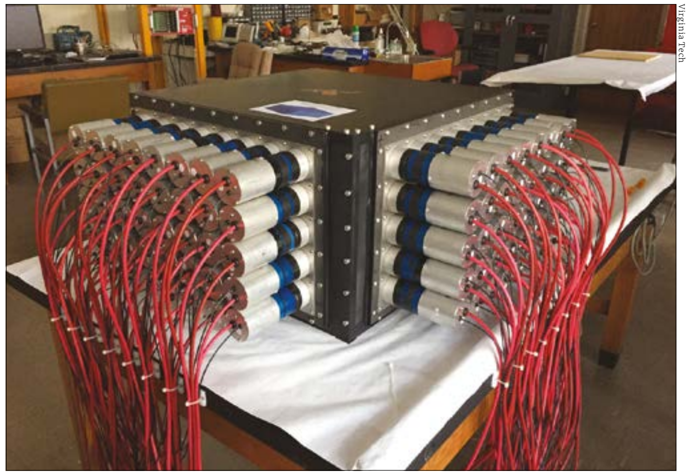
Following the lithium and finely segmented technical paths, the PROSPECT collaboration and the CHANDLER collaboration (see "Rapid deployment" figure), in which I participate, independently reported the detection of a neutrino spectrum with minimal overburden and high detection efficiency in 2018. This is a major milestone in making non-proliferation applications a reality, since it is the first demonstration of the technology needed for tonne-scale detectors capable of monitoring the plutonium content of a nuclear reactor that could be universally deployed without the need for special site preparation.

The main difference between the two detectors is that PROSPECT, which reported its near-final sterile neutrino limit at the Neutrino 2020 conference, uses a traditional approach with liquid scintillator, whereas CHANDLER, currently an R&D project, uses plastic scintillator. The use of plastic scintillator allows the deployment time-frame to be shortened to less than 24 hours. On the other hand, liquid scintillator allows the exploitation of pulse-shape discrimination to reject cosmic-ray neutron backgrounds, allowing PROSPECT to achieve a much better signal-to-background ratio than any plastic detector to date. Active R&D is seeking to improve topological reconstruction in plastic detectors and imbue them with pulse-shape discrimination. In addition, a number of safeguard-specific detector R&D experiments have successfully detected reactor neutrinos using plastic scintillator in conjunction with gadolinium. In the UK, the VIDARR collaboration has seen neutrinos from the Wylfa reactor, and in Japan the PANDA collaboration successfully operated a truck-mounted detector.

In parallel to detector development, studies are being undertaken to understand how reactor monitoring with neutrinos would impact nuclear security and support non-proliferation objectives. Two very relevant situations being studied are the 2015 Iran Deal – the Joint Comprehensive Plan of Action (JCPOA) – and verification concepts for a future agreement with North Korea.

Nuclear diplomacy

One of the sticking points in negotiating the 2015 Iran deal was the future of the IR-40 reactor, which was being constructed at Arak, an industrial city in central Iran. The IR-40 was planned to be a 40 MW reactor fuelled by natural uranium and moderated with heavy water, with a stated purpose of isotope production for medical and scientific use. The choice of fuel and moderator is interesting, as it meshes with Iranian capabilities and would serve the stated purpose well and be cost effective, since no uranium enrichment is needed. Equally, however, if one were to design a plutonium-production reactor for a nascent weapons programme, this combination would be one of the top choices: it does not require uranium enrichment, and with the stated reactor power would result in the annual production of about 10 kg of rather pure plutonium-239. This matches the critical mass of a bare plutonium-239 sphere, and it is known that as little as 4 kg can be used to make an effective nuclear explosive. Within the JCPOA it was eventually agreed that the IR-40 could be redesigned, down-rated in power to 20 MW and the new core fuelled with 3.7% enriched fuel, reducing the annual plutonium production by a factor of six.



Virginia Tech

Rapid deployment *The prototype "MiniCHANDLER" detector at Virginia Tech. Made from plastic rather than liquid scintillator, a robust CHANDLER-type detector could be rapidly deployed at a nuclear reactor.*

A 10 to 20 tonne neutrino detector 20 m from the reactor would be able to measure its plutonium content with a precision of 1 to 2 kg. This would be particularly relevant in the so-called N-th month scenario, which models a potential crisis in Iran based on events in North Korea in June 1994. During the 1994 crisis, which risked precipitating war with the US, the nuclear reactor at Yongbyon was shut down, and enough spent fuel rods removed to make several bombs. IAEA protocols were sternly tested. The organisation's conventional safeguards for operating reactors consist of containment and surveillance – seals, for example, to prevent the unnoticed opening of the reactor, and cameras to record the movement of fuel, most crucially during reactor shutdowns. In the N-th month scenario, the IR-40 reactor, in its pre-JCPOA configuration (40 MW, rather than the renegotiated power of 20 MW), runs under full safeguards for N–1 months. In month N, a planned reactor shutdown takes place. At this point the reactor would contain 8 kg of weapons-grade plutonium. For unspecified reasons the safeguards are then interrupted. In month N+1, the reactor is restarted and full safeguards are restored. The question is: are the 8 kg of plutonium still in the reactor core, or has the core been replaced with fresh fuel and the 8 kg of plutonium illicitly diverted?

The disruption of safeguards could either be due to equipment failure – a more frequent event than one might assume – or due to events in the political realm ranging from a minor unpleasantness to a full-throttle dash for a nuclear weapon. Distinguishing the two scenarios would be a matter of utmost urgency. According to an analysis including realistic backgrounds extrapolated from the PROSPECT results, this could be done in 8 to 12 weeks with a neutrino detector.

No conventional non-neutrino technologies can match this performance without shutting the reactor down and sampling a significant fraction of the highly radioactive fuel. The conventional approach would be extremely disruptive to reactor operations and would put inspectors and plant operators at risk of radiation exposure. Even if the host country were to agree in principle, developing a safe plan and having all sides agree on its feasibility would take months at the very least, creating dangerous ambiguity in the interim and giving hardliners on both sides time to push for an escalation of the crisis. The conventional approach would also be significantly more expensive than a neutrino detector.

New negotiating gambit

The June 1994 crisis at Yongbyon still overshadows negotiations with North Korea, since, as far as North Korea is concerned, it discredited the IAEA. Both during the crisis, and subsequently, international attempts at non-proliferation failed to prevent North Korea from acquiring nuclear weapons – its first nuclear-weapons test took place in 2006 – or even to constrain its progress towards a small-scale operational nuclear force. New approaches are therefore needed, and recent attempts by the US to achieve progress on this issue prompted an international group of about 20 neutrino experts from Europe, the US, Russia, South Korea, China and Japan to develop specific deployment scenarios for neutrino detectors at the Yongbyon nuclear complex.

The main concern is the 5 MWe reactor, which, though named for its electrical power, has a thermal power of 20 MW. This gas-cooled graphite-moderated reactor, fuelled with natural uranium, has been the source of all of North Korea's plutonium. The specifics of this reactor, and in particular its fuel cladding, which makes prolonged wet-storage of irradiated fuel impossible, represent such a proliferation risk that anything but a monitored shutdown prior to a complete dismantling appears inappropriate. To safeguard against the regime reneging on such a deal, were it to be agreed, a relatively modest tonne-scale neutrino detector right outside the reactor building could detect a powering up of this reactor within a day.

North Korea is also constructing the Experimental Light Water Reactor at Yongbyon. A 150 MW water-moderated reactor running with low-enriched fuel, this reactor would not be particularly well suited to plutonium production.

To directly observe the high-frequency oscillations of an eV-scale sterile neutrino you need to get within about 10 m of the reactor

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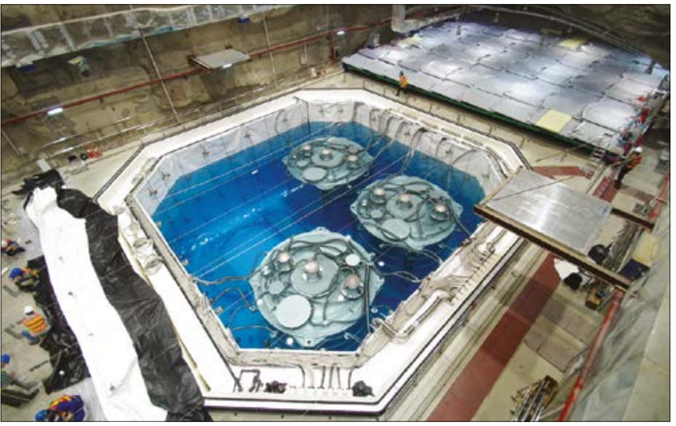
CERN

Daya Bay



A different scenario *Three of the 20 tonne neutrino detectors employed by the Daya Bay experiment in China. To monitor a total shutdown of all reactors at Yongbyon, it would be feasible to bury a 50 tonne single volume detector of similar design under a nearby mountain in North Korea.*

Its design is not dissimilar to much larger reactors used throughout the world to produce electricity, and it could help address the perennial lack of electricity that has limited the development and growth of the country's economy. North Korea may wish to operate it indefinitely. A larger, 10 tonne neutrino detector could detect any irregularities during its refuelling – a tell-tale sign of a non-civilian use of the reactor – on a timescale of three months, which is within the goals set by the IAEA.

In a different scenario, wherein the goal would be to monitor a total shutdown of all reactors at Yongbyon, it would be feasible to bury a Daya-Bay-style 50 tonne single volume detector under the Yak-san, a mountain about 2 km outside of the perimeter of the nuclear installations (see "A different scenario" figure). The cost and deployment timescale would be more onerous than in the other scenarios.

In the case of longer distances between reactor and detector, detector masses must increase to compensate an inverse-square reduction in the reactor-neutrino flux. As cosmic-ray backgrounds remain constant, the detectors must be deployed deep underground, beneath an overburden of several 100 m of rock. To this end, the UK's Science and Technology Facilities Council, the UK Atomic Weapons Establishment and the US Department of Energy, are funding the WATCHMAN collaboration to pursue the construction of a multi-kilo-tonne water-Cherenkov detector at the Boulby mine, 20 km from two reactors in Hartlepool, in the UK. The goal is to demonstrate the ability to monitor the operational status of the reactors, which have a combined power of 3000 MW. In a use-case context this would translate to excluding the operation of an undeclared 10 to 20 MW reactor within a radius of a few kilometres , but no safeguards scenario has emerged where this would give a unique advantage.

Inverse-square scaling eventually breaks down around 100 km, as at that distance the backgrounds caused by civilian reactors far outshine any undeclared small reactor almost anywhere in the northern hemisphere. Small signals also prevent the use of neutrino detectors for nuclear-explosion monitoring, or to confirm the origin of a suspicious seismic event as being nuclear, as conventional technologies are more feasible than the very large detectors that would be needed. A more promising future application of neutrino-detector technology is to meet the new challenges posed by advanced nuclear-reactor designs.

Neutrino detectors could be effective in addressing the safeguard challenges presented by advanced reactors

Advanced safeguards

The current safeguards regime relies on two key assumptions: that fuel comes in large, indivisible and individually identifiable units called "fuel assemblies", and that power reactors need to be refuelled frequently. Most advanced reactor designs violate at least one of these design characteristics. Fuel may come in thousands of small pebbles or be molten, and its coolant may not be transparent, in contrast to current designs, where water is used as moderator, coolant and storage medium in the first years after discharge. Either way, counting and identification of the fuel by serial number may be impossible. And unlike current power reactors, which are refuelled on a 12-to-18-month cycle, allowing in-core fuel to be verified as well, advanced reactors may be refuelled only once in their lifetime.

Neutrino detectors would not be hampered by any of these novel features. Detailed simulations indicate that they could be effective in addressing the safeguard challenges presented by advanced reactors. Crucially, they would work in a very similar fashion for any of the new reactor designs.

In 2019 the US Department of Energy chartered and funded a study (which I co-chair) with the goal of determining the utility of the unique capabilities offered by neutrino detectors for nuclear security and energy applications. This study includes investigators from US national laboratories and academia more broadly, and will engage and interview nuclear security and policy experts within the Department of Energy, the State Department, NGOs, academia, and international agencies such as the IAEA. The results are expected early in 2021. They should provide a good understanding of where neutrinos can play a role in current and future monitoring and verification agreements, and may help to guide neutrino detectors towards their first real-world applications.

The idea of using neutrinos to monitor reactors has been around for about 40 years. Only very recently, however, as a result of a surge of interest in sterile neutrinos, has detector technology become available that would be practical in real-world scenarios such as the JCPOA or a new North Korean nuclear agreement. The most likely initial application will be near-field reactor monitoring with detectors inside the fence of the monitored facility as part of a regional nuclear deal. Such detectors will not be a panacea to all verification and monitoring needs, and can only be effective if there is a sincere political will on both sides, but they do offer more room for creative diplomacy, and a technology that is robust against the kinds of political failures which have derailed past agreements. ●

Further reading

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TESLA'S HIGH-GRADIENT MARCH

Established 30 years ago with a linear electron–positron collider in mind, the TESLA Technology Collaboration has played a major role in the development of superconducting radio-frequency cavities and related technologies for a wide variety of applications.

D Noelle/DESY

Standing tall *Superconducting radio-frequency cavities at DESY.*

Energetic beams of charged particles are essential for high-energy physics research, as well as for studies of nuclear structure and dynamics, and deciphering complex molecular structures. In principle, generating such beams is simple: provide an electric field for acceleration and a magnetic field for bending particle trajectories. In practice, however, the task becomes increasingly challenging as the desired particle energy goes up. Very high electric fields are required to attain the highest energy beams within practical real-estate constraints.

The most efficient way to generate the very high electric fields in a vacuum environment required to transport a beam is to build up a resonant excitation of radio waves inside a metallic cavity. There is something of an art to shaping such cavities to "get the best bang for the buck" for a particular application. The radio-frequency (RF) fields are inherently time-varying, and bunches of charged particles need to arrive with the right timing if they are to see only forward-accelerating electric fields. Desirable very high resonant electric fields (e.g. 5–40 MV/m) require the existence of very high currents in the cavity walls. These currents are simply not sustainable for long durations using even the best normal-conducting materials, as they would melt from resistive heating.

Superconducting materials, on the other hand, can support sustainable high-accelerating gradients with an affordable electricity bill. Early pioneering work demonstrating the first beam-acceleration using superconducting radio-frequency (SRF) cavities took place in the late 1960s and early 1970s at Stanford, Caltech, the University of Wuppertal and Karlsruhe. The potential for real utility was clear, but techniques and material refinements were needed. Several individual laboratories began to take up the challenge for their own research needs. Solutions were developed for electron acceleration at CESR, HERA, TRISTAN, LEP II and CEBAF, while heavy-ion SRF acceleration solutions were developed at Stony Brook, ATLAS, ALPI and others. The community of SRF accelerator physicists was small but the lessons learned were consistently shared and documented. By the early 1990s, SRF technology had matured such that complex large-scale systems were credible and the variety of designs and applications began to blossom.

The TESLA springboard

In 2020, the TESLA Technology Collaboration (TTC) celebrates 30 years of collaborative efforts on SRF technologies. The TTC grew out of the first international TESLA (TeV

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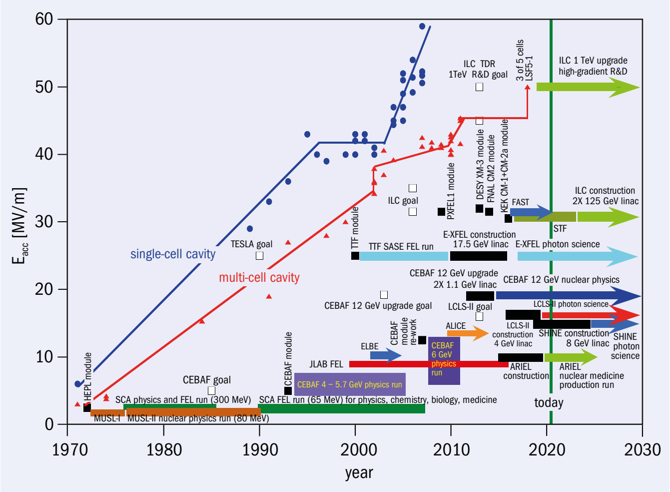

Gradient growth *SRF linac accelerating gradient achievements and application specifications since 1970. CW SRF Linacs – SCA: Stanford Superconducting Accelerator; MUSL: llinois Microtron Using a Superconducting Linac; CEBAF: Continuous Electron Beam Accelerator Facility; JLab FEL: JLab Free Electron Laser; ELBE: HZDR Electron Linear accelerator with high Brillance and Low Emittance; ALICE: STFC Accelerators and Lasers In Combined Experiments; ARIEL: TRIUMF Advanced Rare IsotopE Laboratory; LCLS-II: Linac Coherence Light Source extension; SHINE: Shanghai High Brightness Photon Facility. Pulsed SRF Linacs – FAST: Fermilab Accelerator Science and Technology Facility; STF: KEK Superconducting RF Test Facility; E-XFEL: European X-Ray Free Electron Laser; ILC: International Linear Collider.*

Vertical test *The first cavity of the ESS elliptical section developed by INFN, seen here on the left (next to a large-grain prototype), being prepared for a vertical test at DESY before shipment to CEA Saclay for assembly in the cryomodule.*

Energy Superconducting Linear Accelerator) workshop, which was held at Cornell University in July 1990. Its aim was to define the parameters for a superconducting linear collider for high-energy physics operating in the TeV region and to explore how to increase the gradients and lower the costs of the accelerating structures. It was clear from the beginning that progress would require a large international collaboration, and the Cornell meeting set in motion a series of successes that are ongoing to this day – including FLASH and the European XFEL at DESY (*CERN Courier* July/August 2017 p25). The collaboration also led to proposals for several large SRF-based research facilities including SNS, LCLS-II, ESS, PIP-II and SHINE, as well as a growing number of smaller facilities around the world.

At the time of the first TESLA collaboration meeting, the state-of-the-art in accelerating gradients for electrons was around 5 MV/m in the operating SRF systems of TRISTAN at KEK, HERA at DESY, LEP-II at CERN and CEBAF at Jefferson Lab (JLab), which were then under construction. Many participants in this meeting agreed to push for a five-fold increase in the design accelerating gradient to 25 MV/m to meet the dream goal for TESLA at a centre-of-mass energy of 1 TeV. The initial focus of the collaboration was centred on the design, construction and commissioning of a technological demonstrator, the TESLA Test Facility (TTF) at DESY. In 2004, SRF was selected as the basis for an International Linear Collider (ILC) design and, shortly afterwards, the TESLA collaboration was re-formed as the TESLA Technology Collaboration with a scope beyond the original motivation of high-energy physics. The TTC, with its incredible worldwide collaboration spirit, has had a major role in the growth of the SRF community, facilitating numerous important contributions over the past 30 years.

30 years of gradient march

Conceptually, the objective of simply providing "nice clean" niobium surfaces on RF structures seems pretty straightforward. Important subtleties begin to emerge, however, as one considers that the high RF-surface currents required to support magnetic fields up to ~100 mT flow only in the top 100 nm of the niobium surface, which must offer routine surface resistances at the nano-ohm level over areas of around $1\,\mathrm{m}^2$. Achieving blemish-free, contamination-free surfaces that present excellent crystal lattice structure even in this thin surface layer is far from easy.

The march of progress in cavity gradient for linacs and the many representative applications over the past 50 years (see figure "Gradient growth") are due to breakthroughs in three main areas: material purity, fabrication and processing techniques. The TTC had a major impact on each of these areas.

With some notable exceptions, bulk niobium cavities fabricated from sheet stock material have been the standard, even though the required metallurgical processes present challenges. Cycles of electron-beam vacuum refining, rolling, and intermediate anneals are provided by only a few international vendors. Pushing up the purity of deliverable material required a concerted push, resulting in the avoidance of foreign material inclusions, which can be deadly to performance when uncovered in the final step of surface processing. The figure-of-merit for purity is the ratio of room-temperature to cryogenic normal-conducting resistivity – the residual resistance ratio, RRR. The common cavity-grade niobium material specification has thus come to be known as high-RRR grade.

Low-beta cavities *A half-wave resonator string assembly at Argonne National Laboratory for use in PIP-II at Fermilab.*

Another later pursuit of pure niobium is the so-called "large grain" or "direct-from-ingot" material. Rather than insist on controlled ~30 µm grain-size distribution (grains being microcrystals in the structure), this material uses sheet slices cut directly from large ingots having much larger, but arbitrarily sized, grains. Although not yet widely used, this material has produced the highest gradient TESLA-style cavities to date – 45 MV/m with a quality factor $Q_0 > 10^{10}$. Here again, though the topic was initiated at JLab, this fruitful work was accomplished via worldwide international collaborations.

As niobium is a refractory metal that promptly cloaks itself with about 4 nm of dielectric oxide, welding niobium components has to be performed by vacuum electron beam welding. Collaborative efforts in Europe, North America and Asia refined the parameters required to yield consistent niobium welds. The community gradually realised that extreme cleanliness is required in the surface-weld preparation, since even microscopic foreign material will be vaporised during the weld process, leaving behind small voids that become performance-limiting defects.

Having the best niobium is not sufficient, however. Superconductors have inherent critical magnetic field limitations, or equivalently local surface-current density limitations. Because the current flow is so shallow, local magnetic field enhancements induced by microscopic topography translate into gradient-limiting quench effects. Etching of fabricated surfaces has routinely required a combination of hydrofluoric and nitric acids, buffered with phosphoric acid. This exothermic etching process inherently yields step-edge faceting at grain boundaries, which in turn creates local, even nanoscopic, field enhancements, anomalous losses and quenches as the mean surface field is increased. A progression of international efforts at KEK, DESY, CEA-Saclay and JLab eliminated this problem through the development of electro-polishing techniques. Following a deeper understanding of the underlying electrochemistry, accelerating gradients above 40 MV/m are now attainable with niobium.

Another vexing problem that TTC member institutions helped to solve was the presence of "Q-drop" in the region of high surface magnetic field, for which present explanations point to subtle migration of near-surface oxygen deeper into the lattice, where it inhibits the subsequent formation of lossy nanohydrides on cool-down. Avoidance of nanohydrides, whose superconductivity by proximity effect breaks down in the Q-drop regime, is required to sustain accelerating gradients above 25 MV/m for some structures.

Cleaning up

TTC members have also shared analyses and best practices in cleaning and cleanroom techniques, which have evolved dramatically during the past 30 years. This has helped to beat down the most common challenge for developers and users of SRF accelerating cavities: particulate-induced field emission, whereby very high peak surface electric fields can turn even micron-scale foreign material into parasitic electron field emission sources, with resulting cryogenic and radiation burdens. Extended interior final rinsing with high-pressure ultra-pure water prior to cavity assembly has become standard practice, while preparation and assembly of all beamline vacuum hardware under ISO 4 cleanroom conditions is necessary to maintain these clean surfaces for accelerator operations.

The most recent transformation has come with the recognition that interstitial doping of the niobium surface with nitrogen can reduce SRF surface resistance much more than was dreamed possible, reducing the cryogenic heat load to be cooled. While still the subject of material research, this new capability was rapidly adopted into the specification for LCLS-II cavities and is also being considered for an ILC. The effort started in the US and quickly propagated internationally via the TTC, for example in cavity tests at the European Spallation Source (see "Vertical test" image). Earlier this year, Q-values of $3–4\times10^{10}$ at 2 K at 30 MV/m were reported in TESLA-style

Accelerating gradients above 40 MV/m are now attainable with niobium

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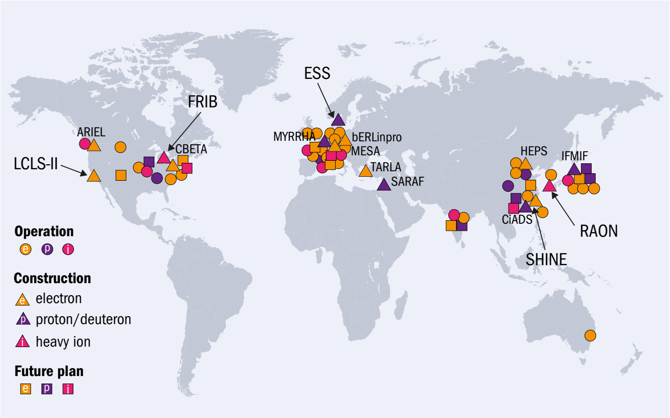

Global view *Distribution of superconducting particle accelerators using SRF structures for electrons (orange), protons (purple) and heavy ions (pink). More than 30 SRF accelerators are in operation (circles), approximately 15 are presently under construction (triangles) and more than 10 future projects are under consideration (squares).*

cavities – representing tremendous progress, but with much optimisation still to be carried out.

One of the main goals of the TTC has been to bridge the gap between state-of-the-art R&D on laboratory prototypes and actual accelerator components in operating facilities, with the clear long-term objective to enable superconducting technology for a TeV-scale linear collider. This objective demanded a staged approach and intense work on the development of all the many peripherals and subcomponents. The collaboration embraced a joint effort between the initial partners to develop the TTF at DESY, which aimed to demonstrate reliable operation of an electron superconducting linac at gradients above 15 MV/m in "vector sum" control – whereby many cavities are fed by a single high-power RF source to improve cost effectiveness. In 1993 the collaboration finalised a 1.3 GHz cavity design that is still the baseline of large projects like the European XFEL, LCLS-II and SHINE, and nearly all L-band-based facilities.

Towards a linear collider

An intense collaborative effort started for the development of all peripheral components, for example power couplers, high-order mode dampers, digital low-level RF systems and cryomodules with unprecedented heat load performances. Several of these components were designed by TTC partners in an open collaborative and competitive effort, and a number of them can be found in existing projects around the world. The tight requirements imposed by the scale of a linear collider required an integrated design of the accelerating modules, containing the cavities and their peripheral components, which led to the concept of the "TESLA style" cryomodules, variants of which provide the building blocks of the linacs in TTF, European XFEL, LCLS-II and SHINE.

The success of the TTF, which delivered its first beam in 1997, led it to become the driver for a next-generation light source at DESY, the VUV-FEL, which produced first light in 2005 and which later became the FLASH facility. The European XFEL built on this strong heritage, its large scale demanding a new level of design consolidation and industrialisation. It is remarkable to note that the total number of such TESLA-style cavities installed or to be installed in presently approved accelerators is more than 1800. Were a 250 GeV ILC to go ahead in Japan, approximately 8000 such units would be required. (Note that an alternative proposal for a high-energy linear collider, the Compact Linear Collider, relies on a novel dual-beam acceleration scheme that does not require SRF cavities.)

Since the partners collaborating on the early TESLA goal of a linear collider were also involved in other national and international projects for a variety of applications and domains, the first decade of the 21st century saw the TTC broaden its reach. For example, we started including reports from other projects, most notably the US Spallation Neutron Source, and gradually opened to the community working on low-beta ion and proton superconducting cavities, such as the half-wave resonator string collaboratively developed at Argonne National Lab and now destined for use in PIP-II at Fermilab (see "Low-beta cavities" image). TTC meetings include topical sessions with industries to discuss how to shorten the path from development to production. Recently, the TTC has also begun to facilitate collaborative exchanges on alternative SRF materials to bulk niobium, such as Nb_3Sn and even hybrid multilayer films, for potential accelerator applications.

Sustaining success

The mission of the TTC is to advance SRF technology R&D and related accelerator studies across the broad diversity of scientific applications. It is to provide a bridge for open communication and sharing of ideas, development and testing across associated projects. The TTC supports and encourages the free and open exchange of scientific and technical knowledge, engineering designs and equipment. Furthermore, it is based on cooperative work on SRF accelerator technology by research groups at TTC member institution laboratories and test facilities. The current TTC membership consists of 60 laboratories and institutes in 12 countries across Europe, North America and Asia. Since progress in cavity performance and related SRF technologies is so rapid, the major TTC meetings have been frequent.

Particle accelerators using SRF technologies have been applied widely, from small facilities for medical applications up to large-scale projects for particle physics, nuclear physics, neutron sources and free-electron lasers (see "Global view" figure). Five large-scale (> 100 cavities) SRF projects are currently under construction in three regions: ESS in Europe, FRIB and LCLS-II in the US, and SHINE (China) and RAON (Korea) in Asia. Close international collaboration will continue to support progress in these and future projects, including SRF thin-film technology relevant for a possible future circular electron–positron collider. Perhaps the next wave of SRF technology will be the maturation of economical small-scale applications with high multiplicity and international standards. As an ultimate huge future SRF project, realising an ILC will indeed require sustained broad international collaboration.

The open and free-exchange model that for 30 years has enabled the TTC to make broad progress in SRF technology is a major contribution to science diplomacy efforts on a worldwide scale. We celebrate the many creative and collaborative efforts that have served the international community well via the TESLA Technology Collaboration. ●

SPIRALLING INTO THE FEMTOSCALE

Now freshly equipped with a new superconducting linac, the SPIRAL2 facility at GANIL will probe short-lived heavy nuclei and address applications in fission and materials science using charged and neutron beams.

R Ferdinand

On the plus side *Inside view of the radio-frequency quadrupole at the entrance to SPIRAL2's superconducting linear accelerator.*

Nuclear physics is as wide-ranging and relevant today as ever before in the century-long history of the subject. Researchers study exotic systems from hydrogen-7 to the heaviest nuclides at the boundaries of the nuclear landscape. By constraining the nuclear equation of state using heavy-ion collisions, they peer inside stars in controlled laboratory tests. By studying weak nuclear processes such as beta decays, they can even probe the Standard Model of particle physics. And this is not to mention numerous applications in accelerator-based atomic and condensed-matter physics, radiobiology and industry. These nuclear-physics research areas are just a selection of the diverse work done at the *Grand Accélérateur National d'Ions Lourds* (GANIL), in Caen, France.

GANIL has been operating since 1983, initially using four cyclotrons, with a fifth *Cyclotron pour Ions de Moyenne Energie* (CIME) added in 2001. The latter is used to reaccelerate short-lived nuclei produced using beams from the other cyclotrons – the *Système de Production d'Ions Radioactifs en Ligne* (SPIRAL1) facility. The various beams produced by these cyclotrons drive eight beams with specialised instrumentation. Parallel operation allows the running of three experiments simultaneously, thereby optimising the available beam time. These facilities enable both high-intensity stable-ion beams, from carbon-12 to uranium-238, and lower intensity radioactive-ion beams of short-lived nuclei, with lifetimes from microseconds to milliseconds, such as helium-6, helium-8, silicon-42 and nickel-68. Coupled with advanced detectors, all these beams allow nuclei to be explored in terms of excitation energy, angular momentum and isospin.

The new SPIRAL2 facility, which is currently being

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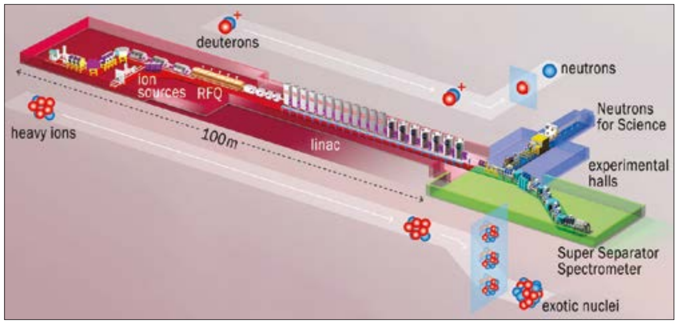


GANIL

High intensity *SPIRAL2's new superconducting linac and its experimental halls.*

commissioned, will take this work into the next decade and beyond. The most recent step forward is the beam commissioning of a new superconducting linac – a major upgrade to the existing infrastructure. Its maximum beam intensity of 5 mA, or 3×10^{16} particles per second, is more than two orders of magnitude higher than at the previous facility. The new beams and state-of-the-art detectors will allow physicists to explore phenomena at the femtoscale right up to the astrophysical scale.

Landmark facility

SPIRAL2 was approved in 2005. It now joins a roster of cutting-edge European nuclear-physics-research facilities which also features the Facility for Antiproton and Ion Research (FAIR), in Darmstadt, Germany, ISOLDE and nTOF at CERN, and the Joint Institute for Nuclear Research (JINR) in Russia. Due to their importance in the European nuclear-physics roadmap, SPIRAL2 and FAIR are both now recognised as European Strategy Forum on Research Infrastructures (ESFRI) Landmark projects, alongside 11 other facilities, including accelerator complexes such as the European X-Ray Free-Electron Laser, and telescopes such as the Square Kilometre Array.

Construction began in 2011. The project was planned in two phases: the construction of a linac for very-high-intensity stable beams, and the associated experimental halls (see "High intensity" figure); and infrastructure for the reacceleration of short-lived fission fragments, produced using deuteron beams on a uranium target through one of the GANIL cyclotrons. Though the second phase is currently on hold, SPIRAL2's new superconducting linac is now in a first phase of commissioning.

Most linacs are optimised for a beam with specific characteristics, which is supplied time and again by an injector. The particle species, velocity profile of the particles being accelerated and beam intensity all tend to be fixed. By tuning the phase of the electric fields in the accelerating structures, charged particles surf on the radio-frequency waves in the cavities with optimal efficiency in a single pass. Though this is the case for most large projects, such as Linac4 at CERN, the Spallation Neutron Source (SNS) in the US and the European Spallation Source in Sweden (*CERN Courier* September/October 2020 p29), SPIRAL2's linac (see "Multitasking" figure) has been designed for a wide range of ions, energies and intensities.

SPIRAL2 joins a roster of cutting-edge European nuclear-physics-research facilities

The multifaceted physics criteria called for an original design featuring a compact multi-cryostat structure for the superconducting cavities, which was developed in collaboration with fellow French national organisations CEA and CNRS. Though the 19 cryomodules are comparable in number to the 23 employed by the larger and more powerful SNS accelerator, the new SPIRAL2 linac has far fewer accelerating gaps. On the other hand, compared to normal-conducting cavities such as those used by Linac4, the power consumption of the superconducting structures at SPIRAL2 is significantly lower, and the linac conforms to additional constraints on the cryostat's design, operation and cleanliness. The choice of superconducting rather than room-temperature cavities is ultimately linked not only to the need for higher beam intensities and energies, but also to the potential for the larger apertures needed to reduce beam losses.

Beams are produced using two specialised ion sources. At 200 kW in continuous-wave (CW) mode, the beam power is high enough to make a hole in the vacuum chamber in less than 35 μs, placing additional severe restrictions on the beam dynamics. The operation of high beam intensities, up to 5 mA, also causes space-charge effects that need to be controlled to avoid a beam halo which could activate accelerator components and generate neutrons – a greater difficulty in the case of deuteron beams.

For human safety and ease of technical maintenance, beam losses need to be kept below 1 W/m. Here, the SPIRAL2 design has synergies with several other high-power accelerators, leading to improvements in the design of quarter-wave resonator cavities. These are used at heavy-ion accelerators such as the Facility for Rare Isotope Beams in the US and the Rare Isotope Science Project in Korea; for producing radioactive-ion beams and improving beam dynamics at intense-light particle accelerators worldwide; for producing neutrons at the International Fusion Materials Irradiation Facility, the ESS, the Myrrha Multi-purpose Hybrid Research Reactor for High-tech Applications, and the SNS; and for a large range of studies relating to materials properties and the generation of nuclear power.

Beam commissioning

Initial commissioning of the linac began by sending beams from the injector to a dedicated system with various diagnostic elements. The injector was successfully commissioned with a range of CW beams, including a 5 mA proton beam, a 2 mA alpha-particle beam, a 0.8 mA oxygen-ion beam and a 25 μA argon-ion beam. In each case, almost 100% transmission was achieved through the radio-frequency quadrupoles. Components of the linac were installed, the cryomodules cooled to liquid-helium temperatures (4.5 K), and the mechanical stability required to operate the 26 superconducting cavities at their design specifications demonstrated.

As GANIL is a nuclear installation, the injection of beams into the linac required permission from the French nuclear-safety authority. Following a rigorous six-year authorisation process, commissioning through the linac began in July 2019. An additional prerequisite was that a large number of safety systems be validated and put into operation. The key commissioning step completed so far is the demonstration of the cavity performance at 8 MV/m – a competitive electric field well above the required 6.5 MV/m. The first beam was injected into the linac in late October 2019. The cavities were tuned and a low-intensity 200 μA beam of protons accelerated to the design value of 33 MeV and sent to a first test experiment in the neutrons for science (NFS) area. A team from the Nuclear Physics Institute in Prague irradiated copper and iron targets and the products formed in the reaction were transported by a fast-automatic system 40 m away, where their characteristic γ-decay was measured. Precise measurements of such cross-sections are important in order to benchmark safety codes required for the operation of nuclear reactors.

GANIL

Multitasking *The nineteen superconducting cryomodules of the SPIRAL2 linac.*

SPIRAL2 is now moving towards its design power by gradually increasing the proton beam current and subsequently the duty cycle of the beam – the ratio of pulse duration to the period of the waveform. A similar procedure with alpha particles and deuteron beams will then follow. Physics programmes will begin in autumn next year.

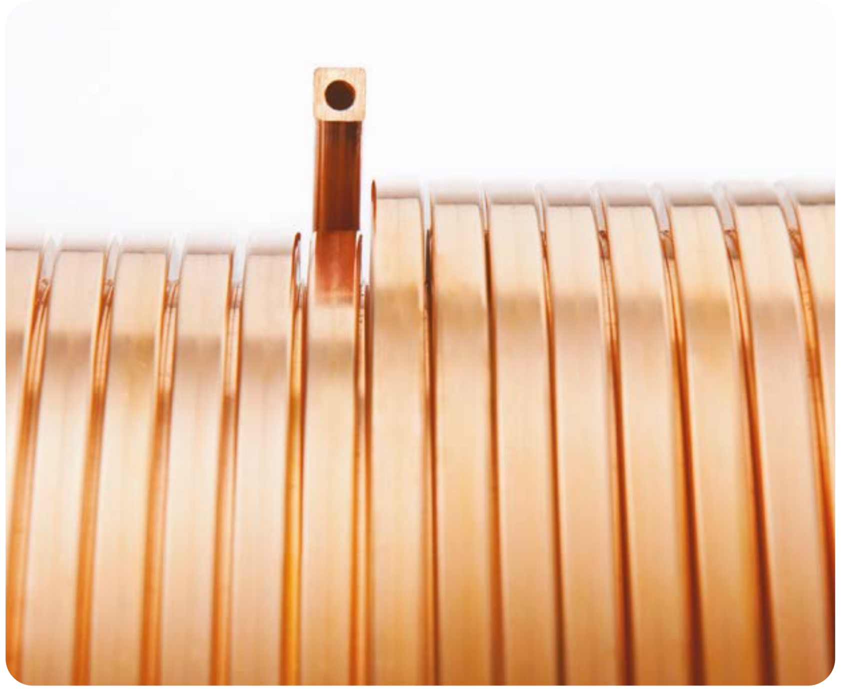
Future physics

With the new superconducting linac, SPIRAL2 will provide intense beams from protons to nickel – up to 14.5 MeV/A for heavy ions – and continuous and quasi-mono energetic beams of neutrons up to 40 MeV. With state-of-the-art instrumentation such as the Super Separator Spectrometer (S^3), the charged particle beams will allow the study of very rare events in the intense background of the unreacted beam with a signal to background fraction of 1 in 10^{13}. The charged particle beams will also characterise exotic nuclei with properties very different from those found in nature. This will address questions related to heavy and super-heavy element/isotope synthesis at the extreme boundaries of the periodic table, and the properties of nuclei such as tin-100, which have the same number of neutrons and protons – a far cry from naturally existing isotopes such as tin-112 and tin-124. Here, ground-state properties such as the mass of nuclei must be measured with a precision of one part in 10^9 – a level of precision equivalent to observing the addition of a pea to the weight of an Airbus A380. SPIRAL2's low-energy experimental hall for the disintegration, excitation and storage of radioactive ions (DESIR), which is currently under construction, will further facilitate detailed studies of the ground-state properties of exotic nuclei fed both by S^3 and SPIRAL1, the existing upgraded reaccelerated exotic-beams facility. The commissioning of S^3 is expected in 2023 and experiments in DESIR in 2025. In parallel, a continuous improvement in the SPIRAL2 facility will begin with the integration of a new injector to substantially increase the intensity of heavy-ion beams.

Thanks to its very high neutron flux – up to two orders of magnitude higher, in the energy range between 1 and 40 MeV, than at facilities like LANSCE at Los Alamos, nTOF at CERN and GELINA in Belgium – SPIRAL2 is also well suited for applications such as the transmutation of nuclear waste in accelerator-driven systems, the design of present and next-generation nuclear reactors, and the effect of neutrons on materials and biological systems. Light-ion beams from the linac, including alpha particles and lithium-6 and lithium-7 impinging on lead and bismuth targets, will also be used to investigate more efficient methods for the production of certain radioisotopes for cancer therapy.

Developments at SPIRAL2 are quickly moving forwards. In September, the control of the full emittance and space-charge effects was demonstrated – a crucial step to reach the design performance of the linac – and a first neutron beam was produced at NFS, using proton beams. The future looks bright. With the new SPIRAL2 superconducting linac now supplementing the existing cyclotrons, GANIL provides an intensity and variety of beams that is unmatched in a single laboratory, making it a uniquely multidisciplinary facility in the world today. ●

Properties must be measured with a level of precision equivalent to observing the addition of a pea to the weight of an Airbus A380



OPINION
VIEWPOINT

A unique period for computing, but will it last?

The increase in computing demands expected this decade puts high-energy physics in a similar position to 1995 when the field moved to PCs, argues Sverre Jarp.

CERN-CO-0101012-01

Stack 'em high *Monica Marinucci and Ivan Deloose at CERN's PC farm in 2001.*

N Jarp

Sverre Jarp *worked at CERN for more than 40 years, during which he held many different positions, including CTO of CERN openlab from 2002 until 2014.*

Twenty-five years ago in Rio de Janeiro, at the 8th International Conference on Computing in High-Energy and Nuclear Physics (CHEP-95), I presented a paper on behalf of my research team titled "The PC as Physics Computer for LHC". We highlighted impressive improvements in price and performance compared to other solutions on offer. In the years that followed, the community started moving to PCs in a massive way, and today the PC remains unchallenged as the workhorse for high-energy physics (HEP) computing.

HEP-computing demands have always been greater than the available capacity. However, our community does not have the financial clout to dictate the way computing should evolve, demanding constant innovation and research in computing and IT to maintain progress. A few years before CHEP-95, RISC workstations and servers had started complementing the mainframes that had been acquired at high cost at the start-up of LEP in 1989. We thought we could do even better than RISC. The increased-energy LEP2 phase needed lots of simulation, and the same needs were already manifest for the LHC. These were our inspirations that led PC servers to start populating our computer centres – a move that was also helped by a fair amount of luck.

The end of CPU scaling demands radical changes to ensure the success of the LHC and other high-energy physics experiments

Fast change

HEP programs need good floating-point compute capabilities and early generations of the Intel x86 processors, such as the 486/487 chips, offered mediocre capabilities. The Pentium processors that emerged in the mid-1990s changed the scene significantly, and the competitive race between Intel and AMD was a major driver of continued hardware innovation.

Another strong tailwind came from the relentless efforts to shrink transistor sizes in line with Moore's law, which saw processor speeds increase from 50/100 MHz to 2000/3000 MHz in little more than a decade. After 2006, when speed increases became impossible for thermal reasons, efforts moved to producing multi-core chips. However, HEP continued to profit. Since all physics events at colliders such as the LHC are independent of all others, it was sufficient to split a job into multiple jobs across all cores.

The HEP community was also lucky with software. Back in 1995 we had chosen Windows/NT as the operating system, mainly because it supported multiprocessing, which significantly enhanced our price/performance. Physicists, however, insisted on Unix. In 1991, Linus Thorvalds released Linux version 0.01 and it quickly gathered momentum as a worldwide open-source project. When release 2.0 appeared in 1996, multiprocessing support was included and the operating system was quickly adopted by our community.

Furthermore, HEP adopted the Grid concept to cope with the demands of the LHC. Thanks to projects such as Enabling Grids for E-science, we built the Worldwide LHC Computing Grid, which today handles more than two million tasks across one million PC cores every 24 hours. Although grid computing remained mainly amongst scientific users, the analogous concept of cloud computing had the same cementing effect across industry. Today, all the major cloud-computing providers overwhelmingly rely on PC servers.

In 1995 we had seen a glimmer, but we had no idea that the PC would remain an uncontested winner during a quarter of a century of scientific computing. The question is whether it will last for another quarter century?

The contenders

The end of CPU scaling, argued a recent report by the HEP Software Foundation, demands radical changes in computing and software to ensure the success of the LHC and other experiments into the 2020s and beyond (*CERN Courier* April 2018 p39). There are many contenders that would like to replace the x86 PC architecture. It could be graphics processors, where both Intel, AMD and Nvidia are active. A wilder guess is quantum computing, whereas a more conservative guess would be processors similar to the x86, but based on other architectures, such as ARM or RISC-V.

During the PC project we collaborated with Hewlett-Packard, which had a division in Grenoble, not too far away. Such R&D collaborations have been vital to CERN and the community since the beginning and they remain so today. They allow us to get insight into forthcoming products and future plans, while our feedback can help to influence the products in plan. CERN openlab, which has been the focal point for such collaborations for two decades, early-on coined the phrase "You make it, we break it". However, whatever the future holds, it is fair to assume that PCs will remain the workhorse for HEP computing for many years to come.

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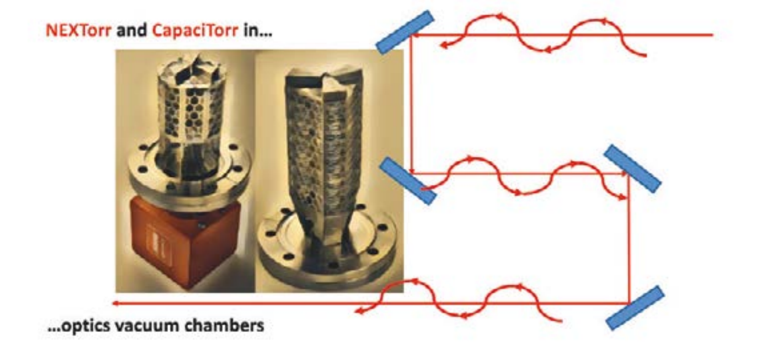
ADVERTISING FEATURE

ZAO® based non-evaporable Getter pumps in optics vacuum chambers

Vacuum engineers and scientists have long known that even if a sample material is initially clean and handled with ultrahigh-vacuum (UHV) standards, a carbon contamination layer will deposit and grow on the material's surface after placing it in a high vacuum (HV) or UHV chamber. This condition is also true for the optics vacuum chambers found in particle accelerators and synchrotron beamlines. For the optics vacuum chambers, this situation is worsened by X-ray irradiation, which can result in a one to two orders of magnitude pressure increase and high yield of carbon contaminants. The effects of carbon contamination on the X-ray optics can significantly reduce the X-ray transmission downstream to the experimental stations, and as next-generation synchrotrons usher in X-ray brightness increases of two to three orders of magnitude, it is critical to minimize these losses from carbon contamination.



Multiple studies have shown that carbon contamination develops on X-ray optics and reduces the transmission of photons near the carbon K edge, around 285 eV, as well as at higher energies around 1000 eV. As early as the 1980s, this carbon contamination layer was shown to cause intensity modulations in X-ray absorption spectra that closely resembled those above the carbon K edge in bulk crystalline graphite. These results suggested the formation of graphitic carbon contamination even under UHV conditions. Carbon contamination is not only experimentally detected; it is also visually evident after a few months to a year of beamline operation. It will usually appear as a black line where the X-rays strike the optics.

Read the full paper online.

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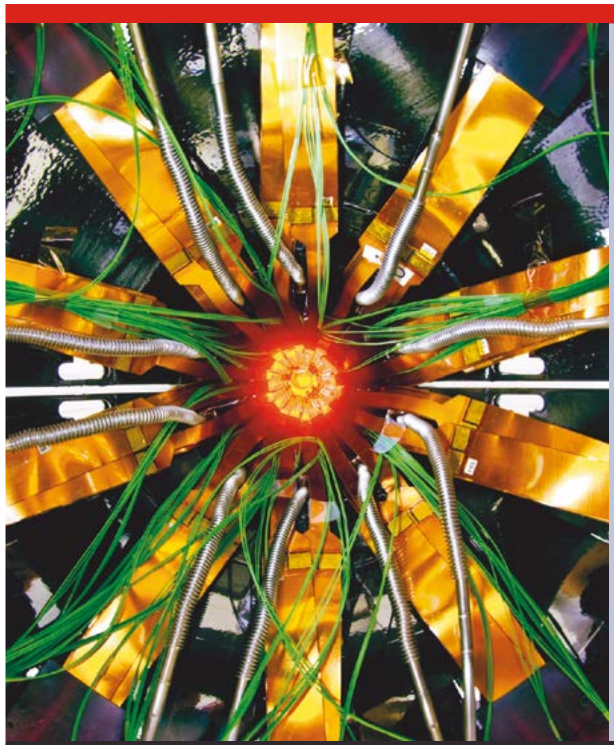


OPINION INTERVIEW

In pursuit of the possible

Theorist Giulia Zanderighi, collider phenomenologist and director at the Max Planck Institute for Physics, discusses fundamental physics at the boundary between theory and experiment.

What do collider phenomenologists do?

I tend to prefer the term particle phenomenology because the collider is just the tool that we use. However, compared to other experiments, such as those searching for dark matter or axions, colliders provide a controlled laboratory where you decide how many collisions and what energy these collisions should have. This is quite unique. Today, accelerators and detectors have reached an immense level of sophistication, and this allows us to perform a vast amount of fundamental measurements. So, the field spans precision measurements of fundamental properties of particles, in particular of the Higgs boson, consistency tests of the Standard Model (SM), direct and indirect searches for new physics, measurements of rare decays, and much more. For essentially all these topics we have had new results in recent years, so it's a very active and continuously evolving field. But of course we do not just measure things for the sake of it. We have big, fundamental questions and we are looking for hints from LHC data as to how to address them.

What's hot in the field today?

One topic that I think is very cool is that we can benefit from the LHC, in its current setup, also as lepton collider. In fact, at the LHC we are looking at elementary collisions between the proton's constituents, quarks and gluons. But since the proton is charged, it also emits photons, and one can talk about the photon parton-distribution function (PDF), i.e. the photonic content of protons. These photons can split into lepton pairs, so when one collides protons one is also colliding leptons. The fascinating thing is that the "content" of leptons in protons is rather democratic, so one can look at collisions between, say, a muon and a tau lepton – something that can't be done even at future proposed lepton colliders. Furthermore, by picking up a lepton from one proton and a quark from the other proton, one can place new constraints on leptoquarks, and plenty of other things. This idea was already proposed in the 1990s, but was essentially forgotten because the lepton PDF was not known. Now we know this very precisely, bringing new possibilities. But let me stress that this is just one idea – there are many other new ideas out there. For instance, one major branch of phenomenology is to use machine learning or deep learning to recognise the SM and extract from data what is not SM-like.

A Griesch/MPP

Giulia Zanderighi *leads the department of novel computational techniques in particle phenomenology at the Max Planck Institute for Physics in Munich.*

How does the Max Planck Institute differ from your previous positions, for example at CERN and Oxford?

A long time ago, somebody told me that the best thing that can happen to you in Germany is the Max Planck Society. It's true. You are given independence and the means to fully focus on research and ideas, largely free of teaching duties or the need to apply for grants. Also, there are very valuable interactions with universities, be it in research or via the International Max Planck Research Schools for PhD students. Our institute in Munich is a very unique place. One can feel it immediately. As a guest in the theory department, for example, you get to sit in the Heisenberg office, which feels like going back in time. Our institute was founded in Berlin in 1917 with Albert Einstein as a first director. In 1958 the institute moved to Munich with Werner Heisenberg as director. After more than 100 years I'm the first female director, which of course is a great responsibility. But I also really loved both CERN and Oxford. At CERN I felt like I was at the centre of the world. It is such a vibrant environment, and I loved the proximity to the experiments and the chats in the cafeteria about calculations or measurements. In Oxford I loved the multidisciplinary aspect, the dinners in college sitting next to other academics working in completely different fields. I guess I'm lucky that I've been in so many and such different places.

What is the biggest challenge to reach higher precision in quantum-field-theory calculations of key SM processes?

The biggest challenge is that often there is no single biggest challenge. For instance, for inclusive Higgs-boson production we have a number of theoretical uncertainties, but they are all quite comparable in size. This means that to reduce the overall uncertainty considerably, one needs to reduce all uncertainties, and they all have very different physics origins and difficulties – from a better understanding of the incoming parton densities and a better knowledge of the strong coupling constant, to higher order QCD or electroweak effects and effects related to heavy particles in virtual loops, etc. Computing power can be a liming factor for certain calculations, so making things numerically more efficient is also important. One of the main goals of the coming year will be the calculation of two to three scattering processes at the LHC at next-to-next-to-leading order (NNLO) in QCD. For instance, a milestone will be the calculation of top-pair production in association with a Higgs boson at that level of accuracy. This is the process where we can measure most directly the top-Yukawa coupling. The importance of this measurement can't be overstressed. While the big discovery at the LHC is so far the Higgs boson, one should also remember that the Yukawa interaction is a new type of fundamental interaction, which is proportional to the mass of the particle, just like gravity, but yet so different from gravity. For some calculations, NNLO is already enough in terms of perturbative precision; going to N^{3}LO doesn't really add much yet. But there are a few cases where it helps already, such as super-clean Drell–Yan processes.

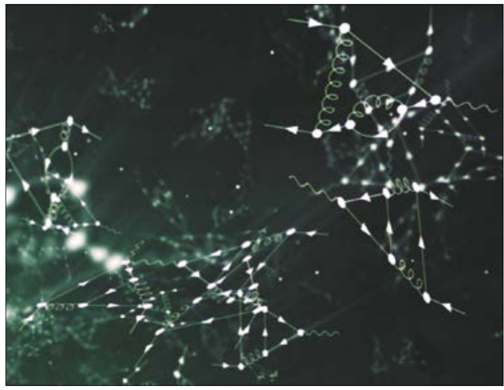
Is there a level of precision of LHC measurements beyond which indirect searches for new physics are no longer fruitful?

We will never rule out precision measurements as a route to search for new physics. We can always extend the reach and enhance the sensitivity of indirect searches. By increasing precision, we are exploring deeper in the ultraviolet region, where we can start to become sensitive to states exchanged in the loops that are more and more heavy. There is a limit, but we are very far from it. It's like looking with a better and better microscope: the better the resolution, the more one can explore. However, the experimental precision has to go hand in hand with theoretical precision, and this is where the real challenge for phenomenologists lies. Of course, if you have a super precise measurement but no theory prediction, or vice versa, then you can't do much with it. With the Higgs boson I am confident that the theory calculations will not be the deal breaker. We will eventually hit the wall in terms of experimental precision, but you can't put a figure on where this will happen. Until you see a deviation you are never really done.

How would you characterise the state of particle physics today?

When I entered the field as a student, there were high expectations that supersymmetry would be discovered quickly at the LHC. Now things have turned out to be different, but this is what makes it exciting and challenging – even more so, because the same mysteries are still there. We have big, fundamental questions. We have hints from theory, from experiments. We have a powerful, multi-purpose machine – the LHC – that is only just getting started and will provide much more data. Of course, expectations like the quick discovery of supersymmetry have not been fulfilled, but nature is how it is. I think that progress in physics is driven by experiments. We have beautiful exceptions where progress comes from theory, like general relativity, or the postulation of the mechanism for electroweak symmetry breaking. When I think about the Higgs mechanism, I am still astonished that such a simple and powerful idea postulated in 1964 turns out to be realised in nature. But these cases, where theory precedes experiments, are the exception not the rule. In most cases progress in physics comes from observations. After all, it is a natural science, it is not mathematics.

There are some questions that are really tough, and we may never really see an answer to. But with the LHC there are many other smaller questions we certainly can address, such as understanding the proton structure or studying the interaction potential between nucleons and strange baryons, which are relevant to understand the physics of neutron stars, and these are still advancing knowledge. The brightest minds are attracted to the biggest problems, and this will always draw young researchers into the field.


Loops and legs *Calculating scattering processes at the LHC at next-to-next-to-leading order in QCD is a high priority for the field.*

D Dominguez/CERN

In most cases progress in physics comes from observations. After all, it is a natural science, it is not mathematics

Is naturalness a good guiding force in fundamental research?

Yes. We have plenty of examples where naturalness, in the sense of a quadratic sensitivity to an unknown ultraviolet scale, leads to postulating a new particle: the energy of the electron field (leading to the positron), the charged and neutral pion mass difference (leading to the rho-meson) or the kaon transition rates and mixing, which led to the postulation of the existence of the charm quark in 1970, before its direct discovery in 1974 at SLAC and Brookhaven. In everyday life we constantly assume naturalness, so yes, it is puzzling that the Higgs mass appears to be fine-tuned. Certainly, there is a lot we still don't understand here, but I would not give up on naturalness, at least not that easily. In the case of the electroweak naturalness problem, it is clear that any solution, such as supersymmetry or compositeness, will also leave an imprint in the Higgs couplings. So the LHC can, in principle, tell us about naturalness even if we do not discover new physics directly; we just have to measure very precisely if the Higgs boson couplings align on a straight line in the mass-versus-coupling plane.

Which collider should follow the LHC?

That is the billion-dollar question – I mean, the 25 billion-dollar question! To me one should go for the machines that explore as much as possible the new energy frontier, namely a 100 TeV hadron collider. It is a compromise between what we might be able to achieve from a machine-building/accelerator/engineering point of view and really exploring a new frontier. For instance, at a 100 TeV machine one can measure the Higgs self-coupling, which is intimately connected with the Higgs potential and to the profound question of the stability of the vacuum.

Which open question would you most like to see answered during your career?

Probably the nature of dark matter. The presence of dark matter is overwhelming in the universe and it is embarrassing that we know little to nothing about its nature and properties. There are many exciting possibilities, ranging from the lightest neutral states in new-physics models to a non-particle-like interpretation, like black holes. Either way, an answer to this question would be an incredible breakthrough.

Interview by **Matthew Chalmers**.

OPINION REVIEWS

Weinberg on astrophysics

Lectures on Astrophysics

By Steven Weinberg

Cambridge University Press

Typical introductions to astrophysics range from 500 to more than 1000 pages. This trend is at odds with many of today's students, who prepare for examinations using search engines and are often put off by ponderous treatises. Steven Weinberg's new book wisely goes in the opposite direction. The 1979 Nobel laureate, and winner last week of a special Breakthrough prize in fundamental physics, has written a self-contained and relatively short 214-page account of the foundations of astrophysics, from stars to galaxies. The result is extremely pleasant and particularly suitable for students and young practitioners in the field.

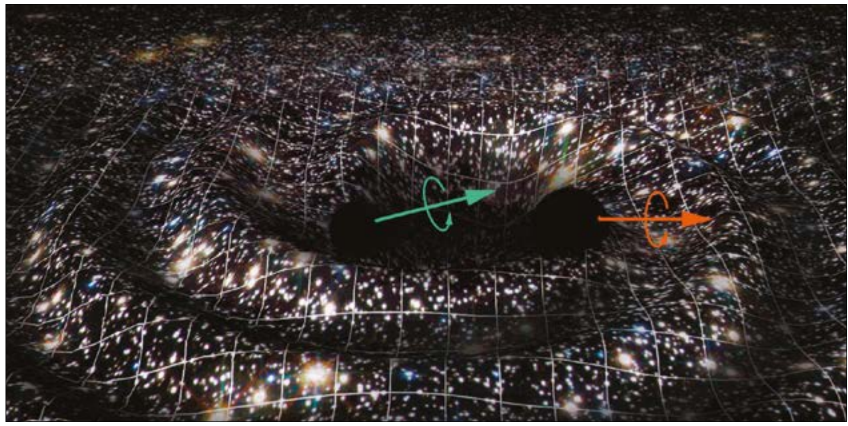
Instead of building a large treatise, Weinberg prioritises key topics that appeared in a set of lectures taught by the author at the University of Texas at Austin. The book has four parts, which deal with stars, binaries, the interstellar medium and galaxies, respectively. The analysis of stellar structure starts from the study of hydrostatic equilibrium and is complemented by various classic discussions including the mechanisms for nuclear energy generation and the Hertzsprung–Russell diagram. In view of the striking observations in 2015 by the LIGO and Virgo interferometers, the second part contains a dedicated discussion of the emission of gravitational waves by binary pulsars and coalescing binaries.

As you might expect from the classic style of Weinberg's monographs, the book provides readers with a kit of analytic tools of permanent value. His approach contrasts with many modern astrophysics and particle-theory texts, where analytical derivations and back-of-the-envelope approximations are often replaced by numerical computations that are mostly performed by computers. By the author's own admission, however, this book is primarily intended for those who care about the rationale of astrophysical formulas and their applications.

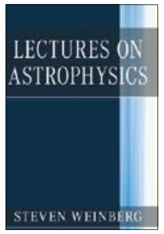
This monograph is also a valid occasion for paying tribute to a collection of classic treatises that inspired the current astrophysical literature and that are still rather popular among the practitioners of the field. The author reveals in his preface that his interest in stellar structure started many years ago after reading the celebrated book of Subrahmanyan Chandrasekhar (*An introduction to Stellar Structure*), which was reprinted by Dover in the late 1950s. Similarly, the discussions on the interstellar medium are inspired by the equally famous monograph of Lyman Spitzer Jr. (*Physical Processes in the Interstellar Medium* 1978, J. Wiley & Sons). For the benefit of curious and alert readers, these as well as other texts are cited in the essential bibliography at the end of each chapter.

Steven Weinberg's books always stimulate a wealth of considerations on the mutual interplay of particle physics, astrophysics and cosmology, and the problems of dark matter, dark energy, gravitational waves and neutrino masses are today so interlocked that it is quite difficult to say where particle physics stops and astrophysics takes over. Modern science calls for multidisciplinary approaches, and while the frontiers between the different areas are now fading away, the potential discovery of new laws of nature will not only proceed from concrete observational efforts but also from the correct interpretation of the existing theories. If we want to understand the developments of fundamental physics in the coming years, *Lectures on Astrophysics* will be an inspiring source of reflections and a valid reference.

Massimo Giovannini *CERN and INFN Milano-Bicocca.*


Unexpected *Earlier this month, LIGO and Virgo observed gravitational waves from the most massive black-hole merger seen so far, between 66 and 85 solar-mass black holes – an astrophysical event thought to be physically impossible.*

R Rubio/Virgo Collaboration



How to find a Higgs boson – and other big mysteries in the world of the very small

By Ivo van Vulpen

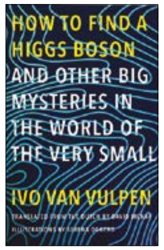
Yale

Finding Higgs bosons can seem esoteric to the uninitiated. The spouse of a colleague of mine has such trouble describing what their partner does that they read from a card in the event that they are questioned on the subject. Do you experience similar difficulties in describing what you do to loved ones? If so, then Ivo van Vulpen's book *How to find a Higgs boson* may provide you with an ideal gift opportunity.

Readers will feel like they are talk- ▷

A realistic representation of what it's like to be a particle physicist

ing physics over a drink with van Vulpen, who is a lecturer at the University of Amsterdam and a member of the ATLAS collaboration. Originally published as *De melodie van de natuur*, the book's Dutch origins are unmistakable. We read about Hans Lippershey's lenses, Antonie van Leeuwenhoeck's microbiology, Antonius van den Broek's association of charge with the number of electrons in an atom, and even Erik Verlinde's theory of gravity as an emergent entropic force. Though the Higgs is dangled at the end of chapters as a carrot to get the reader to keep reading, van Vulpen's text isn't an airy pamphlet cashing in on the 2012 discovery, but a realistic representation of what it's like to be a particle physicist. When he counsels budding scientists to equip themselves better than the North Pole explorer who sets out with a Hugo Boss suit, a cheese slicer and a bicycle, he tells us as much about himself as about what it's like to be a physicist.

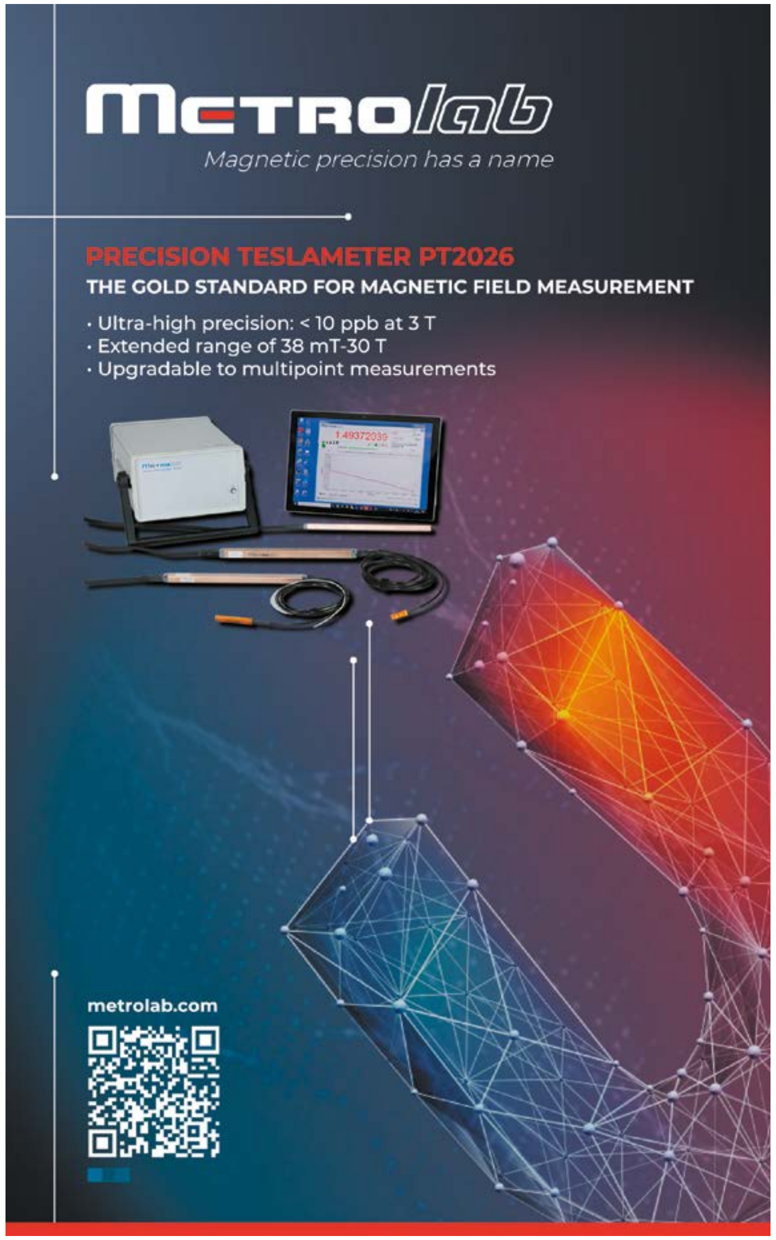


Van Vulpen is a truth teller who isn't afraid to dent the romantic image of serene progress orchestrated by a parade of geniuses. 9999 out of every 10,000 predictions from "formula whisperers" (theorists) turn out to be complete hogwash, he writes, in the English translation by David McKay. Sociological realities such as "mixed CMS–ATLAS" couples temper the physics, which is unabashedly challenging and unvarnished. The book boasts a particularly lucid and intelligible description of particle detectors for the general reader, and has a nice focus on applications. Particle accelerators are discussed in relation to the "colour X-rays" of the Medipix project. Spin in the context of MRI. Radioactivity with reference to locating blocked arteries. Antimatter in the context of PET scans. Key ideas are brought to life in cartoons by Serena Oggero, formerly of the LHCb collaboration.

Attentive readers will occasionally be frustrated. For example, despite a stated aim of the book being to fight "formulaphobia", Bohr's famous recipe for energy levels lacks the crucial minus sign just a few lines before a listing of –3.6 eV (as opposed to –13.6 eV) for the energy of the ground state. Van Vulpen compares the beauty seen by physicists in equations to the beauty glimpsed by musicians as they read sheet music, but then prints Einstein's field equations with half the tensor indices missing. But to quibble about typos in the English translation would be to miss the point of the book, which is to allow readers "to impress friends over a drink," and talk physics "next time you're in a bar". Van Vulpen's writing is always entertaining, but never condescending. Filled with amusing but perceptive one-liners, the book is perfectly calibrated for readers who don't usually enjoy science. Life in a civilisation that evolved before supernovas would have no cutlery, he observes. Neutrinos are the David Bowie of particles. The weak interaction is like a dog on an attometre-long chain.

This book could be the perfect gift for a curious spouse. But beware: fielding questions on the excellent last chapter, which takes in supersymmetry, SO(10), and millimetre-scale extra dimensions, may require some revision.

Mark Rayner *associate editor.*



Beating cardiac arrhythmia

Accelerator engineer Adriano Garonna is CEO and co-founder of EBAMed, which is developing technologies to enable non-invasive treatments of heart arrhythmia using proton beams.

Physicists at heart *EBAMed's technical team (left to right: Saskia Camps, Rosalind Perrin, Jérémie Gringet and Adriano Garonna) at the Campus Biotech Innovation Park in Geneva.*

EBAMed

In December last year, a beam of protons was used to treat a patient with cardiac arrhythmia – an irregular beating of the heart that affects around 15 million people in Europe and North America alone. The successful procedure, performed at the National Center of Oncological Hadrontherapy (CNAO) in Italy, signalled a new application of proton therapy, which has been used to treat upwards of 170,000 cancer patients worldwide since the early 1990s.

In parallel to CNAO – which is based on accelerator technologies developed in conjunction with CERN via the TERA Foundation (*CERN Courier* January/February 2018 p25) – a Geneva-based start-up called EBAMed (External Beam Ablation) founded by CERN alumnus Adriano Garonna aims to develop and commercialise image-guidance solutions for non-invasive treatments of heart arrhythmias. EBAMed's technology is centred on an ultrasound imaging system that monitors a patient's heart activity, interprets the motion in real time and sends a signal to the proton-therapy machine when the radiation should be sent. Once targeted, the proton beam ablates specific heart tissues to stop the local conduction of disrupted electrical signals.

Fast learner

"Our challenge was to find a solution using the precision of proton therapy on a fast and irregular moving target: the heart," explains Garonna. "The device senses motion at a very fast rate, and we use machine learning to interpret the images in real time, which allows robust decision-making." Unlike current treatments, which can be lengthy and costly, he adds, people can be treated as outpatients; the intervention is non-invasive and "completely pain-free".

The recipient of several awards – including TOP 100 Swiss Startups 2019, Venture Business Plan 2018, MassChallenge 2018, Venture Kick 2018 and IMD 2017 Start-up Competition – EBAMed recently received a €2.4 million grant from the European Union to fund product development and the first human tests.

Garonna's professional journey began when he was a summer student at CERN in 2007, working on user-interface software for a new optical position-monitoring system at LHC Point 5 (CMS). Following his graduation, Garonna returned to CERN as a PhD student with the TERA Foundation and École Polytechnique Fédérale de Lausanne, and then as a fellow working for the Marie Curie programme PARTNER, a training network for European radiotherapy. This led to a position as head of therapy accelerator commissioning at MedAustron in Austria – a facility for proton and ion therapy based, like CNAO, on TERA Foundation/CERN technology. After helping deliver the first patient treatments at MedAustron, Garonna returned to CERN and entered informal discussions with TERA founder Ugo Amaldi, who was one of Garonna's PhD supervisors, about how to take the technology further. Along with former CERN engineer Giovanni Leo and arrhythmia expert Douglas Packer, the group founded EBAMed in 2018.

"Becoming an entrepreneur was not my initial purpose, but I was fascinated by the project and convinced that a start-up was the best vehicle to bring it to market," says Garonna. Not having a business background, he benefitted from the CERN Knowledge Transfer entrepreneurship seminars as well as the support from the Geneva incubator Fongit and courses organised by Innosuisse, the Swiss innovation agency. Garonna also drew on previous experience gained while at CERN. "At CERN most of my projects involved exploring new areas. While I benefitted from the support of my supervisors, I had to drive projects on my own, seek the right solutions and build the appropriate ecosystem to obtain results. This certainly developed an initiative-driven, entrepreneurial streak in me."

Healthy competition

Proton therapy is booming, with almost 100 facilities operating worldwide and more than 35 under construction. EBAMed's equipment can be installed in any proton-therapy centre irrespective of its technology, says Garonna. "We already have prospective patients contacting us as they have heard of our device and wish to benefit from the treatment. As a company, we want to be the leaders in our field. We do have a US competitor, who has developed a planning system using conventional radiotherapy, and we are grateful that there is another player on the market as it helps pave the way to non-invasive treatments. Additionally, it is dangerous to be alone, as that could imply that there is no market in the first place."

Leaving the security of a job to risk it all with a start-up is a gradual process, says Garonna. "It's definitely challenging to jump into what seems like cold water… you have to think if it is worth the journey. If you believe in what you are doing, I think it will be worth it."

Craig Edwards *(based on materials published by the Office for CERN Alumni Relations).*

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Appointments and awards

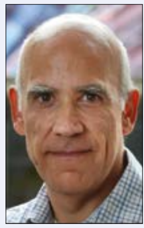
CERN appoints new directors


CERN

R Bello/CERN

Following the re-election of Fabiola Gianotti as CERN Director-General last year, the CERN Council has approved the appointment of four directors for the period 2021–2025. Mike Lamont (pictured top left), a CERN accelerator physicist of more than 30 years and former deputy head of the beams department, has replaced Frédérick Bordry as director for accelerators and technology. Joachim Mnich (top right), who worked on the L3 experiment at LEP and has been director of particle physics at DESY since 2009, succeeds Eckhard Elsen as director for research and computing. Raphaël Bello (lower left), formerly a representative for France at the European Bank for Reconstruction and Development, is the new director for finance and human resources, replacing Martin Steinacher. Charlotte Warakaulle (lower right), who joined CERN in 2016, is reappointed as director for international relations.

CMS management change


CERN

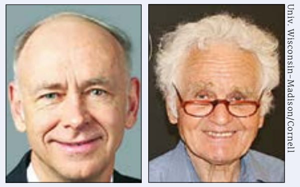
The CMS collaboration has announced its new management for the period 2020–2022. Former deputy spokesperson Luca Malgeri (pictured), who has been a CMS member since 2003, is now spokesperson, with Gautier Hamel de Monchenault and Jim Olsen appointed deputy spokespersons.

2021 APS awards

Several outstanding particle physicists have been recognised by the 2021 spring awards of the American Physical Society (APS). The W K H Panofsky Prize in experimental particle physics has been awarded to Henry Sobel (pictured below left) of the University of California, Irvine and Edward Kearns of Boston University (below right) for pioneering and leadership contributions to large underground experiments for the discovery of neutrino oscillations and sensitive searches for baryon number violation. The J J Sakurai Prize for theoretical particle physics has been given to Vernon Barger (bottom left) of University of Wisconsin–Madison for pioneering work in collider physics contributing to the discovery and characterisation of the W boson, top quark and Higgs boson, and for the development of incisive strategies to test theoretical ideas with experiments. In the field of accelerators, Yuri Fyodorovich Orlov (below right), formerly of Cornell University, was awarded the Robert R Wilson Prize for his pioneering innovation in accelerator theory and practice. Orlov received the news shortly before his passing on 27 September.

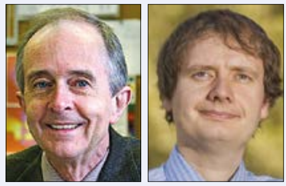

UCI/C Scott

Phiala E Shanahan of MIT (above left) has been granted the 2021 Maria Goeppert Mayer Award, which recognises an outstanding contribution to physics research by a woman, “for key insights into the structure and interactions of hadrons and nuclei using numerical and analytical methods”. The Edward A Bouchet award, which promotes the participation of underrepresented minorities in physics, has been awarded to Chanda Prescod-Weinstein of the University of New Hampshire (below right) for her contributions to theoretical cosmology and particle physics, and for co-creating the Particles for Justice movement.


Univ. Wisconsin–Madison/Cornell


MIT/Univ. New Hampshire

The Herman Feshbach Prize in theoretical nuclear physics has been awarded to Berndt Mueller of Brookhaven National Laboratory (below left) for his contributions to the identification of quark–gluon plasma signatures, while the 2021 Henry Primakoff Award for early-career particle physics has gone to Jaroslav Trnka of the University of California, Davis (below right) for seminal work on the computation of particle scattering amplitudes. Finally, the 2020 Dwight Nicholson Medal for Outreach has been given to Michael Barnett of Lawrence Berkeley National Laboratory (not pictured) “for bringing the discoveries and searches of particle physicists and cosmologists to multitudes of students and lay-people around the world”.


BNL/UC Davies

Rubbia wins energy prize

Carlo Rubbia is one of three winners of the 2020 Global Energy Prize for “the promotion of sustainable nuclear energy use and natural-gas pyrolysis”. The 39 million rouble ($0.5 million) award was announced on 8 September in Kaluga, Russia by the Global Energy Association. Rubbia is more widely known as the winner, alongside Simon van der Meer, of the 1984 Nobel Prize in Physics, for using the SPS to discover the W and Z bosons, before being appointed CERN Director-General in 1989. There have been 42 winners of the annual prize, with 78 scientists from 20 countries put forward this year. Previous winners include former CERN Director-General, Robert Aymar, who was recognised in 2006 for work to develop the scientific and engineering foundation of the ITER project.


Lindau Nobel Laureate Meeting

Pontifical appointment

On 29 September, Pope Francis appointed CERN Director-General Fabiola Gianotti to the Pontifical Academy of Sciences. Candidates for a seat in the academy are chosen “on the basis of their eminent original scientific studies and of their acknowledged moral personality, without any ethnical or religious discrimination”. The body has formally existed since 1936 but its origins go back to 1603 with the founding of the *Accademia dei Lincei*, to which Galileo Galilei was one of the first appointees. Other ordinary members of the academy today include Carlo Rubbia, Ed Witten and Juan Maldacena.


CERN

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Image: NASA astronauts repair the Hubble Space Telescope

PEOPLE OBITUARIES

Horst Wenninger 1938–2020

Relishing the CERN adventure

Horst at his retirement party at CERN in 2003.

CERN

Former CERN director Horst Wenninger, who played key roles in the approval of the LHC and in establishing knowledge transfer at CERN, passed away on 16 July. Horst was universally trusted and his advice was sought regularly by colleagues. He knew his way around CERN like no one else, and knew whom to contact to get things done (and, crucially, how to get them to do it). Before becoming a physicist, Horst had considered becoming a diplomat. Somehow, he managed to combine the two professions, all in the interest of CERN. He cultivated the art of connecting scientists, engineers and administrators – always with the aim of achieving a clear goal.

Born in Wilhelmshaven, Germany in 1938, the third child of a naval officer, Horst earned his PhD in nuclear physics from Heidelberg University in 1966. Two years later he joined CERN to participate in the Big European Bubble Chamber (BEBC). From the outset Horst was inspired by CERN. Early on he saw the importance of the Laboratory for establishing peaceful worldwide collaboration and relished participating in the adventure.

He was soon identified as a leader, first as physics coordinator for the BEBC in 1974. In 1980 he went to DESY to work on electron–positron collider physics in preparation for LEP, returning to CERN in 1982 to lead the BEBC group. In 1984 he became head of the experimental facilities division, providing support for Omega, UA1 and UA2. For the R&D and construction of the LEP detectors Horst needed to implement a new style of collaboration: for the first time, major parts of the detectors had to be financed, developed and provided by outside groups with central CERN coordination. In 1990 he became leader of the accelerator technologies division, and in 1993 he was appointed LHC deputy project leader, where his profound knowledge of CERN was vital for the reassessment of the LHC project.

Horst's five-year term as CERN research and technical director began in 1994 – the year LHC approval was expected. The day before the crucial vote by the CERN Council in December of that year, the German delegation was still not authorised to vote in support of the project. In a late-night action Horst managed to arrange contact with the office of the German chancellor, with the mission to sway the minister responsible for the decision. His cryptic reaction was conveniently interpreted by the supportive German delegate as a green light, a determined move for the good of CERN. Horst was later awarded the Order of Merit (First Class) of the German Republic.

In 2000 Horst helped launch the CERN technology transfer division and chaired the technology advisory board. Also, thanks largely to his drive, the 2017 book *Technology Meets Research – 60 Years of CERN Technology: Selected Highlights* was published. Horst retired from CERN in 2003, but continued to make major contributions. He was asked to provide guidance for the FAIR project at GSI Darmstadt, where he was instrumental in arranging the involvement of CERN accelerator experts and later steered the complex and delicate organisation of major international "in-kind" contributions. When, in 2019 the EU approved the "South-East European International Institute for Sustainable Technologies" (SEEIIST), Horst was appointed to coordinate the project's first phase.

Horst left his mark on CERN. The wider community also benefited immensely from his contributions in advisory roles throughout his active life. We have lost an outstanding colleague and a good friend from whose enthusiasm, advice and wisdom we all benefited tremendously.

His friends and colleagues.

(Editor's note: Horst was much appreciated as a source of wisdom and good humoured advice for the editors of CERN Courier*, past and present, and as a former member of the advisory board.)*

John Thompson 1939–2020

A first rate, hands-on physicist

John Thompson played a prominent role in ALEPH, among other experiments.

Family photograph

John Thompson, a senior physicist at the UK's Rutherford Appleton Laboratory (RAL), passed away on 20 August.

John obtained his PhD in nuclear physics for work on the Van de Graaff accelerator at the University of Liverpool in the early 1960s before moving to the University of Manitoba, Canada to work on particle physics. He then took a post at Daresbury Laboratory in the UK to work on experiments using the 5 GeV electron synchrotron, NINA. His first experiment involved a measurement of the total hadron photoproduction cross sections for energies from 1 to 4 GeV. These precise measurements have never been superseded and remain the definitive values documented by the Particle Data Group.

John was central to the formation of Daresbury's LAMP group, which focused on a series of hadronic photoproduction experiments. He played a leading role in the development of the 480-element lead-glass array for studies of neutral particle production in the final phase of the LAMP experiment.

During this period, following the discovery of deep inelastic scattering at SLAC and DESY, John together with his colleagues became involved in the plans to study deep inelastic scattering at the higher energies afforded by the Super Proton Synchrotron (SPS) at CERN. He became a founding member of the European Muon Collaboration ▷

(EMC), which would go on to do experiments in the high-intensity muon beam at CERN.

As NINA came to the end of its life and Daresbury moved to host one of the first dedicated "light sources", John moved with other colleagues in particle physics to RAL. Interested in the production of high-energy photons at the EMC, he organised the transfer of the LAMP lead-glass array from the UK to CERN to study the production of photons in the forward direction. In the final phase of the EMC activities he successfully led a team from RAL that implemented the change to a polarised target – a very difficult procedure that had to be done in just a few months.

In the 1980s John led the RAL group into the ALEPH experiment at CERN's Large Electron Positron collider, LEP. The group undertook the task of building the end-cap electromagnetic calorimeters, which worked successfully during the 11 years of ALEPH operations. John became heavily involved with early results for which the calorimeter performance was crucial, such as its use in counting the number of neutrino species from the radiative return reaction $e^+e^- \to \nu\bar{\nu}\gamma$. During the LEP2 period in the late 1990s, John's major contribution concerned the measurement of the W mass and width. This led to a highly productive collaboration between the Imperial College and RAL ALEPH teams, and saw John become instrumental in guiding students. Following his retirement from RAL, he was appointed visiting professor at Imperial where he was lead author on the publication of the final ALEPH W-mass measurements. He continued to advise and guide students, and took charge of graduate lectures until recently, when failing health made it difficult for him to do so.

John was a first rate, hands-on experimental physicist. He had a talent for understanding the difficulties of others and involving himself selflessly to help them progress. He always had a patient, calm, happy and relaxed manner, and will be sadly missed.

His friends and colleagues.

Max Zolotorev 1941–2020

Curiosity, creativity and rigour

Max Zolotorev was an inspiring mentor and teacher.

F Izrailev

Max Samuilovich Zolotorev, a pioneer of experimental studies of atomic parity violation, passed away on 1 April in his home in Oregon, US.

Max was born in Petrovsk, a small town not far from the Russian city of Saratov, where his mother found herself evacuated from the advancing German army. Upon graduating from secondary school, despite showing unusual talent and ability from an early age, he was not admitted to an institute or even a vocational school because he was Jewish. After eventually securing a position with the Novosibirsk Electro Technical Institute in Siberia, where he demonstrated outstanding academic performance, he was able to transfer to the newly founded Novosibirsk State University. He graduated in 1966, before obtaining his first and second doctoral degrees in 1974 and 1979 at the Institute of Nuclear Physics in Novosibirsk Academgorodok.

Max started out by working on measurements of the hyperon magnetic moments. However, in the early 1970s he was drawn into studying fundamental physics using the methods of atomic, molecular and optical physics. Together with his mentor and colleague Lev Barkov, he was the first to discover parity violation in atoms by observing optical rotation of the plane of polarisation of light propagating through a bismuth vapour.

The 1978 measurement came at a crucial time in the development of the Standard Model. While observations of high-energy neutrino scattering on nuclei at CERN in 1973 provided evidence of neutral weak currents, there was no evidence that the neutral weak current violated parity as predicted by the Glashow–Weinberg–Salam (GWS) model. Furthermore, earlier atomic parity violation experiments had produced null results, in contradiction with theoretical predictions. The observation of parity violation in bismuth, followed later by measurements of parity-violating electron scattering at SLAC, was crucial evidence that the GWS model was indeed the correct description of the weak interaction.

Max and his colleagues also established the foundation for some of today's most sensitive magnetometers with their measurements in the late 1980s of nonlinear Faraday rotation, clearly identifying the crucial role of quantum coherences. In 1989 Max emigrated to the US and took up a research position at SLAC, later moving to Lawrence Berkeley National Laboratory, where he worked until his retirement in 2018. At SLAC, Max and colleagues proposed using lasers to cool hadrons in colliders as a variation on van der Meer's stochastic cooling method. The "optical stochastic cooling" concept will soon be tested at Fermilab by a group led by a former student of Max's. Another of his co-inventions is the so-called "slicing method" to produce ultra-short pulses of X-rays essential for time-resolved studies of the properties of condensed matter.

Max Zolotorev was an inspiring mentor and teacher who always set the highest expectations for his students. His ability to find "weak spots" in one's scientific logic was legendary. One of Max's great insights was that, as physicists, we should never design our experiments around what was sitting in our labs or in our heads. Instead, we should choose deep and important problems, think hard about them and develop the cleverest way to approach them that we can, learn new subjects, build new apparatus, and push our boundaries and limits. Max's work exemplified the curiosity, creativity and rigour of physics at its best.

Derek F Jackson Kimball, Dmitry Budker, Valeriy V Yashchuk, his friends and colleagues *(based on an article previously published in* Physics Today*).*

David Newton 1937–2020

Focusing on photons

Family photograph

David Newton was also an excellent teacher.

David Newton was educated at Manchester Grammar School, UK, and after National Service became a student at the University of Oxford. Following his postgraduate studies in particle physics, he then took a position at Lawrence Berkeley National Laboratory in the US, returning to the UK in 1968 as a lecturer in physics at the recently formed particle-physics group at Lancaster University. He quickly became interested in high-energy photon interactions, initially carrying out experiments at Daresbury Laboratory.

With the development of the SPS accelerator ▷

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at CERN he initiated a programme of research to extend these studies to much higher energies. He was involved in the design of the electron beam at CERN that was needed to produce the photons. Their interactions with protons in a hydrogen target were studied using the Omega spectrometer. A large international collaboration was formed to further these studies, which included several members of the Lancaster group. David became spokesperson of this collaboration, generating a happy and productive atmosphere, and spent several years at CERN working on the project. He then joined the H1 collaboration at DESY, where he made a reputation for very precise measurements – in particular of the magnetic-field distributions in the H1 magnet, performed by him with the help of others.

David will be remembered as an excellent teacher who continued to help young people up until a few months before his death. Clarity of thought was his main strength, and his ability to see a simple solution if it was available was most admirable. He truly enjoyed understanding physics and was happy to discuss whatever physics problem was brought to him. He loved the countryside, especially walking with his wife, Jennifer, who was an expert botanist. The world is a poorer place with the loss of David Newton.

Terry Sloan *Lancaster University.*

Philippe Mermod 1978–2020

An intense career cut short

Philippe Mermod, a member of the ATLAS and SHiP collaborations at CERN, passed away on 20 August.

Born in Geneva in 1978, Philippe obtained his Master's degree in 2002 from the University of Geneva and his PhD in 2006 from Uppsala University in Sweden. He joined ATLAS in 2007, affiliated first with Stockholm University and then with the University of Oxford and, in 2011, rejoined the University of Geneva as a research associate, becoming assistant professor in 2014.


P Mermod

Philippe was always curious to explore new paths.

Philippe made several contributions to ATLAS. Among them, he pioneered the search for displaced heavy neutral leptons and led the effort on the search for highly ionising particles in Run 2. He also made important contributions to the trigger system. Philippe's preferred topic was the search for magnetic monopoles, which he performed using various techniques in ATLAS, MoEDAL and other experiments.

Always looking for more science, he also participated in the proposed SHiP experiment. Moreover, he recently made significant contributions to the design and construction of the time-of-flight detector for the near-detector upgrade of the T2K collaboration in Japan; this is the first modern neutrino detector applying this technology.

Philippe was an intense scientist, curious to explore new paths, who devoted his attention and efforts to fundamental phenomena and who sought the answer to questions rather than personal promotion. He was also an active citizen, conscious of the need for fairness and sustainability if humanity was to have a future, whether he would see it himself or, alas, not. We will miss his energy, ideas and vision.

His colleagues and friends.

Ronald Fortune 1929–2019

At CERN from its beginnings

Experimental physicist Ronald Fortune, who joined CERN's first nuclear research group in January 1956, passed away on 16 June 2019 at the age of 90.

Ron graduated with a degree in physics and mathematics from the University of Aberdeen, UK, before joining electrical engineering firm AEI in Manchester, where he acquired valuable practical training in several departments and research experience in high-voltage techniques and electron-microscope design. This training was put to immediate use in his first post as scientific officer in the British Royal Naval Scientific Service, where he developed automated instrumentation for the study of atomic-weapon explosions at the Woomera test range in Australia.


M Fortune

Ron Fortune joined CERN just over a year after it had been established.

Ron's main career was as a senior scientist at CERN, where he spent 17 years engaged in a wide variety of projects. This included six years in high-energy physics research studying K-mesons, relativistic ionisation effects and hunting for quarks, during which Ron pioneered methods for identifying high-energy particles by measurement of their momentum and ionising power, and developed high-precision optical equipment for the photography of high-energy particles. For his work on relativistic ionisation, he was awarded a doctorate by the University of Geneva. The next eight years were spent in CERN's applied-physics divisions, where he was a member of the team that developed the world's first radio-frequency particle separator. Ron also coordinated a large CERN–Berkeley–Rutherford team in the extensive study of accelerator shielding problems. The final phase of his career at CERN was spent in organising the large-scale production of particle detectors (wire chambers) for the nuclear-physics divisions.

In 1973 Ron resigned his staff position at CERN to direct an independent consultancy in physics, engineering-physics and project management. In 1976 the firm signed a contract with the Dutch government, where he was charged with the construction of a five-metre superconducting solenoid for the muon channel of the National Institute for Nuclear Physics Research in Amsterdam, which was successfully brought into operation in 1981.

In later years Ron actively collaborated in neuroscience research carried out at the Geneva University Hospital, co-authoring several peer-reviewed articles in specialised journals.

Ron was a most charming person, always very cheerful and positive with an extraordinary sense of humour.

Helli Merica Fortune *his wife and colleague.*

Eugène Cremmer 1942–2019

A modest and original thinker

Theorist Eugène Cremmer, who passed away in October 2019, left his mark in superstring and supergravity theory. He will be remembered across the world as a brilliant colleague, as original as he was likeable.

Born in Paris in 1942, his parents ran a bookstore. The neighbourhood children were firmly oriented towards vocational schools and Eugène was trained in woodworking. He was eventually spotted by a mathematics teacher, obtained a technical Baccalauréat degree and then pursued mathematics at École Normale Supérieure (ENS) in Paris in 1962. In 1968–1969, following a triggering of research into dual models by Daniele Amati and Martinus Veltman, Eugène began to compute higher loop diagrams in a remarkable series of technically impressive papers. The first one was written with André Neveu, and others with Joël Scherk in 1971–1972 while a postdoc at CERN. At that time, CERN was an important cradle of string theory, with groups from different countries forming a critical mass.


ENS

Cremmer had an important role in 11D supergravity.

In late 1974 Eugène returned to ENS with a small group of pilgrims from the theoretical-physics group at Orsay. He worked with Jean-Loup Gervais on string field theory and later collaborated with Scherk, the author, and several visitors on supersymmetry, supergravity and applications to string theory. His revolutionary 1976 paper with Scherk introduced the linking number of a cyclic dimension by a closed string. This would turn out to be crucial for heterotic string models, T duality and mirror symmetry, for the so-called Scherk–Schwarz compactification, and was soon applied to branes. The 1977 proposal with Scherk of spontaneous compactification of the six extra dimensions of space remains central in modern string theory. In 1978–1979 his pioneering papers on 11D supergravity and 4D $N = 8$ supergravity made the 11th dimension unescapable and exhibited exceptional (now widely used) duality symmetries. For these works, Eugène received the CNRS silver medal in 1983. Some 15 years later, duality symmetries were extended to higher degree forms.

The successes of Eugène's work led to many invitations abroad. Though he chose to remain in France, he maintained collaborations and activities at a high level. He was director of the ENS theoretical-physics laboratory in 2002–2005.

Eugène was as regular as clockwork, arriving and leaving the lab at the same time every day – the only exception I witnessed was due to Peter van Nieuwenhuizen's work addiction, which he enjoyably inflicted upon us for a while. At 12:18 p.m. Eugène would always gather all available colleagues to go to lunch, and this led Guido Altarelli to observe "Were Eugène to disappear the whole lab would starve to death!" Eugène kept his papers in an encrypted pre-computer order, and nobody could understand how he was able to extract any needed reference in no time, always remembering most of the content. He cultivated his inner energy by walking quickly while absorbed in thought. We have lost a role model and a modest, full-time physicist.

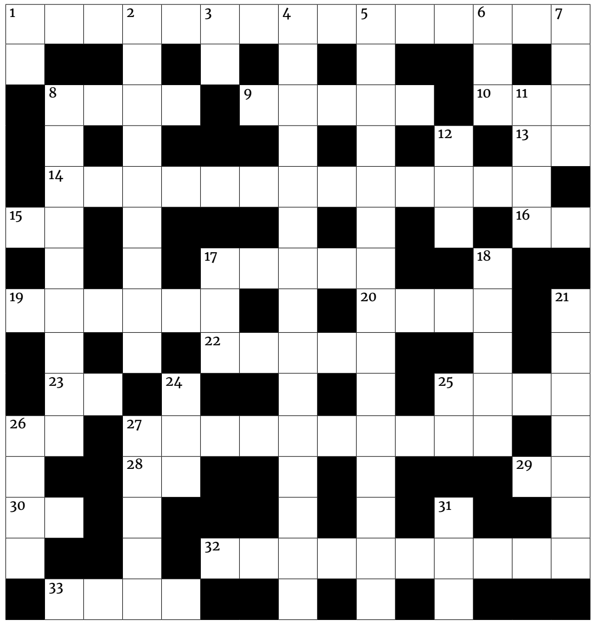
Bernard Julia *École Normale Supérieure.*

BACKGROUND

Notes and observations from the high-energy physics community

End-of-year crossword

Pit your wits against fellow *CERN Courier* readers and review the year in particle physics with our inaugural cryptic crossword, compiled by associate editor Mark Rayner. The first correct entry to reach cern.courier@cern.ch will win a mystery prize.



Across

1 Amount of data collected so far at the LHC (4,2,3,6)
8 Robert, François and Peter seem to have predicted this coupling correctly too (4)
9 Control and monitoring software beloved of DAQ experts like Gilgamesh (5)
10 Parenthetical quantum state (3)
13 Unstable academic position discovered by the Curies (2)
14 Cosmic plumber, fixed a leak for $100 million (4,9)
15 No wimps allowed in this noble medium – but maybe axions? (2)
16 Biological effectiveness is a factor for this absolute unit (2)
17 Status of baguette after LHC switched on (5)
19 Seriously tense constant now microwaves look closed not flat (6)
20 Simon says focus your neutrino beam with this (4)
22 Jejune quark model, struggles when things get non-perturbative (5)
23 Elementary for spotting neutrinos, according to Yankee time projections (2)
25 NA62's neutral sibling will first knock off trillions o' background (4)
26 Could symmetries actually emerge here, initially, and dissolve in the extreme ultraviolet? (2)
27 Island lab to ditch an ion for an electron by the end of the decade (10)
28 Ideal surname for academic preeminence – enough to drive colleagues to drink (2)
29 Presidential baryon that decays to a hyperon and a pion (2)
30 Initially, a European bid to triangulate gravitational waves (2)
32 Now dissolved in a super detector, will tag neutrons in a flash (10)
33 Lab with emissions equivalent to a cruise liner, says new report (4)

Down

1 Letters bestowed to avoid paying grad students (2)
2 *Courier* policy on paying contributors in order: in favour of a writer (9)
3 Seems just as rigid as Mg and Si, weirdly – thanks to 14 across we can double check (2)
4 Planned sequel to Japanese smash hit, will face spicy competition from Denis Villeneuve's sci-fi epic (5,10)
5 Figurative status of a Director-General with a fresh mandate (4,2,3,6)
6 Once again the world's most luminous lab – the belle of the ball, you might say (3)
7 Bye-bye for now to Homi Bhabha's institute (4)
8 Tetraquark interpretation going out of fashion given hidden beauty of recent observation? (9)
11 Sexy asteroid first spotted in 1898 (4)
12 Program that can be read and changed in any order, before folk and jazz influences (3)
17 Number of large-hadron years celebrated in 2020 – not counting the false start (3)
18 A middle way does exist, at least in condensed matter, whatever Bose and Fermi say (5)
21 Supercool substance central to success at 26 down and 33 across (7)
24 Functionally, its product with 10 across can be a matrix or plain old number (3)
25 Initially $1/2\ |d\phi/dt|^2$, for example (2)
26 Latin journey to Gallic fusion (4)
27 Beloved elephant, now getting on a bit, maintains he saw too many tau leptons (5)
31 Solar cycle first observed by Borexino this year (3)

From the archive: November 1980

Tunnel vision

On 18 September 1980 the CERN Finance Committee approved a contract with a Franco-Swiss consortium for a tunnel under the Jura mountains, where it is planned to build the large electron-positron storage ring, LEP. Ten kilometres of LEP's 30 km circumference would pass under the Jura and, though the probable tunnelling conditions around the rest of the ring are known from SPS construction experience, it is felt important to gain knowledge of the sub-Jura conditions before launching the project.


CERN-PHOTO-8107558

Drilling a borehole along the proposed line of the LEP tunnel in 1981 to reveal conditions likely to be encountered during excavation.

- Based on *CERN Courier* November 1980 p345.

Compiler's note

The LEP tunnel, Europe's largest civil-engineering project prior to the Channel Tunnel, will serve the physics community well for half a century. It housed LEP from 1989 until 2000, when it was recycled to accommodate the LHC, which is expected to run with increased luminosity until around 2038.

And then? On 19 June the CERN Council approved an update to the European strategy for particle physics, recommending further studies towards a huge 100 km Future Circular Collider at CERN. If built, the FCC will be a dream project for tunnel engineers. The region around CERN will confront them with almost every known subterranean challenge, going where no tunnel has gone before (CERN Courier *Sep/Oct 2019 p26).*