WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the March 2018 issue of *CERN Courier*.

The humble hydrogen atom has taught us much during the past two centuries, ultimately leading to the atomic picture of Bohr. As this month's cover feature argues, physicists are morally obligated to subject anti-hydrogen to the same analytical tools – in particular to test if antimatter obeys the same fundamental symmetries as matter. Following a long campaign, the ALPHA collaboration at CERN's Antiproton Decelerator (AD) has recently measured the antihydrogen 1S–2S transition and other spectral properties of antihydrogen, opening a new direction of exploration. Meanwhile, the AD's BASE experiment has measured the antiproton magnetic moment with exquisite precision, further testing symmetries such as CPT. We also describe a Cornell-Brookhaven project to build the first superconducting multi-turn energy recovery linac, survey the latest attempts to test the validity of the Pauli exclusion principle, and report on an initiative to establish a world-class research infrastructure in South-East Europe following the CERN model.

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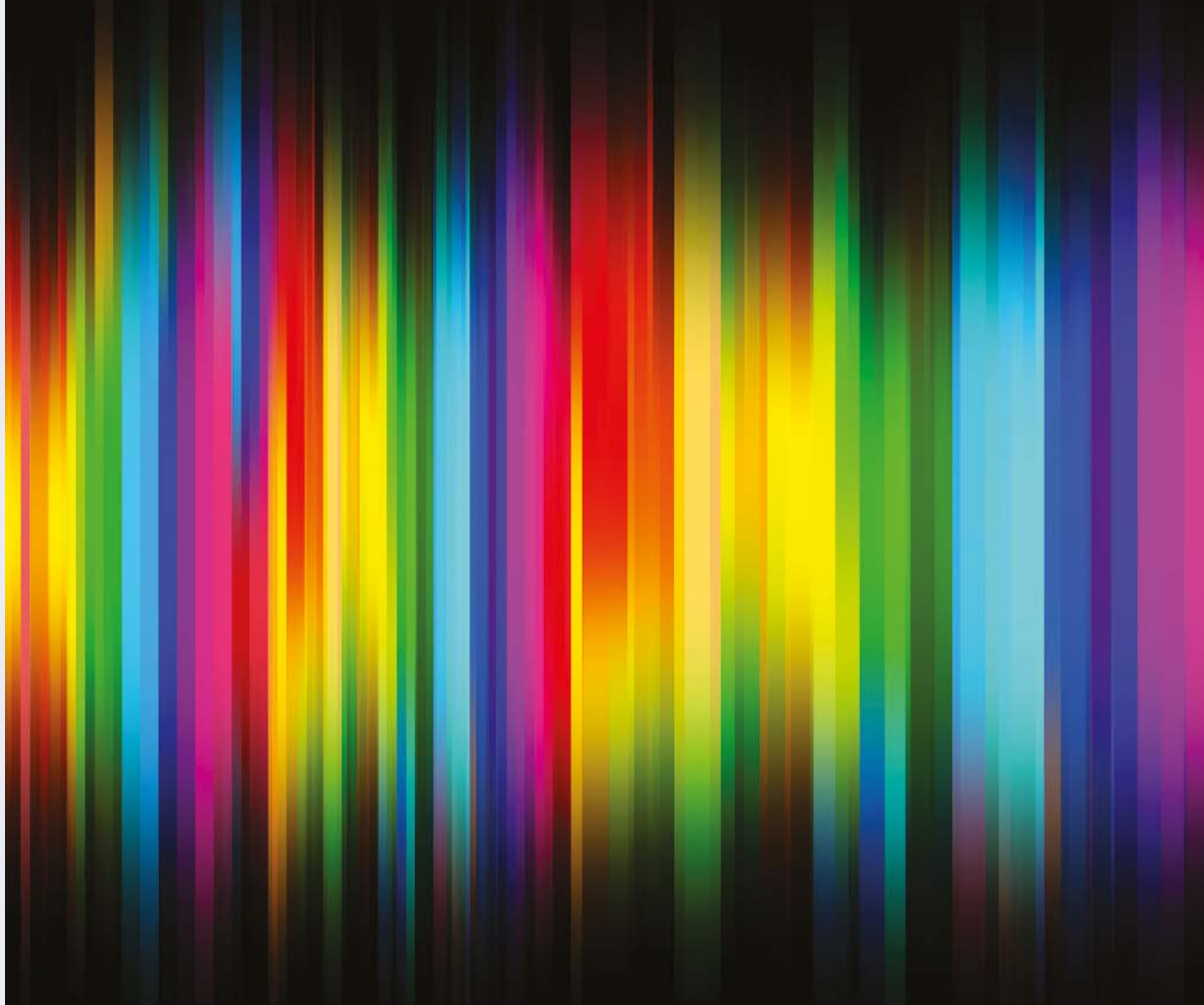
Illuminating antimatter



Pauli principle on trial • Energy-saving accelerators • Science for peace

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Covering current developments in high-energy physics and related fields worldwide

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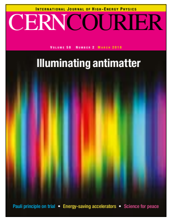


On the cover: Artistic illustration of the visible spectrum.

Viewpoint

Shaping science in South-East Europe

An international scientific facility following the CERN model would stimulate the region.

Government of Montenegro

Delegates at a scientific forum at the ICTP in Trieste in January explored a new world-class research infrastructure for South-East Europe.

By Herwig Schopper

In the autumn of 2016, at a meeting in Dubrovnik, Croatia, trustees of the World Academy of Art and Science discussed a proposal to create a large international research institute for South-East Europe. The facility would promote the development of science and technology and help mitigate tensions between countries in the region, following the CERN model of "science for peace". A platform for internationally competitive research in South-East Europe would stimulate the education of young scientists, transfer and reverse the brain drain, and foster greater cooperation and mobility in the region.

The South-East Europe initiative received first official support by the government of Montenegro, independent of where the final location would be, thanks to the engagement of Montenegro science minister Sanja Damjanovic, who is also a physicist with a long tradition working at CERN.

On 25 October last year at a meeting at CERN, ministers of science or their representatives from countries in the region signed a Declaration of Intent (DOI) to establish a South-East Europe International Institute for Sustainable Technologies (SEEIIST) with the above objectives. The initial signatories were Albania, Bosnia and Herzegovina, Bulgaria, Kosovo*, The Former Yugoslav Republic of Macedonia, Montenegro, Serbia and Slovenia. Croatia agreed in principle, while Greece participated as an observer. CERN's role was to provide a neutral and inspirational venue for the meeting.

The signature of the DOI was followed by a scientific forum on 25–26 January at the International Centre for Theoretical Physics (ICTP) in Trieste, Italy, held under the auspices of UNESCO, the International Atomic Energy Agency (IAEA) and the European Physical Society. The forum attracted more than 100 participants ranging from scientists and engineers at universities to representatives of industry, government agencies and international organisations including ESFRI and the European Commission. Its aim was to present two scientific options for SEEIIST: a fourth-generation synchrotron light source that would offer users intense beams from infrared to X-ray wavelengths; and a state-of-the-art patient treatment facility for cancer using protons and heavy ions, also with a strong biomedical research programme. The concepts behind each proposal were worked out by two groups of international experts.

With SEEIIST's overarching goal to be a world-class research infrastructure, the training of scientists, engineers and technicians is essential. Whichever project is selected, it will require several years of effort, during which people will be trained for the operation of the machines and user communities will also be formed. Capacity-building and technology-transfer activities will further trigger developments for the whole region, such as the development of powerful digital networks and big-data handling.

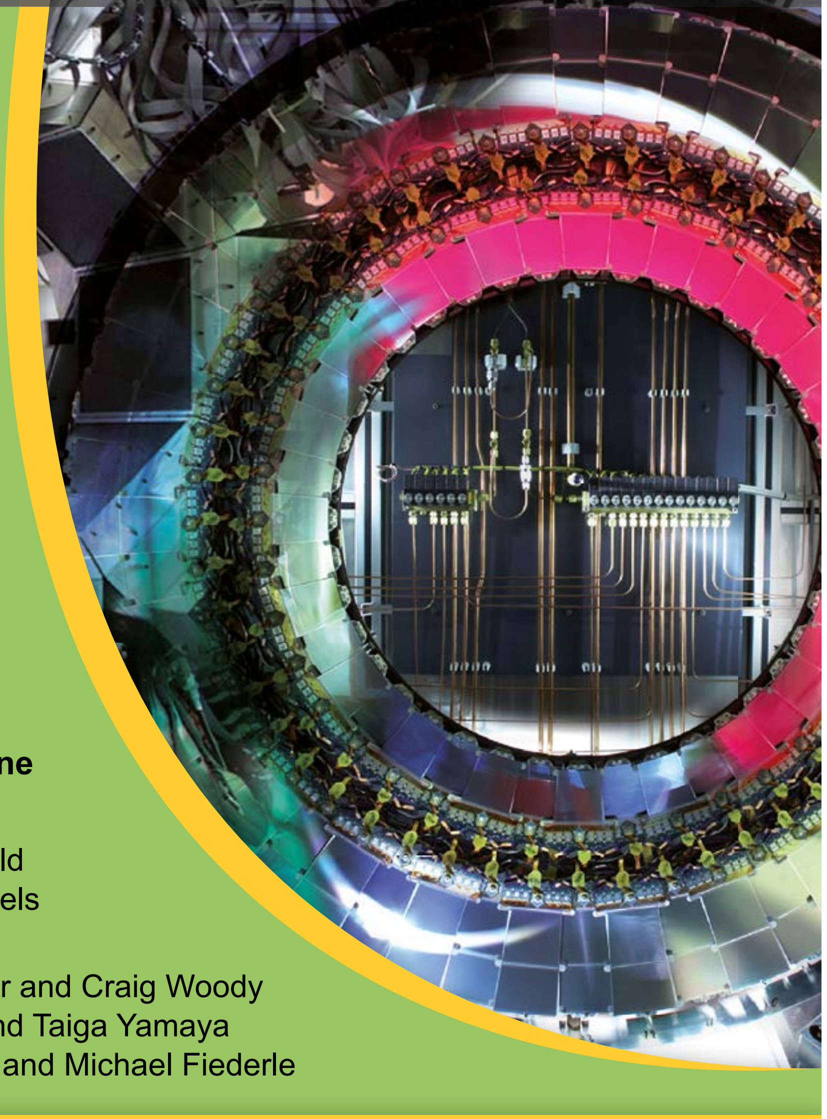
Reports and discussions from the ICTP forum have provided an important basis for the next steps. Representatives of IAEA declared an interest in helping with the training programme, while European Union (EU) representatives are also looking favourably at the project – potentially providing resources to support the preparation of a detailed conceptual design and eventual concrete proposal.

The initiative is gathering momentum. On 30 January the first meeting of the SEEIIST steering committee, chaired initially by the Montenegro science minister, took place in Sofia, Bulgaria. Sofia was chosen at the invitation of Bulgaria since it currently holds the EU presidency, and the meeting was introduced by Bulgarian president Rumen Radew, who expressed strong interest in SEEIIST and promised to support the initiative. Officials have underlined that a decision between the two scientific options should be taken as soon as possible – a task that we are now working towards.

SEEIIST wouldn't be the first organisation to be inspired by the CERN model. The European Southern Observatory, European Molecular Biology Laboratory and the recently operational SESAME facility in Jordan – a third-generation light source governed by a council made up of representatives from eight members in the Middle East and surrounding region – each demonstrate the power of fundamental science to advance knowledge and bring people and countries together.

Herwig Schopper is the proponent of the SEEIIST initiative. He was Director-General of CERN from 1981–1988 and first president of the SESAME Council from 2004–2008.

This designation is without prejudice to positions on status and is in line with UNSC 1244/1999 and the ICJ opinion on the Kosovo Declaration of Independence.



News

ASTROPARTICLE PHYSICS

Europe defines astroparticle strategy

Multi-messenger astronomy, neutrino physics and dark matter are among several topics in astroparticle physics set to take priority in Europe in the coming years, according to a report by the Astroparticle Physics European Consortium (APPEC).

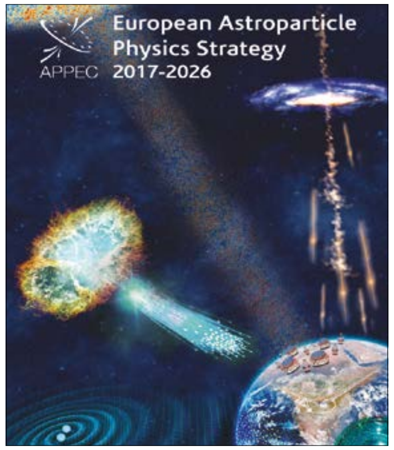
The APPEC strategy for 2017–2026, launched at an event in Brussels on 9 January, is the culmination of two years of consultation with the astroparticle and related communities. It involved some 20 agencies in 16 countries and includes representation from the European Committee for Future Accelerators, CERN and the European Southern Observatory (ESO).

Lying at the intersection of astronomy, particle physics and cosmology, astroparticle physics is well placed to search for signs of physics beyond the standard models of particle physics and cosmology. As a relatively new field, however, European astroparticle physics does not have dedicated intergovernmental organisations such as CERN or ESO to help drive it. In 2001, European scientific agencies founded APPEC to promote cooperation and coordination, and specifically to formulate a strategy for the field.

Building on earlier strategies released in 2008 and 2011, APPEC's latest roadmap presents 21 recommendations spanning scientific issues, organisational aspects and societal factors such as education and industry, helping Europe to exploit tantalising potential for new discoveries in the field.

The recent detection of gravitational waves from the merger of two neutron stars (*CERN Courier* December 2017 p16) opens a new line of exploration based on the complementary power of charged cosmic rays, electromagnetic waves, neutrinos and gravitational waves for the study of extreme events such as supernovae, black-hole mergers and the Big Bang itself. "We need to look at cross-fertilisation between these modes to maximise the investment in facilities," says APPEC chair Antonio Masiero of the INFN and the University of Padova. "This is really going to become big."

APPEC strongly supports Europe's next-generation ground-based gravitational interferometer, the Einstein Telescope, and the space-based LISA detector. In the neutrino sector, KM3NeT is being completed for high-energy cosmic neutrinos at its site in Sicily, as well as for precision studies of atmospheric neutrinos at its French site near Toulon. Europe is also heavily involved in the upgrade of the leading cosmic-ray facility the Pierre Auger Observatory in Argentina. Significant R&D work is taking place at CERN's neutrino platform for the benefit of long- and short-baseline neutrino experiments in Japan and the US (*CERN Courier* July/August 2016 p21), and Europe is host to several important neutrino experiments. Among them are KATRIN at KIT in Germany, which is about to begin measurements of the neutrino absolute mass scale, and experiments searching for neutrinoless double-beta decay (NDBD) such as GERDA and CUORE at INFN's Gran Sasso National Laboratory (*CERN Courier* December 2017 p8).



The APPEC report makes 21 recommendations for the astroparticle-physics community.

There are plans to join forces with experiments in the US to build the next generation of NDBD detectors. APPEC has a similar vision for dark matter, aiming to converge next year on plans for an "ultimate" 100-tonne scale detector based on xenon and argon via the DARWIN and Argo projects. APPEC also supports ESA's Euclid mission, which will establish European leadership in dark-energy research, and encourages continued European participation in the US-led DES and LSST ground-based projects. Following from ESA's successful Planck mission, APPEC strongly endorses a European-led satellite mission, such as COrE, to map the cosmic-microwave background and the consortium plans to enhance its interactions with its present observers ESO and CERN in areas of mutual interest.

"It is important at this time to put together the human forces," says Masiero. "APPEC will exercise influence in the European Strategy for Particle Physics, and has a significant role to play in the next European Commission Framework Project, FP9."

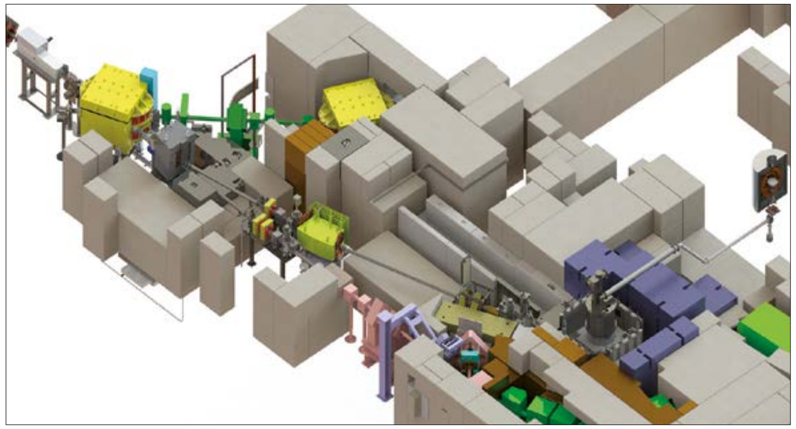
A substantial investment is needed to build the next generation of astroparticle-physics research, the report concedes. According to Masiero, European agencies within APPEC currently invest around €80 million per year in astroparticle-related activities, in addition to funding large research infrastructures. A major effort in Europe is necessary for it to keep its leading position. "Many young people are drawn into science by challenges like dark matter and, together with Europe's existing research infrastructures in the field, we have a high technological level and are pushing industries to develop new technologies," continues Masiero. "There are great opportunities ahead in European astroparticle physics."

● View the full report at www.appec.org.

Sommaire en français

TRIUMF

Neutrons cooled for interrogation


TRIUMF

A proton beamline at TRIUMF branches off to a tungsten spallation target, producing neutrons that are slowed to ultracold speeds in cryostats and directed to the UCN experimental area (right). The EDM cell is magnetically shielded by cylindrical layers.

Researchers at TRIUMF in Canada have reported the first production of ultracold neutrons (UCN), marking an important step towards a future neutron electric dipole moment (nEDM) experiment at the Vancouver laboratory. Precision measurements of the nEDM are a sensitive probe of physics beyond the Standard Model: if a nonzero value were to be measured, it would suggest a new source of CP violation, possibly related to the baryon asymmetry of the universe.

The TUCAN collaboration (TRIUMF UltraCold Advanced Neutron source) aims to measure nEDM a factor 30 better than the present best measurement, which has a precision of 3×10^{-26} e cm and is consistent with zero. For this to be possible, physicists need to provide the world's highest density of ultracold neutrons. In 2010 a collaboration between Canada and Japan was established to realise such a facility and a prototype UCN source was shipped to Canada and installed at TRIUMF in early 2017.

The setup uses a unique combination of proton-induced spallation and a superfluid helium UCN source that was pioneered in Japan. A tungsten block stops a beam of protons, producing a stream of fast neutrons that are then slowed in moderators and converted to ultracold speeds (less than around $7\,\mathrm{ms}^{-1}$) by phonon scattering in superfluid helium. The source is based on a non-thermal down-scattering process in superfluid helium below 1 K, which gives the neutrons an effective temperature of a few mK. The ultracold temperature is below the neutron optical potential for many materials, which means the neutrons are totally reflected for all angles of incidence and can be stored in bottles for periods of up to hundreds of seconds.

Tests late last year demonstrated the highest current operation of this particular source, resulting in the most UCNs it has ever produced (> 300,000) in a single 60-second-long irradiation at a 10 μA proton beam current. This is a record for TRIUMF, but the UCN source intensity is still two orders of magnitude below what is needed for the nEDM experiment.

Funding of C$15.7 million to upgrade the UCN facility, a large proportion of which was granted by the Canada Foundation for Innovation in October 2017, will enable the TUCAN team to increase the production of neutrons at higher beam current to levels competitive with other planned nEDM experiments worldwide. These include proposals at the Paul Scherrer Institute in Switzerland, Los Alamos National Laboratory in the US, the Institut Laue–Langevin in France and others in Germany and Russia. The neutron EDM is experiencing intense competition, with most projects differing principally in the way they propose to produce the ultracold neutrons (*CERN Courier* September 2016 p27).

The nEDM experimental campaign at TRIUMF is scheduled to start in 2021. "The TRIUMF UCN source is the only one combining a spallation source of neutrons with a superfluid helium production volume, providing the project its uniqueness and competitive edge," says team member Beatrice Franke.

INTERNATIONAL

Lithuania formalises CERN membership


Office of the President of the Republic of Lithuania

Lithuania president Dalia Grybauskaitė (left) and CERN Director-General Fabiola Gianotti, pictured at the 2018 World Economic Forum in Davos, signed the agreement in June last year.

On 8 January the Republic of Lithuania formally became an associate Member State of CERN, following the completion of its internal approval procedures (*CERN Courier* July/August 2017 p7). Lithuania's relationship with CERN dates back to an International Cooperation Agreement signed in 2004, with Lithuanian researchers contributing to the CMS experiment since 2007. Its new status strengthens the long-term partnership between CERN and the Lithuanian scientific community, makes Lithuanian scientists eligible for staff appointments, and entitles Lithuanian industry to bid for CERN contracts.

LHC REPORT

LHC prepares for final year of Run 2


M Brice/CERN

Installation of a collimator at LHC point 1.

Since 4 December, around 500 technicians and engineers have been working flat-out to maintain and upgrade the Large Hadron Collider (LHC) and other parts of the CERN accelerator complex. The current year-end technical stop will last until 9 March, and preparations for the machine and its infrastructure for the High Luminosity LHC (HL-LHC) have been a focus of activities.

Collimators are key to operating the HL-LHC, which will have roughly twice the stored energy (700 MJ) as the present machine. These devices control losses from the circulating proton beams so that they can be constrained to a small section of the machine's circumference. Continuing work undertaken during last year's extended year-end stop (*CERN Courier* March 2017 p9), two new collimators are being installed at point 1 containing a wire that generates an electromagnetic field to compensate for long-range beam–beam effects.

Higher performing injectors that can produce more intense particle beams are another demand of the HL-LHC, and this aspect is being managed by the LHC Injector Upgrade (LIU) project (*CERN Courier* October 2017 p32). An upgraded kicker magnet, one of eight fast-pulsed magnets that inject particle beams coming from the Super Proton Synchrotron (SPS) into the LHC, will be installed at point 8. A special coating applied to the inner wall of the ceramic pipe of the magnet is one of several techniques developed to reduce the heating of components in the harsher HL-LHC environment.

While work steps up on the LHC, which has been temporarily emptied of its 120 tonnes of helium coolant, brand-new accelerator technology that will help the HL-LHC achieve its unprecedented luminosities is being prepared for tests in the SPS. Two prototype radiofrequency crab cavities – designed to tilt particle bunches before they collide to maximise the overlapping of the beams and increase the probability of collisions – have been installed for testing during 2018. In around five years from now, during Long Shutdown 3 (LS3), the full system will be installed in the LHC.

Further down the accelerator chain, a major de-cabling campaign is taking place in the Proton Synchrotron (PS) to create space for the deployment of the LIU project during Long Shutdown 2 (LS2) beginning next year. The transfer line linking the PS to the SPS is also having all of its 43 quadrupole magnets replaced, among numerous other works. The whole CERN injector chain is undergoing an annual check-up, in particular concerning the cooling, ventilation, cryogenics and electrical supply systems. Other important activities are taking place to consolidate the infrastructure, such as the installation of a new lift at LHC point 8, and to update the beam control systems.

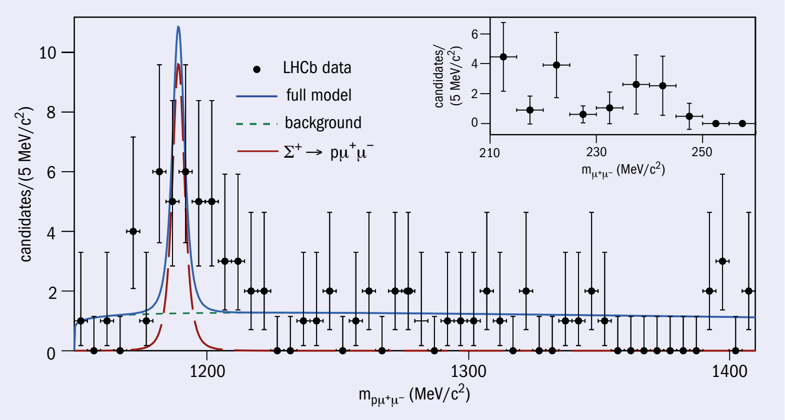
During the 2018 LHC performance workshop, held in Chamonix from 29 January to 2 February, the performance of the LHC during 2017 was reviewed and operational scenarios for 2018 were discussed. A particular focus of the workshop was on the status of the LIU and HL-LHC projects, which will be rolled-out in LS2 and LS3, respectively. There was lively discussion about the organisation and planning of activities for LS2, and the final session of the workshop covered the full energy exploitation of the LHC. Until LS2 the machine will run at a centre-of-mass energy of 13 TeV, but prospects for running at 14 TeV after LS2 and eventuallly even 15 TeV were also discussed.

LHC EXPERIMENTS

Rare hyperon-decay anomaly under the spotlight

The LHCb collaboration has shed light on a long-standing anomaly in the very rare hyperon decay $\Sigma^+ \to p\mu^+\mu^-$ first observed in 2005 by Fermilab's HyperCP experiment. The HyperCP team found that the branching fraction for this process is consistent with Standard Model (SM) predictions, but that the three signal events observed exhibited an interesting feature: all muon pairs had invariant masses very close to each other, instead of following a scattered distribution.

This suggested the existence of a new light particle, X^0, with a mass of about $214\,\mathrm{MeV}/c^2$, which would be produced in the Σ^+ decay along with the proton and would decay subsequently to two muons. Although this particle has been long sought in various other decays and at several experiments, ▷



The invariant mass distribution of $\Sigma^+ \to p\mu^+\mu^-$ candidates and, in the inset, the background-subtracted distribution of the dimuon invariant mass.

no experiment other than HyperCP has so far been able to perform searches using the same Σ^+ decay mode.

The large rate of hyperon production in proton–proton collisions at the LHC has recently allowed the LHCb collaboration to search for the $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay. Given the modest transverse momentum of the final-state particles, the probability that such a decay is able to pass the LHCb trigger requirements is very small. Consequently, events where the trigger is activated by particles produced in the collisions other than those in the decay under study are also employed.

This search was performed using the full Run 1 dataset, corresponding to an integrated luminosity of 3 fb^{-1} and about 10^{14} Σ^+ hyperons. An excess of about 13 signal events is found with respect to the background-only expectation, with a significance of four standard deviations. The dimuon invariant-mass distribution of these events was examined and found to be consistent with the SM expectation, with no evidence of a cluster around 214 MeV/c^2. The signal yield was converted to a branching fraction of $(2.1^{+1.6}_{-1.2}) \times 10^{-8}$ using the known $\Sigma^+ \rightarrow p\pi^0$ decay as a normalisation channel, in excellent agreement with the SM prediction. When restricting the sample explicitly to the case of a decay with the putative X^0 particle as an intermediate state, no excess was found. This sets an upper limit on the branching fraction at 9.5×10^{-9} at 90% CL, to be compared with the HyperCP result $(3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$.

This result, together with the recent search for the rare decay $K_S \rightarrow \mu^+\mu^-$ shows the potential of LHCb in performing challenging measurements with strange hadrons. As with a number of results in other areas reported recently, LHCb is demonstrating its power not only as a b-physics experiment but as a general-purpose one in the forward region. With current data, and in particular with the upgraded detector thanks to the software trigger from Run 3 onwards, LHCb will be the dominant experiment for the study of both hyperons and K_S mesons, exploiting their rare decays to provide a new perspective in the quest for physics beyond the SM.

- **Further reading**

LHCb Collaboration 2017 arXiv:1712.08606.
LHCb Collaboration 2017 *Eur. Phys. J. C* **77** 678.
HyperCP Collaboration 2005 *Phys. Rev. Lett.* **94** 021801.

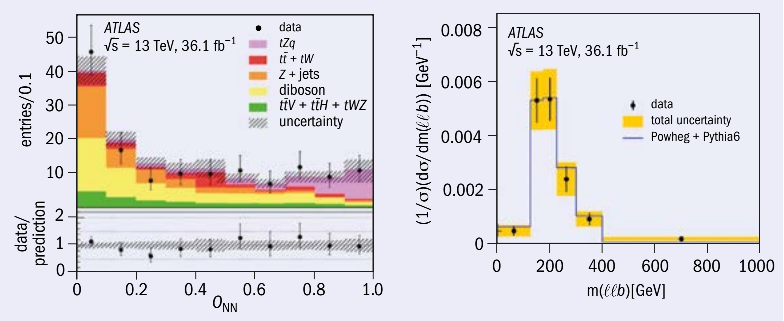
ESO

A new national facility at La Silla Observatory in Chile, operated by the European Southern Observatory (ESO), made its first observations at the beginning of the year. ExTrA (Exoplanets in Transits and their Atmospheres) will search for Earth-sized planets orbiting nearby red dwarf stars, its three 0.6 m-diameter near-infrared telescopes (pictured) increasing the sensitivity compared to previous searches. ExTrA is a French project also funded by the European Research Council and the telescopes will be operated remotely from Grenoble.

ESO

LHC EXPERIMENTS

ATLAS measures rare top plus boson production



(left) Multivariate discriminator output distribution for the events selected by the tZ analysis, with data in black, signal simulation in pink and backgrounds in other colours. (right) Normalised differential tW cross-sections as a function of the mass of the two charged leptons and the b-jet unfolded from data, compared with a Monte Carlo prediction.

Measuring the production of the top quark with vector bosons can provide fresh insight into the Standard Model (SM), in particular by testing the top quark and heavy vector boson vertices, which may be modified by extensions to the SM. In two new results, ATLAS presents strong evidence for the production of a single top quark in association with a Z boson (tZ) and has for the first time extracted differential cross-sections for the production of a top quark in association with a W boson (tW). While tW production was already measured during LHC Run 1, the next in line, the tZ process, is much harder to observe because its production rate is about one hundredth lower.

For both the tZ and tW processes, separating them from background events is critical. ATLAS searched for events containing leptons (electrons or muons), jets and transverse momentum imbalance. All the information from the measured particles is condensed into one multivariate discriminator (MVA) trained to separate the signal from the background.

The new ATLAS results use data collected in 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb^{-1}. For the tZ analysis, 25 signal events are found after selection, together with 120 background events. Applying the MVA allows the signal and background to be better separated (see figure, left), leading to a signal significance of 4.2 standard deviations. This constitutes strong evidence that the associated production of a single top quark and a Z boson has been seen, and the observed production rate agrees with that predicted by the SM.

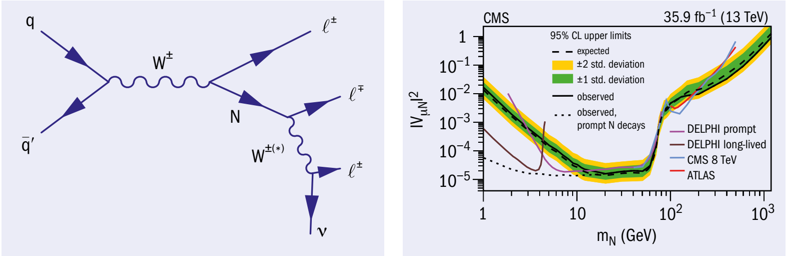
The extraction of differential cross-sections for tW is particularly challenging, as top quarks almost always decay into a b quark and a W boson, leaving two W bosons in the final state. The dominant background from the production of a top quark with a top antiquark has an 11 times larger inclusive production rate. Applying the MVA it is possible to select events with a signal to background ratio of about 1:2, which allows the signal cross-section to be extracted as a function of kinematic observables. Differential cross-sections have been measured as a function of several variables and measured and compared to predictions implemented in different Monte Carlo programmes (see figure, right). The uncertainty on the measurements is at the 20–50% level, dominated by statistical effects. While the analysis was not able to exclude particular models, the data tend to have more events with high-momentum particles than predicted.

With the additional data to be collected over the next years, ATLAS will study both tW and tZ production in more detail, and improve its searches for the even rarer and more elusive production of a (single) top quark in association with a Higgs boson.

- **Further reading**

ATLAS Collaboration 2017 arXiv:1712.01602.
ATLAS Collaboration 2017 arXiv:1712.03659.

CMS hunts for heavy neutral leptons



(Left) Diagram showing the production and decay of heavy neutral leptons. (Right) Exclusion region at 95% CL in the $|V_{\mu N}|^2$ m_N *planes. The dashed black curve is the expected upper limit (with one and two sigma bands in green and yellow) and the solid black curve is the observed upper limit. The dotted black curve is the observed limit in the approximation of prompt N decays. Also shown are the upper limits from other direct searches at DELPHI and ATLAS.*

The quest to search for new physics inspires searches in CMS for very rare processes, which, if discovered, could open the door to a new understanding of particle physics.

One such process is the production and decay of heavy sterile Majorana neutrinos, a type of heavy neutral lepton (HNL) introduced to describe the very small neutrino masses via the so-called seesaw mechanism. Two further fundamental puzzles of particle physics can be solved by adding three HNLs to the Standard Model (SM) particle spectrum: the lightest (with a mass of a few keV) can serve as a dark-matter

▷

candidate; the two heavier ones (heavier than about a GeV) could, when mass-degenerate, be responsible for a sizable amount of CP violation and thus help explain the cosmological matter–antimatter asymmetry.

Through their mixing with the SM neutrinos (see figure, left), the heavier HNLs could be produced at the LHC in leptonic W-boson decays. Subsequently, the HNL can decay to another W boson and a lepton, leading to a signal containing three isolated leptons. Depending on how weakly the new particles couple to the SM neutrinos, characterised by the parameters $|V_{eN}|^2$, $|V_{\mu N}|^2$ and $|V_{\tau N}|^2$, they can either decay shortly after production, or after flying some distance in the detector.

A new search performed with data collected in 2016 by CMS focuses on prompt trilepton (electrons or muons) signatures of HNL production. It explores a mass range from 1 GeV to 1.2 TeV, more than doubling the scope of LHC results so far. It also probes a mass regime that was unexplored since the days of the Large Electron-Positron collider (LEP), indicating that eventually the LHC will supersede these results with more data.

The trilepton final state does not lead to a sharp peak in an invariant mass spectrum, and therefore the search has to employ various kinematic properties of the events to be able to detect a possible presence of HNLs. To be sensitive to very low HNL masses, the search uses soft muons (with $p_T > 5$ GeV) and electrons ($p_T > 10$ GeV). While no signs of HNL have been found so far (see figure, right), the constraints on $|V_{\mu N}|^2$ ($|V_{eN}|^2$ is similar) in the high-mass region are the strongest to date. In the low mass region, the analysis has comparable sensitivity to previous searches.

Using dedicated analysis techniques, it is foreseen to extend this search to explore the parameter space where HNLs have longer lifetimes and so travel large distances in the detector before they decay. Together with more data this will enable CMS to significantly improve the sensitivity at low masses and eventually probe unexplored territory in this important region of HNL parameter space.

- **Further reading**

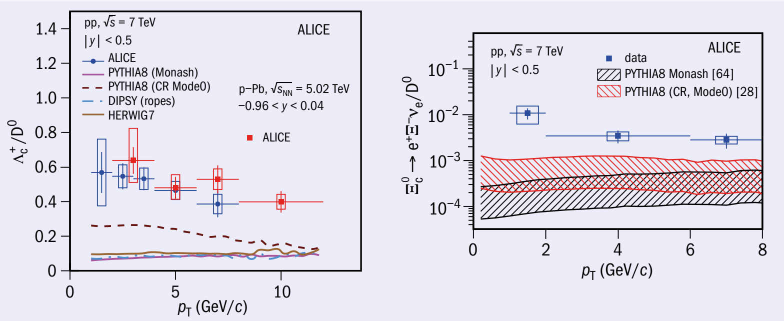
CMS Collaboration 2018 (in preparation).

ALICE investigates charm-quark hadronisation

In two publications submitted to the *Journal of High Energy Physics* and *Physics Letters B* in December, the ALICE collaboration reports new production cross-section measurements of the charmed baryons Λ_c^+ and Ξ_c^0 in proton–proton collisions at an energy of 7 TeV and in proton–lead collisions at a collision energy of 5.02 TeV per nucleon–nucleon pair. The Λ_c^+ were reconstructed in the hadronic decay modes $\Lambda_c^+ \rightarrow pK^- \pi^+$ and $\Lambda_c^+ \rightarrow p K_S^0$, and in the semileptonic channel $\Lambda_c^+ \rightarrow e^+ \nu_e \Lambda$ (and charge conjugates). For the Ξ_c^0 analysis, the semi-leptonic channel $\Xi_c^0 \rightarrow e^+ \nu_e \Xi^-$ was used.

The comparison of charm baryon and meson cross-sections provides information on c-quark hadronisation. Surprisingly, the measured values of the Λ_c^+/D^0 baryon-to-meson ratio were significantly larger than those previously measured in other experiments in collisions involving electron beams at different centre-of-mass energies, rapidity and p_T intervals.

The results (see figure, left) are compared with the expectations obtained from perturbative QCD calculations and Monte Carlo event generators. None of the models reproduce the data, indicating that the fragmentation of charm quarks is not well understood. A similar pattern is seen when comparing the Ξ_c^0/D^0 baryon-to-meson ratio with predicted values (see figure, right), where the latter have a sizable uncertainty due to the unknown branching ratio of the decay.



(Left) The Λ_c^+/D^0 baryon-to-meson ratio measured in pp and p–Pb collisions as a function of transverse momentum, compared with different event generators for pp collisions. (Right) The ratio of the p_T differential cross-sections of Ξ_c^0 baryons (multiplied by the branching ratio into $e^+ \nu_e \Xi^-$) as a function of transverse momentum, showing the large uncertainty on the $\Xi_c^0 \rightarrow e^+ \nu_e \Xi^-$ branching ratio (shaded bands).

These two results suggest that charmed baryon formation might not be universal, and that the baryon/meson ratio depends on the collision system. Hints of non-universality of the fragmentation functions are also seen when comparing beauty-baryon production measurements at the Tevatron and LHC with those at LEP. The ratios measured in pPb collisions are similar to the result in pp collisions.

The statistical precision of the Λ_c^+ and Ξ_c^0 measurements is expected to be improved with data collected during the LHC Run 2, and with data from Run 3 and Run 4 following a major upgrade of the ALICE apparatus. This set of measurements also provides a reference for future investigation of Λ_c^+ and Ξ_c^0 production in lead–lead collisions, where the formation and kinematic properties of charm baryons are expected to be affected by the presence of the quark–gluon plasma.

- **Further reading**

ALICE Collaboration 2017 arXiv:1712.09581.
ALICE Collaboration 2017 arXiv:1712:04242.

***Les physiciens des particules du monde entier sont invités** à apporter leurs contributions au CERN Courier, en français ou en anglais. Les articles retenus seront publiés dans la langue d'origine. Si vous souhaitez proposer un article, faites part de vos suggestions à la rédaction à l'adresse cern.courier@cern.ch.*

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Sciencewatch

Compiled by John Swain, Northeastern University

Origin of Hypatia stone questioned

The Hypatia stone, found in western Egypt in 1996, is believed to have formed about 28 million years ago in a meteorite impact. In 2013 it was confirmed to be of extraterrestrial origin and possibly the first sample of a comet nucleus. Now Georgy Belyanin of the University of Johannesburg in South Africa and colleagues have found compounds including polyaromatic hydrocarbons and silicon carbide associated with a nickel phosphide compound not found in the solar system before. Other facts supporting the other-worldly origin of the stone include ratios of silicon to carbon opposite to those of the Earth, Mars or Venus, but consistent with interstellar dust, and mineral grains that contain phosphorus and metallic elements not in the ratios expected. The Hypatia stone challenges the generally accepted view of how the solar system was formed and the study of its history continues.


M di Martino/INAF

Fragments from the Hypatia stone uncovered in south-west Egypt in the Libyan Desert Glass Field, measuring around 1 cm across.

● **Further reading**

G Belyanin *et al.* 2018 *Geochim. Cosmochim. Acta* **223** 462.

Recipes for DNA assembly

DNA can be designed to assemble into specific shapes, but the range of possibilities has been limited – until now. A clutch of papers published in the same issue of *Nature* describe several approaches to making very large structures. Lulu Qian and colleagues at Caltech used simple assembly rules recursively to create 2D arrays with areas up to 0.5 μm^2, while Peng Yin and team at Harvard University used DNA "bricks" to make 3D nanostructures of more than 10,000 components. Hendrik Dietz and colleagues at the Technical University of Munich, meanwhile, show that large objects can be efficiently assembled in a multi-stage process using DNA building blocks with optimised shape and interaction patterns, also demonstrating a scalable, cost-efficient method for making the required DNA strands. The results make it clear that DNA can be made to self-assemble into a wide variety of large structures with the aim of building synthetic cellular machines for research, engineering and medical applications.

● **Further reading**

G Tikhomirov *et al.* 2017 *Nature* **552** 67; L Ong *et al.* 2017 *Nature* **552** 72; K Wagenbauer *et al.* 2017 *Nature* **552** 78; F Praetorius *et al.* 2017 *Nature* **552** 84.

Equivalence principle in space

The weak equivalence principle, a cornerstone of general relativity, says that all bodies should fall at the same rate. Recent results from the MICROSCOPE satellite, launched in April 2016 and operated by the French space centre CNES, show that this key physics principle holds to unprecedented precision. The experiment measured the force needed to keep two similar floating test masses made of different alloys in the same orbit as the satellite completed more than 1500 orbits. No deviation from the equivalence principle was found up to the level of one part in 10^{14}, strongly constraining theories containing very weakly coupled particles.

● **Further reading**

P Touboul *et al.* 2017 *Phys. Rev. Lett.* **119** 231101.

Topology and water waves

Mysteriously, ocean and atmospheric waves near the equator all share the property that they travel eastwards. Now, Pierre Delplace of the University of Lyon and colleagues have suggested a topological origin to this effect, with time-reversal symmetry broken by Earth's rotation. Remarkably, the work points to a formal analogy between equatorially trapped waves and topological insulators, showing yet another example of the unity of physics.

● **Further reading**

P Delplace *et al.* 2017 *Science* **358** 1075.

Sound from water to air

Normally, it's all but impossible to hear underwater sounds from above the water surface due to reflection at the interface. By placing a novel metamaterial in contact with the surface, however, Sam Lee of Yonsei University in Seoul and colleagues show that the structure enhances sound by a factor of 160 and allows 30% of the sound energy to get through. The metamaterial is a cylindrical shell with a thin plastic membrane divided into segments and with a mass in the centre, and was designed to respond to sound with secondary waves that interfere destructively, boosting transmission. Possible applications range from better underwater microphones to non-contact ultrasonic imaging.

● **Further reading**

E Bok *et al.* 2018 *Phys. Rev. Lett.* **120** 044302.

Supercool water

Water's complicated phase diagram may need to be updated. Kyung Hwan Kim of Stockholm University and colleagues used femtosecond X-ray laser pulses to probe micrometre-sized water droplets supercooled in a vacuum. Measuring the diameter of the drops as they evaporate and cool, the team found evidence for a supercooled liquid phase at 229 K for water and 233 K for heavy water (consistent with a "Widom line" separating the two liquid phases). Remarkably, water can remain liquid down to –42.55 °C.

● **Further reading**

K Kim *et al.* 2017 *Science* **358** 1589.

Astrowatch

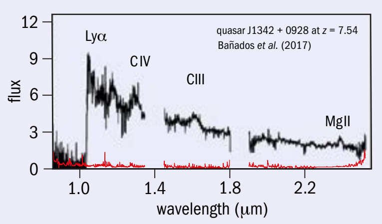
Compiled by Merlin Kole, Department of Particle Physics, University of Geneva

Ancient black hole lights up early universe

Many questions remain about what happened in the first billion years of the universe. At around 100 million years old, the universe was a dark place consisting of mostly neutral hydrogen without many objects emitting detectable radiation. This situation changed as stars and galaxies formed, leading to a phase transition known as reionisation where the neutral hydrogen was ionised. Exactly when reionisation started and how long it took is still not fully clear, but a recent discovery of the oldest massive black hole ever found can help answer this important question.

Up to about 300,000 years after the Big Bang, the universe was hot and dense, and electrons and protons were fully separated. As the universe started to expand, it cooled down and underwent a first phase transition where electrons and protons formed neutral gases such as hydrogen. The following period is known as the cosmic dark ages. During this period, protons and electrons were mostly combined into neutral hydrogen, but the universe had to cool much further before matter could condense to the level where light-producing objects such as stars could form. These new objects started to emit both the radiation we can now detect to study the early universe and also the radiation responsible for the last phase transition – the reionisation of the universe. Some of the brightest and therefore easiest-to-detect objects are quasars: massive black holes surrounded by discs of hot accreting matter that emit radiation over a wide but distinctive spectrum.

Using data from a range of large-area surveys by different telescopes, a group led by Eduardo Bañados from the Carnegie Institution for Science has discovered a distant quasar called J1342+0928, with the black hole at its centre found to be eight million solar masses. After the radiation was emitted by J1342+0928, it travelled through the expanding universe, increasing its wavelength or "red shifting" in proportion to its travel time. Using known spectral features of quasars, the redshift (and therefore the moment at which the radiation was emitted) can be calculated.



The spectrum from J1342+0928, with the red line showing the modelled original spectrum before absorption by both neutral and ionised hydrogen.

The spectrum of J1342+0928, shown in the figure, demonstrates that the universe was only 690 million years old – just 5% of its current age – at the time we see J1342+0928. The spectrum also shows a second interesting feature: the absorption of a part of the spectrum by neutral hydrogen, which implies that at the time we are observing the black hole, the universe was not fully ionised yet. By modelling the emission and absorption, Bañados and co-workers found that the spectrum from J1342+0928 is compatible with emission in a universe where half the hydrogen was ionised, putting the time of emission right in the middle of the epoch of reionisation.

The next mystery is to explain how a black hole weighing eight million solar masses could form so early in the universe. Black holes grow as they accrete mass surrounding them, but the accreting mass radiates and this radiation pushes other accreting mass away from the black hole. As a result, there is a theoretical limit on the amount of matter a black hole can accrete. Forming a black hole the size of J1342+0928 with such accretion limits would require black holes in the very early universe with sizes that challenge current theoretical models. One possible explanation, however, is that this particular black hole is a peculiar case and was formed by a merger of several smaller black holes.

Thanks to continuous data taking from a range of existing telescopes and upcoming new instrumentation, we can expect more objects like J1342+0928 or even older to be discovered, offering a probe of the universe at even earlier stages. The discovery of further objects would allow a more exact date for the period of reionisation, which can be compared with indirect measurements coming from the cosmic microwave background. At the same time, more measurements will show if black holes of this size in the early universe are just an anomaly or if there are more. In either case, such observations would provide important input for research on early black hole formation.

● Further reading

E Bañados *et al.* 2018 *Nature* **553** 473.

Picture of the month

This small planetary nebula, NGC 7027, was first spotted in 1878, only 450 years after the nebula first started expanding. The name "planetary nebula" is a misnomer, however. It dates back to William Herschel, who classified these objects based on their rounded planet-like shape. We now know that planetary nebulae are not related to planets but are instead created as massive stars come towards the end of their lives and eject large amounts of gas due to the high radiation pressure from the dying star. NGC 7027 consists of a neutral gas cloud surrounding an elliptical inner cloud of ionised gas known to emit X-rays. The high temperature of the inner cloud needed to emit X-rays is thought to be a result of an accretion disc surrounding the star in the centre, which is now a white dwarf.

Hubble/NASA/ESA/J Schmidt

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Cornell University

The main linac cryomodule for the Cornell-Brookhaven CBETA facility being moved into place in February 2017.

Small accelerator promises big returns

Under construction in the US, the CBETA multi-turn energy-recovery linac will pave the way for accelerators that combine the best of linear and circular machines.

When deciding on the shape of a particle accelerator, physicists face a simple choice: a ring of some sort, or a straight line? This is about more than aesthetics, of course. It depends on which application the accelerator is to be used for: high-energy physics, advanced light sources, medical or numerous others.

Linear accelerators (linacs) can have denser bunches than their circular counterparts, and are widely used for research. However, for both high-energy physics collider experiments and light sources, linacs can be exceedingly power-hungry because the beam is essentially discarded after each use. This forces linacs to operate at an extremely low current compared to ring accelerators, which in turn limits the data rate (or luminosity) delivered to an experiment. On the other hand, in a collider ring there is a limit to the focusing of the bunches at an interaction point as each bunch has to survive the potentially disruptive collision process on each of millions of turns. Bunches from a linac have to collide only once and can therefore be focused to aggressively collide at a higher luminosity.

Linacs could outperform circular machines for light-source and collider applications, but only if they can be operated with higher currents by not discarding the energy of the spent beam. Energy-recovery linacs (ERLs) fill this need for a new accelerator type with both linac-quality bunches and the large currents more typical of circular accelerators. By recovering the energy of the spent beam through deceleration in superconducting radio-frequency (SRF) cavities, ERLs can recycle that energy to accelerate new bunches, combining the dense beam of a linear accelerator with the high current of a storage ring to achieve significant RF power savings.

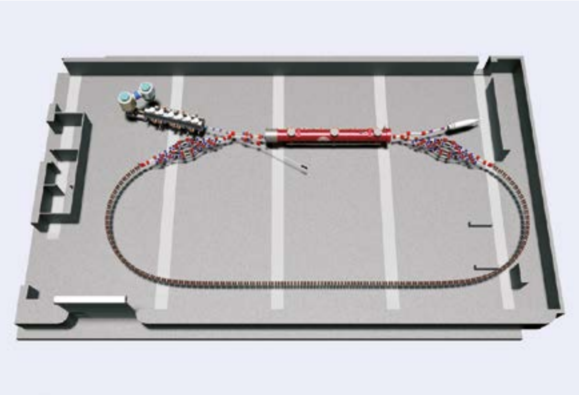
A new facility called CBETA (Cornell-Brookhaven ERL Test Accelerator) that combines some of the best traits of linear and circular accelerators has recently entered construction at Cornell University in the US. Set to become the world's first multi-turn SRF ERL, with a footprint of about 25 × 15 m, CBETA is designed to accelerate an electron beam to an energy of 150 MeV. As an additional innovation, this four-turn ERL relies on only one return loop for its four beam energies, using a single so-called fixed-field alternating-gradient return loop that can accommodate a large range of different electron energies. To further save energy, this single return loop is constructed from permanent Halbach magnets (an arrangement of permanent magnets that augments the magnetic field on the beam side while cancelling the field on the outside).

Initially, CBETA is being built to test the SRF ERL and the single-return-loop concept of permanent magnets for a proposed future electron-ion collider (EIC). Thereafter, CBETA will provide beam for applications such as Compton-backscattered hard X-rays and dark-photon searches. This future ERL technology could be an immensely important tool for researchers who rely on the luminosity of colliders as well as for those that use synchrotron radiation at light sources. ERLs are envisioned for nuclear and elementary particle-physics colliders, as in the proposed eRHIC and LHeC projects, but are also proposed for basic-research coherent X-ray sources, medical applications and industry, for example in lithography sources for the production of yet-smaller computer chips.

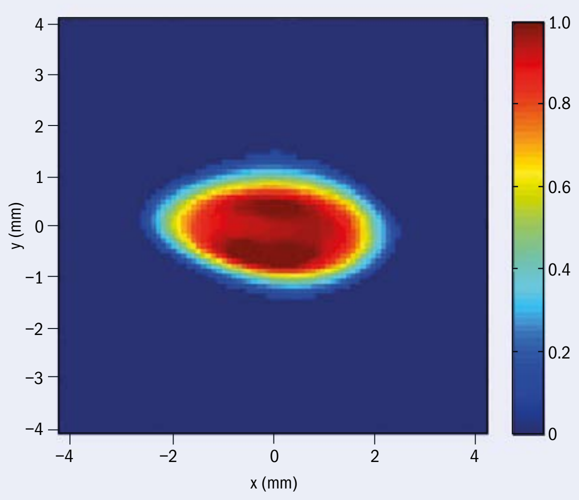
The first multi-turn SRF ERL

The theoretical concept of ERLs was introduced long before a functional device could be realised. With the introduction of the CBETA accelerator, scientists are following up on a concept first introduced by physicist Maury Tigner at Cornell in 1965. Similarly, non-scaling fixed-field alternating-gradient optics for beams of largely varying energies were introduced decades ago and will be implemented in an operational accelerator for only the second time with CBETA, after a proof-of-principle test at the EMMA facility at Daresbury Laboratory in the UK, which was commissioned in 2010.

The key behind the CBETA design is to recirculate the beam four times through the SRF cavities, allowing electrons to be accelerated to four very different energies. The beam with the highest energy (150 MeV) will be used for experiments, before being decelerated in the same cavities four times. During deceleration, energy is taken out of the electron beam and is transferred to electromagnetic fields in the cavities, where the recovered energy is then used to accelerate new particles. Reusing the same cavities multiple times significantly reduces the construction and operational costs, and also the overall size of the accelerator.


Cornell University

A floor plan showing the Cornell-Brookhaven ERL test accelerator located at Cornell's Wilson Laboratory.



Cornell University

Measured cross-section of the first beam accelerated by the main linac cryomodule captured on a beam screen in May 2017.

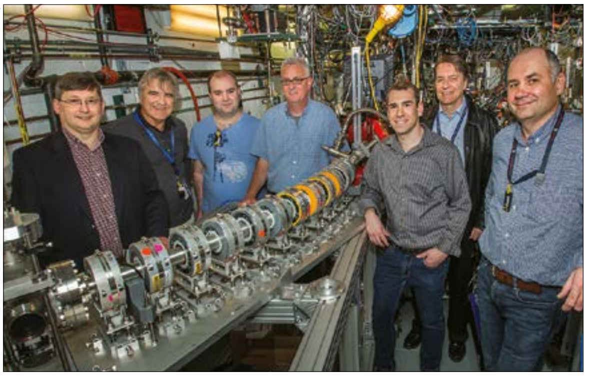
The energy-saving potential of the CBETA technology cannot be understood, and is a large consideration for the project's funding agency the New York State Energy Research and Development Authority. By incrementally increasing the energy of the beam through multiple passes in the accelerator section, CBETA can achieve a high-energy beam without a high initial energy at injection – characteristics more commonly found in storage rings. CBETA's use of permanent magnets provides further energy savings. The precise energy savings from CBETA are difficult to estimate at this stage, but the machine is expected to require about a factor of 20 less RF power than a traditional linac. This saving factor would be even larger for future ERLs with higher beam energy.

The energy-saving potential of CBETA technology cannot be understood.

SRF linacs have been operated in ERL mode before, for example at Jefferson Lab's infrared free-electron laser, where a single-pass energy recovery has reclaimed nearly all of the electron's energy. CBETA will be the first SRF ERL with more than one turn and is unique in its use of a single return loop for all beams. Simultaneously transporting beam at four very different energies (from 42 to 150 MeV) requires a different bending field strength for each energy. While traditional beamlines are simply unable to keep beams with very different energies on the same "track", the CBETA design relies on fixed-field alternating-gradient optics. To save energy, permanent Halbach magnets containing all four beam energies in a single 70 mm-wide beam pipe were designed and prototyped at Brookhaven National Laboratory (BNL). The special optics for a large energy range had already been proposed in the 1960s, but a modern rediscovery began in 1999 at the POP accelerator at KEK in Japan. This concept has various applications, including medicine, nuclear energy, and in nuclear and particle physics, culminating so far with the construction of CBETA. Important aspects of these optics will be investigated at CBETA, including the following: time-of-flight control, maintenance of performance in the presence of errors, adiabatic transition between curved and straight regions, the creation of insertions that maintain the large energy acceptance, the operation and control of multiple beams in one beam pipe, and harmonic correction of the fields in the permanent magnets.


Cornell University

CBETA principal investigator Georg Hoffstaetter and Cornell University president Martha Pollack in front of the main linac cryomodule installed for RF testing.


Brookhaven National Laboratory

Members of the CBETA team testing a fixed-field alternating-gradient beam transport line made with permanent magnets at Brookhaven. Left to right: Mark Palmer, Dejan Trbojevic, Stephen Brooks, George Mahler, Steven Trabocchi, Thomas Roser and Mikhail Fedurin.

Harmonic field correction is achieved by an elegant invention first used in CBETA: in order to overcome the magnetisation errors present in the NdFeB blocks and to produce magnets with 10^{-3} field accuracy, 32 to 64 iron wires of various lengths are inserted around the magnet bore, with lengths chosen to minimise the lowest 18 multipole harmonics.

A multi-turn test ERL was proposed by Cornell researchers following studies that started in 2005. Cornell was the natural site, given that many of the components needed for such an accelerator had been prototyped by the group there. A collaboration with BNL was formed in the summer of 2014; the test ERL was called CBETA and construction started in November 2016.

CBETA has some quite elaborate accelerator elements. The most complex components already existed before the CBETA collaboration, constructed by Cornell's ERL group at Wilson Lab: the DC electron source, the SRF injector cryomodule, the main ERL cryomodule, the high-power beam stop, and a diagnostic section to map out six-dimensional phase-space densities. They were designed, constructed and commissioned over a 10-year period and hold several world records in the accelerator community. These components have produced the world's largest electron current from a photo-emitting source, the largest continuous current in an SRF linac and the largest normalised brightness of an electron bunch.

Setting records

Meanwhile, the DC photoemission electron gun has set a world record for the average current from a photoinjector, demonstrating operation at 350 kV with a continuous current of 75 mA with 1.3 GHz pulse structure. It operates with a KCsSb cathode, which has a typical quantum efficiency of 8% at a wavelength of 527 nm and requires a large ceramic insulator and a separate high voltage, high current, power supply to be able to support the high voltage and current. The present version of the Cornell gun has a segmented insulator design with metal guard rings to protect the ceramic insulator from punch-through by field emission, which was the primary limiting factor in previous designs. This gun has been processed up to 425 kV under vacuum, typically operating at 400 kV.

The SRF injector linac, or injector cryomodule (ICM), set new records in current and normalised brightness. It operates with a bunch train containing a series of five two-cell 1.3 GHz SRF cavities, each with twin 50 kW input couplers that receive microwaves from high-power klystrons, and the input power couplers are adjustable to allow impedance matching for a variety of different beam currents. The ICM is capable of a total energy gain of around 15 MeV, although CBETA injects beam at a more modest energy of 6 MeV. The high-current CW main linac cryomodule, meanwhile, has a maximum energy gain of 70 MeV and a beam current of up to 40 mA, and for CBETA will accelerate the beam by 36 MeV on each of the four beam passes.

Several other essential components that have also been commissioned include a high-power beam stop and diagnostics tools for high-current and high-brightness beams, such as a beamline for measuring 6D phase-space densities, a fast wire scanner for beam profiles and beam-loss diagnostics. All these components are now being incorporated in CBETA. While the National Science Foundation provided the bulk funding for the development of all these components, the LCLS-II project contributed funding to investigate the utility of Cornell's ERL technology, and the company ASML contributed funds to test the use of ERL components for an industrial EUV light source.

Complementary development work has been ongoing at BNL, and last summer the BNL team successfully tested a fixed-field alternating-gradient beam transport line at the Accelerator Test Facility. It uses lightweight, 3D-printed frames to hold blocks of permanent magnets and uses the above-mentioned innovative method for fine-tuning the magnetic field to steer multiple beams at different energies through a single beam pipe. With this design, physicists can accelerate particles through multiple stages to higher and higher energies within a single ring of magnets, instead of requiring more than one ring to achieve these energies. The beams reached a top momentum that was more than 3.8 times that of the lowest transferred momentum, which is to be compared to the previous result in EMMA, where the highest momentum was less than twice that of the lowest one. The properties of the permanent Halbach magnets match or even surpass those of electromagnets, which require much more precise engineering and machining to create each individual piece of metal. The success of this proof-of-principle experiment reinforces the CBETA design choices.

The initial mission for CBETA is to prototype components for BNL's proposed version of an EIC called eRHIC, which would be built using the existing Relativistic Heavy Ion Collider infrastructure at BNL. JLAB also has a design for an EIC, which requires an ERL for its electron cooler and therefore also benefits from research at CBETA. Currently, the National Academy of Sciences is studying the scientific potential of an EIC. More than 25 scientists, engineers and technicians are collaborating on CBETA and they are currently running preliminary beam tests, with the expectation of completing CBETA installation by the summer of 2019. Then we will test and complete CBETA commissioning by the spring of 2020, and begin to explore the scientific applications of this new acceleration and energy-saving technique.

● Further reading

G Hoffstaetter *et al.* 2017 arXiv:1706.04245.

Résumé

Petit accélérateur, grandes perspectives

Une nouvelle machine, appelée Cornell-Brookhaven ERL Test Accelerator *(CBETA), est en cours de construction aux États-Unis. Cette machine, d'une empreinte d'environ 25 × 15 m, sera le premier linac à récupération d'énergie (ERL) supraconducteur, et accélérera un faisceau d'électrons pour le porter à 150 MeV. Les ERL combinent certains avantages d'un accélérateur linéaire avec ceux d'un accélérateur circulaire. Le CBETA permettra initialement de produire des éléments prototypes pour un futur collisionneur électron-ion. La machine fait l'objet actuellement de tests de faisceau préliminaires ; l'installation devrait être terminée d'ici à l'été 2019.*

Georg Hoffstaetter and **Rick Ryan**, Cornell University.

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CA200BW0.4-7383RP	200MHz ± 0.2MHz	200kW	~ 1.1ms	3.30%	Water
CA324BW10-7181RP	324MHz ± 5MHz	120kW	210 ~ 600μs	3.00%	Air
CA358BW2-6878RP	358.54MHz ± 1MHz	64kW	10ms	10.00%	Water&Air
CA509MBW6-7373R	509MHz ± 3MHz	20kW	CW	100%	Water&Air
CA571BW2-6070RP	571MHz ± 1MHz	10kW	10 ~ 100μs	0.50%	Water
CA1300BW10-6372R	1300MHz ± 5MHz	16kW	CW	100%	Water
CA2856BW20-5861RP	2856MHz ± 10MHz	1.2kW	5μs	0.05%	Air
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GA102M252 Series	1000MHz ～ 2500MHz	50W ～ 2kW CW	Air
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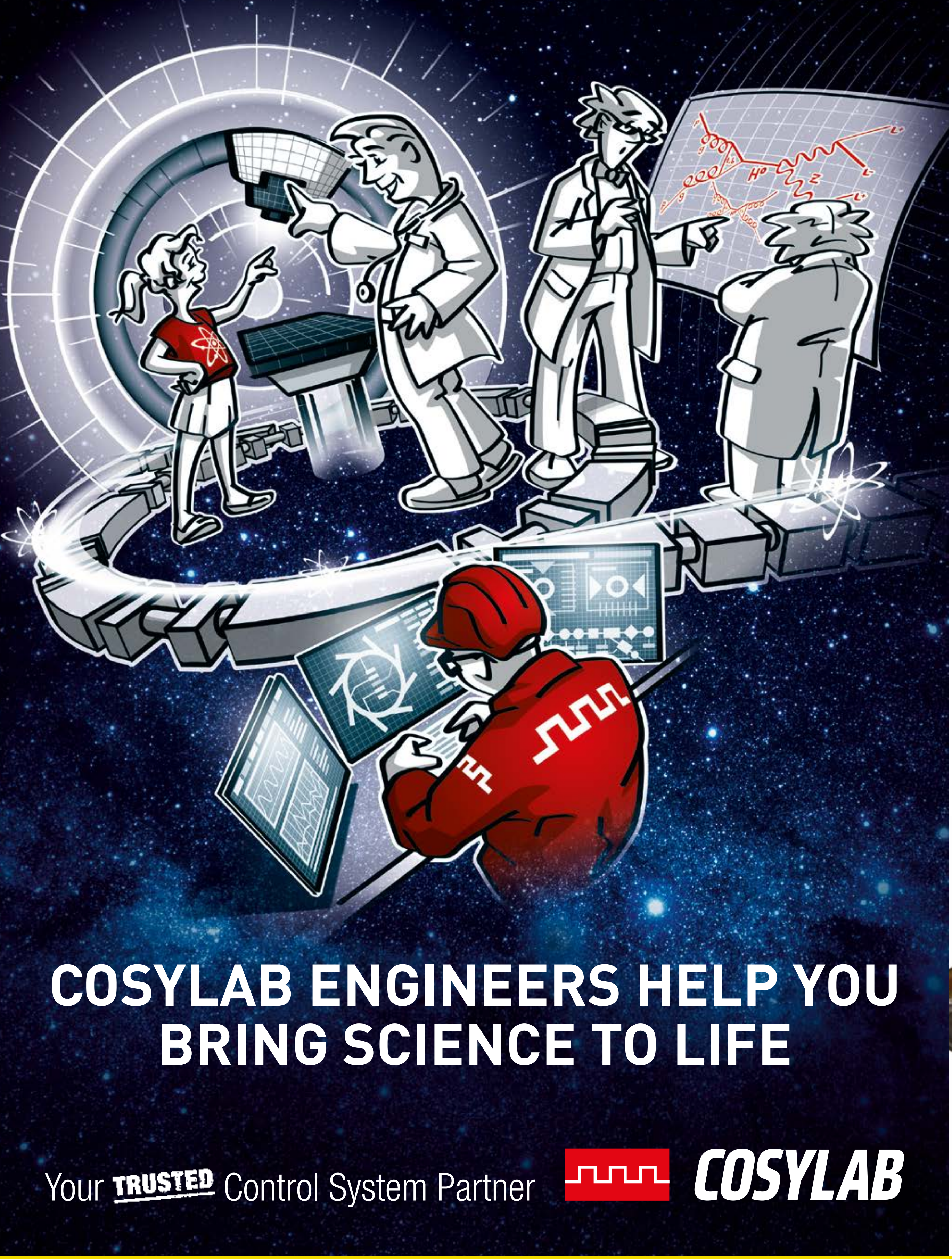
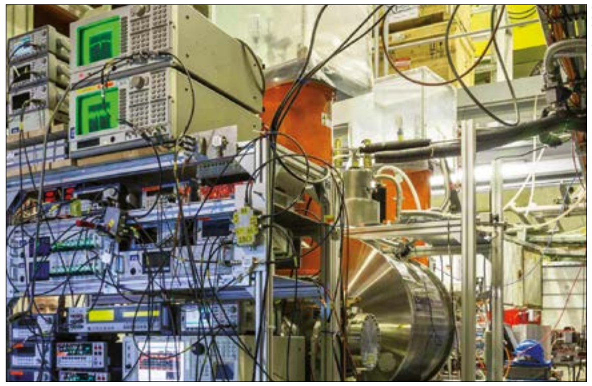


Experiment of the moment

The BASE collaboration at CERN has measured the antiproton magnetic moment with extraordinary precision, offering more than 100-fold improved limits on certain tests of charge–parity–time symmetry.


S Sellner/RIKEN

The BASE setup at CERN's Antiproton Decelerator.

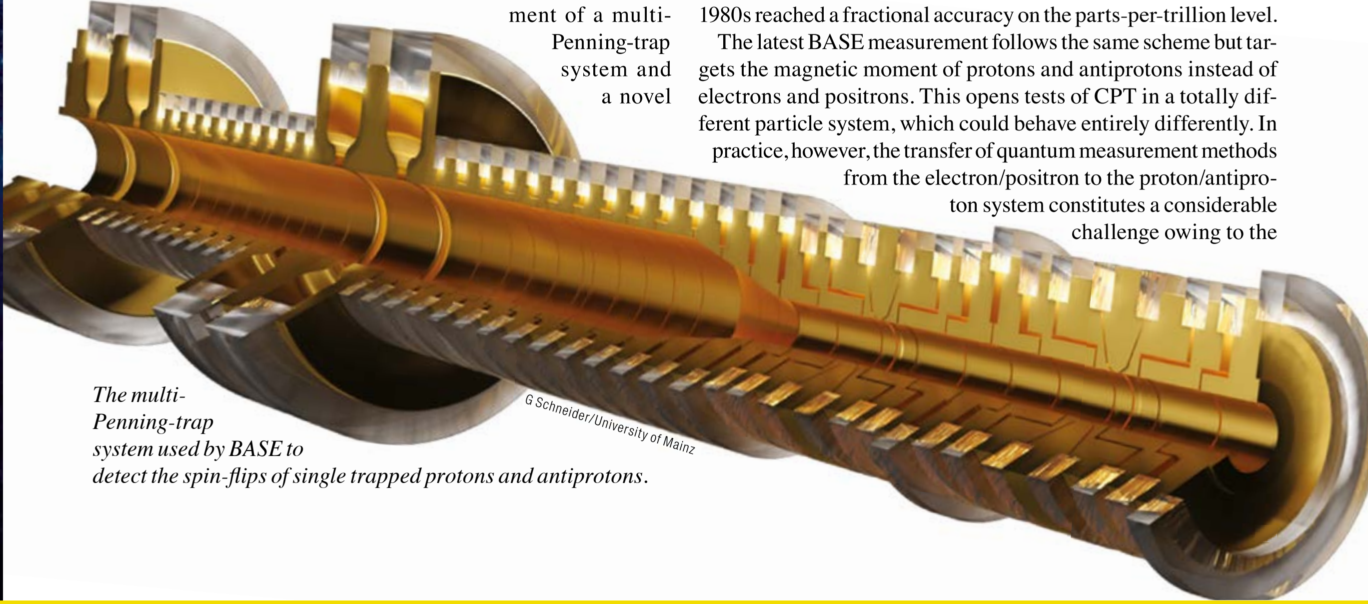
The enigma of why the universe contains more matter than antimatter has been with us for more than half a century. While charge–parity (CP) violation can, in principle, account for the existence of such an imbalance, the observed matter excess is about nine orders of magnitude larger than what is expected from known CP-violating sources within the Standard Model (SM). This striking discrepancy inspires searches for additional mechanisms for the universe's baryon asymmetry, among which are experiments that test fundamental charge–parity–time (CPT) invariance by comparing matter and antimatter with great precision. Any measured difference between the two would constitute a dramatic sign of new physics. Moreover, experiments with antimatter systems provide unique tests of hypothetical processes beyond the SM that cannot be uncovered with ordinary matter systems.

The Baryon Antibaryon Symmetry Experiment (BASE) at CERN, in addition to several other collaborations at the Antiproton Decelerator (AD), probes the universe through exclusive antimatter "microscopes" with ever higher resolution. In 2017, following many years of effort at CERN and the University of Mainz in Germany, the BASE team measured the magnetic moment of the antiproton with a precision 350 times better than by any other experiment before, reaching a relative precision of 1.5 parts per billion (figure 1). The result followed the development of a multi-Penning-trap system and a novel two-particle measurement method and, for a short period, represented the first time that antimatter had been measured more precisely than matter.

Non-destructive physics

The BASE result relies on a quantum measurement scheme to observe spin transitions of a single antiproton in a non-destructive manner. In experimental physics, non-destructive observations of quantum effects are usually accompanied by a tremendous increase in measurement precision. For example, the non-destructive observation of electronic transitions in atoms or ions led to the development of optical frequency standards that achieve fractional precisions on the 10^{-18} level. Another example, allowing one of the most precise tests of CPT invariance to date, is the comparison of the electron and positron g-factors. Based on quantum non-demolition detection of the spin state, such studies during the 1980s reached a fractional accuracy on the parts-per-trillion level.

The latest BASE measurement follows the same scheme but targets the magnetic moment of protons and antiprotons instead of electrons and positrons. This opens tests of CPT in a totally different particle system, which could behave entirely differently. In practice, however, the transfer of quantum measurement methods from the electron/positron to the proton/antiproton system constitutes a considerable challenge owing to the


G Schneider/University of Mainz

The multi-Penning-trap system used by BASE to detect the spin-flips of single trapped protons and antiprotons.

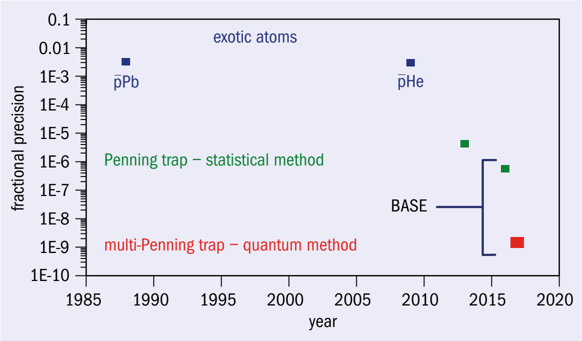


Fig. 1. The fractional precision achieved in measurements of the antiproton magnetic moment. Exotic atom spectroscopy (ASACUSA) reached fractional uncertainties at the per-mille level, while statistical methods with single particles in Penning traps (ATRAP and BASE) reached the parts-per-million level.

smaller magnetic moments and higher masses involved.

The idea is to store single particles in ultra-stable, high-precision Penning traps, where they oscillate at characteristic frequencies. By measuring those frequencies, we can access the cyclotron frequency, ν_c, which defines the particle's revolutions per second in the trap's magnetic field. Together with a measurement of the spin precession frequency ν_L, the g-factor can be extracted from the relation $\frac{g_{\bar{p}}}{2} = \frac{\nu_L}{\nu_c}$. To determine ν_c we use a technique called image-current detection. The oscillation of the antiproton in the trap induces tiny image currents in the trap electrodes, which are picked up by highly sensitive superconducting tuned circuits.

The measurement of ν_L, on the other hand, relies on single-particle spin-transition spectroscopy – comparable to performing NMR with a single antiproton. The idea is to switch the spin of the individual antiproton from one state to the other and then detect the flip. To this end a smart trick is used: the continuous Stern–Gerlach effect, which imprints the collapsed spin state of the single antiproton on its axial oscillation frequency (a parameter that can be measured non-destructively). We use a special Penning trap configuration in which an inhomogeneous magnetic bottle is superimposed on the homogeneous magnetic field of the ideal Penning trap (figure 2, top). The inhomogeneous field adds a spin-dependent quadratic magnetic potential to the axial electrostatic trapping potential and, consequently, the continuously measured axial oscillation frequency of the trapped antiproton becomes a function of the spin eigenstate.

This challenge has become the passion of the BASE collaboration for the past decade.

In practice, to detect spin quantum-transitions we first measure the axial frequency, then inject a magnetic radio-frequency to drive spin transitions, and finally measure the axial frequency again. The observation of an axial frequency jump corresponds to the clear signature that a spin-transition was driven, and by repeating such measurements many times and for different drive frequencies, we obtain the spin-flip probability as a function of the drive frequency. The corresponding resonance curve gives ν_L (figure 2, bottom).

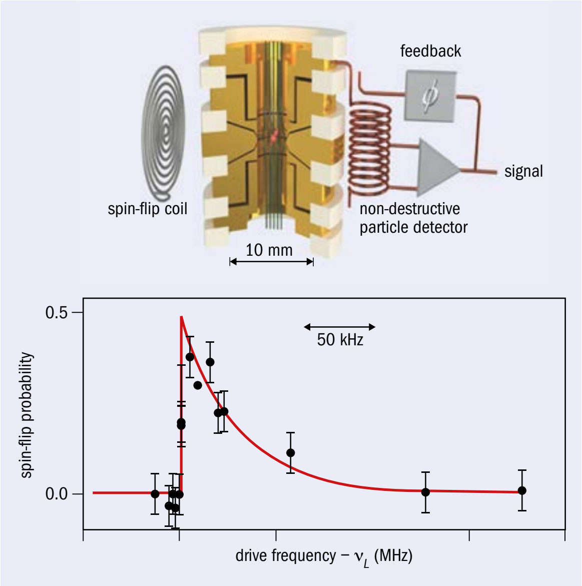


Fig. 2. A Penning trap with a superimposed magnetic bottle used to detect spin quantum transitions (top), and a Larmor resonance with a steep slope at the spin precession frequency (bottom).

Doubling up

This challenge has become the passion of the members of the BASE collaboration for the past decade. A trap was developed at Mainz with a superimposed magnetic inhomogeneity of 300,000 T/m^2, which corresponds to a magnetic field change of about 1 T over a distance of about 1.5 mm! In this extreme magnetic environment, a proton/antiproton spin transition induces an axial frequency shift of only 170 mHz when driven at a frequency of around 650 kHz.

Using this unique device, in 2011 we reported the first observation of spin flips with a single trapped proton. This was followed by the unambiguous quantum-non-demolition detection of proton spin-transitions, which was later also demonstrated with antiprotons (figure 3). The high-fidelity detection of the spin state, however, requires the particle to be cooled to temperatures of the order of 100 mK. This was achieved by sub-thermal cooling of the particle's cyclotron mode by means of cryogenic resistors, but is an inconceivably time-consuming procedure.

The high-fidelity resolution of single-spin quantum transitions is the key to measuring the antiproton magnetic moment at the parts-per-billion level. The elegant double-trap technique that makes this possible was invented at Mainz and applied with great success in tests of bound-state quantum electrodynamics, in collaboration with GSI Darmstadt and the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, both institutes also being part of the BASE collaboration. This double Penning-trap technology separates the sensitive frequency measurements of ν_L and ν_c, and the spin analysis measurements into two traps: a homogeneous "precision trap" (PT) and the spin state "analysis trap" (AT) with the superimposed strong magnetic bottle. The magnetic field in the PT is about 100,000 times more homogeneous than that of the AT and allows sampling of the spin-flip resonance at much higher resolution, compared to measurements solely carried out in the inhomogeneous AT.

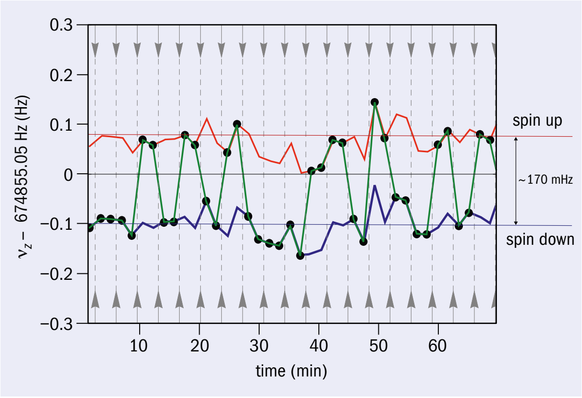


Fig. 3. Single antiproton spin transitions resolved in the BASE analysis trap by applying the continuous Stern–Gerlach effect.

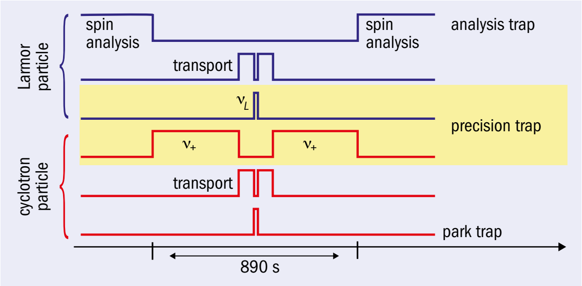


Fig. 4. The two-particle scheme used to measure the magnetic moment of the antiproton. The "Larmor particle" is at a radial temperature of on average 120 mK, cold enough for high-fidelity detection of the spin state, while the cyclotron particle at a radial temperature of about 300 K is used as a magnetometer. The measurements of ν_L and ν_c are carried out in the precision trap.

The single-particle "double-trap method", however, comes with the drawback that each frequency measurement in the PT heats the particle's radial mode to about room-temperature and requires repeated particle preparation to sub-thermal radial energy, a condition that is ultimately required for the high-fidelity detection of spin transitions. Each of these sub-thermal-energy preparation cycles takes several hours, while a well resolved g-factor resonance contains at least 400 individual data points. We applied this method at BASE to measure the proton magnetic moment with parts-per-billion precision in a measurement campaign that took, including systematic studies and maintenance of the instrument, about half a year (*CERN Courier* March 2017 p7).

To reduce the total measurement time, we invented the novel two-particle method in which the precision frequency measurements and the high-fidelity spin-state analysis are carried out using two particles: a hot "cyclotron particle" and a cold "Larmor particle", in addition to adding a third trap called the "park trap" (figure 4). We first identify the spin state of the cold antiproton in the AT. Then we measure the cyclotron frequency with the hot particle in the PT, move this particle to the park trap and transport the cold antiproton to the PT, where spin-flip drives are irradiated. Afterwards, the cold particle is shuttled back to the AT and the hot particle to the PT. There, the cyclotron frequency is measured again, and in a last step the spin state of the cold particle in the AT is identified. By repeating this scheme many times and for different drive frequencies, the spin-flip probability as a function of the spin-flip drive frequency, normalized to the measured cyclotron frequency, is obtained – a g-factor resonance – with all the required frequency information sampled in the homogeneous PT. This novel two-particle scheme drastically reduces the measurement time, since it avoids the time-consuming preparation of sub-thermal radial energy-states.

Successfully implementing this new method, we were able to sample about 1000 data points over a period of just two months. From this campaign we extracted the antiproton magnetic moment as $\mu_{\bar{p}} = -2.792\,847\,344\,1\,(42)\,\mu_N$, the value having a fractional precision of 1.5 parts per billion and thereby improving the previous best value by BASE by a factor of 350. The result is consistent with our most precise measurement of the proton magnetic moment, $\mu_p = 2.792\,847\,350\,(9)\,\mu_N$, and thus supports CPT invariance.

Trappings of success

Underpinning this rapid achievement of the initially defined major experimental goal of the BASE collaboration was another BASE invention called the reservoir trap (RT) method. This RT, being one of four traps in the BASE trap-stack, is loaded with a shot of antiprotons and provides single particles to the precision measurement traps on request. The method allows BASE to operate antiproton experiments even during the winter shut-down of CERN's accelerators and practically doubles the available experiment time. Indeed, we have demonstrated antiproton trapping and experiment optimisation for a period of more than 400 days and operated the entire 2016 run with antiprotons captured in 2015. This long storage time also allows us to set limits on directly measured antiproton lifetime.

Together with the proton-to-antiproton charge-to-mass ratio comparison with a fractional precision of 69 parts in a trillion (*CERN Courier* September 2015 p7), which was carried out during the 2014 antiproton run, BASE has set tighter constraints on all the fundamental antiproton parameters that are directly accessible by this type of experiment. So far, all the BASE results are consistent with CPT invariance.

The latest triple-trap measurement of the antiproton magnetic moment sets new constraints on CPT violating coefficients in the Standard Model extension (SME) – an effective theory that allows the sensitivities of different experiments at different locations to be compared with respect to CPT violation. The recent BASE magnetic-moment measurement addresses a total of six combinations of SME coefficients and improves the limits on all of them by more than two orders of magnitude. Finding a non-zero coefficient would, for example, indicate the discovery of a new type of exchange boson that couples exclusively to antimatter and immediately raise the

BASE

question of its role in the universal baryon asymmetry.

Although up to now all results are CPT-consistent, this not-yet-understood asymmetry is one of the motivations to further improve the experimental resolution of the AD experiments. The recent successes reported by the ALPHA collaboration herald the first ultra-high-precision measurements on the optical spectrum of antihydrogen (see p30). Improved methods in measurements on antiprotonic helium by the ASACUSA collaboration will lead to even higher resolution results in comparisons of the antiproton-to-electron mass ratio, while the ATRAP collaboration continues to contribute independent measurements of antiprotons and antihydrogen.

Gravitational sensitivity

A new branch of experiments at CERN's AD, AEgIS, GBAR and ALPHA-g, will soon investigate the gravitational acceleration of antimatter in Earth's gravitational field – which has never been directly observed before. Indirect measurements were carried out with antiprotons by the TRAP collaboration at the AD's predecessor, LEAR, and by BASE, which set constrains on antigravity effects.

The AD community aims to verify the laws of physics with antimatter in various ways, thereby testing fundamental CPT invariance. The experiments are striving to access yet unmeasured quantities, or to improve their sensitivities to new physics. In this respect, the BASE–Mainz experiment succeeded recently in measuring the proton magnetic moment at an 11-fold improved precision, reaching a fractional uncertainty of 0.3 parts per billion. By applying these even further advanced methods to the antiproton, BASE will improve the sensitivity of the CPT invariance test by at least another factor of five.

● Further reading

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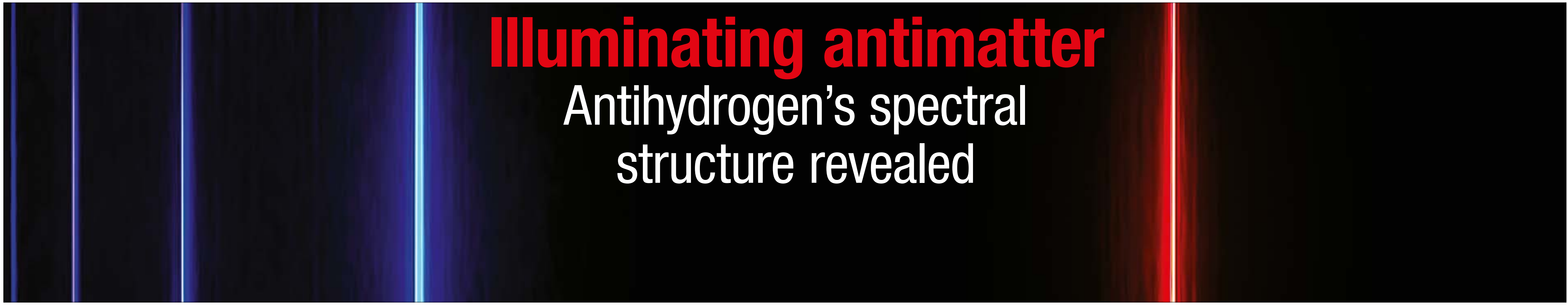
Résumé

Un moment très précis

L'expérience BASE (expérience sur la symétrie baryon-antibaryon), située au CERN, a mesuré le moment magnétique de l'antiproton avec une précision extraordinaire, contribuant à l'étude de la symétrie charge-parité-temps. En 2017, après des années d'efforts, l'équipe de BASE a mesuré le moment magnétique de l'antiproton avec une précision 350 fois supérieure à celle obtenue par les expériences précédentes, atteignant une précision relative de 1,5 milliardième.

Stefan Ulmer, **Christian Smorra** and **Stefan Sellner**, RIKEN



D Dominguez

Illuminating antimatter

Antihydrogen's spectral structure revealed

Following 30 years of effort by the low-energy antimatter community at CERN, the ALPHA collaboration has made seminal measurements of antihydrogen's spectral structure in a bid to test nature's fundamental symmetries.

The physics programme at CERN's Antiproton Decelerator (AD) is concerned with fundamental studies of the properties and behaviour of antimatter. Diverse experiments endeavour to study the basic characteristics of the antiproton (BASE, ATRAP), the spectra of antiprotonic helium (ASACUSA) and antihydrogen (ALPHA, ASACUSA, ATRAP), and gravitational effects on antimatter (GBAR, AEGIS, ALPHA-g). These innovative experiments at the AD – itself a unique facility in the world – can test fundamental symmetries such as charge–parity–time (CPT) and search for indications of physics beyond the Standard Model involving systems that have never before been studied.

Lurking in the background to all this is the baryon asymmetry problem: the mystery of what happened to all the antimatter that should have been created after the Big Bang. This mystery forces us to question whether antimatter and terrestrial matter really obey the same laws of physics. There is no guarantee that AD experiments will find any new physics, but if you can get your hands on some antimatter, it seems prudent to take a good, hard look at it.

We live in interesting times for antimatter. In addition to experiments at the AD, physicists study potential matter–antimatter asymmetries at the energy frontier at the LHCb experiment, and search for evidence of primordial antimatter streaming through space using the AMS-02 spectrometer onboard the International Space Station. Antihelium-4 nuclei were observed for the first time at Brookhaven's Relativistic Heavy Ion Collider (RHIC) in 2011, while the LHC's ALICE collaboration observed and studied antideuterons and antihelium-3 nuclei in 2015. By contrast, the experiments at the AD are low-energy affairs: we are essentially dealing with antimatter at rest.

One of the unique advantages of AD physics, therefore, is that we can address antimatter using precision techniques from modern atomic and ion-trap physics. Following three decades of development in advanced experimental techniques by the low-energy antimatter community, the ALPHA collaboration has recently achieved the major goal of examining the spectrum of antihydrogen atoms for the first time. These results herald the start of a new field of inquiry that should enable some of the most precise comparisons between matter and antimatter ever attempted.

Unprecedented precision

If you want to measure something precisely, you should probably ask an atomic physicist. For example, the measured frequency of the electronic transition between the ground state and the first excited state in hydrogen (the so-called 1S–2S transition) is 2 466 061 413 187 035 (10) Hz, corresponding to an uncertainty of 4.2×10^{-15}, and the measurement is referenced directly to a cesium time standard. Sounds impressive, but, to quote a recent article in *Nature Photonics*, "Atomic clocks based on optical transitions approach uncertainties of 10^{-18}, where full frequency descriptions are far beyond the reach of the SI second". In other words, the current time standard just isn't good enough anymore, at least not for matter. For comparison, the current best value for the mass of the Higgs boson is 125.09 ± 0.24 GeV/c^2, representing an uncertainty of about 2×10^{-3}.

To be fair, scientists had already been observing hydrogen's spectrum for about 200 years by the time the Higgs was discovered. Fraunhofer is credited with mapping out absorption lines, some of which are due to hydrogen, in sunlight in 1814. From there we can trace a direct path through Kirchhoff and Bunsen (1859/1860), who associated Fraunhofer lines with emission lines from distinct elements, to Rydberg, Balmer, Lyman and ultimately to Niels Bohr, who revolutionised atomic physics with his quantum theory in 1913. It is no exaggeration to say that physicists learned modern atomic physics by studying hydrogen, and we are therefore morally obligated to subject antihydrogen to all of the analytical tools at our disposal.

Anti-atomic spectra are not the only hot topic in precision physics at the AD. In 2015 the BASE collaboration determined that the charge-to-mass ratios for the proton and antiproton agree to 69 parts per trillion (*CERN Courier* September 2015 p7). The following year, the ASACUSA experiment – which has been making precision measurements on antiprotonic helium for more than a decade – reported that the antiproton-to-electron mass ratio agrees with its proton counterpart to a level of 8×10^{-10} (*CERN Courier* December 2016 p19). One of the long term and most compelling goals of the AD programme has always been to compare the properties of hydrogen and antihydrogen to precisions like these.

A word of caution is in order here. In searching for deviations from existing theories, it is tempting to use dimensionless uncertainties such as $\Delta m/m$, $\Delta f/f$ or $\Delta q/q$ (corresponding to mass, frequency or charge) to compare the merits of different types of measurements. Yet, it is of course not obvious that a hitherto unknown mechanism that breaks CPT or Lorentz invariance, or reveals some other new physics, should create an observable effect that is proportional to the mass, frequency or charge of the state being studied. An alternative approach is to consider the absolute energy scale to which a measurement is sensitive. There is good historical precedent for this in the quantum mechanics of atoms. Roughly speaking, atomic structure, fine structure, hyperfine structure and the Lamb shift reflect different energy scales describing the physical effects that became apparent as experimental techniques became more precise in the 20th century.

It is clearly "game on" for precision comparisons of matter and antimatter

At the time of the construction of the AD in the late 1990s, the gold standard for tests of CPT violation was the neutral kaon system. The oft-quoted limit for the fractional difference between the masses of the neutral kaon and anti-kaon was of the order 10^{-18}. Although there are many other tests of CPT using particle/antiparticle properties, this one in particular stands out for its precision. In the most recent review of the Particle Data Group, the kaon limit is presented as an absolute mass difference of less than 4×10^{-19} GeV. Although purists of metrology will argue that nothing has actually been measured with a precision of 10^{-18} here, the AD physics programme needed a potential goal that could compete, at least in principle, with this level of precision.

The holy grail

Thus the hydrogenic 1S–2S transition became a kind of "holy grail" for antihydrogen physics. The idea was that if the transition in antihydrogen could be measured to the same precision (10^{-15}) as in hydrogen, any difference between the two transition frequencies could be determined with a precision approaching that of the kaon system. On an absolute scale, the 1S–2S transition energy is about 10.2 eV, so a precision of 10^{-15} in this value corresponds to an energy sensitivity of 10^{-14} eV (10^{-23} GeV). Other features in hydrogen such as the ground-state hyperfine splitting or the Lamb shift have even smaller energies, on the order of μeV. They are also of fundamental interest in antihydrogen and test different types of physical phenomena than the 1S–2S transition. The BASE antiproton experiment probes CPT invariance in the baryon sector at the atto-electron volt scale – 10^{-27} GeV – and recently measured the magnetic moment of the antiproton to a precision of 1.5 parts-per-billion (see p25). Amazingly, the result was better than the most precise measurement of the proton at the time.

It is sobering to reflect on the state of antihydrogen physics when the AD started operations in 2000. The experiments at CERN's Low Energy Antiproton Ring (LEAR) in 1996 and at the Accumulator at Fermilab in 1998 had detected nine and 66 relativistic atoms of antihydrogen, respectively, which were produced by interactions between a stored antiproton beam and a gas-jet target. These experiments proved the existence of antihydrogen, but they held no potential for precision measurements.

The pioneering TRAP experiment had already developed the techniques needed for stopping and trapping antiprotons from

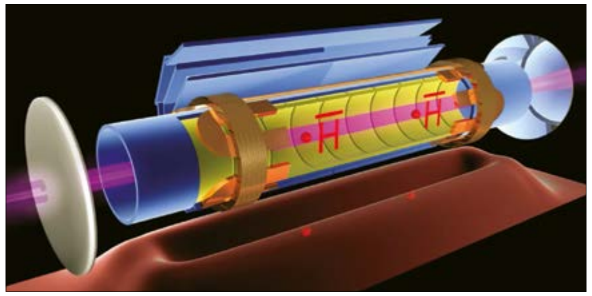


Fig. 1. A schematic cutaway of the ALPHA-2 apparatus, showing the Penning-trap electrodes (yellow), the atom-trap octupole and mirror coils (copper), and the three-layer silicon vertex detector. The mirrors for the Fabry–Pérot cavity are not to scale, and the internal diameter of the Penning-trap electrodes is about 44.5 mm. The lower part of the image illustrates the shape of the magnetic trapping potential in which antihydrogen can be confined.

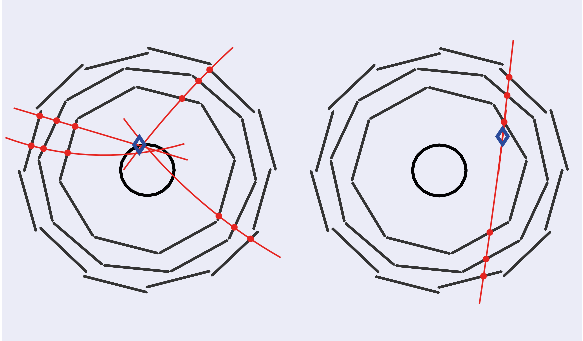


Fig. 2. The dominant background in ALPHA when searching for antihydrogen annihilations comes from cosmic rays. The left panel shows a typical topology of pion tracks resulting from an antiproton annihilation, while the right panel illustrates a typical cosmic-ray event.

LEAR, and demonstrated the first capture of antiprotons way back in 1986. The PS200 collaboration succeeded in trapping up to a million antiprotons from LEAR, and TRAP compared the charge-to-mass ratio of protons and antiprotons to a relative precision of about 10^{-9}. However, no serious attempt had yet been made to synthesise "cold" antihydrogen by the time LEAR stopped operating in 1996.

In 2002 the ATHENA experiment won the race to produce low-energy antihydrogen and the global number of antihydrogen atoms jumped dramatically to 50,000, observed over a few weeks of data taking. This accomplishment had a dramatic effect on world awareness of the AD via the rapidly growing Internet, and it even featured on the front page of the *New York Times*. Today in ALPHA, which succeeded ATHENA in 2005, we can routinely produce about 50,000 antihydrogen atoms every four minutes.

The antihydrogen atoms produced by ATHENA, and subsequently by ATRAP and ASACUSA, were not confined; they would quickly encounter normal matter in the walls of the production apparatus and annihilate. It would take until 2010 for ALPHA to show that it was possible to trap antihydrogen atoms. Although antihydrogen atoms are electrically neutral, they can be confined through the interaction of their magnetic moments with an inhomogeneous magnetic field. Using superconducting magnets, we can trap antihydrogen atoms that are created with a kinetic energy of less than 43 μeV, or about 0.5 K in temperature units.

In ALPHA's milestone 2010 experiment, we could trap on average one atom of antihydrogen every eight times we tried, with a single attempt requiring about 20 minutes. Today, in the second-generation ALPHA-2 apparatus, we trap up to 30 atoms in a procedure that takes four minutes. We have also learned how to "stack" antihydrogen atoms. In December 2017 we accumulated more than 1000 anti-atoms at once – limited only by the time available to mess about like this without measuring anything useful! It is no exaggeration to say that no one would have found this number credible in 2000 when the AD began running.

We can routinely produce about 50,000 antihydrogen atoms every four minutes

Since the first demonstration of trapped antihydrogen, we have induced quantum transitions in anti-atoms using microwaves, probed the neutrality of antihydrogen, and carried out a proof-of-principle experiment on how to study gravitation by releasing trapped antihydrogen atoms. These experiments were all performed with a trapping rate of about one atom per attempt. In 2016 we made several changes to our antihydrogen synthesis procedure that led to an increase in trapping rate of more than a factor of 10, and we also learned how to accumulate multiple shots of anti-atoms. At the same time, the laser system and internal optics necessary for exciting the 1S–2S transition were fully commissioned in the ALPHA-2 apparatus, and we were finally able to systematically search for this most sought-after spectral line in antimatter.

Antihydrogen's colours

The ALPHA-2 apparatus for producing and trapping antihydrogen is shown in figure 1. It involves various Penning traps that utilise solenoidal magnetic fields and axial electrostatic wells to confine the charged antiprotons and positrons from which antihydrogen is synthesised. Omitting 30 years of detail, we produce cold antihydrogen by gently merging trapped clouds of antiprotons and positrons that have carefully controlled size, density and temperature. The upshot is that we can combine about 100,000 antiprotons with about two million positrons to produce 50,000 antihydrogen atoms. We trap only a small fraction of these in the superconducting atom trap, which comprises an octupole for transverse confinement and two "mirror coils" for longitudinal confinement.

Anti-atoms that are trapped can be stored for at least 1000 s, but we have yet to carefully characterise the upper limit of the storage lifetime, which depends on the quality of the vacuum. The internal components of ALPHA are cooled to 4 K by liquid helium, and antihydrogen annihilations are detected using a three-layer silicon vertex detector (SVD) surrounding the production region. The SVD senses the charged pions that result from the antiproton annihilation, and event topology is used to differentiate the latter from cosmic rays, which constitute the dominant background (figure 2).

	Atoms knocked out (events)	Expected background (events)	Atoms left over (events)	Expected background (events)
Laser on resonance	79 ± 8.9	28.4	67 ± 8.2	0.7
Laser off resonance	27 ± 5.2	28.4	159 ± 13	0.7
No laser	30 ± 5.5	28.4	142 ± 12	0.7

Fig. 3. The number of raw events that are used by ALPHA to measure the antihydrogen 1S–2S transition must be scaled by an overall detection efficiency to represent the actual numbers of atoms. In this table, the detection efficiencies are different for the first column (0.376) and the third column (0.688) because the algorithms used to distinguish annihilations from cosmic rays are tuned differently in order to reflect the very different observation times (600 s versus 1.5 s for each trial).

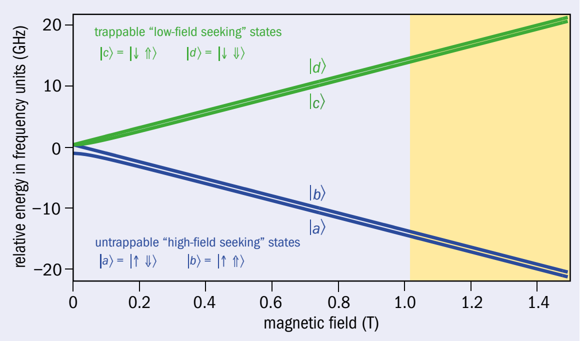


Fig. 4. A Breit–Rabi diagram showing the hyperfine energy levels of hydrogen in a magnetic field. The arrows in the state labels refer to the electron (left) and proton spin orientations, while the yellow shaded region illustrates the range of magnetic field strength in the ALPHA trap.

A tough catch

Trapping antihydrogen is extremely challenging because the trapped, charged particles that are needed to synthesise it start out with energies measured in eV (in the case of positrons) or keV (antiprotons), whereas the atom can only be confined if it has sub-meV energy. The antihydrogen is trapped due to the interaction of its magnetic moment, which is dominated by the positron spin, with an inhomogeneous magnetic field. Even with very careful preparation of the trapped positron and antiproton clouds in a cryogenic trap, only a small fraction of the produced antiatoms are "cold" enough to be trapped. The good news is that once you have trapped them, the antiatoms stick around for long enough to perform experiments.

Compared to atomic physics with normal matter, one has to somehow make up for the dramatic reduction – at least 20 orders of magnitude – in particle number at the source. The key to this is twofold: the long interaction times available with trapped particles, and the single-atom detection sensitivity afforded by antimatter annihilation. The annihilation of an antihydrogen atom is a microscopically violent event, releasing almost 2 GeV of mass-energy that can be easily detected. This is perhaps the only good thing about working with antihydrogen: if you lose it, even just one atom of it, you know it. Conversely, the loss of a single atom of hydrogen in an equivalent experiment would go unnoticed and un-mourned if there are, say, 10^{12} remaining (a typical number for trapped hydrogen). Thus, the two experiments recently reported by ALPHA are conceptually simple: trap some antihydrogen atoms; illuminate them with electromagnetic radiation that causes the anti-atoms to be lost from the trap when the radiation is on-resonance; sit back and watch what falls out.

Let's consider first the "holy grail" (1S–2S) transition, which is excited by two, counter-propagating ultraviolet photons with a wavelength of 243 nm. The power from our Toptica 243 nm laser is enhanced in a Fabry–Pérot cavity formed by two mirrors inside the cryogenic, ultra-high vacuum system. (This cavity owes its existence to the paucity of atoms available; without the optical power buildup achieved, the experiment would not be currently possible.) The 1S–2S transition has a very narrow linewidth – this is what makes it interesting – so the laser frequency needs to be just right to excite it. The other side of the same coin is that the 2S state lives for a relatively long time, about one eighth of a second, so there can be time for an excited antihydrogen atom to absorb a third photon, which will ionise it. Stripped of its positron, the antiproton is no longer confined in the magnetic trap and is free to escape to the wall and annihilate. There is also a chance that an un-ionised 2S state atom will suffer a positron spin-flip in the decay to the ground state, in which case the atom is also lost.

In the actual experiment, we illuminate trapped antihydrogen atoms with a laser for about 10 minutes, then turn off the trap (in a period of 1.5 s) and use the SVD to count any remaining atoms as they escape. Also, using the SVD we can observe any antihydrogen atoms that are lost during the laser illumination. In this way, we obtain a self-consistent picture of the fate of the atoms that were initially trapped. The evidence for the laser interaction comes from comparing what happens when the laser has the "right" frequency, compared to what happens when we intentionally de-tune the laser to a frequency where no interaction is expected (for hydrogen). As a control, and to monitor the varying trapping rate, we perform the same sequence with no laser present. The whole thing can be summarised in a simple table (figure 3), which shows the results of 11 trials of each type.

A quick glance reveals that the off-resonance and no-laser numbers are consistent with each other and with "nothing going on". In contrast, the on-resonance numbers show excess events due to atoms knocked out when the laser is on, and a dearth of events left over after the exposure. If we consider the overall inventory of antihydrogen atoms and compare the on- and off-resonance data only, we see that about 138 atoms (79–27)/0.376 have been knocked out, and 134 atoms (159–67)/0.688 are missing from the left-over sample, so our interpretation is self-consistent within the uncertainties.

This initial "go/no-go" experiment demonstrates that the transition is where we expect it to be for hydrogen and localises it to a frequency of about 400 kHz (the laser detuning for the off-reso-

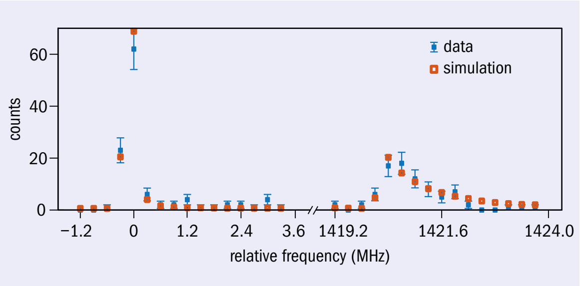


Fig. 5. The number of detected annihilation events plotted versus microwave frequency. The two spectral lines represent the c *to* b *(left) and the* d *to* a *transitions (see main text and figure 4).*

nance trials) out of 2.5×10^{15} Hz. That's a relative precision of about 2×10^{-10}, or 2×10^{-18} GeV in absolute energy units, just for showing up, and this was achieved by employing a total of just 650 or so trapped atoms. The next step is obviously to measure more frequencies around the resonance to study the shape of the spectral line, which will allow more precise determination of the resonance frequency. Note that CPT invariance requires that the shape must be identical to that expected for hydrogen in the same environment. Determination of this lineshape was the main priority for ALPHA's 2017 experimental campaign, so stay tuned.

To hyperfine splitting and beyond

A similar strategy can be used to study other transitions in antihydrogen, in particular its hyperfine splitting. With ALPHA we can drive transitions between different spin states of antihydrogen in the magnetic trap. In a magnetic field, the 1S ground state splits into four states that correspond, at high fields, to the possible alignments of the positron and antiproton spins with the field (figure 4). The upper two states can be trapped in ALPHA's magnetic trap and, using microwaves at a frequency of about 30 GHz, it is possible to resonantly drive transitions from these two states to the lower energy states, which are not trappable and are thus expelled from the trap.

We concentrate on the two transitions $|d\rangle \rightarrow |a\rangle$ and $|c\rangle \rightarrow |b\rangle$, which in the ALPHA trapping field (minimum 1 T) correspond to positron spin flips. We had previously demonstrated that these transitions are observable, but in 2016 we took the next step and actually characterised the spectral shapes of the two discrete transitions in our trap. We are now able to accumulate antihydrogen atoms, scan the microwave frequency over the range corresponding to the two transitions, and watch what happens using the SVD. The result, which may be considered to be the first true antihydrogen spectrum, is shown in figure 5.

The difference between the onset frequencies of the two spectral lines gives us the famous ground-state hyperfine splitting (in hydrogen, the ground-state hyperfine transition is the well known "21 cm line", so beloved of radioastronomers and those searching for signs of extraterrestrial life). From figure 5 we extract a value for this splitting of 1420.4 ± 0.5 MHz, for a relative precision of 3.5×10^{-4}; the energy sensitivity is 2×10^{-18} GeV. In normal hydrogen this number has been measured to be 1420.405751768 (2) MHz – that's 1.2×10^{-12} relative precision or a shockingly small 10^{-26} GeV. ALPHA is busily improving the precision of the antihydrogen hyperfine measurement, and the ASACUSA collaboration at the AD hopes to measure the same quantity to the ppm level using a challenging antihydrogen-beam technique; an analogous experiment on hydrogen was recently reported (*CERN Courier* December 2017 p23).

The antihydrogen atom still holds many structural secrets to be explored. Near-term perspectives in ALPHA include the Lyman-alpha (1S–2P) transition, with its notoriously difficult-to-produce 121.5 nm wavelength in the vacuum ultraviolet. We are currently attempting to address this with a pulsed laser, with the ultimate goal to laser-cool antihydrogen for studies in gravitation and for improved resolution in spectroscopy. To give a flavour of the pace of activities, a recent daily run meeting saw ALPHA collaborators actually debate which of the three antihydrogen transitions we should study that day, which was somewhat surreal. In the longer term, even the ground-state Lamb shift should be accessible using ALPHA's trapped antiatoms.

It is clearly "game on" for precision comparisons of matter and antimatter at the AD. It is fair to say that the facility has already exceeded its expectations, and the physics programme is in full bloom. We have some way to go before we reach hydrogen-like precision in ALPHA, but the road ahead is clear. With the commissioning of the very challenging gravity experiments GBAR, AEGIS and ALPHA-g over the next few years, and the advent of the new low-energy ELENA ring at the AD (*CERN Courier* December 2016 p16), low-energy antimatter physics at CERN promises a steady stream of groundbreaking results, and perhaps a few surprises.

● Further reading

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Résumé

La structure spectrale de l'antihydrogène révélée

Après 30 ans d'efforts des équipes travaillant au CERN sur l'antimatière à basse énergie, la collaboration ALPHA a réalisé des mesures déterminantes de la structure spectrale de l'antihydrogène, dans une recherche portant sur les symétries fondamentales de la nature. La collaboration a déterminé pour la première fois la transition 1S–2S – pierre de touche des mesures de précision – dans l'antihydrogène, et elle s'intéresse à présent à la séparation hyperfine de l'état fondamental et à d'autres caractéristiques de ces antiatomes simples. La structure de l'antihydrogène conserve de nombreux mystères, et la précision des mesures d'ALPHA continuera à augmenter.

Jeffrey Hangst, Aarhus University and ALPHA spokesperson.

Putting the Pauli exclusion principle on trial

The exclusion principle is part of the bedrock of physics, but that hasn't stopped experimentalists from devising cunning ways to test it.

Portrait of a young Pauli at Svein Rosseland's institute in Oslo in the early 1920s, when he was thinking deeply on the applications of quantum mechanics to atomic physics.

PAULI-ARCHIVE-PHO-011-1

If we tightly grasp a stone in our hands, we neither expect it to vanish nor leak through our flesh and bones. Our experience is that stone and, more generally, solid matter is stable and impenetrable. Last year marked the 50th anniversary of the demonstration by Freeman Dyson and Andrew Lenard that the stability of matter derives from the Pauli exclusion principle. This principle, for which Wolfgang Pauli received the 1945 Nobel Prize in Physics, is based on ideas so prevalent in fundamental physics that their underpinnings are rarely questioned. Here, we celebrate and reflect on the Pauli principle, and survey the latest experimental efforts to test it.

The exclusion principle (EP), which states that no two fermions can occupy the same quantum state, has been with us for almost a century. In his Nobel lecture, Pauli provided a deep and broad-ranging account of its discovery and its connections to unsolved problems of the newly born quantum theory. In the early 1920s, before Schrödinger's equation and Heisenberg's matrix algebra had come along, a young Pauli performed an extraordinary feat when he postulated both the EP and what he called "classically non-describable two-valuedness" – an early hint of the existence of electron spin – to explain the structure of atomic spectra.

At that time the EP met with some resistance and Pauli himself was dubious about the concepts that he had somewhat recklessly introduced. The situation changed significantly after the introduction in 1925 of the electron-spin concept and its identification with Pauli's two-valuedness, which derived from the empirical ideas of Lande, an initial suggestion by Kronig, and an independent paper by Goudsmit and Uhlenbeck. By introducing the picture of the electron as a small classical sphere with a spin that could point in just two directions, both Kronig, and Goudsmit and Uhlenbeck, were able to compute the fine-structure splitting of atomic hydrogen, although they still missed a critical factor of two. These first steps were followed by the relativistic calculations of Thomas, by the spin calculus of Pauli, and finally, in 1928, by the elegant wave equation of Dirac, which put an end to all resistance against the concept of spin.

Pauli himself was puzzled by the principle.

However, a theoretical explanation of the EP had to wait for some time. Just before the Second World War, Pauli and Markus Fierz made significant progress toward this goal, followed by the publication in 1940 by Pauli of his seminal paper "The connection between spin and statistics". This paper showed that (assuming a relativistically invariant form of causality) the spin of a particle determines the commutation relations, i.e. whether fields commute or anticommute, and therefore the statistics that particles obey. The EP for spin-½ fermions follows as a corollary of the spin-statistics connection, and the division of particles into fermions and bosons based on their spins is one of the cornerstones of modern physics.

Beguilingly simple

The EP is beguilingly simple to state, and many physicists have tried to skip relativity and find direct proofs that use ordinary quantum mechanics alone – albeit assuming spin, which is a genuinely relativistic concept. Pauli himself was puzzled by the principle, and in his Nobel lecture he noted: "Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions. I had always the feeling and I still have it today, that this is a deficiency. …The impression that the shadow of some incompleteness fell here on the bright light of success of the new quantum mechanics seems to me unavoidable.” Even Feynman – who usually outshone others with his uncanny intuition – felt frustrated by his inability to come up with a simple, straightforward justification of the EP: “It appears to be one of the few places in physics where there is a rule which can be stated very simply, but for which no one has found a simple and easy explanation… This probably means that we do not have a complete understanding of the fundamental principle involved. For the moment, you will just have to take it as one of the rules of the world.”

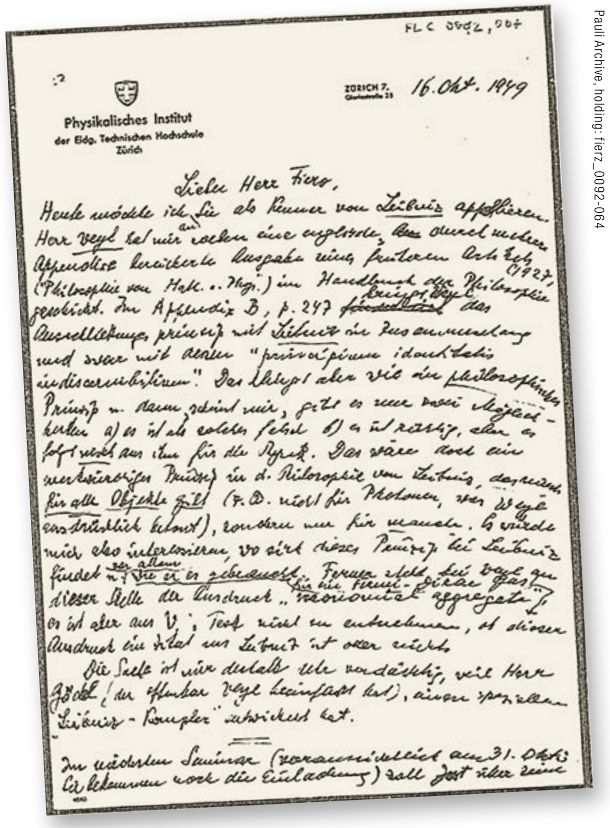
Of special interest

After further theoretical studies, which included new proofs of the spin-statistics connection and the introduction of so-called parastatistics by Green, a possible small violation of the EP was first considered by Reines and Sobel in 1974 when they reanalysed an experiment by Goldhaber and Scharff in 1948. The possibility of small violations was refuted theoretically by Amado and Primakoff in 1980, but the topic was revived in 1987. That year, Russian theorist Lev Okun presented a model of violations of the EP in which he considered modified fermionic states which, in addition to the usual vacuum and one-particle state, also include a two-particle state. Okun wrote that “The special place enjoyed by the Pauli principle in modern theoretical physics does not mean that this principle does not require further and exhaustive experimental tests. On the contrary, it is specifically the fundamental nature of the Pauli principle that would make such tests, over the entire periodic table, of special interest.”

Okun’s model, however, ran into difficulties when attempting to construct a reasonable Hamiltonian, first because the Hamiltonian included nonlocal terms and, second, because Okun did not succeed in constructing a relativistic generalisation of the model. Despite this, his paper strongly encouraged experimental tests in atoms. In the same year (1987), Ignatiev and Kuzmin presented an extension of Okun’s model in a strictly non-relativisitic context that was characterised by a “beta parameter” $|\beta| \ll 1$. Not to be confused with the relativistic factor v/c, β is a parameter describing the action of the creation operator on the one-particle state. Using a toy model to illustrate transitions that violate the EP, Ignatiev and Kuzmin deduced that the transition probability for an anomalous two-electron symmetric state is proportional to $\beta^2/2$, which is still widely used to represent the probability of EP violation.

This non-relativistic approach was criticized by A B Govorkov, who argued that the naive model of Ignatiev and Kuzmin could not be extended to become a fully-fledged quantum field theory. Since causality is an important ingredient in Pauli’s proof of the spin-statistics connection, however, Govorkov’s objections could be bypassed: later in 1987, Oscar Greenberg and Rabindra Mohapatra at the University of Maryland introduced a quantum field theory with continuously deformed commutation relations that led to a violation of causality. The deformation parameter was denoted by the letter *q*, and the theory was supposed to describe new hypothetical particles called “quons”. However, Govorkov was able to show that even this sleight of hand could not trick quantum field theory into small violations of the EP, demonstrating that the mere existence of antiparticles – again a true relativistic hallmark of quantum field theory – was enough to rule out small violations. The take-home message was that the violation of locality is not enough to break the EP, even “just a little”.

A violation of the EP would be revolutionary.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Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

ZÜRICH 7, Gloriastrasse 35 16. Okt. 1949

Lieber Herr Fierz,

Heute möchte ich Sie als Kenner von Leibniz apostrophieren. Herr Weyl hat mir soeben eine englische, um einige Appendices erweiterte Ausgabe seines früheren Artikels (1927) („Philosophie der Math. u. Nat.“) im Handbuch der Philosophie geschickt. Im Appendix B, p. 247 bringt Weyl das Ausschließungsprinzip mit Leibniz in Zusammenhang und zwar mit dessen “principium identitatis indiscernibilium”. Das klingt aber wie ein philosophisches Prinzip u. dann scheint mir, gibt es nur zwei Möglichkeiten a) es ist als solches falsch b) es ist richtig, aber es folgt nichts aus ihm für die Physik. Das wäre doch ein merkwürdiges Prinzip in d. Philosophie von Leibniz, das nicht für alle Objekte gilt (z. B. nicht für Photonen, was Weyl ausdrücklich betont), sondern nur für manche. Es würde mich also interessieren, wo sich dieses Prinzip bei Leibniz findet und vor allem wie er es gebraucht. Ferner steht bei Weyl an dieser Stelle der Ausdruck „horizontal aggregate“ für ein Fermi-Dirac Gas; es ist aber aus W.’s Text nicht zu entnehmen, ob dieser Ausdruck ein Zitat aus Leibniz ist oder nicht.

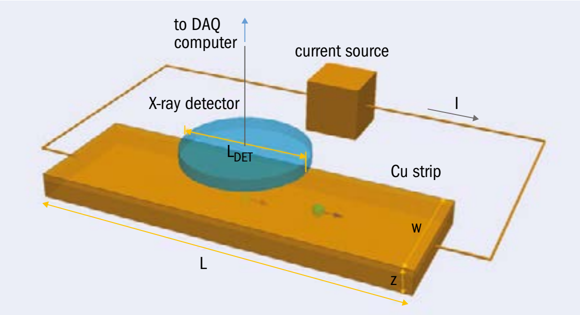
Die Sache ist mir deshalb etwas verdächtig, weil Herr Gödel (der offenbar Weyl beeinflusst hat), einen speziellen “Leibniz-Komplex” entwickelt hat.

Im nächsten Seminar (voraussichtlich am 31. Okt.; Sie bekommen noch die Einladung) soll Jost über seine

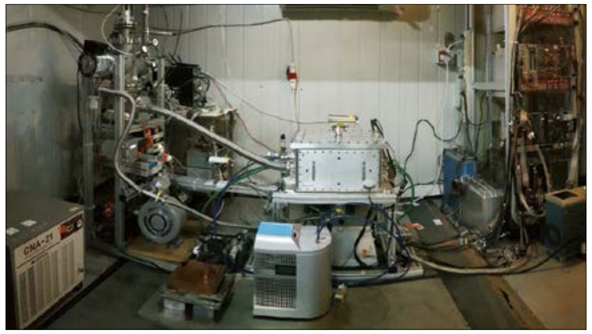
Pauli Archive, holding: fierz_0092-064

Part of a letter written by Pauli to Fierz in October 1949, where Pauli discusses Leibnitz’s principle of the “identity of the indiscernibles” in connection with the exclusion principle.

The connection between the intrinsic spin of particles and the statistics that they obey are at the heart of quantum field theory and therefore should be tested. A violation of the EP would be revolutionary. It could be related either to the violation of CPT, or violation of locality or Lorentz invariance, for example. However, we have seen how robust the EP is and how difficult it is to frame a violation within current quantum field theory. Experiments face no lesser difficulties, as noted as early as 1980 by Amado and Primakoff, and there are very few experimental options with which to truly test this tenet of modern physics.



A conceptual scheme of the Ramberg and Snow experiment. “Anomalous” electrons in the copper bar can be captured by copper atoms, followed by the emission of X-rays. The extent of EP violation can be estimated from the number of detected X-rays. The same conceptual scheme is used by the VIP experiment at LNGS.



The VIP2 experimental setup installed at the underground LNGS laboratory in Gran Sasso, Italy.

One of the difficulties faced by experiments is that the identicalness of elementary particles implies that Hamiltonians must be invariant with respect to particle exchange, and, as a consequence, they cannot change the symmetry of any given state of multiple identical particles. Even in the case of a mixed symmetry of a many-particle system, there is no physical way to induce a transition to a state of different symmetry. This is the essence of the Messiah–Greenberg superselection rule, which can only be broken if a physical system is open.

Breaking the rules

The first dedicated experiment in line with this breaking of the Messiah–Greenberg superselection rule was performed in 1990 by Ramberg and Snow, who searched for Pauli-forbidden X-ray transitions in copper after introducing electrons into the system. The idea is that a power supply injecting an electric current into a copper conductor acts as a source of electrons, which are new to the atoms in the conductor (see figure at top of page). If these electrons have the “wrong” symmetry they can be radiatively captured into the already occupied 1S level of the copper atoms and emit electromagnetic radiation. The resulting X-rays are influenced by the unusual electron configuration and are slightly shifted towards lower energies with respect to the characteristic X-rays of copper.

Ramberg and Snow did not detect any violation but were able to put an upper bound on the violation probability of $\beta^2/2 < 1.7 \times 10^{-26}$. Following their concept, a much improved version of the experiment, called VIP (violation of the Pauli principle), was set up in the LNGS underground laboratory in Gran Sasso, Italy, in 2006. VIP improved significantly on the Ramberg and Snow experiment by using charge-coupled devices (CCDs) as high-resolution X-ray detectors with a large area and high intrinsic efficiency. In the original VIP setup, CCDs were positioned around a pure-copper cylinder; X-rays emitted from the cylinder were measured without and with current up to 40 A. The cosmic background in the LNGS laboratory is strongly suppressed – by a factor of 10^6 thanks to the overlying rock – and the apparatus was also surrounded by massive lead shielding.

Setting limits

After four years of data taking, VIP set a new limit on the EP violation for electrons at $\beta^2/2 < 4.7 \times 10^{-29}$. To further enhance the sensitivity, the experiment was upgraded to VIP2, where silicon drift detectors (SDDs) replace CCDs as X-ray detectors. The VIP2 construction started in 2011 and in 2016 the setup was installed in the underground LNGS laboratory, where, after debugging and testing, data-taking started. The SDDs provide a wider solid angle for X-ray detection and this improvement, together with higher current and active shielding with plastic scintillators to limit background, leads to a much better sensitivity. The timing capability of SDDs also helps to suppress background events.

The experimental programme testing for a possible violation of the EP for electrons made great progress in 2017 and had already improved the upper limit set by VIP in the first two months of running time. With a planned duration of three years and alternating measurement with and without current, a two-orders-of-magnitude improvement is expected with respect to the previous VIP upper bound. In the absence of a signal, this will set the limit on violations of the EP at $\beta^2/2 < 10^{-31}$.

Experiments like VIP and VIP2 test the spin-statistics connection for one particular kind of fermions: electrons. The case of EP violations for neutrinos was also theoretically discussed by Dolgov and Smirnov. As for bosons, constraints on possible statistics violations come from high-energy-physics searches for decays of vector (i.e. spin-one) particles into two photons. Such decays are forbidden by the Landau–Yang theorem, whose proof incorporates the assumption that the two photons must be produced in a permutation-symmetric state. A complementary approach is to apply spectroscopic tests, as carried out at LENS in Florence during the 1990s, which probe the permutation properties of ^{16}O nuclei in polyatomic molecules by searching for transitions between states that are antisymmetric under the exchange of two nuclei. If the nuclei are bosons, as in this case, such transitions, if found, violate the spin-statistics relation. High-sensitivity tests for photons were also performed with spectroscopic methods. As an example, using Bose–Einstein-statistics-forbidden two-photon excitation in barium, the probability for two photons to be in a “wrong” permutation-symmetry state was shown by English and co-workers at Berkeley in 2010 to be less than 4×10^{-11} – an improvement of more than three orders of magnitude compared to earlier results.

To conclude, we note that the EP has many associated philosophical issues, as Pauli himself was well aware of, and these are being studied within a dedicated project involving VIP collaborators, and supported by the John Templeton Foundation. One such issue is the notion of "identicalness", which does not seem to have an analogue outside quantum mechanics because there are no two fundamentally identical classical objects.

This ultimate equality of quantum particles leads to all-important consequences governing the structure and dynamics of atoms and molecules, neutron stars, black-body radiation and determining our life in all its intricacy. For instance, molecular oxygen in air is extremely reactive, so why do our lungs not just burn? The reason lies in the pairing of electron spins: ordinary oxygen molecules are paramagnetic with unpaired electrons that have parallel spins, and in respiration this means that electrons have to be transferred one after the other. This sequential character to electron transfers is due to the EP, and moderates the rate of oxygen attachment to haemoglobin. Think of that the next time you breathe!

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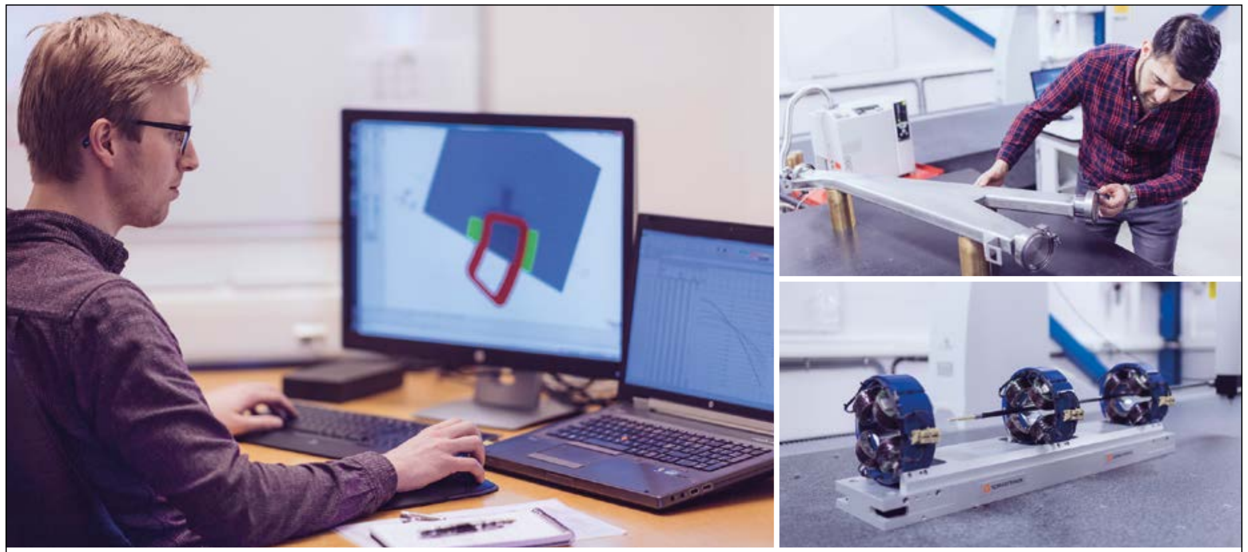
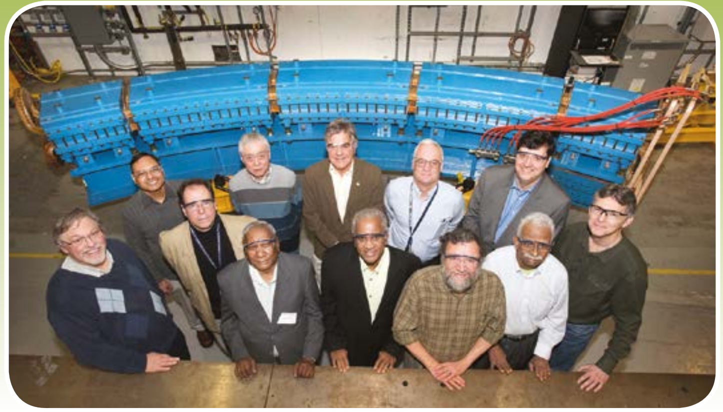
Résumé

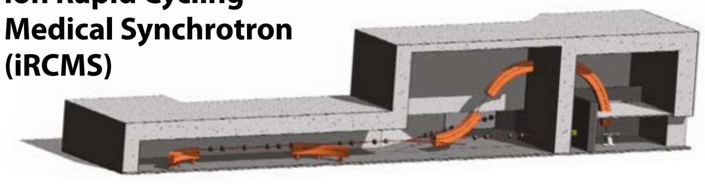
Le principe d'exclusion de Pauli à l'épreuve

Le principe d'exclusion fait partie des fondements de la physique, mais cela n'arrête pas les expérimentateurs désireux de le mettre à l'épreuve. Si un écart est mis en évidence, il pourrait être lié à une violation de CPT ou à une violation du principe de localité ou de l'invariance de Lorentz. La première expérience spécifique à ce sujet a été réalisée en 1990 avec la recherche de rayons X résultant de transitions dans le cuivre interdites par le principe de Pauli. Une version moderne de cette expérience, appelée VIP2, est en cours au laboratoire du Gran Sasso. Elle a déjà établi de nouvelles limites concernant les violations du principe de Pauli. Au cours des trois prochaines années, sa précision sera portée à un niveau de 10^{-31}.

Catalina Curceanu, LNF-INFN, **Dmitry Budker**, Helmholtz Institute, JGU Mainz and UC Berkeley, **Edward J Hall**, Harvard University, **Johann Marton**, Stefan Meyer Institute, Vienna, and **Edoardo Milotti**, University of Trieste and INFN–Sezione di Trieste.







Faces & Places

APPOINTMENTS

New director for Los Alamos

LANL

Terry Wallace is a forensic seismology expert.

Los Alamos National Laboratory (LANL) in the US has appointed a new director – the 11th in the laboratory's nearly 75 year history. Terry Wallace, who holds higher degrees in geophysics from Caltech and previously was principal associate director for global security, took up the role on 1 January, replacing Charlie McMillan. Wallace is an expert in forensic seismology and an international authority on the detection and quantification of nuclear tests. He will oversee a budget of around $2.5 billion, employees and contractors numbering nearly 12,000, and a 36-square-mile site of scientific laboratories, nuclear facilities, experimental capabilities, administration buildings and utilities. "I am honoured and humbled to be leading LANL," he said.

DPG elects next president

University of Bonn

Dieter Meschede succeeds Rolf-Dieter Heuer.

The board of directors of the Deutsche Physikalische Gesellschaft (DPG) has elected Dieter Meschede of the University of Bonn as its next president, beginning in April. Meschede takes over from former CERN Director-General Rolf-Dieter Heuer, who will assume the DPG vice presidency, and the position will last for two years. Meschede is group leader of the quantum technologies group at Bonn, with interests including quantum information processing and fibre-cavity QED. The DPG, which has around 62,000 members, selects successors more than a year before the end of the term of office of the acting president to familiarise them with the complex role.

Change of spokespersons at Pierre Auger

Ralph Engel and Antonella Castellina.

The international Pierre Auger Observatory has elected Ralph Engel and Antonella Castellina as spokesperson and co-spokesperson, respectively. Engel is senior scientist and currently acting director of the Institute for Nuclear Physics at the Karlsruhe Institute of Technology in Germany, with research interests including ultra-high-energy cosmic rays and neutrinos. Castellina is senior scientist at the National Institute of Astrophysics in Torino, Italy, and an associate at the INFN, and her current research work focuses on cosmic-ray composition and hadronic interactions at ultra high energy, in addition to detector development. Started in 2000 and located in the Argentinian Pampa, the Auger Observatory has shown that cosmic rays with energies above 8×10^{18} eV are of extra-galactic origin. To probe the sources of such events further, the facility is undergoing a major upgrade of its surface stations (*CERN Courier* June 2016 p29).

Mark Thomson set to head up UK research council

Experimental particle physicist Mark Thomson of the University of Cambridge has been appointed executive chair of the UK's Science and Technology Facilities Council (STFC), beginning 1 April. Thomson, who will succeed current chief-executive Brian Bowsher, has interests in a number of areas, including collider physics and neutrinos. He is currently co-spokesperson for the Deep Underground Neutrino Experiment (DUNE), the prototype detector modules of which are being developed at CERN, and was instrumental in securing a recent £65 million UK investment in the US-based facility. His term as co-spokesperson of DUNE ends in March.

The position of executive chair of STFC, which funds UK research in particle physics, astrophysics and nuclear physics, has been created following a major reorganisation of the UK's research administration. Bringing together the UK's seven existing research councils and two others (Innovate UK and Research England) from April this year, the UK's science spend will be overseen by a single body called UK Research and Innovation (UKRI). Recently appointed UK minister for higher education, Sam Gyimah, said: "Boosting research and development is at the heart of our modern industrial strategy and the role of executive chairs for the research councils will have a fundamental role in not only setting the priorities for their particular areas of interest, but of UKRI as a whole."

STFC

Thomson will take the reins at STFC in April.

AWARDS

Sackler Prize for work on quantum field theory


Stony Brook University

Perimeter Institute

Komargodski (left) and Vieira will receive their awards at Tel-Aviv University on 13 March.

Zohar Komargodski from the Weizmann Institute, Israel, and the Simons Center for Geometry and Physics, US, and Pedro Vieira from the Perimeter Institute, Canada and the ICTP-SAIFR, Brazil, have been awarded the 2018 Raymond and Beverly Sackler International Prize in Physics for their outstanding work probing quantum field theory (QFT) in non-perturbative regimes. The prize amount of $100,000 will be split evenly between the two laureates.

Komargodski is recognized for insights that have shed light on many aspects of QFT, including renormalisation group flows, dualities and phase structure, conformal field theories, and effective field theories for broken supersymmetry and long strings. Vieira is awarded the prize for bringing the power of integrability to bear on a variety of observables in N = 4 supersymmetric Yang–Mills QFT, including operator anomalous dimensions and correlation functions, Wilson loops and scattering amplitudes, as well as for developing a new S-matrix approach to constraining amplitudes in massive QFTs.

Winners of Buchalter Prize announced

The winners of the 2017 Buchalter Cosmology Prize were announced in January at a meeting of the American Astronomical Society in Washington, DC. The annual prize, created by Ari Buchalter in 2014, rewards ideas or discoveries that have the potential to produce a breakthrough in our understanding of the origin, structure and evolution of the universe.

The $10,000 first prize was awarded to Lasha Berezhiani of the Max Planck Institute for Physics and Justin Khoury of the University of Pennsylvania, for their work entitled "Theory of Dark Matter Superfluidity" (arXiv:1507.01019), while the $5000 second prize was awarded to Steffen Gielen of the University of Nottingham and Neil Turok of the Perimeter Institute, for their work "Perfect Quantum Cosmological Bounce" (arXiv:1510.00699). The $2500 third prize was awarded to Peter Adshead of the University of Illinois, Diego Blas of CERN, Cliff Burgess and Peter Hayman of McMaster University and the Perimeter Institute for Theoretical Physics, and Subodh Patil of the Niels Bohr Institute, for their work entitled "Magnon Inflation: Slow Roll with Steep Potentials" (arXiv:1604.06048).

Emmy Noether distinction

On 1 December the spring–summer 2017 Emmy Noether distinction for women in physics was presented to Catalina Curceanu of Frascati National Laboratory (LNF-INFN), Italy, on behalf of the European Physical Society (EPS). The award, which was presented during a workshop on quantum foundations at Frascati, cited her outstanding research work in experimental nuclear, hadronic and quantum physics, substantial contributions to low-energy QCD, her pioneering research in foundational issues, and successful outreach and education. The Emmy Noether distinction is awarded twice a year to female physicists for their personal achievements in physics research, education, outreach or other physics-related work, and aims to help attract women into a physics career.


J Marton

Catalina Curceanu with Nicola Bianchi, director of research at INFN (left), and Lucia Di Ciaccio, chair of the EPS equal opportunities committee (right).

EVENTS

Event breathes new life into CERN history

On 1–2 February experts in the history of science and related fields came to CERN to discuss a new initiative to record CERN's history. It has been more than 20 years since the original CERN History Project concluded, culminating in the publication of a three-volume series that covered the period from CERN's creation to the late 1970s. "CERN History Days" was a first step to relaunch the project, and more than 50 people attended. The two-day event took the form of an open symposium to stimulate general reflection from the contributions of invited speakers, followed by a closed workshop with sessions about written, oral, digital and other aspects of the project. The organisers will now digest the rich discussions and produce a roadmap to be proposed to CERN management for a resumption of the history project.

M Brice/CERN

CERN is a treasure-trove for historians, as discussed at the two-day event.

EVENTS

Creating a shared future in a fractured world

WEF

Panel discussion on 23 January with (left to right): Christine Lagarde (director IMF), Erna Solberg (prime minister of Norway), Ginni Rometty (president and CEO of IBM), Chetna Sinha (social activist), Fabiola Gianotti (CERN Director-General), Sharan Burrow (general secretary of the International Trade Union Confederation) and Isabelle Kocher (CEO of Engie).

CERN Director-General Fabiola Gianotti was a co-chair of the annual meeting of the World Economic Forum (WEF) in Davos, 23–29 January, speaking at several events. Among them was a panel discussion among co-chairs entitled "Creating a shared future in a fractured world" (pictured), where she spoke about the universal and unifying nature of science and how institutions such as CERN and SESAME exemplify the commitment and shared goals of the international community.

On 25 January Gianotti took part in a panel discussion on "Creating a shared future through education and empowerment" alongside Canadian prime minister Justin Trudeau and Nobel peace prize laureate Malala Yousafzai, where she emphasised the value of evidence-based assessment and the meaning of a measurement and its uncertainty.

This was the first time that the head of a scientific organisation had been asked to serve as a WEF co-chair. "It provided a unique opportunity to promote the crucial role of science in addressing the major challenges facing society today to an audience of leaders of government, industry and civil society," she said. "It is my hope that science will have an equally prominent place at future annual meetings of the WEF, as an essential component of global discussions about the direction our world is taking."

Human interactions leave indelible tracks at CERN


C Bourdarios

B Warmbein

CERN people past and present enjoyed presentations and a banquet in the CMS hall.

The kick-off event of the CERN alumni programme, named "First Collisions", took place on 2 and 3 February. It was a truly unforgettable experience, certainly for the organisers, who put all our energy into the organisation of the very first reunion of CERN alumni. The participants – some 360 people coming from all over the world – gathered at CERN with their wealth of history, experiences and skills that are now part of all of us thanks to the fruitful exchanges we shared. Some of the participants came to reunite with former colleagues, others to develop their network, others to just see what CERN is like today. It was an invaluable opportunity to be able to obtain feedback about the new network and expectations for its future development.

The talks delivered by CERN alumni were the heartbeat of the event. They included Pierre Darriulat, spokesperson of the UA2 experiment and CERN's research director from 1987–1994, who delivered important messages about science without borders, and Christer Fuglesang, director of KTH Space Center, talking about swapping CERN's underground installations for a career in space. The inspiring speakers were able to trigger interesting discussions among the participants, which continued during the networking breaks and the dinner held in the CMS experimental hall. We enjoyed spending time in a very relaxed atmosphere, which transformed a normally experimental worksite into a cosy venue for one special evening.

First Collisions was also an opportunity for many families and friends to explore the various corners of CERN together. Many of the experimental sites that participants and their families visited had been opened exclusively for them, and in many cases the spokespersons of the various experiments played the role of guides for our alumni – a unique opportunity for all concerned.

The event is now over, but it is a case of "see you soon" for all the members of the network. Indeed, we are just at the beginning. The CERN alumni network will continue to grow and will be shaped by the needs, enthusiasm and involvement of its members. This will require a lot of work and a strong vision, and a roadmap for the future based on these initial few months of collaboration is being prepared.

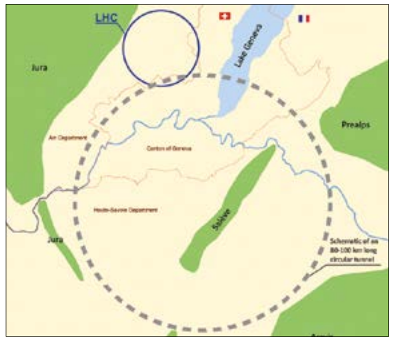
MEETINGS

Physics fest for a future circular collider

The second Future Circular Collider (FCC) physics workshop was held at CERN on 15–19 January, gathering particle physicists from around the world for talks and detailed discussions on the physics capabilities of future electron–positron, electron–proton, and proton–proton colliders.

The FCC study, which emerged following the 2013 European Strategy for Particle Physics, is a five-year project led by CERN to investigate a circular collider built in a new 100 km-circumference tunnel in the Geneva region. Such a tunnel could host an e^+e^- collider (called FCC-ee), a 100 TeV proton–proton collider (FCC-hh) or an electron–proton collider (FCC-eh). Further opportunities include the collision of heavy ions in FCC-hh and FCC-eh, and fixed-target experiments using the injector complex.

Last year saw a significant evolution in the maturity of the physics studies for these machines, with many detailed results presented. These results include new techniques to determine the properties of the Higgs boson, such as the all-important Higgs potential, and how these relate to fundamental questions at the smallest distance scales. New ideas about how to search for new particles interacting very weakly with normal matter – such as new species of neutrinos, dark photons or other new light scalar particles – were also studied in depth.



CERN

The LHC would be part of the injection system for a future circular collider.

The January workshop was preceded by a dedicated meeting to determine whether the unprecedented precision of physics measurements provided by FCC machines could be compared against equally high-precision theoretical predictions. The results of this study were affirmative, as reported on the first day of the FCC physics workshop.

A major theme that emerged during the workshop was the depth of complementarity between the capacities of the different FCC modes in exploring the questions that will remain open after the completion of the LHC programme. Combining their individual strengths will enable comprehensive exploration in search of answers to the pending questions in particle physics.

Project to assess impact of research infrastructures

At an event in Brussels on 19 January, the European Commission launched the RI Impact Pathways project to develop a model for analysing the socio-economic impacts of its research infrastructures (RIs). The €1.5 million project aims to identify and quantify the broader value of RIs and their plans for improvements, initiating a "comprehensive stocktaking exercise" on the existing approaches for impact assessment of Europe's research infrastructures.

The long-term benefits of research infrastructures to society at large are undisputed. Training, industrial innovation and the creation of cultural goods are among the main benefits that emerge from these highly international, collaborative environments for society. As RIs become larger, more complex and attract more users, their costs increase, hence it is important to have a common framework to assess the societal impact.

P Charitos

The kick-off meeting for RI Impact Pathways took place in Brussels on 19 January.

RI Impact Pathways will undertake an extensive consultation over the next two years with the research community, policy makers and funding agencies in Europe. According to project manager Alasdair Reid, it "aims to develop an operational model and a toolkit to help RI managers, funders and decision makers to understand the full range of benefits that can occur from investment in RIs". Project participants include CSIL (Italy), DESY (Germany) and the European Molecular Biology Laboratory, among several others.

CERN participates via the Future Circular Collider (FCC) study, which is exploring the feasibility and opportunities of a post-LHC particle collider. A report commissioned last year by the FCC group showed that entering in CERN procurement had a statistically significant effect on the long-term operating revenues and profitability of LHC suppliers, driven mostly driven by high-tech orders, and the benefits of future colliders is expected to be at least as high.

CLIC workshop focuses on strategy

M Volpi

The participants of the 2018 CLIC workshop outside CERN's main building.

The Compact Linear Collider (CLIC) workshop is the main annual gathering of the CLIC accelerator and detector communities, and this year attracted more than 220 participants to CERN on 22–26 January. CLIC is a proposed electron-positron linear collider envisaged for the era beyond the high-luminosity LHC (HL-LHC), that would operate a staged programme over a period of 25 years with collision energies at 0.38, 1.5, and 3 TeV. This year the CLIC workshop focused on preparations for the update of the European Strategy for Particle Physics in 2019–2020.

The initial CLIC energy stage is optimised to provide high-precision Higgs boson and top-quark measurements, with the higher-energy stages enhancing sensitivity to effects from beyond-Standard Model (BSM) physics (*CERN Courier* November 2016 p20). Following a 2017 publication on Higgs physics, the workshop heard reports on recent developments in top-quark physics and the BSM potential at CLIC, both of which are attracting significant interest from the theory community.

Speakers also reported extensive progress in the validation and performance of the new detector model. To ensure that its performance meets the challenging specifications, a new approach to tracking has been commissioned, and the particle flow analysis and flavour-tagging capabilities have been consolidated. Updates were presented on the broad and active R&D programme on the vertex and tracking detectors, which aims to find technologies that simultaneously fulfil all the CLIC requirements. Reports were given on test-beam campaigns with both hybrid and monolithic assemblies, and on ideas for future developments. Many of the tracking and calorimeter technologies under study for the CLIC detector are also of interest to the HL-LHC, where the high granularity and time-resolution needed for CLIC are equally crucial.

For the accelerator, studies with the aim of reducing the cost and power have particular priority, presenting the initial CLIC stage as a project requiring resources comparable to what was needed for LHC. Key activities in this context are high-efficiency RF systems, permanent magnet studies, optimised accelerator structures and overall implementation studies related to civil engineering, infrastructure, schedules and tunnel layout.

A key aspect of the ongoing accelerator development is moving towards industrialisation of the component manufacture, by fostering wider applications of the CLIC 12 GHz X-band technology with external partners. In this respect, the CLIC workshop coincided with the kick-off meeting for the CompactLight project recently funded by the Horizon 2020 programme, which aims to design an optimised X-ray free-electron laser based on X-band technology for more compact and efficient accelerators (*CERN Courier* December 2017 p8).

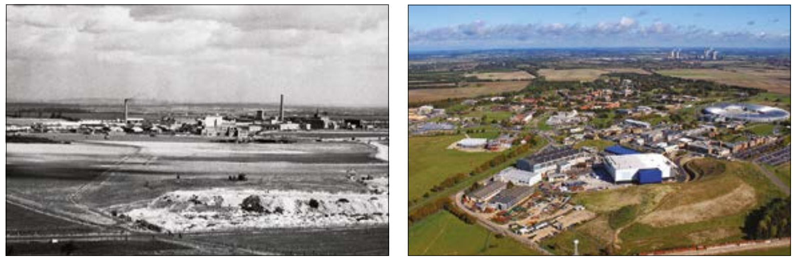
Last year also saw the realisation of the CERN Linear Electron Accelerator for Research (CLEAR), a new user facility for accelerator R&D whose programme includes CLIC high-gradient and instrumentation studies (*CERN Courier* November 2017 p8). Presentations at the workshop addressed the programmes for instrumentation and radiation studies, plasma-lensing, wakefield monitors and high-energy electrons for cancer therapy.

During 2018 the CLIC accelerator and detector and physics collaborations will prepare summary reports focusing on the 380 GeV initial CLIC project implementation as inputs for the update of the European Strategy for Particle Physics, including plans for the project preparation phase in 2020–2025.

ANNIVERSARY

Rutherford Appleton Laboratory turns 60

The UK's Rutherford Appleton Laboratory (RAL) marked its 60th anniversary in late 2017, highlighting its many roles in fundamental research over the decades. RAL started off in 1957 as the National Institute for Research in Nuclear Science to operate the Rutherford High Energy Laboratory, at a time when the Harwell campus (a former airbase) was rising in prominence as a centre for nuclear research, and is now part of the Science and Technology Facilities Council (STFC).


STFC

The Rutherford Appleton Laboratory (RAL) site in the 1960s (left) and today, showing RAL in the foreground and the Diamond Light Source on the right.

Since its inception, RAL has been at the core of particle-physics research and played host to a variety of accelerators including the early proton synchrotron NIMROD. The experimental focus of the laboratory has since shifted focus to higher energy centres overseas such as CERN and SLAC, and also beyond particle physics, including the space sector and materials science.

Computing is also at the core of RAL's history. In 1961 the laboratory was home to the Atlas 1 computer, at that time the most powerful computer in the world, while the cutting-edge CGI and animation technologies developed at the site prompted the *Financial Times* to dub the Oxfordshire laboratory "the home of computer animation in Britain".

VISITS


M Brice/CERN

On 24 January the prime minister of the Republic of Estonia, **Jüri Ratas**, visited CERN, during which he toured the ATLAS underground experimental area. Estonian scientists have been active members of the CERN community since joining the CMS collaboration in 1997, and the country operates a Tier-2 Grid computing centre in Tallinn.


J Ordan

Patrick Vallance, president of research and development at GlaxoSmithKline GB, came to CERN on 26 January. Taking advantage of the accelerator winter shutdown, he visited the LHC tunnel followed by ATLAS and the computing centre.


J Ordan/CERN

On 19 January newly appointed director general of the European Southern Observatory, **Xavier Barcons**, spent a day at CERN, during which he saw the AWAKE facility, the CMS underground experimental area, and magnet and robotics facilities.

J Ordan/CERN

Kostas Gavroglu, Greek minister for education, research and religious affairs, visited CERN on 1–2 February. In addition to participating in the CERN History Days (see p42), he visited the LHC tunnel, the CMS underground area, and signed the guest book with director for international relations Charlotte Warakaulle.

OBITUARIES

John D'Auria 1939–2017

John D'Auria, who was a driving force behind the TRIUMF laboratory's emergence as a radioactive ion beam (RIB) facility, passed away on 22 October after a courageous fight with amyotrophic lateral sclerosis. He was 78 years old.

John earned his PhD in nuclear science at Yale University in 1966, specialising in nuclear spectroscopy. Following a postdoc at Columbia University, in 1967 he was appointed as assistant professor of chemistry at the newly established Simon Fraser University (SFU) in Canada. SFU created its nuclear-science programme early on in anticipation of TRIUMF, which was founded in 1968, and John participated in the early planning for the lab.

A fateful sabbatical at CERN's ISOLDE facility in 1975–1976 set the course for both John's and TRIUMF's future. At ISOLDE he was the first author of the paper reporting the discovery of ^{74}Rb, and he became very interested in the isotope-separation technology at ISOLDE. This ultimately led John (along with Richard Azuma of the University of Toronto) to lead a group with modest funding and much resourcefulness to build the TRIUMF TISOL facility. ISOLDE and TISOL collaborated fruitfully, including an episode where TRIUMF imported, diagnosed and repaired a failed ISOLDE front-end. Notable TISOL successes included the so-called Red Giant experiment for studying alpha capture on carbon, which was of prime importance in astrophysics, as well as launching the TRINAT neutral radioactive atom trap programme, which is still active today.


U Köster

John D'Auria was a pioneer of TRIUMF's radioactive ion beam capabilities.

TISOL's success and John's persistent advocacy for a RIB programme at TRIUMF set the stage for the lab's decision to pursue construction of its ISAC facilities. His expertise was critical in ISAC's early days as the new generation of RIB scientists was being trained. He was project leader for ISAC's flagship experimental facility, the DRAGON mass separator, and under John's leadership, DRAGON became the world's premier facility for the study of radiative capture using radioactive beams.

John retired from SFU in 2004, but continued research that combined mass separators with his long-standing interest in medical applications for radioisotopes. In recognition of his outstanding contributions to nuclear science and major developments at TRIUMF, John was elected a fellow of the American Physical Society in 2015. When he became ill, John was still very active in the planning for a new TRIUMF facility for the mass production of ^{225}Ac for targeted alpha cancer therapy.

John created a worldwide network of collaborators and nurtured a generation of students into the worldwide nuclear astrophysics community. ISAC has opened up new fields of study at TRIUMF, not only in nuclear astrophysics but also in nuclear structure, in tests of the Standard Model, in unique applications in condensed-matter physics and in nuclear medicine. TRIUMF's upcoming ARIEL facility can trace its roots to his rare ability to generate enthusiasm and excitement for the projects he championed. John D'Auria was one of a kind, and his talents and booming laugh will be sorely missed.

● *His colleagues at TRIUMF.*

Raoul Gatto 1930–2017

The passing of Raoul Raffaele Gatto in Meyrin, Geneva, on 30 September is a big loss for science and for a whole generation of particle theorists. After graduating at the Scuola Normale in Pisa, and a short stay at La Sapienza (Rome), Gatto held prominent positions at Berkeley and Frascati before occupying, successively, the chair of theoretical physics in Cagliari, Florence, Padua, Rome and, eventually, at the University of Geneva.

A member of the Accademia dei Lincei, the Accademia delle Scienze of Turin and the American Physical Society, he received numerous recognitions such as the Enrico Fermi medal and the prize of the President of the Italian Republic. For several decades he was editor of *Physics Letters B* and deputy director of the *Rivista del Nuovo Cimento*.


Gatto family

Raoul Gatto transmitted Fermi's legacy to the next generation.

Gatto's contributions to theoretical physics are too many to be listed here. We may just recall his joint work with Cabibbo on the muon neutrino and on weak hyperon decays (which formed the basis of Cabibbo's discovery of the angle that carries his name), the Ademollo-Gatto theorem on the absence of first-order breaking of flavour symmetry in weak hadronic decays, his pioneering work on scale and conformal invariance in quantum field theory, and a series of papers on composite Higgs models.

While in terms of scientific achievements Gatto clearly belonged to the class of the theorists of his generation, he was head and shoulders above the crowd as a teacher. It is not easy to pin down the secret of his success in attracting young researchers to theoretical physics and in helping them grow and develop their own individual qualities. Both Luciano Maiani and myself, for instance, were dragged from experimental high-energy physics to theory by his charming, attractive personality. Luciano had already graduated as an experimentalist before joining Gatto's group in 1964. I had to go through a long period of study and work before being accepted, but it was worthwhile.

When Gatto came to Florence, a group of very promising young researchers followed him one after another: Altarelli, Buccella, Celeghini, Gallavotti, Maiani and Preparata. Gatto created a stimulating, healthy, competitive atmosphere by distributing among us original, challenging research projects. We had to work things out without much help from him, except for letting us know, occasionally and very gently, that there was something that had to be changed in our approach. The whole group (soon dubbed the "gattini") grew in strength and reputation, and soon we became capable of doing independent research. More senior theorists who were already in Florence (among them Ademollo, Chiuderi and Longhi) were also integrated in the new structure, together with students like myself, Casalbuoni and Dominici. This success story repeated itself when Gatto moved to Padue (with Sartori, Tonin and Feruglio) and then again in Rome (with Ferrara and Parisi).

It is often said that Enrico Fermi created the Italian school of particle physics after World War Two. I believe that, for theoretical physics, Raoul Gatto was the heir of Fermi, who best transmitted his legacy to the next generation.

● *Gabriele Veneziano.*

Ernst Heer 1928–2017

Born in 1928 in Switzerland, Ernst Heer attended the Argovian cantonal school (gymnasium) in Aarau, where Einstein obtained his scientific Matura about 50 years earlier. Heer studied physics at ETH Zürich, obtaining his doctorate in 1955 under the direction of Paul Scherrer and Wolfgang Pauli. From 1958 he continued his studies at the University of Rochester in the US before returning to Switzerland in 1961 as a full professor in nuclear physics at the University of Geneva, where he founded the department of particle physics. In addition to managing and decommissioning the nuclear reactor made available to the university, Heer's research concentrated mainly on nuclear interactions between protons, neutrons and antiprotons, with experiments done at CERN and at the Paul Scherrer Institute (PSI).


Ernst Heer founded the University of Geneva's particle physics department.

Parallel to his academic activities he managed the department of particle physics and became vice-rector of the university from 1967 to 1973, and then rector between 1973 and 1977. Thanks to his rigour and remarkable talents as an organiser, he became president of the Swiss Physical Society and of the *Comité consultatif* of the Swiss Nuclear Research Institute (presently the PSI), and represented Switzerland on the CERN Council.

In 1992 Heer established a successful European mobility scheme for physics students called EMSPS, based on his experience with a similar initiative in Switzerland. He gave a true impulse to this project, which was financially supported by the ERASMUS programme and had administrative support from the European Physical Society. EMSPS was the seed of further European networks such as EUPEN (European Physics Education Network), STEPS (Stakeholders Tune European Physics Studies), STEPS TWO and HOPE (Horizons in Physics Education), which ended just recently. All these networks would have been unthinkable without the original work by Ernst Heer.

A widower by the age of 59, he is survived by his older sister, his son Fabio, his daughter Livia and his four grandchildren.

● *Martin Pohl, Hendrik Ferdinande and Peter Sauer.*

Frank Paige 1944–2017

Frank Paige, senior scientist emeritus at Brookhaven National Laboratory (BNL), passed away on 16 October following a stroke. Frank was born in Philadelphia and obtained his PhD in physics at MIT in 1970 under the supervision of Kerson Huang. He then went to BNL as a postdoc, where he would spend his entire career – apart from a two-year period in 1991–1993 when he was a senior scientist at the Superconducting Supercollider (SSC) laboratory in Texas.

Frank's research interests included perturbative QCD, collider phenomenology, detailed simulation of events for high-energy particle collisions, supersymmetry phenomenology, and in later years, experimental collider physics. In 1979, when QCD was still in its infancy, Frank (with J Kubar-Andre) was one of the first to correctly calculate the first-order α_s QCD correction to Drell–Yan processes, finding that the correction was significant. That same year, this time with S Protopopescu, he released the world's first publicly available event generator for hadron colliders, ISAJET. Originally ISAJET was conceived to simulate jet production for the ISABELLE pp collider at BNL, which was eventually cancelled. But it ultimately proved to be instrumental in the discovery of the W and Z bosons at CERN by UA1 and UA2, and was also used for most of the event generation for D0 for Run1 at Fermilab's Tevatron. Together with H Baer and X Tata, Frank expanded ISAJET in the early 1990s to include supersymmetric particle cascade decays. They also built, in 1994, the first public renormalisation group code for calculating superparticle mass spectra, a part of ISAJET called ISASUGRA, which they used to propose collider exploration of the iconic m_0 vs $m_{½}$ plane of supergravity models.


CERN

Frank Paige was a member of the ATLAS collaboration.

During the 1980s and 1990s, Frank was a leading figure in the US community in its deliberations over the future of high-energy physics, serving, for example, as an editor on the influential 1982 Snowmass study on future facilities. He studied signatures and backgrounds for a variety of physics processes for the SSC and lower energy hadron colliders, including signatures for the top quark, for Higgs bosons and for supersymmetric particles. Although many of these studies went unpublished, they diffused into the collective knowledge-base of the high-energy physics community. Among his published works, in 1991 Frank was one of the first to propose a search for the Higgs boson in the ttH production mode (along with Bill Marciano, following the realization that the top quark was heavy). In a 1997 paper with Ian Hinchliffe and other collaborators, he proposed the study of a variety of kinematical end points arising from invariant mass distributions to obtain supersymmetric particle masses in possibly complex cascade decay chains.

Frank joined the ATLAS collaboration at the LHC in 1994, following the demise of the SSC, and worked primarily in the SUSY and jet/missing E_T groups. He was an early convener of the SUSY group, helping to develop many of the initial physics studies and projections. He plunged head-first into nitty-gritty details of experimental work, for example providing the first ATLAS jet energy calibration. He was also a bit of a software guru, though in his characteristic modesty he would deny this.

Above all, Frank cared deeply about physics; he was driven by constantly trying to come up with new ideas, whether large or small, abstract or technical. He set a great example to younger people and was always generous with his time. Upon news of his death, there was a significant outpouring of memories and thoughts of gratitude from many colleagues, from ATLAS and elsewhere. He leaves behind no immediate family, but many of us came to believe that a little bit of him belonged to each one of us.

● *His friends and colleagues.*

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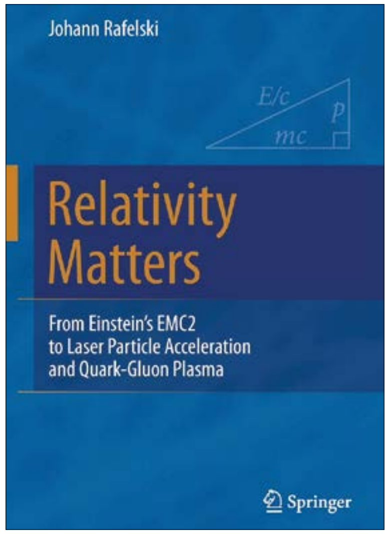
Compiled by Virginia Greco, CERN



Relativity Matters: From Einstein's EMC2 to Laser Particle Acceleration and Quark-Gluon Plasma

By Johann Rafelski
Springer
Also available at the CERN bookshop

This monograph on special relativity (SR) is presented in a form accessible to a broad readership, from pre-university level to undergraduate and graduate students. At the same time, it will also be of great interest to professional physicists.

Relativity Matters has all the hallmarks of becoming a classic with further editions, and appears to have no counterpart in the literature. It is particularly useful because at present SR has become a basic part not only of particle and space physics, but also of many other branches of physics and technology, such as lasers. The book has 29 chapters organised in 11 parts, which cover topics from the basics of four-vectors, space–time, Lorentz transformations, mass, energy and momentum, to particle collisions and decay, the motion of charged particles, covariance and dynamics.

The first half of the book derives basic consequences of the SR assumptions with a minimum of mathematical tools. It concentrates on the explanation of apparently paradoxical results, presenting and refuting counterarguments as well as debunking various incorrect statements in elementary textbooks. This is done by cleverly exploiting the Galilean method of a dialogue between a professor, his assistant and a student, to bring out questions and objections.

The importance of correctly analysing the consequences for extended and accelerating bodies is clearly presented. Among the many "paradoxes", one notes the accelerating rocket problem that the late John Bell used to tease many of the world's most prominent physicists with. Few of them provided a perfectly satisfactory answer.

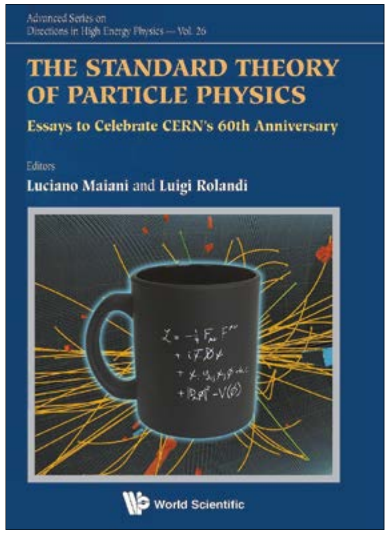
The second half of the book, starting from part VII, covers the usual textbook material and techniques at graduate level, illustrated with examples from the research frontier. The introductions to the various chapters and subsections are still enjoyable for a broader readership, requiring little mathematics. The author does not avoid technicalities such as vector and matrix algebra and symmetries, but keeps them to a minimum. However, in the parts dealing with electromagnetism, the reader is assumed to be reasonably familiar with Maxwell's equations.

There are copious concrete exercises and solutions. Throughout the book, indeed, every chapter is complemented by a rich variety of problems that are fully worked out. These are often used to illustrate quantitatively intriguing topics, from space travel to the laser acceleration of charged particles.

An interesting afterword concluding the book discusses how very strong acceleration becomes a modern limiting frontier, beyond which SR in classical physics becomes invalid. The magnitude of the critical accelerations and critical electric and magnetic fields are qualitatively discussed. It also briefly analyses attempts by well-known physicists to side-step the problems that arise as a consequence.

Relativity Matters is excellent as an undergraduate and graduate textbook, and should be a useful reference for professional physicists and technical engineers. The many non-specialist sections will also be enjoyed by the general, science-interested public.

● *Torleif Ericson, CERN*



The Standard Theory of Particle Physics: Essays to Celebrate CERN's 60th Anniversary

By Luciano Maiani and Luigi Rolandi (eds.)
World Scientific
Also available at the CERN bookshop

This book is a collection of articles dedicated to topics within the field of Standard Model physics, authored by some of the main players in both its theory and experimental development. It is edited by Luciano Maiani and Luigi Rolandi, two well-known figures in high-energy physics.

The volume has 21 chapters, most of them devoted to very specific subjects. The first chapters take the reader through a fascinating tour of the history of the field, starting from the earliest days, around the time when CERN was established. I particularly enjoyed reading some recollections of Gerard 't Hooft, such as: "Asymptotic freedom was discovered three times before 1973 (when Politzer, Gross and Wilczek published their results), but not recognised as a new discovery. This is just one of those cases of miscommunication. The 'experts' were so sure that asymptotic freedom was impossible, that signals to the contrary were not heard, let alone believed. In turn, when I did the calculation, I found it difficult to believe that the result was still not known."

In chapter three, K Ellis reviews the evolution of our understanding of quantum chromodynamics (QCD) and deep-inelastic scattering. Among many things, he shows how the beta function depends on the strong coupling constant, α_s, and explains why many perturbative calculations can be made in QCD, when the interactions take place at high-enough energies. At the hadronic scale, however, α_s is too large and the perturbative expansion tool no longer works, so alternative methods have to be used. Many non-perturbative effects can be studied with the lattice QCD approach, which is addressed in chapter five. The experimental status regarding α_s is reviewed in the following chapter, where G Dissertori shows the remarkable progress in measurement precision (with LHC values reaching per-cent level uncertainties and

Bookshelf

covering an unprecedented energy range), and how the data is in excellent agreement with the theoretical expectations.

Through the other chapters we can find a large diversity of topics, including a review of global fits of electroweak observables, presently aimed at probing the internal consistency of the Standard Model and constraining its possible extensions given the measured masses of the Higgs boson and of the top quark. Two chapters focus specifically on the W-boson and top-quark masses. Also discussed in detail are flavour physics, rare decays, neutrino masses and oscillations, as is the production of W and Z bosons, in particular in a chapter by M Mangano.

The Higgs boson is featured in many pages: after a chapter by J Ellis, M Gaillard and D Nanopoulos covering its history (and pre-history), its experimental discovery and the measurement of its properties fill two further chapters. An impressive amount of information is condensed in these pages, which are packed with many numbers and (multi-panel) figures. Unfortunately, the figures are printed in black and white (with only two exceptions), which severely affects the clarity of many of them. A book of this importance deserved a more colourful destiny.

The editors make a good point in claiming the time has come to upgrade the Standard Model into the "Standard Theory" of particle physics, and I think this book deserves a place in the bookshelves of a broad community, from the scientists and engineers who contributed to the progress of high-energy physics to younger physicists, eager to learn and enjoy the corresponding inside stories.

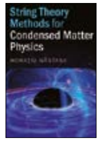
● *Carlos Lourenço, CERN*

Books received

String Theory Methods for Condensed Matter Physics

Horaţiu Năstase

Cambridge University Press



This book provides an introduction to various methods developed in string theory to tackle problems in condensed-matter physics. This is the field where string theory has been most largely applied, thanks to the use of the correspondence between anti-de Sitter spaces (AdS) and conformal field theories (CFT). Formulated as a conjecture 20 years ago by Juan Maldacena of the Institute for Advanced Study, the AdS/CFT correspondence relates string theory, usually in its low-energy version of supergravity and in a curved background space–time, to field theory in a flat space–time of fewer dimensions. This correspondence is holographic, which means in some sense that the physics in the higher dimension is projected onto a flat surface without losing information.

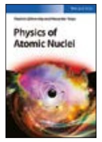
The book is articulated in four parts. In the first, the author introduces modern topics in condensed-matter physics from the perspective of a string theorist. Part two gives a basic review of general relativity and string theory, in an attempt to make the book as self-consistent as possible. The other two parts focus on the applications of string theory to condensed-matter problems, with the aim of providing the reader with the tools and methods available in the field. Going into more detail, part three is dedicated to methods already considered as standard – such as the pp-wave correspondence, spin chains and integrability, AdS/CFT phenomenology and the fluid-gravity correspondence – while part four deals with more advanced topics that are still in development, including Fermi and non-Fermi liquids, the quantum Hall effect and non-standard statistics.

Aimed at graduate students, this book assumes a good knowledge of quantum field theory and solid-state physics, as well as familiarity with general relativity.

Physics of Atomic Nuclei

By Vladimir Zelevinsky and Alexander Volya

Wiley



This new textbook of nuclear physics aims to provide a review of the foundations of this branch of physics as well as to present more modern topics, including the important developments of the last 20 years. Even though well-established textbooks exist in this field, the authors propose a more comprehensive essay for students who want to go deeper both in understanding the basic principles of nuclear physics and in learning about the problems that researchers are currently addressing. Indeed, a renewed interest has lately revitalised this field, following the availability of new experimental facilities and increased computational resources.

Another objective of this book, which is based on the lectures and teaching experience of the authors, is to clarify, at each step, the relationship between theoretical equations and experimental observables, as well as to highlight useful methods and algorithms from computational physics.

The last few chapters cover topics not normally included in standard courses of nuclear physics, and reflect the scientific interests – and occasionally the point of view – of the authors. Many problems are also provided at the end of each chapter, and some of them are fully solved.

CERN Courier Archive: 1975

A look back to CERN Courier vol. 15, March 1975, compiled by Peggie Rimmer

NEWS

Assembly of the ESO telescope

Construction of the 3.6 m telescope, in which CERN is collaborating with the European Southern Observatory (ESO), has now reached the important stage of testing. To check the rigidity of the telescope, which weighs more than 200 tonnes, and to finalise the control system, which will be fully automated, the telescope is being assembled in one of the halls of the Société Creusot-Loire at St. Chamond, France.

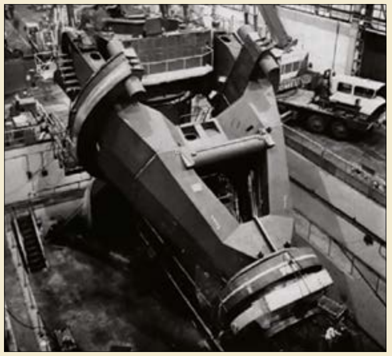
Tests will continue until April when the telescope will be dismantled and sent by sea to Chile, where assembly will start at the beginning of 1976. At the receiving end, on the La Silla mountain, work is well advanced on the building that will house it.

When the telescope comes into operation it will provide European astronomers with a first-class instrument for observing the comparatively unexplored Southern skies. Objects of particular interest are the central region of the Milky Way Galaxy and the Magellanic Clouds. The Clouds are outside the galaxy and can be seen only from the Southern Hemisphere. They contain old stars, young stars and stars in formation, and are thus a magnificent natural laboratory.

● Compiled from texts on pp71–72 .

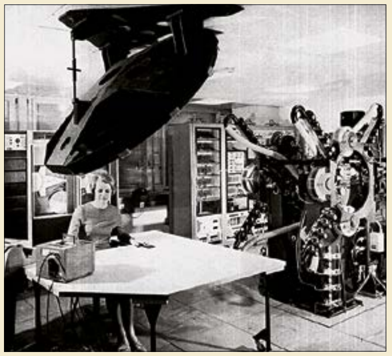

Creusot-Loire

The van being lowered into the pit, where the 3.6 m ESO telescope is installed, plays an important part in the tests now underway. It is a mini-electronics laboratory for controlling the telescope operation, equipped by the ESO unit working at CERN.

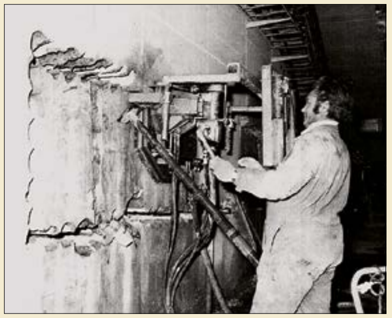

Creusot-Loire

The top part of the telescope structure. In the foreground is the main body of the polar axle and the U-shaped journal bearing fitted with its two counter-weights.

EVENTS AT CERN


CERN 271.1.69

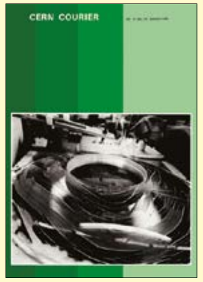
(Top) On 26 February, the Spiral Readers at CERN clocked up their millionth measured event on bubble chamber film. This type of semi-automatic measuring machine was initiated at Berkeley. Two have been built at CERN, the first coming into action for regular film measurement in 1970. They both now operate at a rate of about 70 vertices per hour.


CERN 108.1.75

(Bottom) The last physical obstacle to the free passage of protons between the PS and SPS falls to the drill during the annual shutdown. The wall is in the beam transfer tunnel where protons are taken from the PS to the ISR. At this point, protons will be bent off down a tunnel leading to the underground 400 GeV synchrotron ring.

● Compiled from text on p70.

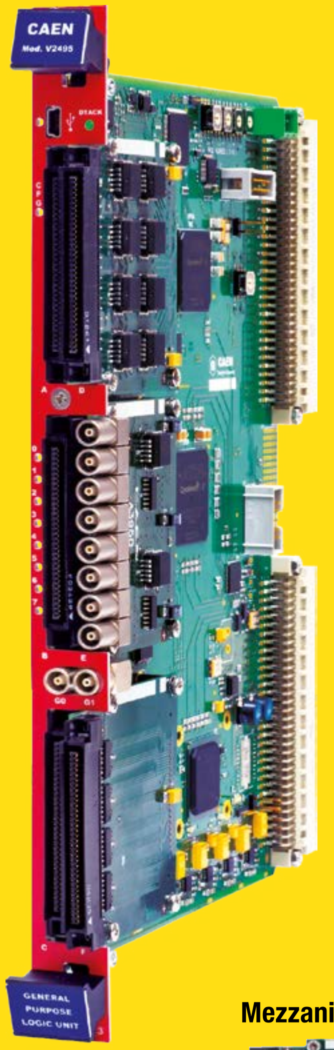
Compiler's note



In 1962 five European governments set up ESO in the style and spirit of CERN, and by 1969 an observatory site had been procured at La Silla, 2400 m high in the Atacama desert, Chile. But the fledgling organisation was not only based on CERN, it was based at CERN prior to establishing its own headquarters in Garching, Germany, in 1980. And so, apart from the huge mirror, ESO's 3.6 m optical telescope was built at CERN.

And the local link continues. A consortium, led by Michael Mayor from the Geneva University Observatory, built HARPS, a High Accuracy Radial Velocity Planet Searcher. Installed on the 3.6 m telescope in 2003, this spectrograph can detect "wobbles" smaller than 4 km/h in the radial velocity of a star, caused by the gravitational pull of orbiting planets. Such exceptional precision has revealed the existence of hundreds of extrasolar planets. Some of them, super-Earths, have masses of a few terrestrial masses, and some of these lie in the so-called Goldilocks zone of their host star, where life might be sustainable.

To survey the northern skies, HARPS-N was installed on the Italian 3.58 m Telescopio Nazionale Galileo at the Observatorio del Roque de los Muchachos, La Palma island, Canaries, in 2012. Now those little green men (and women) have nowhere to hide.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