WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the December 2016 issue of *CERN Courier*.

Ever since the discovery of the positron in 1932, physicists have undertaken countless experiments to look for differences in the behaviour of antimatter versus matter. CERN has played a vital role in this effort: in 1995 it created the first atoms of antihydrogen, followed by more complex antiprotonic helium. In the pursuit of ever more precise antimatter studies, CERN has completed a major upgrade to its Antiproton Decelerator facility. Called ELENA, the new synchrotron will make the difficult process of catching and trapping antiprotons much more efficient, allowing powerful tests of Lorentz and CPT symmetries. These concepts, which form the cornerstones of our modern understanding of space–time, have come under renewed scrutiny in recent years in the search for physics beyond the Standard Model. Antimatter is also being probed from space courtesy of the AMS experiment, in which CERN plays a critical role. This issue summarises the first five years of AMS data, which contain mysterious features in the cosmic-ray spectrum that have implications for dark matter. Taking things back to Earth, we also report on groundbreaking results from CERN's CLOUD experiment that could increase the precision of climate predictions, and review what has been a record-breaking year for proton operations at the LHC.

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CERNCOURIER

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

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Volume 56 Number 10 December 2016

FEATURES

On the cover: A magnetic longitudinal pick-up used for beam observation in ELENA, surrounded by copper to shield the pick-up from electromagnetic perturbations in the AD hall. (Image credit: M Brice/CERN.)

Viewpoint

A record year for the LHC

The success of the CERN accelerator's 2016 proton run augurs well for future projects.

M Brice

Celebrations in the CERN Control Centre on 25 March 2016, as Run 2 of the LHC got under way.

By Frédérick Bordry

LHC proton running for 2016 reached a conclusion on 26 October, after seven months of colliding protons at an energy of 13 TeV. The tally for the year is truly impressive. I could mention the fact that the machine's design luminosity of 10^{34} cm^{-2}s^{-1} was regularly achieved and exceeded by 30 to 40%. Or I could say that with an integrated luminosity of 40 fb^{-1} delivered in 2016, we comfortably exceeded our year target of 25 fb^{-1} – allowing the LHC experiments to accumulate sizable data samples in time for the biennial ICHEP conference in August.

But what impresses me the most, and what really sets a marker for the future, is the availability of the machine. For 60% of its 2016 operational time, the LHC was running with stable beams delivering high-quality data to the experiments. This is unprecedented. Typical availability figures for big energy-frontier machines are around 50%, and that is the target we set ourselves for the LHC this year. Given the scale and complexity of the LHC, even that seemed ambitious. To put it in perspective, CERN's previous and much simpler flagship facility, the Large Electron Positron (LEP) collider, achieved a figure of 30% over its operational lifetime from 1989 to 2000.

After hitting its design luminosity on 26 June, the LHC's peak luminosity was further increased by using smaller beams from the injectors and reducing the angle at which the beams cross inside the ATLAS and CMS experiments. The resulting luminosity topped out at around 1.4×10^{34} cm^{-2}s^{-1}, 40% above design. This year's proton operation also included successful forward-physics runs for the TOTEM/CT-PPS, ALFA and AFP experiments.

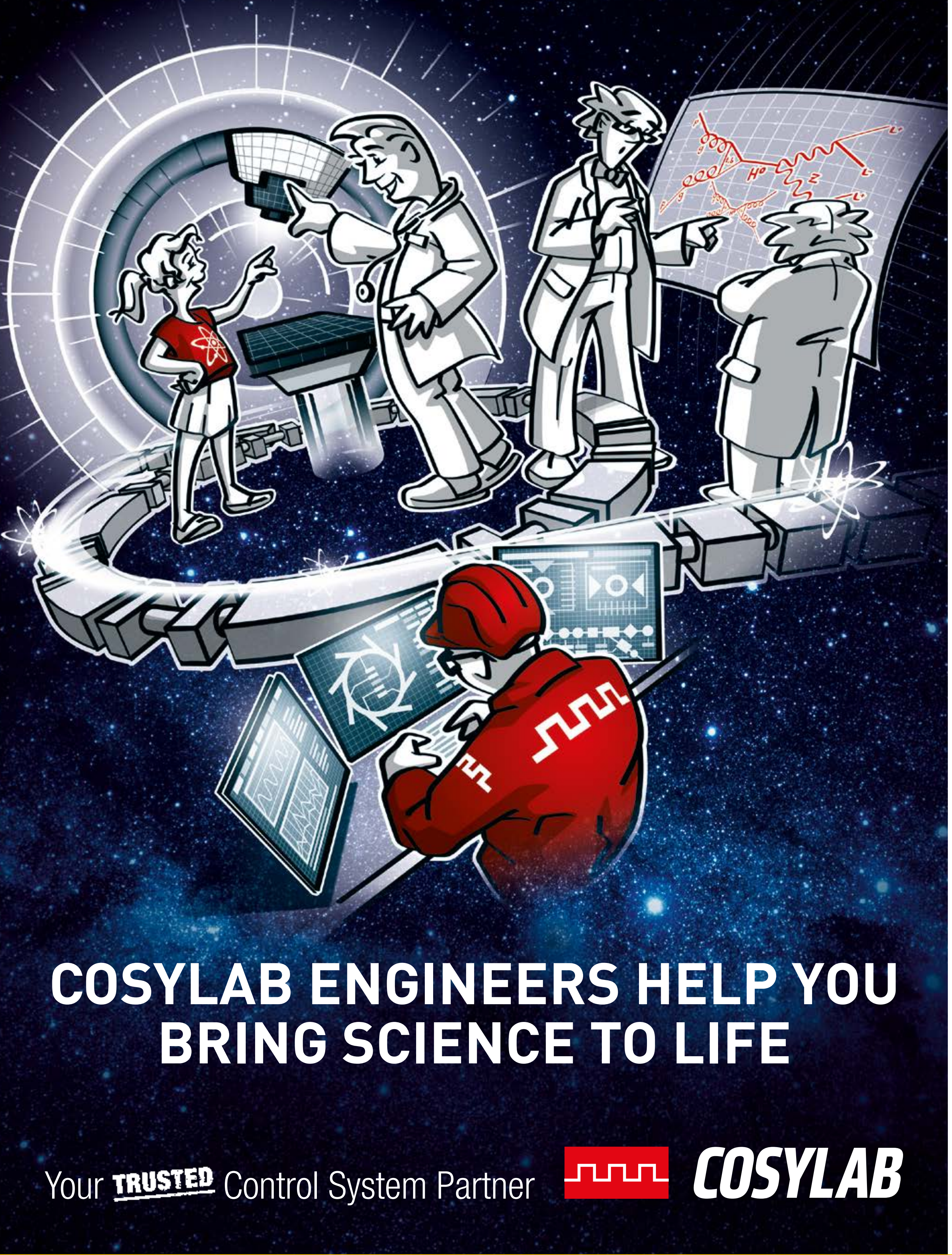
The LHC is no ordinary machine. The world's largest, most complex and highest-energy collider is also the world's largest cryogenic facility. The difficulties we had when commissioning the machine in 2008 are well documented, and there is more to do: we are still not running at the design energy of 14 TeV, for example. But this does not detract from the fact that the 2016 run has shown what a fundamentally good design the LHC is, what a fantastic team it has running it, and that clearly it is possible to run a large-scale cryogenic facility with metronomic reliability.

This augurs well for the future of the LHC and its high-luminosity upgrade, the HL-LHC, which will take us well into the 2030s. But it is not only a good sign for particle physics. Other upcoming cryogenic facilities such as the ITER fusion experiment under construction in France can also take heart from the LHC's performance, and who knows where else this technology might take us? If it is possible to run a 27 km-circumference superconducting particle accelerator with high reliability, then a superconducting electrical-power-distribution network, for example, does not seem so unrealistic. With developments in high-temperature superconductors proceeding apace, that possibility looks tantalisingly close.

With the way that the LHC has performed this year, it would be easy to be complacent, but the 2016 run has not been without difficulties. From the unfortunate beech marten that developed a short-lived taste for the high-voltage connections of an outdoor high-voltage transformer in May to rather more challenging technical issues, the LHC team has had numerous problems to solve, and the upcoming end-of-year technical stop will be a busy one. With a machine as complex as the LHC, its entire operational lifetime is a learning curve for accelerator physicists.

Which brings me back to the question of the LHC's design energy. With proton running finished for another year, the LHC has now moved into a period of heavy-ion physics. When that is over, we will conclude the year with two weeks dedicated to re-training the magnets in two of the machine's eight sectors, with a view to 14 TeV running. News from this work will provide valuable input to the LHC performance workshop in January, which will set the scene for the coming years at the energy frontier.

Frédérick Bordry has been CERN's director for accelerators and technology since January 2014. (Image credit: CERN.)



News

INTERNATIONAL

Ukraine becomes associate Member State of CERN


A Pantelia

Former Ukrainian vice prime minister K I Gryschenko signing the agreement with former CERN Director-General Rolf-Dieter Heuer in 2013, leading to today's associate membership status.

On 5 October, Ukraine became an associate Member State of CERN, following official notification to CERN that Ukraine's parliament has ratified an agreement signed with CERN in October 2013. "Our hard and consistent work over the past two decades has been crowned today by a remarkable event – granting Ukraine the status of CERN associate member," says Yurii Klymenko, Ukraine's ambassador to the United Nations in Geneva. "It is an extremely important step on the way of Ukraine's European integration."

Ukraine has been a long-time contributor to the ALICE, CMS and LHCb experiments at the LHC and to R&D in accelerator technology. Ukraine also operates a Tier-2 computing centre in the Worldwide LHC Computing Grid.

Ukraine and CERN first signed a co-operation agreement in 1993, followed by a joint declaration in 2011, but Ukraine's relationship with CERN dates back much further through the Joint Institute of Nuclear Research (JINR) in Dubna, Russia, of which Ukraine is a member. CERN-JINR co-operation in the field of high-energy accelerators started in the early 1960s, and ever since, the two institutions have formed a bridge between East and West that has made important contributions to the development of global, peaceful scientific co-operation.

Associate membership will open a new era of co-operation that will strengthen the long-term partnership between CERN and the Ukrainian scientific community. It will allow Ukraine to participate in the governance of CERN, in addition to allowing Ukrainian scientists to become CERN staff and to participate in CERN's training and career-development programmes. Finally, it will allow Ukrainian industry to bid for CERN contracts, thus opening up opportunities for industrial collaboration in areas of advanced technology.

"It is a great pleasure to warmly welcome Ukraine into the CERN family," says CERN Director-General Fabiola Gianotti.

ATMOSPHERIC PHYSICS

CLOUD experiment sharpens climate predictions

Future global climate projections have been put on more solid empirical ground, thanks to new measurements of the production rates of atmospheric aerosol particles by CERN's Cosmics Leaving OUtdoor Droplets (CLOUD) experiment.

According to the Intergovernmental Panel on Climate Change, the Earth's mean temperature is predicted to rise by between 1.5–4.5 °C for a doubling of carbon dioxide in the atmosphere, which is expected by around 2050. One of the main reasons for this large uncertainty, which makes it difficult for society to know how best to act against climate change, is a poor understanding of aerosol particles in the atmosphere and their effects on clouds.

To date, all global climate models use relatively simple parameterisations for aerosol production that are not based on experimental data, in contrast to the highly detailed modelling of atmospheric chemistry and greenhouse gases. Although the models agree with current observations, predictions start to diverge when the models are wound forward to project the future climate.

Now, data collected by CLOUD have been used to build a model of aerosol production based solely on laboratory measurements. The new CLOUD study establishes the main processes responsible for new particle formation throughout the troposphere, which is the source of around half of all cloud seed particles. It could therefore reduce the variation in projected global temperatures as calculated by complex global-circulation models.

"This marks a big step forward in the reliability and realism of how models describe aerosols and clouds," says CLOUD spokesperson Jasper Kirkby. "It's addressing the largest source of uncertainty in current climate models and building it on a firm experimental foundation of the fundamental processes."

Aerosol particles form when certain

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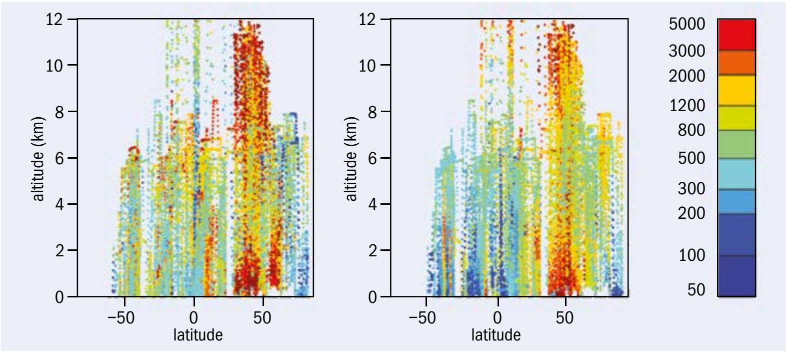
Sommaire en français

trace vapours in the atmosphere cluster together, and grow via condensation to a sufficient size that they can seed cloud droplets. Higher concentrations of aerosol particles make clouds more reflective and long-lived, thereby cooling the climate, and it is thought that the increased concentration of aerosols caused by air pollution since the start of the industrial period has offset a large part of the warming caused by greenhouse-gas emissions. Until now, however, the poor understanding of how aerosols form has hampered efforts to estimate the total forcing of climate from human activities.

E Dunne *et al.*



Observed (left) and modelled (right) particle concentrations (per cubic centimetre; >3 nm diameter) versus latitude and altitude, with the latter based solely on CLOUD measurements.

Thanks to CLOUD's unique controlled environment, scientists can now understand precisely how new particles form in the atmosphere and grow to seed cloud droplets. In the latest work, published in *Science*, researchers built a global model of aerosol formation using extensive laboratory-measured nucleation rates involving sulphuric acid, ammonia, ions and organic compounds. Although sulphuric acid has long been known to be important for nucleation, the results show for the first time that observed concentrations of particles throughout the atmosphere can be explained only if additional molecules – organic compounds or ammonia – participate in nucleation. The results also show that ionisation of the atmosphere by cosmic rays accounts for nearly one-third of all particles formed, although small changes in cosmic rays over the solar cycle do not affect aerosols enough to influence today's polluted climate significantly.

Early this year, CLOUD reported in *Nature* the discovery that aerosol particles can form in the atmosphere purely from organic vapours produced naturally by the biosphere (*CERN Courier* July/August 2016 p11). In a separate modelling paper published recently in *PNAS*, CLOUD shows that such pure biogenic nucleation was the dominant source of particles in the pristine pre-industrial atmosphere. By raising the baseline aerosol state, this process significantly reduces the estimated aerosol radiative forcing from anthropogenic activities and, in turn, reduces modelled climate sensitivities.

"This is a huge step for atmospheric science," says lead-author Ken Carslaw of the University of Leeds, UK. "It's vital that we build climate models on experimental measurements and sound understanding, otherwise we cannot rely on them to predict the future. Eventually, when these processes get implemented in climate models, we will have much more confidence in aerosol effects on climate. Already, results from CLOUD suggest that estimates of high climate sensitivity may have to be revised downwards."

- **Further reading**

E Dunne *et al.* 2016 *Science* DOI: 10.1126/science.aaf2649.
H Gordon *et al.* 2016 *PNAS* DOI:10.1073/pnas.1602360113.
J Kirkby *et al.* 2016 *Nature* **533** 521.

BIG-BANG NUCLEOSYNTHESIS

n_TOF deepens search for missing cosmic lithium

An experiment at CERN's neutron time-of-flight (n_TOF) facility has filled in a missing piece of the cosmological-lithium problem puzzle, according to a report published in *Physical Review Letters*. Along with a few other light elements such as hydrogen and helium, much of the lithium in the universe is thought to have been produced in the very early universe during a process called Big-Bang nucleosynthesis (BBN). For hydrogen and helium, BBN theory is in excellent agreement with observations. But the amount of lithium (^{7}Li) observed is about three times smaller than predicted – a discrepancy known as the cosmological-lithium problem.

The n_TOF facility studies neutron-nucleus interactions for neutron energies ranging from a few meV to several GeV.

The n_TOF collaboration has now made a precise measurement of one of the key processes involved – ^{7}Be(n,α)^{4}He – in an attempt to solve the mystery. The production and destruction of the unstable ^{7}Be isotope regulates the abundance of cosmological lithium, but estimates of the probability of ^{7}Be destruction via this channel have relied on a single measurement made in 1963 of thermal energies at the Ispra reactor in Italy. Therefore, a possible explanation for the higher theoretical value could be an underestimation of the destruction of primordial ^{7}Be, in particular in reactions with neutrons.

Now, n_TOF has measured the cross-section of the ^{7}Be(n,α)^{4}He reaction over a wide range of neutron energies with a high level of accuracy. This was possible thanks to the extremely high luminosity of the neutron beam in the recently constructed experimental area (EAR2) at the n_TOF facility.

The results indicate that, at energies relevant for BBN, the probability for this reaction is 10 times smaller than that used in theoretical calculations. The destruction rate of ^{7}Be is therefore even smaller than previously supposed, ruling out this channel as the source of the missing lithium and deepening the mystery of the cosmological-lithium problem.

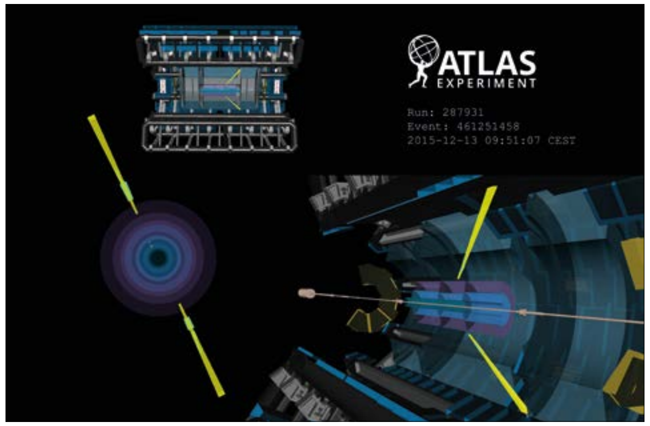
- **Further reading**

M Barbagallo *et al.* (n_TOF Collaboration) 2016 *Phys. Rev. Lett.* **117** 152701.

LHC EXPERIMENTS

ATLAS spots light-by-light scattering

During the early years of quantum electrodynamics (QED), Heisenberg and his student Euler realised that photons may scatter off of each other through a quantum-loop process involving virtual electron and positron pairs. This phenomenon of light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$), albeit very rare, breaks the linearity of Maxwell's equations and is one of the oldest predictions of QED.



Light-by-light scattering, a fundamental prediction of QED, is evidenced in the ATLAS detector.

The $\gamma\gamma \rightarrow \gamma\gamma$ process proceeds at lowest order via virtual one-loop box diagrams involving fermions, leading to a severe suppression in the cross-section and thus making it very challenging to observe experimentally. To date, light-by-light scattering via an electron–positron loop has been tested precisely, but indirectly, in measurements of the anomalous magnetic moments of the electron and muon. Closely related observations are Delbrück scattering and photon splitting, both of which involve the scattering of a photon from the nuclear Coulomb field, and the fusion of photons into pseudoscalar mesons observed in electron–positron colliders. The direct observation of light-by-light scattering has, however, remained elusive.

It has recently been proposed that light-by-light scattering can be studied using photons produced in relativistic heavy-ion collisions at large impact parameters. Since the electric-field strength of relativistic ions scales with the square of their charge, collisions lead to huge electromagnetic field strengths relative to proton–proton collisions. The phenomenon manifests itself as beams of nearly real photons, allowing for the process $\gamma\gamma \rightarrow \gamma\gamma$ to occur directly, while the nuclei themselves generally stay intact. Light-by-light scattering is thus distinguished by the observation of two low-energy photons, back-to-back in azimuth, with no additional activity measured in the detector. Possible backgrounds can arise from misidentified electrons from the QED process $\gamma\gamma \rightarrow e^+e^-$, as well as from the central exclusive production of two photons from the fusion of two gluons ($gg \rightarrow \gamma\gamma$).

The ATLAS experiment has conducted a search for light-by-light scattering in 480 μb^{-1} of lead–lead data recorded at a nucleon–nucleon centre-of-mass energy of 5.02 TeV during the 2015 heavy-ion run. While almost four-billion strongly interacting events were provided by the LHC, only 13 diphoton candidates were observed. From the expectation of 7.3 signal events and 2.6 background events, a significance of 4.4σ was obtained for observing one of the most fundamental predictions of QED. With the additional integrated luminosity expected in upcoming runs, further study of the $\gamma\gamma \rightarrow \gamma\gamma$ process will allow tests of extensions of the Standard Model, in which new particles can participate via the loop diagrams, providing an additional window into new physics at the LHC.

- **Further reading**

ATLAS Collaboration 2016 ATLAS-CONF-2016-111.
D d'Enterria and G Silveira 2013 *Phys. Rev. Lett.* **111** 080405.

Studies of electroweak-boson production by CMS

It is quite improbable for two colliding protons to produce a W or Z electroweak gauge boson. Producing two or more W or Z bosons in the same collision is even less likely.

When such events do arise, however, the non-Abelian SU(2) nature of electroweak bosons – which are generally denoted V – allows the bosons to interact directly with each other. Of particular interest are the direct interactions of three electroweak gauge bosons, whose rate depends on the corresponding triple-gauge-boson-coupling (TGC) strength. Measurement of the rates of single V and double VV (diboson) production and of the strength of TGC interactions represent fundamental tests of the electroweak sector of the Standard Model (SM).

The inclusive production rates of single W or Z bosons at the LHC have been calculated in the SM to an accuracy of about 3%, while the ratio of the W-to-Z-boson production rate is predicted to even greater precision because certain uncertainties cancel. The CMS collaboration has recently measured the W and Z boson inclusive production rates and finds their ratio to be 10.46±0.17, in agreement with the SM prediction at the per cent level. CMS has also measured the ZZ, WZ and WW diboson production rates, finding agreement with the SM predictions within a precision of about 14, 12 and 9%, respectively. These results are based on leptonic-decay modes, specifically decays of a W boson to an electron or muon and the associated neutrino, and of a Z boson to an electron–positron pair or to a muon–antimuon pair.

Leptonic decays provide an unambiguous experimental signature for a W or Z boson but suffer in statistical precision because of relatively small branching fractions. A complementary strategy is to use hadronic decay modes, namely decays of a W or Z boson to a quark–antiquark pair,

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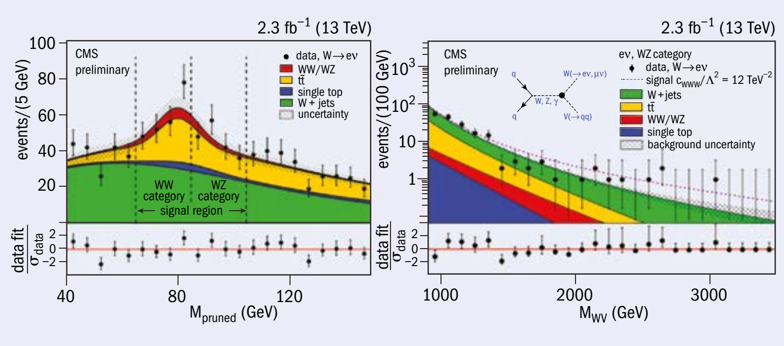
which benefit from much larger branching fractions but are experimentally more challenging. Each quark or antiquark appears as a collimated stream of particles, or jet, in the detector. Thus the experimental signature for hadronic decays is the presence of two jets. Discriminating between the hadronic decay of a W boson with a mass of 81 GeV and that of a Z boson (91.2 GeV) is difficult on an event-by-event basis due to the finite jet-energy resolution. Nonetheless, the separation can be performed on a statistical basis for highly energetic jets (see figure).

CMS has selected WV diboson events in which a W boson decays leptonically and a highly energetic V boson decays hadronically. Because of the high V boson energy, the two jets from the V boson decay are partially merged and the WV system can have a very large mass. As a result, the analysis probes a regime where physics beyond the SM might be present. Searches are performed as a function of the mass of the WV system and are used to set limits on anomalous TGC interactions.



Left: The reconstructed mass (M_{pruned}) of a hadronically decaying vector boson ($V = W$ or Z) candidate detected as a two-jet substructure component inside a jet with a wide jet definition. Right: The reconstructed mass of WV candidates (M_{WV}), where the magenta curve represents the sum of the SM contributions with that of a hypothetical anomalous TGC signal.

Results obtained so far have established the viability of the techniques, but much greater sensitivity to the presence of anomalous TGC interactions is expected with the larger data samples that will be analysed in the future.

- **Further reading**

CMS Collaboration 2016 CERN-EP-16-169.
CMS Collaboration 2016 CERN-EP-2016-174.
CMS Collaboration 2016 CMS-PAS-SMP-15-004.
CMS Collaboration 2016 CMS-PAS-SMP-16-006.
CMS Collaboration 2016 CMS-PAS-SMP-16-012.

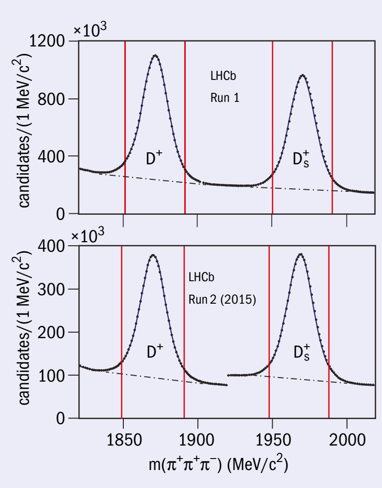
LHCb searches for strong CP violation

CP violation, which relates to an asymmetry between matter and antimatter, is a well-established feature of the weak interaction that mediates decays of strange, charm and beauty particles. It arises in the Standard Model from a single complex phase in the Cabibbo–Kobayashi–Maskawa matrix that relates the mass and flavour eigenstates of the quarks. However, the strength of the effect is well below what is needed to explain the dominance of matter over antimatter in the present universe. The LHCb collaboration has now looked for evidence of CP violation in the strong interaction, which binds quarks and gluons within hadrons.

In principle, the theory of the strong interactions, quantum chromodynamics (QCD), allows for a CP-violating component, but measurements of the electric dipole moment of the neutron have shown that any effect in QCD must be very small indeed. This apparent absence of CP violation in QCD is known as "the strong CP problem".

One way to look for evidence of CP violation in strong interactions is to search for η and $\eta'(958)$ meson decays to pairs of charged pions: $\eta^{(\prime)} \rightarrow \pi^+\pi^-$, both of which would violate CP symmetry. The LHCb collaboration has recently used its copious production of charm mesons to perform such a search, establishing a new method to isolate potential samples of η and η' decays into two pions. The D^+ and D_s^+ mesons (and their opposite sign modes) have well-measured decay modes to $\eta\pi^+$ and $\eta'\pi^+$, as well as to $\pi^+\pi^+\pi^-$. Therefore, any η or η' decays to $\pi^+\pi^-$ would potentially show up as narrow peaks in the $\pi^+\pi^-$ mass spectra from D and D_s decays to $\pi^+\pi^+\pi^-$.

The LHCb team used a sample of about 25 million each of D^+ and D_s^+ meson decays to $\pi^+\pi^+\pi^-$ collected during Run 1 and the first year of Run 2 of the LHC (figure 1). The analysis used a boosted decision tree to suppress backgrounds, with fits to the $\pi^+\pi^-$ mass spectra from the D^+ and D_s^+ decays used to set limits on the amount of η and η' that could be present. No evidence for the CP-violating decays was found and upper limits were set on the branching fractions, at 90% confidence level, of less than 1.6×10^{-5} for $\eta \rightarrow \pi^+\pi^-$ and 1.8×10^{-5} for $\eta'(958) \rightarrow \pi^+\pi^-$. The result for the η meson is comparable with the current world best, while that for the η' is a factor three below the previous best, further constraining the possibility for a new CP-violating mechanism in strong interactions.



Mass spectra of $D_s^+ \rightarrow \pi^+\pi^+\pi^-$ candidates, showing fits after the application of a boosted decision tree (BDT) to suppress backgrounds. The vertical lines indicate optimised signal regions used in the analysis. The discontinuity in the Run 2 spectrum comes from the fact that the trigger has two separate output streams and there are different BDT selections for D^+ and D_s^+.

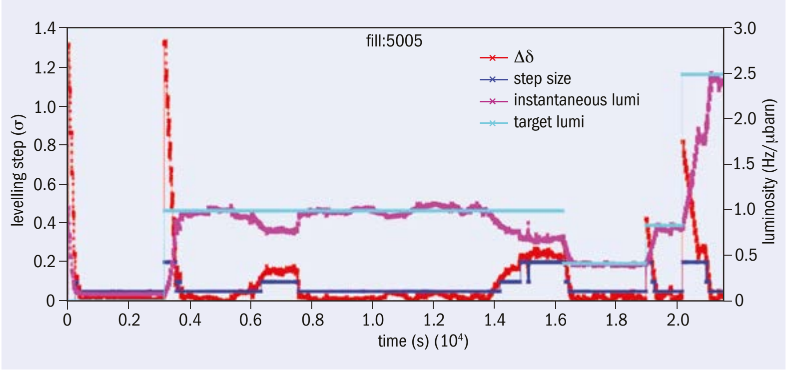
- **Further reading**

LHCb Collaboration 2016 LHCb-PAPER-2016-046.

ALICE prepares for high-luminosity LHC

The LHC is preparing for a major high-luminosity upgrade (HL-LHC) with the objective to increase the instantaneous luminosity to around $2 \times 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$ for proton–proton (pp) collisions and $6 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$ for lead–lead (Pb–Pb) collisions. To fully exploit this new and unique accelerator performance, the ALICE experiment has engaged an ambitious upgrade programme that will allow the inspection of Pb–Pb collisions at an expected rate of 50 kHz while preserving and even enhancing its unique capabilities in particle identification and low transverse-momentum measurements. This will open a new era in the high-precision characterisation of the quark–gluon plasma (QGP), the state of matter at extreme temperatures.

Measurements of pp collisions serve as vital reference measurements to calibrate the Pb–Pb measurements. However, to limit the event "pile-up" during pp collisions (i.e. the number of pp collisions per bunch crossing) and to ensure a high-quality data set, the instantaneous luminosity must be limited in ALICE at a value of $10^{30}\,\text{cm}^{-2}\text{s}^{-1}$. This is achieved by applying a beam–beam separation in the horizontal plane of up to several σ (beam-size units): first, once the beams are ready for physics, a controlled and automatic luminosity ramp-up sets in to reach the target luminosity defined by ALICE. Next, fine-tuning is carried out during the fill – a procedure known as luminosity levelling, which requires algorithms running synchronously on the ALICE and LHC sides.



At ~3000 s, the target luminosity is set at 1 Hz/μb (light-blue curve, right scale) then the difference between the beam separations $\Delta\delta$ (red curve, left scale) goes from 0 up to 1.3σ units. At the same time, the step size (blue curve, left scale) increases from 0.05 to 0.2σ to speed up the beam steering. While the instantaneous luminosity (magenta curve) is approaching the target, the $\Delta\delta$ goes to 0 and the step size goes down to 0.1 and then 0.05σ for a smooth convergence. After $1.8\,10^4$ s, different target luminosities are set and the repetition of the cycle is shown.

Following detailed simulations and several tests at the LHC, a new luminosity levelling algorithm has been in operation since June this year. The algorithm calculates the beam separation for both the target luminosity and the measured instantaneous luminosity, and uses the difference of the two separations to calculate step sizes. These are then transmitted to the LHC, which steers the beams until the target luminosity is reached within ±5%. When the beams approach the final separation in the horizontal plane, much smaller step sizes are applied to ensure a smooth and precise convergence of the luminosity to the target (see figure). This automatic procedure speeds up the collider operation and also prevents luminosity overshooting, which can occur during manual operations. Thanks to this new procedure, ALICE has increased its data-taking efficiency and can safely change the target luminosity even during fills with thousands of colliding bunches, a necessary step in anticipation of the high luminosities to be delivered by the LHC in the near future.

- **Further reading**

cds.cern.ch/record/2069130/files/CERN-ACC-2015-0140.pdf.

FACILITIES

KATRIN celebrates first beam

On 14 October, the KArlsruhe TRItium Neutrino (KATRIN) experiment, which is presently being assembled at Tritium Laboratory Karlsruhe on the KIT Campus North site, Germany, celebrated "first light". For the first time, electrons were guided through the 70 m-long beamline towards a giant spectrometer, which allows the kinetic energy of the beta electron from tritium beta decays to be determined very precisely. Although actual measurements will not get under way until next year, it marks the beginning of KATRIN operation.

Patrick Langer, KIT

The KATRIN team flips the switch.

The goal of the technologically challenging KATRIN experiment, which has been a CERN-recognised experiment since 2007, is to determine the absolute mass scale of neutrinos in a model-independent way. Previous experiments using the same technique set an upper limit to the electron antineutrino mass of 2.3 eV/c², but KATRIN will either improve on this by one order of magnitude or, if neutrinos weigh more than 0.35 eV/c², discover the actual mass.

KATRIN involves more than 150 scientists, engineers and technicians from 12 institutions in Germany, the UK, Russia, the Czech Republic and the US.

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European XFEL enters commissioning phase

On 6 October, commissioning began at the world's largest X-ray laser: the European XFEL in Hamburg, Germany. The 3.4 km-long European XFEL will generate ultrashort X-ray flashes with a brilliance one billion times greater than the best conventional X-ray radiation sources based on synchrotrons. The beams will be directed towards samples at a rate of 27,000 flashes per second, allowing scientists from a broad range of disciplines to study the atomic structure of materials and to investigate ultrafast processes *in situ*. Commissioning will take place over the next few months, with external scientists able to perform first experiments in summer 2017.


European XFEL

Guests celebrate the beginning of commissioning at the European XFEL.

The linear accelerator that drives the European XFEL is based on superconducting "TESLA" technology, which has been developed by DESY and its international partners. Since 2005, DESY has been operating a free-electron laser called FLASH, which is a 260 m-long prototype of the European XFEL that relies on the same technology.

The European XFEL is managed by 11 member countries: Denmark, France, Germany, Hungary, Italy, Poland, Russia, Slovakia, Spain, Sweden and Switzerland. On 1 January 2017, surface-physicist Robert Feidenhans'l, currently head of the Niels Bohr Institute at the University of Copenhagen, was appointed as the new chairman of the European XFEL management board taking over from Massimo Altarelli, who had been in the role since 2009.

Compiled by John Swain, Northeastern University

Happy bumblebees

Charles Darwin believed that insects experience emotion. A new study strongly suggests he was correct, at least in the case of bees. Clint Perry of Queen Mary University in London and colleagues found dopamine-dependent positive emotion-like states in bees that were given sucrose and subjected to decision-making tests. This was not explicable simply in terms of the bees becoming more exploratory, and their apparent "good mood" was abolished by the dopamine-antagonist fluphenazine. The work opens up opportunities for understanding emotions in simpler organisms and for studying how emotional states affect decision-making in animals.


Shutterstock/claire norman

Unexpected rewards induce positive emotion-like state changes in bumblebees.

● **Further reading**
C Perry *et al.* 2016 *Science* **353** 1529.

Lifespan limit

The oldest well-documented human lived to the age of 122, but is there an upper limit to the human lifespan? Or could medical advances extend it indefinitely? By studying demographic literature in detail, Xiao Dong of the Albert Einstein College of Medicine in New York and colleagues have found strong evidence that there is indeed an upper limit determined by our biology, perhaps a byproduct of our fixed genetic programmes for early life events. Despite advances in medicine, the age at death of the oldest person has not increased since the 1990s.

● **Further reading**
Xiao Dong *et al.* 2016 *Nature* **538** 257.

Constraining B modes

Gravitational lensing of the cosmic microwave background (CMB) can obscure some signals, converting E-mode into B-mode polarisation and acting as a source of noise in the search for inflationary gravitational-wave signatures. Patricia Larsen of the Institute of Astronomy and the Kavli Institute for Cosmology in Cambridge and colleagues have now demonstrated delensing of Planck temperature maps using the cosmic infrared background. Using Planck maps at 545 and 857 GHz, the delensed CMB temperature anisotropies are measured at lower frequencies, with a sharpening of the acoustic peaks detected with a significance of 16 standard deviations. The technique is expected to be essential for further high-precision constraints on inflationary B-mode polarisation.

● **Further reading**
P Larsen *et al.* 2016 *Phys. Rev. Lett.* **117** 151102.

Acoustic holograms

Researchers have reported a novel technique for making holograms using sound waves instead of light. Previously, manipulating the 3D structure of acoustic waves was only possible with a conventional array of acoustic transducers. Kai Melde of the Max Planck Institute for Intelligent Systems in Stuttgart, Germany, and colleagues used just one transducer coupled to a 3D printed monolithic element (a contoured solid-plastic block), which determines the shape of the pressure wave produced. Such acoustic holograms can manipulate and direct microscale objects and also have potential for medical imaging and selective heating.

Ultrasonic waves were used to push a collection of microparticles into the shape of Picasso's peace dove. (Image credit: K Melde/MPI for Intelligent Systems.)

● **Further reading**
K Melde *et al.* 2016 *Nature* **537** 518.

Gut bugs and chemo

Microbes in the gut can dramatically boost the effectiveness of a common anticancer drug, at least in mice. That's the finding of Laurence Zitvogel of Gustave Roussy Cancer Campus in Vellejuif, France, and colleagues, who looked at the anticancer antibiotic cyclophosphamide in treated mice. In those mice lacking a protein that restricts the growth of two spices of gut bacteria (*Enterococcus hirae* and *Barnesiella intestinihominis*), the drug was almost twice as effective at reducing tumour size. The work suggests that gut bacteria could be used to optimise cancer therapies.

● **Further reading**
R Daillère *et al.* 2016 *Immunity* **45** 931.

Printing bone

Synthetic bone printed on a 3D printer stimulates bone regeneration when implanted into animals, according to a new study. Ramille Shah of Northwestern University and colleagues printed "hyperelastic bone" out of hydroxyapatite (a mineral similar to that in natural bone) mixed with one of two polymers already used in medicine. Implanted into mice, rats and one macaque, the samples were integrated into tissue and caused new bone to grow without negative side effects. A printed "bone" shaped like a human femur was able to withstand natural loads, and the ease with which various shapes can be printed makes the technique promising for humans.

● **Further reading**
A Jakus *et al.* 2016 *Sci. Transl. Med.* **8** 358ra127.

Factory Acceptance Testing at Buckley Systems

Mobile "Roamer" CMM used to confirm dimensions are within tolerance on a quadrupole magnet.

General

Buckley Systems manufactures sophisticated magnets, and it is certified ISO 9001:2008 for the following scope: the design and manufacture of precision electromagnets, ion-beam physics hardware, and high vacuum equipment used in the semiconductor - ion implant industry, laboratory research and particle accelerators. Nevertheless, from the customer's point of view, the manufacturing job is not complete until the Factory Acceptance Test (FAT) is successfully completed. Buckley System "FATs" are described in the Coils, and Magnets sections.

A Quality Control (QC) programme is in place to ensure that machined parts and assemblies meet dimensional tolerances (and other specified customer constraints) throughout the manufacturing process. Several high-accuracy Coordinate Measuring Machines (CMM) measure dimensions to 10 µm including a "roamer" which has "touchscan" capability meaning that its finger can be drawn along a surface rather than just touching a surface at several points. Ceramic gauge blocks measure magnet gaps to 1 µm accuracy.

Coils

Buckley Systems achieves FATs for National Laboratories that are comprehensive and stringent. All measurements within the temperature controlled test building must be within a set tolerance to achieve a pass. A sample list of typical measurements follows:

(i) electrical resistance tests,
(ii) inductance tests,
(iii) pressure and flow rate tests of the cooling water,
(iv) insulation resistance and high electric potential tests with coils immersed in salted water (<1,000 Ω-m) and leakage currents <50 µA,
(v) impulse-tested for turn-to-turn integrity over a range of voltages with rejection based on frequency shifts or damping rates changing as a function of voltage, or non-conformance to customer supplied waveforms,
(vi) thermal-switch open/close testing as a function of temperature.

Magnets

Buckley Systems accommodates magnets with apertures ranging from 8 mm to 2000 mm, and has Hall probes with 3.5 m of travel at its disposal. Completed magnets must also undergo FATs and a sampling of what these entail follows:

(i) the nominal mechanical resonant frequency orthogonal to the magnet axis,
(ii) Magnetic measurements for dipole magnets through a range of excitation-currents include for example:
    (a) integrated field homogeneity to one part in 10^4 over a "good field" range in the mid-plane, (b) integrated dipole field over length of yoke and including fringe field region, (c) end field maps and chamfer adjustments to minimize integrated field errors, and (d) B/I curve at the midpoint,
(iii) Magnetic measurements for quadrupole, sextupole, and octupole magnets over a range of excitation-currents include:
    (a) integrated field harmonics up to a maximum-pole (42-pole in some cases) at a set radius, (b) integrated field measurements over length of yoke and including fringe field region, (c) end chamfer adjustments to minimize integrated harmonic terms of the customer's choice, (d) magnetic centre measurement to better than ±50 microns, (e) magnetic length, and (f) field angle,
(iv) Leak rate tests for high vacuum and ultra high vacuum chambers with the appropriate bake-out procedures observed.

Lastly, Buckley Systems can model particle trajectories through the measured magnetic fields and compare the magnet's performance based on the measured fields to the simulated performance. This has been particularly useful in ascertaining whether magnetic spectrometer systems have achieved their design resolution or not.

Magnetic Field Measurements on a Dipole Magnet.

BUCKLEY SYSTEMS

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Astrowatch

COMPILED BY MARC TÜRLER, ISDC AND OBSERVATORY OF THE UNIVERSITY OF GENEVA, AND CHIPP, UNIVERSITY OF ZURICH

Hubble misses 90% of distant galaxies

A team of astronomers has estimated that the number of galaxies in the observable universe is around two trillion (2×10^{12}), which is 10 times more than could be observed by the Hubble Space Telescope in a hypothetical all-sky survey. Although the finding does not affect the matter content of the universe, it shows that small galaxies unobservable by Hubble were much more numerous in the distant, early universe.

Asking how many stars and galaxies there are in the universe might seem a simple enough question, but it has no simple answer. For instance, it is only possible to probe the observable universe, which is limited to the region from where light could reach us in less time than the age of the universe. The Hubble Deep Field images captured in the mid-1990s gave us the first real insight into this fundamental question: myriad faint galaxies were revealed, and extrapolating from the tiny area on the sky suggested that the observable universe contains about 100 billion galaxies.

Now, an international team led by Christopher Conselice of the University of Nottingham in the UK has shown that this number is at least 10 times too low. The conclusion is based on a compilation of many published deep-space observations from Hubble and other telescopes. Conselice and co-workers derived the distance and the mass of the galaxies to deduce how the number of galaxies in a given mass interval evolves over the history of the universe. The team extrapolated its results to infer the existence of faint galaxies, which the current generation of telescopes cannot observe, and found that galaxies are less big and more numerous in the distant universe compared with local regions. Since less-massive galaxies are also the dimmest and therefore the most difficult to observe at great distances, the researchers conclude that the Hubble ultra-deep-field observations are missing about 90% of all galaxies in any observed area in the sky. The total number of galaxies in the observable universe, they suggest, is more like two trillion.

NASA, ESA/Hubble

A region of the sky observed by Hubble reveals some of the most distant and faint galaxies visible with current technology, but a new study suggests that this is the tip of the iceberg.

This intriguing result must, however, be put in context. Critically, the galaxy count depends heavily on the lower limit that one chooses for the galaxy mass: since there are more low-mass than high-mass galaxies, any change in this value has huge effects. Conselice and his team took a stellar-mass limit of one million solar masses, which is a very small value corresponding to a galaxy 1000 times smaller than the Large Magellanic Cloud (which is itself about 20–30 times less massive than the Milky Way). The authors explain that were they to take into account even smaller galaxies of 100,000 solar masses, the estimated total number of galaxies would be seven times greater.

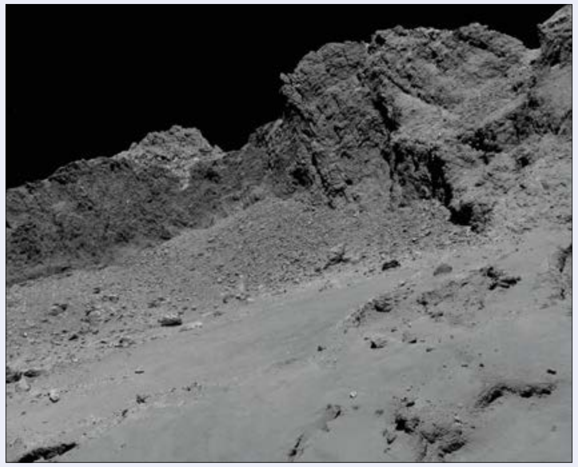
The result also does not mean that the universe contains more visible matter than previously thought. Rather, it shows that the bigger galaxies we see in the local universe have been assembled via multiple mergers of smaller galaxies, which were much more numerous in the early, distant universe. While the vast majority of these small, faint and remote galaxies are not yet visible with current technology, they offer great opportunities for future observatories, in particular the James Webb Space Telescope (Hubble's successor), which is planned for launch in 2018.

● **Further reading**

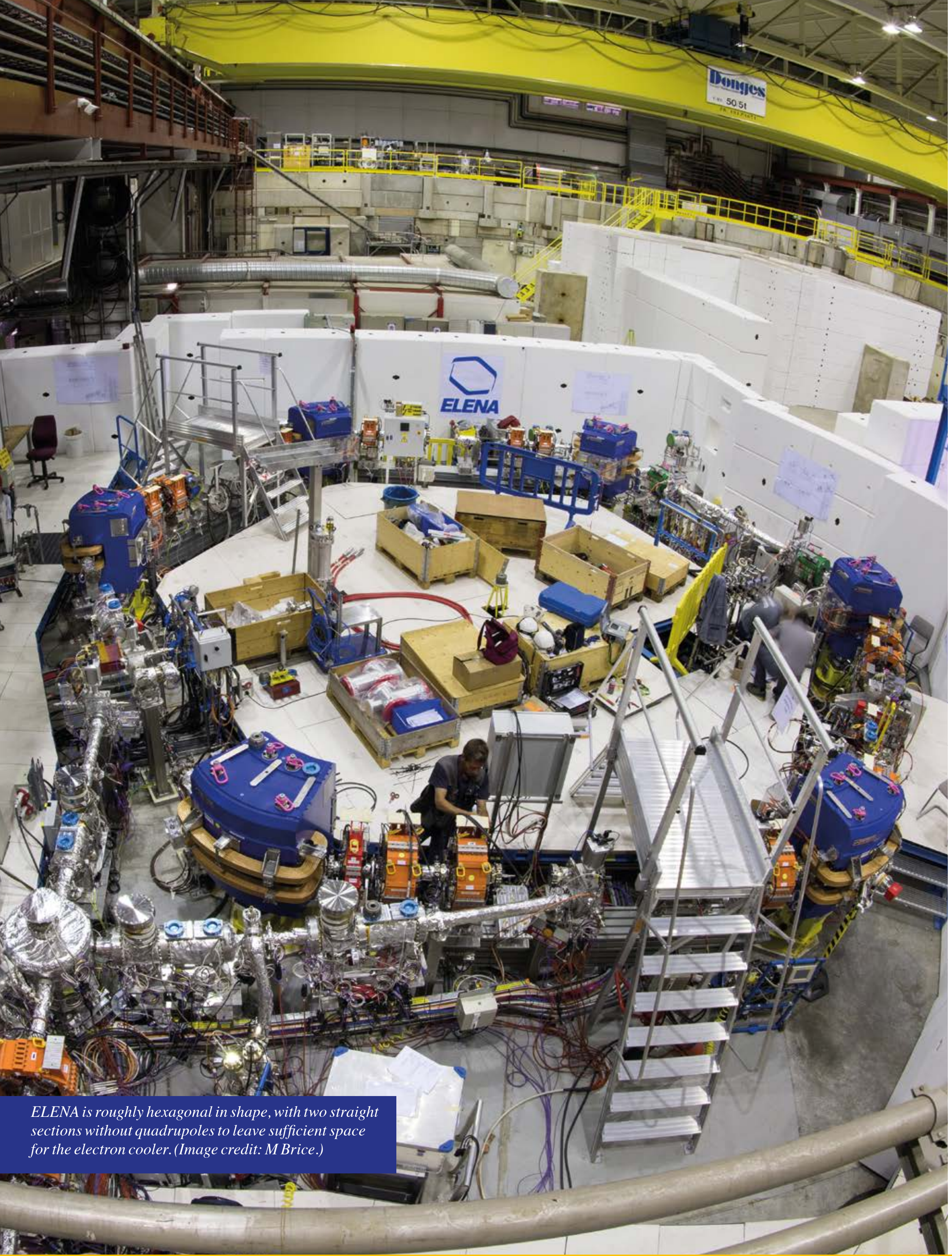
C J Conselice 2016 *ApJ* **830** 83.

Picture of the month

It could be a landscape on the Moon, but in fact this spectacular view shows the Comet 67P/Churyumov–Gerasimenko. The image was captured by the OSIRIS camera aboard ESA's Rosetta spacecraft, which was launched on 2 March 2004 and reached the comet after more than 10 years of interplanetary travel (*CERN Courier* October 2014 p17). This is one of the last images taken by the mission, and was recorded from a distance of 16 km during the spacecraft's final descent onto the comet on 30 September 2016. This was the date chosen by ESA to perform a controlled impact of the two-tonne spacecraft onto the comet's surface. The highlight of the mission was the release of a small lander called Philae, which was sent out onto the comet on 12 November 2014. The lander, however, bounced on the surface and came to rest in a shadowy place, which prevented proper communication and illumination of its solar panels. Its fate was confirmed only recently when Philae was finally spotted on its side in a dark crack, in a Rosetta image released on 5 September.



ESA/Rosetta/MPS for OSIRIS Team



ELENA is roughly hexagonal in shape, with two straight sections without quadrupoles to leave sufficient space for the electron cooler. (Image credit: M Brice.)

CERN soups up its antiproton source

The ELENA facility, which is nearing completion at CERN's Antiproton Decelerator, will increase the number of available antiprotons for experiments by up to two orders of magnitude, allowing precise comparisons between the properties of matter and antimatter. **Christian Carli**, **Tommy Eriksson** and **Stefan Ulmer** explain.

The Antiproton Decelerator (AD) facility at CERN, which has been operational since 2000, is a unique source of antimatter. It delivers antiprotons with very low kinetic energies, enabling physicists to study the fundamental properties of baryonic antimatter – namely antiprotons, antiprotonic helium and antihydrogen – with great precision. Comparing the properties of these simple systems to those of their respective matter conjugates therefore provides highly sensitive tests of CPT invariance, which is the most fundamental symmetry underpinning the relativistic quantum-field theories of the Standard Model (SM). Any observed difference between baryonic matter and antimatter would hint at new physics, for instance due to the existence of quantum fields beyond the SM (see page 21).

In the case of matter particles, physicists have developed advanced experimental techniques to characterise simple baryonic systems with extraordinary precision. The mass of the proton, for example, has been determined with a fractional precision of 89 parts in a trillion (ppt) and its magnetic moment is known to a fractional precision of three parts in a billion. Electromagnetic spectroscopy on hydrogen atoms, meanwhile, has allowed the ground-state hyperfine splitting of the hydrogen atom to be determined with a relative accuracy of 0.7 ppt and the 1S/2S electron transition in hydrogen to be determined with a fractional precision of four parts in a quadrillion – a number that has 15 digits.

In the antimatter sector, on the other hand, only the mass of the antiproton has been determined at a level comparable to that in the baryon world (see table overleaf). In the late 1990s, the TRAP collaboration at CERN's LEAR experiment used advanced trapping and cooling methods to compare the charge-to-mass ratios of the antiproton and the proton with a fractional uncertainty of 90 ppt. This was, among others, one of the crucial steps that inspired CERN to start the AD programme. Over the past 20 years, CERN has made huge strides towards our understanding of antimatter (see panel overleaf). This includes the first ever production of anti-atoms – antihydrogen, which comprises an antiproton orbited by a positron – in 1995 and the production of antiprotonic helium (in which an antiproton and an electron orbit a normal helium nucleus).

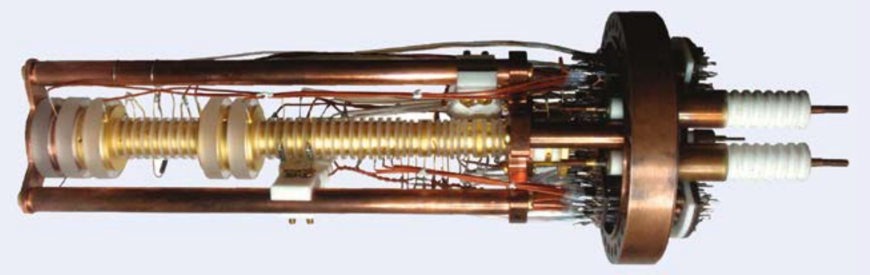
CERN has decided to boost its AD programme by building a brand new synchrotron that will improve the performance of its antiproton source. Called the Extra Low ENergy Antiproton ring (ELENA), this new facility is now in the commissioning phase. Once it enters operation, ELENA will lead to an increase by one to two orders of magnitude in the number of antiprotons captured by experiments using traps and also make new types of experiments possible (see figure overleaf). This will provide an even more powerful probe of new physics beyond the SM.

Combined technologies

The production and investigation of antimatter relies on combining two key technologies: high-energy particle-physics sources and classical low-energy atomic-physics techniques such as traps and lasers. One of the workhorses of experiments in the AD facility is the Penning trap. This static electromagnetic cage for antiprotons serves for both high-precision measurements of the fundamental properties of single trapped antiprotons and for trapping large amounts of antiprotons and positrons for antihydrogen production.

The AD routinely provides low-energy antiprotons to a dynamic and growing user community. It comprises a ring with a circumference of 182.4 m, which currently supplies five operational experiments devoted to studying the properties of antihydrogen, antiprotonic helium and bare antiprotons with high precision: ALPHA, ASACUSA, ATRAP, AEgIS and BASE (see panel). All of these experiments are located in the existing experimental zone, covering approximately one half of the space inside the AD ring. With this present scheme, one bunch containing about 3×10^7 antiprotons is extracted roughly every 120 seconds at a kinetic energy of 5.3 MeV and sent to a particular experiment.

Although there is no hard limit for the lowest energy that can be achieved in a synchrotron, operating a large machine at low energies requires magnets with low field strengths and is therefore subject to perturbations due to remanence, hysteresis and external ▷



The high-precision four-Penning-trap system used by the BASE collaboration for antiproton magnetic-moment and charge-to-mass ratio measurements.

matter sector		antimatter sector	
proton lifetime (direct)	>1.67 e34 y	antiproton lifetime (direct)	>1.2 y
proton m/u	89 ppt	antiproton m/u	112 ppt
proton magnetic moment	3.3 ppb	antiproton magnetic moment	4.4 ppm
hydrogen 1S/2S	0.004 ppt	antihydrogen 1S/2S	?
hydrogen GSHFS	0.7 ppt	antihydrogen GSHFS	?

Fractional precisions achieved for the fundamental properties of baryonic matter (left) and antimatter (right). GSHFS stands for "ground-state hyperfine splitting".

stray-field effects. The AD extraction energy of 5.3 MeV is a compromise: it allows beam to be delivered under good conditions given the machine's circumference, while enabling the experiments to capture a reasonable quantity of antiprotons. Most experiments further decelerate the antiprotons by sending them through foils or using a radiofrequency quadrupole to take them down to a few keV so that they can be captured. This present scheme is inefficient, however, and less than one antiproton in 100 that have been decelerated with a foil can be trapped and used by the experiments.

The ELENA project aims to further decelerate the antiprotons from 5.3 MeV down to 100 keV in a controlled way. This is achieved via a synchrotron equipped with an electron cooler to avoid losses during deceleration and to generate dense bunches of antiprotons for users. To achieve this goal, the machine has to be smaller than the AD; a circumference of 30.4 metres has been chosen, which is one sixth of the AD. The experiments still have to further decelerate the beam either using thinner foils or other means, but the lower energy from the synchrotron makes this process more efficient and therefore increases the number of captured antiprotons dramatically.

With ELENA, the available intensity will be distributed to several (the current baseline is four) bunches, which are sent to several experiments simultaneously. Despite the reduction in intensity, the higher beam availability for a given experiment means that a given experiment will receive beam almost continuously 24 hours per day, as opposed to during an eight-hour-long shift a few times per week, as is the case with the present AD.

The ELENA project started in 2012 with the detailed design of the machine and components. Installations inside the AD hall and inside the AD ring itself began in spring 2015, in parallel to AD operation for the existing experiments. Installing ELENA inside the AD ring is a simple cost-effective solution because no large additional building to house a synchrotron and a new experimental area had to be constructed, plus the existing experiments have been able to remain at their present locations. Significant external contributions from the user community include a H^- ion and proton source for commissioning, and very sensitive profile monitors for the transfer lines.

Low-energy challenges

Most of the challenges and possible issues of the ELENA project are a consequence of its low energy, small size and low intensity. The low beam energy makes the beam very sensitive to perturbations such that even the Earth's magnetic field has a significant impact, for instance deforming the "closed orbit" such that the beam is no longer located at the centre of the vacuum chamber. The circumference of the machine has therefore been chosen to be as small as possible, thus demanding higher-field magnets, to mitigate these effects. On the other hand, the ring has to be long enough to install all necessary components.

For similar reasons, magnets have to be designed very carefully to ensure a sufficiently good field quality at very low field levels, where hysteresis effects and remanence become important. This challenge triggered thorough investigations by the CERN magnet experts and involved several prototypes using different types of yokes, resulting in unexpected conclusions relevant for any project that relies on low-field magnets. The initially foreseen bending magnets based on "diluted" yokes, with laminations made of electrical steel alternated with thicker non-magnetic stainless steel laminations, were found to have larger remnant fields and to be less suitable. Based on this unexpected empirical observation, which was later explained by theoretical considerations, it has been decided that most ELENA magnets will be built with conventional yokes. The corrector magnets have been built without magnetic yoke to completely suppress hysteresis effects.

Electron cooling is an essential ingredient for ELENA: cooling on an intermediate plateau is applied to reduce emittances and losses during deceleration to the final energy. Once the final energy is reached, electron cooling is applied again to generate dense bunches with low emittances and energy spread, which are then transported to the experiments. At the final energy, so-called intra beam scattering (IBS) caused by Coulomb interactions between different particles in the beam increases the beam "emittances" and the energy spread, which, in turn, increases the beam size. This phenomenon will be the dominant source of beam degradation in ELENA, and the equilibrium between IBS and electron cooling will determine the characteristics of the bunches sent to the experiments.

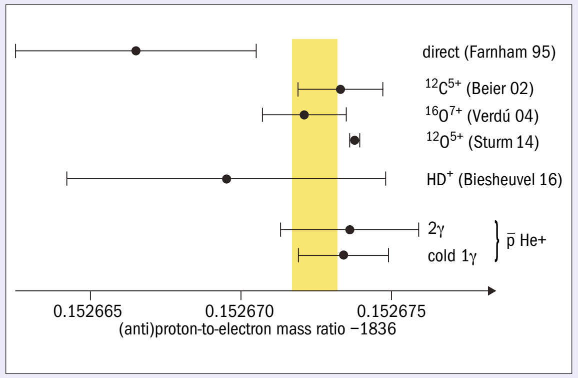
ELENA will be exploited by six approved experiments.

CERN's AD facility opens new era of precision antimatter studies

CERN's Antiproton Decelerator (AD) was approved in 1997, just two years after the production of the first antihydrogen atoms at the Low Energy Antiproton Ring (LEAR), and entered operation in 2000. Its debut discovery was the production of cold antihydrogen in 2002 by the ATHENA and ATRAP collaborations. These experiments were joined by the ASACUSA collaboration, which aims at precision spectroscopy of antiprotonic helium and Rabi-like spectroscopy of the antihydrogen ground-state hyperfine splitting. Since then, techniques have been developed that allow trapping of antihydrogen atoms and the production of a beam of cold antihydrogen atoms. This culminated in 2010 in the first report on trapped antihydrogen by the ALPHA collaboration (the successor of ATHENA). In the same year, ASACUSA produced antihydrogen using a cusp trap, and in 2012 the ATRAP collaboration also reported on trapped antihydrogen.

TRAP, which was based at LEAR and was the predecessor of ATRAP, is one of two CERN experiments that have allowed the first direct investigations of the fundamental properties of antiprotons. In 1999, the collaboration published a proton-to-antiproton charge-to-mass ratio with a factional precision of 90 ppt based on single-charged-particle spectroscopy in a Penning trap using data taken up to 1996. Then, published in 2013, ATRAP measured the magnetic moment of the antiproton with a fractional precision of 4.4 ppm. The BASE collaboration, which was approved in the same year, is now preparing to improve the ATRAP value to the ppb level. In addition, in 2015 BASE reported on a comparison of the proton-to-antiproton charge-to-mass ratio with a fractional precision of 69 ppm. So far, all measured results are consistent with CPT invariance.

The ALPHA, ASACUSA and ATRAP experiments, with the goal of performing precise antihydrogen spectroscopy, are challenging because they need antihydrogen first to be produced and then to be trapped. This requires the accumulation of both antiprotons and positrons, in addition to antihydrogen production via three-body reactions in a nested Penning trap. In 2012, ALPHA reported on a first spectroscopy-type experiment and published the observation of resonant quantum transitions in antihydrogen (see figure) and, later, ASACUSA reported in 2014 on the first production of a beam of cold antihydrogen atoms. The reliable production/trapping scheme of ALPHA, meanwhile, enabled several high-resolution studies, including the precise investigation of the charge neutrality of antihydrogen with a precision at the 0.7 ppb level.



The ASACUSA collaboration has recently measured the antiproton-to-electron mass ratio (bottom data point) from the single-photon transition frequencies of antiprotonic helium. Other data points show measured proton-to-electron mass ratios, with the yellow band representing the CODATA2010 value (Science, *in press*).

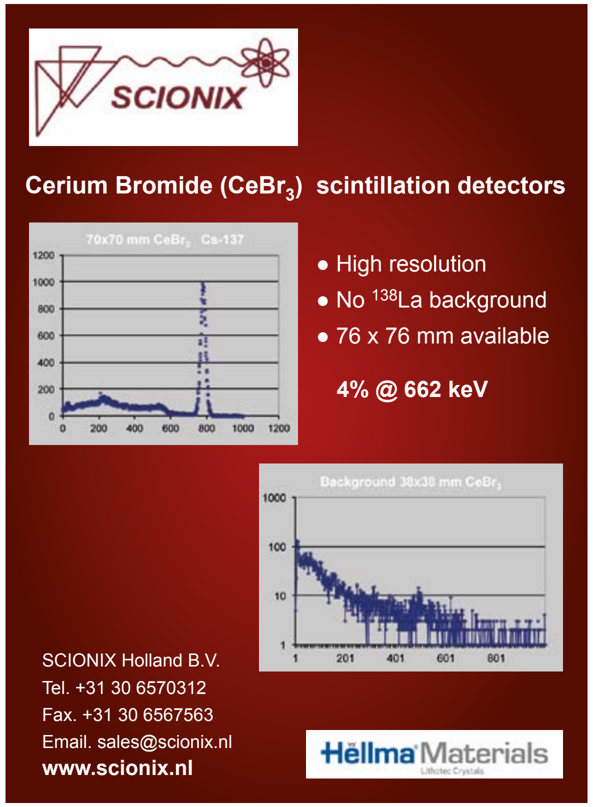
The ASACUSA, ALPHA and ATRAP collaborations are now preparing their experiments to produce the first electromagnetic spectroscopy results on antihydrogen. This is difficult because ALPHA typically reports on about one trapped antihydrogen atom per mixing cycle, while ASACUSA detects approximately six antihydrogen atoms per shot. Both numbers demand for higher antihydrogen production rates, and to further boost AD physics, CERN built the new low-energy antiproton synchrotron ELENA. In parallel to these efforts, proposals to study gravity with antihydrogen were approved. This led to the formation of the AEgIS collaboration in 2008, which is currently being commissioned, and the GBAR project in 2012.

Another possible limitation for a low-energy machine such as ELENA is the large cross-section for scattering between antiprotons and the nuclei of at-rest gas molecules, which leads to beam loss and degradation. This phenomenon is mitigated by a carefully designed vacuum system that can reach pressures as low as a few 10^{-12} mbar. Furthermore, ELENA's low intensities and energy mean that the beam can generate only very small signals and therefore makes beam diagnostics challenging. For example, the currents of the circulating beam are less than $1\,\mu A$, which is well below what can be measured with standard beam-current transformers and therefore demands that we seek alternative techniques to estimate the intensity.

An external source capable of providing 100 keV H^- and proton beams will be used for a large part of the commissioning. Although this allows commissioning to be carried out in parallel with AD operation for the experiments, it means that commissioning starts at the most delicate low-energy part of the ELENA cycle where perturbations have the most impact. Another advantage of ELENA's low energy is that the transfer lines to the experiments are electrostatic – a low-cost solution that allows for the installation of many focusing quadrupoles and makes the lines less sensitive to perturbations.

Towards first beam

As of the end of October 2016, all sectors of the ELENA ring – except for the electron cooler, which has temporarily been replaced by a simple vacuum chamber, and a few transfer lines required for the commissioning of the ring – have been installed and baked to reach the very low rest-gas density required. Following hardware tests, commissioning with beam is under way and will be resumed in early 2017, only interrupted for the installation of the electron cooler some time in spring. ▷



ELENA will be ready from 2017 to provide beam to the GBAR experiment, which will be installed in the new experimental area (see panel). The existing AD experiments, however, will be connected only during CERN's Long Shutdown 2 in 2019–2020 to minimise the period without antiprotons and to optimise the exploitation of the experiments. GBAR, along with another AD experiment called AEgIS, will target direct tests of the weak-equivalence principle by measuring gravitational acceleration based on antihydrogen. This is another powerful way to test for any violations between the way the fundamental forces affect matter and antimatter. Although the first antimatter fall experiments were reported by the ALPHA collaboration in 2013, these results will potentially be improved by several orders of magnitude using the dedicated gravity experiments offered by ELENA.

ELENA is expected to operate for at least 10 years and be exploited by a user community consisting of six approved experiments. This will take physicists towards the ultimate goal of performing spectroscopy on antihydrogen atoms at rest, and also to investigate the effect of gravity on matter and antimatter. A potential discovery of CPT violation will constitute a dramatic challenge to the relativistic quantum-field theories of the SM and will potentially contribute to an understanding of the striking imbalance of matter and antimatter observed on cosmological scales.

● Further reading

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Résumé

Le CERN augmente le débit de sa source d'antiprotons

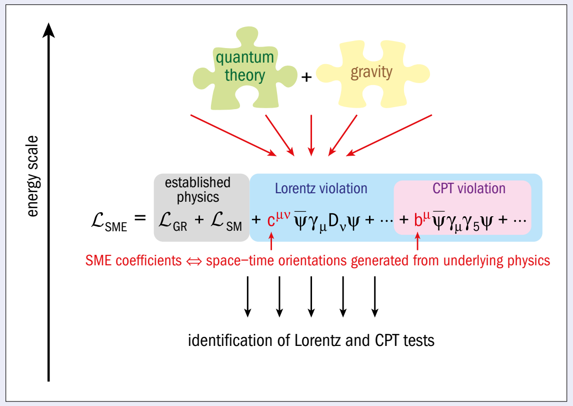
Le Décélérateur d'antiprotons (AD) du CERN est une source d'antimatière unique en son genre, qui fournit à plusieurs expériences des antiprotons à très basses énergies cinétiques, grâce auxquels les physiciens peuvent étudier avec une grande précision les propriétés fondamentales de l'antimatière baryonique.
Le CERN a maintenant intensifié le programme de l'AD en construisant un tout nouveau synchrotron, l'anneau d'antiprotons de basse énergie, baptisé ELENA. Cette nouvelle installation est à présent dans sa phase de mise en service. Une fois qu'elle sera en exploitation, dans quelques années, ELENA permettra d'augmenter d'un ou deux ordres de grandeur le nombre d'antiprotons capturés par les pièges des expériences, et également de réaliser de nouveaux types d'expériences. Il sera ainsi possible de sonder encore plus profondément la physique au-delà du Modèle standard.

Christian Carli and **Tommy Eriksson**, CERN, and **Stefan Ulmer**, RIKEN.

Testing times for space–time symmetry

An enormous range of experiments are being undertaken to test for violations of Lorentz and CPT symmetry, many of which involve CERN and in particular the ELENA facility. **Ralf Lehnert** surveys the state of the art.

The Standard Model Extension



At the core of attempts to detect violations in space–time symmetry is the Standard Model Extension (SME) – an effective field theory that contains not just the SM but also general relativity and all possible operators that break Lorentz symmetry. It can be expressed as a Lagrangian in which each Lorentz-violating term has a coefficient that leads to a testable prediction of the theory.

Throughout history, our notion of space and time has undergone a number of dramatic transformations, thanks to figures ranging from Aristotle, Leibniz and Newton to Gauss, Poincaré and Einstein. In our present understanding of nature, space and time form a single 4D entity called space–time. This entity plays a key role for the entire field of physics: either as a passive spectator by providing the arena in which physical processes take place or, in the case of gravity as understood by Einstein's general relativity, as an active participant.

Since the birth of special relativity in 1905 and the CPT theorem of Bell, Lüders and Pauli in the 1950s, we have come to appreciate both Lorentz and CPT symmetry as cornerstones of the underlying structure of space–time. The former states that physical laws are unchanged when transforming between two inertial frames, while the latter is the symmetry of physical laws under the simultaneous transformations of charge conjugation (C), parity inversion (P) and time reversal (T). These closely entwined symmetries guarantee that space–time provides a level playing field for all physical systems independent of their spatial orientation and velocity, or whether they are composed of matter or antimatter. Both have stood the tests of time, but in the last quarter century these cornerstones have come under renewed scrutiny as to whether they are indeed exact symmetries of nature. Were physicists to find violations, it would lead to profound revisions in our understanding of space and time and force us to correct both general relativity and the Standard Model of particle physics.

Accessing the Planck scale

Several considerations have spurred significant enthusiasm for testing Lorentz and CPT invariance in recent years. One is the observed bias of nature towards matter – an imbalance that is difficult, although perhaps possible, to explain using standard physics. Another stems from the synthesis of two of the most successful physics concepts in history: unification and symmetry breaking. Many theoretical attempts to combine quantum theory with gravity into a theory of quantum gravity allow for tiny departures from Lorentz and CPT invariance. Surprisingly, even deviations that are suppressed by 20 orders of magnitude or more are experimentally accessible with present technology. Few, if any, other experimental approaches to finding new physics can provide such direct access to the Planck scale.

Unfortunately, current models of quantum gravity cannot accurately pinpoint experimental signatures for Lorentz and CPT violation. An essential milestone has therefore been the development of a general theoretical framework that incorporates Lorentz and CPT violation into both the Standard Model and general relativity: the Standard Model Extension (SME), as formulated by Alan Kostelecký of Indiana University in the US and coworkers beginning in the early 1990s. Due to its generality and independence of the underlying models, the SME achieves the ambitious goal of allowing the identification, analysis and interpretation of all feasible Lorentz and CPT tests (see panel above). Any putative quantum-gravity remnants associated with Lorentz breakdown enter the SME as a multitude ▷

The seventh triennial CPT conference

A host of experimental efforts to probe space–time symmetries were the focus of the week-long Seventh Meeting on CPT and Lorentz Symmetry

(CPT'16) held at Indiana University, Bloomington, US, on 20–24 June, which are summarised in the main text of this article. With around 120 experts from five continents discussing the most recent developments in the subject, it has been the largest of all meetings in this one-of-a-kind triennial conference series. Many of the sessions included presentations involving experiments at CERN, and the discussions covered a number of key results from experiments at the Antiproton Decelerator and future improvements expected from the commissioning of ELENA. The common thread weaving through all of these talks heralds an exciting emergent era of low-energy Planck-reach fundamental physics with antimatter.

of preferred directions criss-crossing space–time. As a result, the playing field for physical systems is no longer level: effects may depend slightly on spatial orientation, uniform velocity, or whether matter or antimatter is involved. These preferred directions are the coefficients of the SME framework; they parametrise the type and extent of Lorentz and CPT violation, offering specific experiments the opportunity to try to glimpse them.

Lorentz and CPT research is unique in the exceptionally wide range of experiments it offers. The SME makes predictions for symmetry-violating effects in systems involving neutrinos, gravity, meson oscillations, cosmic rays, atomic spectra, antimatter, Penning traps and collider physics, among others. In the case of free particles, Lorentz and CPT violation lead to a dependence of observables on the direction and magnitude of the particles' momenta, on their spins, and on whether particles or antiparticles are studied. For a bound system such as atomic and nuclear states, the energy spectrum depends on its orientation and velocity and may differ from that of the corresponding antimatter system.

The vast spectrum of experiments and latest results in this field were the subject of the triennial CPT conference held at Indiana University in June this year (see panel above), highlights from which form the basis of this article.

CERN matters

As host to the world's only cold-antiproton source for precision antimatter physics (the Antiproton Decelerator, AD) and the highest-energy particle accelerator (the Large Hadron Collider, LHC), CERN is in a unique position to investigate the microscopic structure of space–time. The corresponding breadth of measurements at these extreme ends of the energy regime guarantees complementary experimental approaches to Lorentz and CPT symmetry at a single laboratory. Furthermore, the commissioning of the new ELENA facility at CERN is opening brand new tests of Lorentz and CPT symmetry in the antimatter sector (see panel opposite).

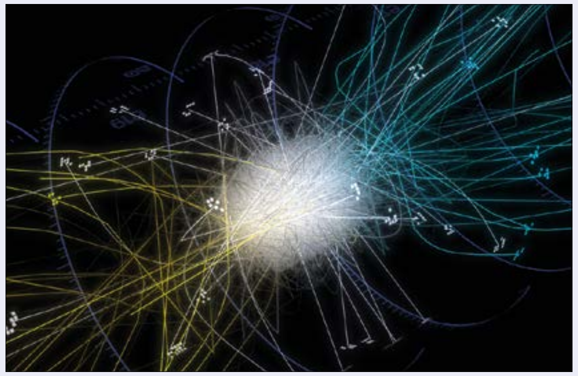
CERN is in a unique position to investigate the microscopic structure of space–time.

Regarding the LHC, the latest Lorentz- and CPT-violation physics comes from the LHCb collaboration, which studies particles made up of b quarks. The experiment's first measurements of SME coefficients in the B_d and B_s systems, published in June this year, have improved existing results by up to two orders of magnitude. LHCb also has competition from other major neutral-meson experiments. These involve studies of the B_s system at the Tevatron's DØ experiment, recent searches for Lorentz and CPT violation with entangled kaons at KLOE and the upcoming KLOE-2 at DAΦNE in Italy, as well as results on CPT-symmetry tests in B_d mixing and decays from the BaBar experiment at SLAC. The LHC's general-purpose ATLAS and CMS experiments, meanwhile, hold promise for heavy-quark studies. Data on single-top production at these experiments would allow the world's first CPT test for the top quark, while the measurement of top–antitop production can sharpen by a factor of 10 the earlier measurements of CPT-even Lorentz violation at DØ.

Other possibilities for accelerator tests of Lorentz and CPT invariance include deep inelastic scattering and polarised electron–electron scattering. The first ever analysis of the former offers a way to access previously unconstrained SME coefficients in QCD employing data from, for example, the HERA collider at DESY. Polarised electron–electron scattering, on the other hand, allows constraints to be placed on currently unmeasured Lorentz violations in the Z boson, which are also parameterised by the SME and have relevance for SLAC's E158 data and the proposed MOLLER experiment at JLab. Lorentz-symmetry breaking would also cause the muon spin precession in a storage ring to be thrown out of sync by just a tiny bit, which is an effect accessible to muon g-2 measurements at J-PARC and Fermilab.

Historically, electromagnetism is perhaps most closely associated with Lorentz tests, and this idea continues to exert a sustained influence on the field. Modern versions of the classical Michelson–Morley experiment have been realised with tabletop resonant cavities as well as with the multi-kilometre LIGO interferometer, with upcoming improvements promising unparalleled measurements of the SME's photon sector. Another approach for testing Lorentz and CPT symmetry is to study the energy- and direction-dependent dispersion of photons as predicted by the SME. Recent observations by the space-based Fermi Large Area Telescope severely constrain this effect, placing tight limits on 25 individual non-minimal SME coefficients for the photon.

Cold antiprotons offer powerful tests of CPT symmetry



Chukman So/UCB

Simulation of antihydrogen tracks in the ALPHA experiment.

CPT – the combination of charge conjugation (C), parity inversion (P) and time reversal (T) – represents a discrete symmetry between matter and antimatter. As the standard CPT test framework, the Standard Model Extension (SME) possesses a feature that might perhaps seem curious at first: CPT violation always comes with a breakdown of Lorentz invariance. However, an extraordinary insight gleaned from the celebrated CPT theorem of the 1950s is that Lorentz symmetry already contains CPT invariance under "mild smoothness" assumptions: since CPT is essentially a special Lorentz transformation with a complex-valued velocity, the symmetry holds whenever the equations of physics are smooth enough to allow continuation into the complex plane. Unsurprisingly, then, the loss of CPT invariance requires Lorentz breakdown, an argument made rigorous in 2002. Lorentz violation, on the other hand, does not imply CPT breaking.

That CPT breaking comes with Lorentz violation has the profound experimental implication that CPT tests do not necessarily have to involve both matter and antimatter: hypothetical CPT violation might also be detectable via the concomitant Lorentz breaking in matter alone. But this feature comes at a cost: the corresponding Lorentz tests typically cannot disentangle CPT-even and CPT-odd signals and, worse, they may even be blind to the effect altogether. Antimatter experiments decisively brush aside these concerns, and the availability at CERN of cold antiprotons has thus opened an unparalleled avenue for CPT tests. In fact, all six fundamental-physics experiments that use CERN's antiprotons have the potential to place independent limits on distinct regions of the SME's coefficient space. The upcoming Extra Low ENergy Antiproton (ELENA) ring at CERN (see p16) will provide substantially upgraded access to antiprotons for these experiments.

One exciting type of CPT test that will be conducted independently by the ALPHA, ATRAP and ASACUSA experiments is to produce antihydrogen, an atom made up of an antiproton and a positron, and compare its spectrum to that of ordinary hydrogen. While the production of cold antihydrogen has already been achieved by these experiments, present efforts are directed at precision spectroscopy promising clean and competitive constraints on various CPT-breaking SME coefficients for the proton and electron.

At present, the gravitational interaction of antimatter remains virtually untested. The AEgIS and GBAR experiments will tackle this issue by dropping antihydrogen atoms in the Earth's gravity field. These experiments differ in their detailed set-up, but both are projected to permit initial measurements of the gravitational acceleration, g, for antihydrogen at the per cent level. The results will provide limits on SME coefficients for the couplings between antimatter and gravity that are inaccessible with other experiments.

A third fascinating type of CPT test is based on the equality of the physical properties of a particle and its antiparticle, as guaranteed by CPT invariance. The ATRAP and BASE experiments have been advocating such a comparison between protons and antiprotons confined in a cryogenic Penning trap. Impressive results for the charge-to-mass ratios and g factors have already been obtained at CERN and are poised for substantial future improvements. These measurements permit clean bounds on SME coefficients of the proton with record sensitivities.

AMO techniques

Experiments in atomic, molecular and optical (AMO) physics are also providing powerful probes of Lorentz and CPT invariance and these are complementary to accelerator-based tests. AMO techniques excel at testing Lorentz-violating effects that do not grow with energy, but they are typically confined to normal-matter particles and cannot directly access the SME coefficients of the Higgs or the top quark. Recently, advances in this field have allowed researchers to carry out interferometry using systems other than light, and an intriguing idea is to use entangled wave functions to create a Michelson–Morley interferometer within a single Yb^+ ion. The strongly enhanced SME effects in this system, which arise due to the ion's particular energy-level structure, could improve existing limits by five orders of magnitude.

Other AMO systems, such as atomic clocks, have long been recognised as a backbone of Lorentz tests. The bright SME prospects arising from the latest trend toward optical clocks, which are several orders of magnitude more precise than traditional varieties based on microwave transitions, are being examined by researchers at NIST and elsewhere. Also, measurements on the more exotic muonium atom by J-PARC and by the PSI can place limits on the SME's muon coefficients, which is a topic of significant interest in light of several current puzzles involving the muon.

From neutrinos to gravity

Unknown neutrino properties, such as their mass, and tension between various neutrino measurements have stimulated a wealth of recent research including a number of SME analyses. The breakdown of Lorentz and CPT symmetry would cause the ordinary neutrino–neutrino and antineutrino–antineutrino oscillations to exhibit unusual direction, energy and flavour dependence, and would also induce unconventional neutrino–antineutrino mixing and kinematic effects – the latter leading to modified velocities and dispersion, as measured in time-of-flight experiments. Existing and planned neutrino experiments offer a wealth of opportunities to examine such effects. For example: upcoming results from the Daya Bay experiment should yield improved limits on Lorentz violation from antineutrino–antineutrino mixing; EXO has ▷

obtained the first direct experimental bound on a difficult-to-access "counter-shaded" coefficient extracted from the electron spectrum of double beta decay; T2K has announced new constraints on the a-and-c coefficients tightened by a factor of two using the muon-neutrino; and IceCube promises extreme sensitivities to "non-minimal" effects with kinematical studies of astrophysical neutrinos, such as Cherenkov effects of various kinds.

The feebleness of gravity makes the corresponding Lorentz and CPT tests in this SME sector particularly challenging. This has led researchers from HUST in China and from Indiana University to use an ingenious tabletop experiment to seek Lorentz breaking in the short-range behaviour of the gravitational force. The idea is to bring gravitationally interacting test masses to within submillimetre ranges of one another and observe their mechanical resonance behaviour, which is sensitive to deviations from Lorentz symmetry in the gravitational field. Other groups are carrying out related cutting-edge measurements of SME gravity coefficients with laser ranging of the Moon and other solar-system objects, while analysis of the gravitational-wave data recently obtained by LIGO has already yielded many first constraints on SME coefficients in the gravity sector, with the promise of more to come.

After a quarter century of experimental and theoretical work, the modern approach to Lorentz and CPT tests remains as active as ever. As the theoretical understanding of Lorentz and CPT violation continues to evolve at a rapid pace, it is remarkable that experimental studies continue to follow closely behind and now stretch across most subfields of physics. The range of physical systems involved is truly stunning, and the growing number of different efforts displays the liveliness and exciting prospects for a research field that could help to unlock the deepest mysteries of the universe.

Further reading

For more about CPT'16, see www.indiana.edu/~lorentz/cpt16/.

V A Kostelecký and N Russell 2011 *Rev. Mod. Phys.* **83** 11 (arXiv:0801.0287v9).

Résumé

L'heure de vérité pour la symétrie de l'espace-temps

La symétrie de Lorentz et la symétrie CPT sont devenues des piliers de notre compréhension de l'espace-temps. Ces symétries étroitement entrelacées font de l'espace un terrain neutre pour tous les systèmes physiques, indépendamment de leur orientation spatiale et de leur vitesse, ou du fait qu'ils soient composés de matière ou d'antimatière. Jusqu'ici, elles ont résisté à l'épreuve du temps mais, depuis un quart de siècle, les physiciens se demandent si ce sont vraiment des symétries exactes de la nature. Aujourd'hui, de très nombreuses expériences sont menées pour chercher des violations de la symétrie de Lorentz et de la symétrie CPT, violations qui nous forceraient à revoir à la fois le Modèle standard et la relativité générale. Plusieurs de ces expériences ont lieu auprès d'installations du CERN, et notamment auprès de la nouvelle venue, ELENA, qui réalisera les premiers tests sur l'interaction gravitationnelle de l'antimatière.

Ralf Lehnert, Indiana University Center for Spacetime Symmetries, Bloomington, US.

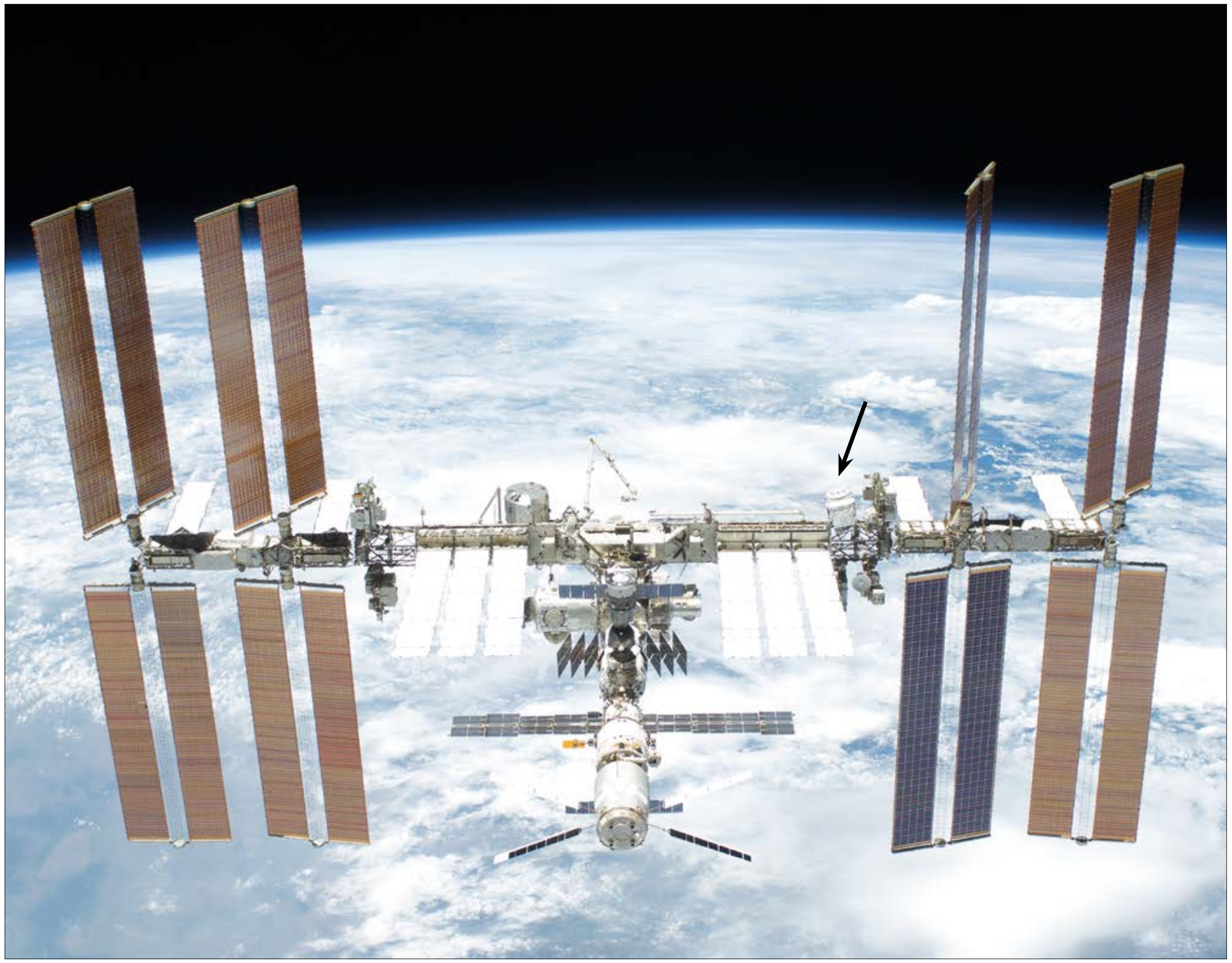
Cosmic rays continue to confound

The first five years of data from the AMS experiment on board the International Space Station reveal intriguing features in the cosmic-ray spectrum that could shed light on dark matter and other exotic phenomena, explains **Samuel Ting**.

The International Space Station (ISS) is the largest and most complex engineering project ever built in space. It has also provided a unique platform from which to conduct the physics mission of the Alpha Magnetic Spectrometer (AMS). Over the past five years on board the ISS, AMS has orbited the Earth every 93 minutes at an altitude of 400 km and recorded 85 billion cosmic-ray events with energies reaching the multi-TeV range. AMS has been collecting its unprecedented data set and beaming it down to CERN since 2011, and is expected to continue to do so for the lifetime of the ISS.

AMS is a unique experiment in particle physics. The idea for a space-based detector developed after the cancellation of the Superconducting Super Collider in the US in 1993. The following year, an international group of physicists who had worked together for many years at CERN's LEP collider had a discussion with Roald Sagdeev, former director of the Soviet Institute of Space Research, about the possibility of performing a precision particle-physics experiment in space. Sagdeev arranged for the team to meet with Daniel Goldin, the administrator of NASA, and in May 1994 the AMS collaboration presented the science case for AMS at NASA's headquarters. Goldin advised the group that use of the ISS as a platform required strong scientific endorsement from the US Department of Energy (DOE) and, after the completion of a detailed technical review of AMS science, the DOE and NASA formalised responsibilities for AMS deployment on the ISS on 20 September 1995.

A 10 day precursor flight of AMS (AMS-01) was carried out in June 1998, demonstrating for the first time the viability of using a precision, large-acceptance magnetic spectrometer in space for a multi-year mission. The construction of AMS-02 for the ISS started immediately afterwards in collaborating institutes around the world. With the loss of the shuttle *Columbia* in 2003 and the resulting redirection of space policy, AMS was removed from the space-shuttle programme in October 2005. However, the importance of performing fundamental science on the ISS was widely recognised and supported by the NASA Space Station management under the leadership of William Gerstenmaier. In 2008, the US Congress unanimously agreed that AMS be reinstated, mandating an additional flight for the shuttle *Endeavour* with AMS as its prime payload. Shortly after installation on the ISS in May 2011, AMS was powered on and began collecting and transmitting data (*CERN Courier* July/August 2011 p18).



NASA

AMS in position on the ISS (black arrow). The experiment is controlled from the Payload Operations Control Centre and Science Operations Centre, both located at CERN, and detector operations are also monitored in Taiwan at night to reduce the night-shift burden at CERN.

The first five years

Much has been learnt in the first five years of AMS about operating a particle-physics detector in space, especially the challenges presented by the ever changing thermal environment and the need to monitor the detector elements and electronics 24 hours per day, 365 days per year. Communications with NASA's ISS Mission Control Centers are also an essential requirement to ensure the operations of the ISS – such as sudden, unscheduled power cuts and attitude changes – do not disrupt the operations of AMS or imperil the detector.

Of course, it is the data recorded by AMS from events in the distant universe that are the most rich scientifically. AMS is able to detect both elementary particles – namely electrons, positrons, protons and antiprotons – in addition to nuclei of helium, lithium and heavier elements up to indium. The large acceptance and multiple redundant measurements allow AMS to analyse the data to an accuracy of approximately 1%. Combined with its atmosphere-free window on the cosmos, its long-duration exposure time and its extensive calibration at the CERN test beam, this allows AMS to greatly improve the accuracy of previous charged cosmic-ray observations. This is opening up new avenues through which to investigate the nature of dark matter, the existence of heavy antimatter and the true properties of primordial cosmic rays.

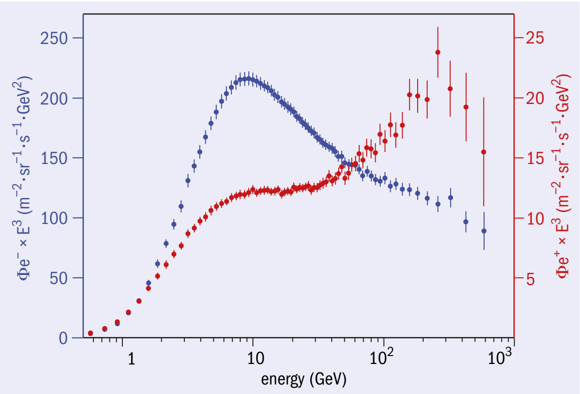
The importance of precision studies of positrons and antiprotons as a means to search for the origin of dark matter was first pointed out by theorists John Ellis and, independently, by Michael Turner and Frank Wilczek. They noted that annihilations of the leading dark-matter candidate, neutralinos, produce energies that transform neutralinos into ordinary particles such as positrons and antiprotons. Crucially, this characteristic excess of positrons and antiprotons in cosmic rays can be measured. The characteristic signature of dark-matter annihilations is a sharp drop-off of these positron and antiproton excesses at high energies, due to the finite mass of the colliding neutralinos. In addition, since dark matter is ubiquitous, the excesses of the fluxes should be isotropic.

Early low-energy measurements by balloons and satellites indicated that both the positron fraction (that is, the ratio of the positron flux to the flux of electrons and positrons) and the antiproton-to-proton fluxes are larger than predicted by models based on the collisions of cosmic rays. The superior precision of AMS over previous experiments is now allowing researchers to investigate such features, in particular the drop-off in the positron and antiproton excesses, in unprecedented detail.

The first major result from AMS came in 2013 and concerned the positron fraction (*CERN Courier* October 2013 p22). This highly accurate result showed that, up to a positron energy of 350 GeV, the positron fraction fits well to dark-matter models. This result generated widespread interest in the community and motivated many new interpretations of the positron-fraction excess, for instance whether it is due to astrophysical sources or propagation effects. In 2014, AMS published the positron and electron fluxes, which showed that their behaviours are quite different from each other and that neither can be fitted with the single-power-law assumption underpinning the traditional understanding of cosmic rays.

A deepening mystery

The latest AMS results are based on 17.6 million electrons and positrons and 350,000 antiprotons. In line with previous AMS measurements, the positron flux exhibits a distinct difference from the electron flux, both in its magnitude and energy ▷



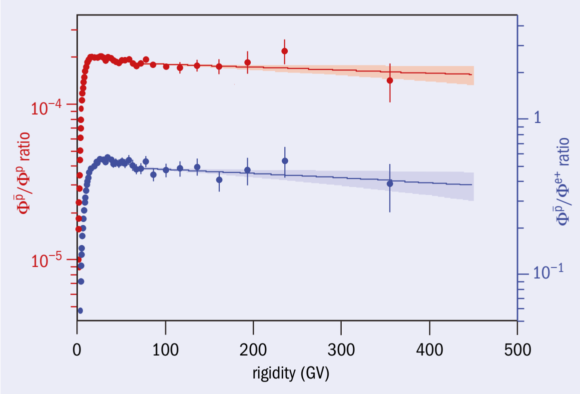


Fig. 1. (Left) The latest AMS data on the electron and positron fluxes, multiplied (for display purposes) by E^3, where E is the electron or positron energy. The electron results (blue, left axis) are based on 16.5 million events and the positron results (red, right axis) are based on 1.1 million events. Fig. 2. (Right) The measured antiproton-to-proton (red, left axis) and the antiproton-to-positron (blue, right axis) flux ratios as a function of the absolute value of the rigidity from 1 to 450 GV. The solid lines show the best straight-line fits above the lowest rigidity consistent with rigidity independence (60 GV), together with the 68% C.L. ranges of the slopes and mean values (shaded regions).

dependence (figure 1, overleaf). The positrons show a unique feature: they have a tendency to drop-off sharply at energies above 300 GeV, as expected from dark-matter collisions or new astrophysical phenomena. The positron fraction decreases with energy and reaches a minimum at 8 GeV. It then increases with energy and rapidly exceeds the predictions from cosmic-ray collisions, reaching a maximum at 265 GeV and then beginning to fall off. Whereas neither the electron flux nor the positron flux can be described by a single power law, surprisingly the sum of the electron and positron fluxes can be described very accurately by a single power law above an energy of 30 GeV.

Since astrophysical sources of cosmic-ray positrons and electrons may induce some degree of anisotropy in their arrival directions, it is also important to measure the anisotropy of cosmic-ray events recorded by AMS. Using the latest data set, a systematic search for anisotropies has been carried out on the electron and positron samples in the energy range 16–350 GeV. The dipole-anisotropy amplitudes measured on 82,000 positrons and 1.1 million electrons are 0.014 for positrons and 0.003 for electrons, which are consistent with the expectations from isotropy.

The latest AMS results on the fluxes and flux ratio of electrons and positrons exhibit unique and previously unobserved features. These include the energy dependence of the positron fraction, the existence of a maximum at 265 GeV in the positron fraction, the exact behaviour of the electron and positron fluxes and, in particular, the sharp drop-off of the positron flux. These features require accurate theoretical interpretation as to their origin, be it from dark-matter collisions or new astrophysical sources.

No one has a clue what could be causing these spectacular effects.

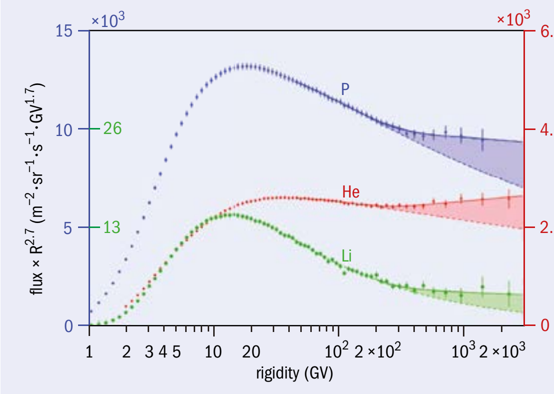
Concerning the measured antiproton-to-proton flux ratio (figure 2), the new data show that this ratio is independent of rigidity (defined as the momentum per unit charge) in the rigidity range 60–450 GV. This is contrary to traditional cosmic-ray models, which assume that antiprotons are produced only in the collisions of cosmic rays and therefore that the ratio decreases with rigidity. In addition, due to the large mass of antiprotons, the observed excess of the antiproton-to-proton flux ratio cannot come from pulsars. Indeed, the excess is consistent with some of the latest model predictions based on dark-matter collisions as well as those based on new astrophysical sources. Unexpectedly, the antiproton-to-positron flux ratio is also independent of rigidity in the range 60–450 GV (*CERN Courier* October 2016 p8). This is considered as a major result from the five-year summary of AMS data.

The upshot of these new findings in elementary-particle cosmic rays is that the rigidity dependences of the fluxes of positrons, protons and antiprotons are nearly identical, whereas the electron flux has a distinctly different rigidity dependence. This is unexpected because electrons and positrons lose much more energy in the galactic magnetic fields than do protons and antiprotons.

Nuclei in cosmic rays

Most of the cosmic rays flying through the cosmos comprise protons and nuclei, and AMS collects nuclei simultaneously with elementary particles to enable an accurate understanding of both astrophysical phenomena and cosmic-ray propagation. The latest AMS results shed light on the properties of protons, helium, lithium and heavier nuclei in the periodic table. Protons, helium, carbon and oxygen are traditionally assumed to be primary cosmic rays, which means they are produced directly from a source such as supernova remnants.

Protons and helium are the two most abundant charged cosmic rays. They have been measured repeatedly by many experiments over many decades, and their energy dependence has traditionally been assumed to follow a single power law. In the case of lithium, which is assumed to be produced from the collision of primary cosmic rays with the interstellar medium and therefore yields a single power law but with a different spectral index, experimental data have been very limited.



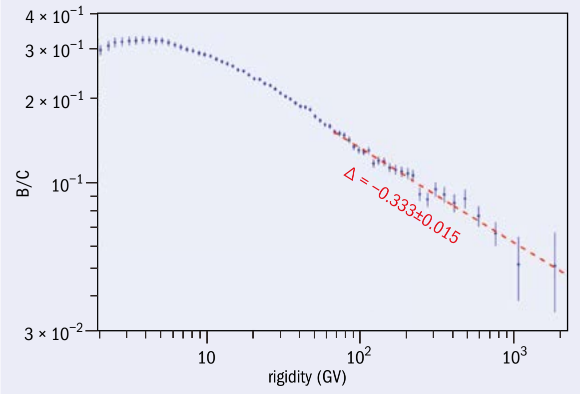


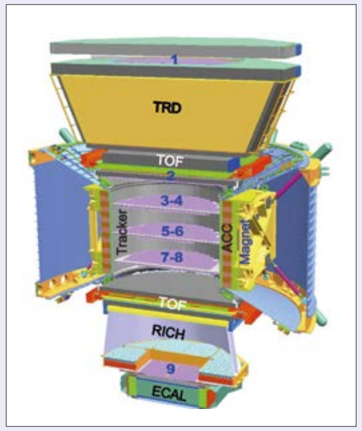
Fig. 3. (Left) The latest AMS measurements of the proton flux, based on 300 million events (blue, left axis); helium flux, based on 50 million events (red, right axis); and lithium flux, based on two million events (green, left axis). All fluxes are multiplied by $R^{2.7}$ for display purposes, where R is the rigidity. The dashed lines show that a single power law fits the data from 45 to around 200 GV. The shaded regions are the excesses above the traditional single-power-law fits. Unexpectedly, the three spectra are well fitted with double power laws (solid lines) above 45 GV. Fig. 4. (Right) The latest AMS results on the boron-to-carbon flux ratio (B/C). Fitting the data with $B/C \propto R^{\Delta}$ above 65 GV yields $\Delta = -0.333\pm0.015$.

The latest AMS data reveal, with approximately 1% accuracy, that the proton, helium and lithium fluxes as a function of rigidity all deviate from the traditional single-power-law dependence at a rigidity of about 300 GV (figure 3). It is completely unexpected that all three deviate from a single power law, that all three deviations occur at about the same rigidity and increase at higher rigidities, and that the three spectra can be fitted with double power laws above a rigidity of 45 GV. In addition, it has long been assumed that since both protons and helium are primary cosmic rays with the same energy dependence at high energies, their flux ratio would be independent of rigidity. The AMS data show that above rigidities of 45 GV, the flux ratio decreases with rigidity and follows a single-power-law behaviour. Despite being a secondary cosmic ray, lithium also exhibits the same rigidity behaviour as protons and helium. It is fair to say that, so far, no one has a clue what could be causing these spectacular effects.

The latest AMS measurement of the boron-to-carbon flux ratio (B/C) also contains surprises (figure 4). Boron is assumed to be produced through the interactions of primary cosmic rays such as carbon and oxygen with the interstellar medium, which means that B/C provides information both on cosmic-ray propagation and on the properties of the interstellar medium. The B/C ratio does not show any significant structures, in contrast to many cosmic-ray propagation models that assume such behaviour at high rigidities (including a class of propagation models that explain the observed AMS positron fraction). Cosmic-ray propagation is commonly modelled as relativistic gas diffusion through a magnetised plasma, and models of the magnetised plasma predict different behaviours of B/C as a function of rigidity. At rigidities above 65 GV, the latest AMS data can be well fitted by a single power law with spectral index Δ in agreement with the Kolmogorov model of turbulence, which predicts $\Delta = -1/3$ asymptotically.

▷

Building a spectrometer in space



AMS is a precision, multipurpose TeV spectrometer measuring 5 × 4 × 3 m and weighing 7.5 tonnes. It consists of a transition radiation detector (TRD) to identify electrons and positrons; a permanent magnet together with nine layers of silicon tracker (labelled 1 to 9) to measure momentum up to the multi-TeV range and to identify different species of particles and nuclei via their energy loss; two banks of time-of-flight (TOF) counters to measure the direction and velocity of cosmic rays and identify species by energy loss; veto counters (ACC) surrounding the inner bore of the magnet to reject cosmic rays from the side; a ring-image Cherenkov counter (RICH) to measure the cosmic-ray energy and identify particle species; and an electromagnetic calorimeter (ECAL) to provide 3D measurements of the energy and direction of electrons and positrons, and distinguish them from antiprotons, protons and other nuclei.

Future directions

Much has been learnt from the unexpected physics results from the first five years of AMS. Measuring many different species of charged cosmic rays at the same time with high accuracy provides unique input for the development of a comprehensive theory of cosmic rays, which have puzzled researchers for a century. AMS data are also providing new information that is essential to our understanding of the origin of dark matter, the existence of heavy antimatter, and the properties of charged cosmic rays in the cosmos.

The physics potential of AMS is the reason why the experiment receives continuous support. AMS is a US DOE and NASA-sponsored international collaboration and was built with European participation from Finland, France, Germany, Italy, Portugal, Spain and Switzerland, together with China, Korea, Mexico, Russia, Taiwan and the US. CERN has provided critical support to AMS, with CERN engineers engaged in all phases of the construction. Of particular importance was the extensive calibration of the AMS detector with different particle test beams at various energies, which provided key reference points for verifying the detector's operation in space.

AMS will continue to collect data at higher energies and with high precision during the lifetime of the ISS, at least until 2024. To date, AMS is the only long-duration precision magnetic spectrometer in space and, given the challenges involved in such a mission, it is likely that it will remain so for the foreseeable future.

● Further reading

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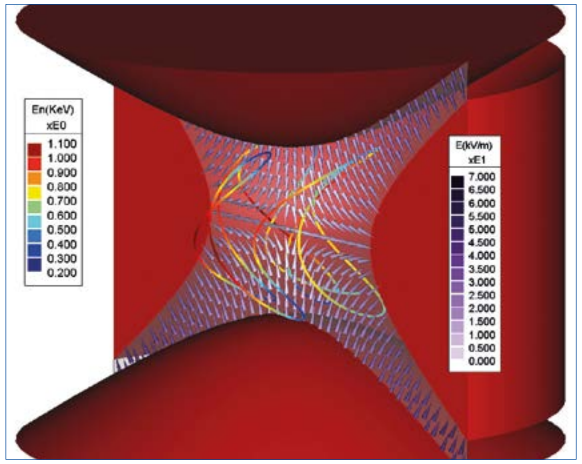
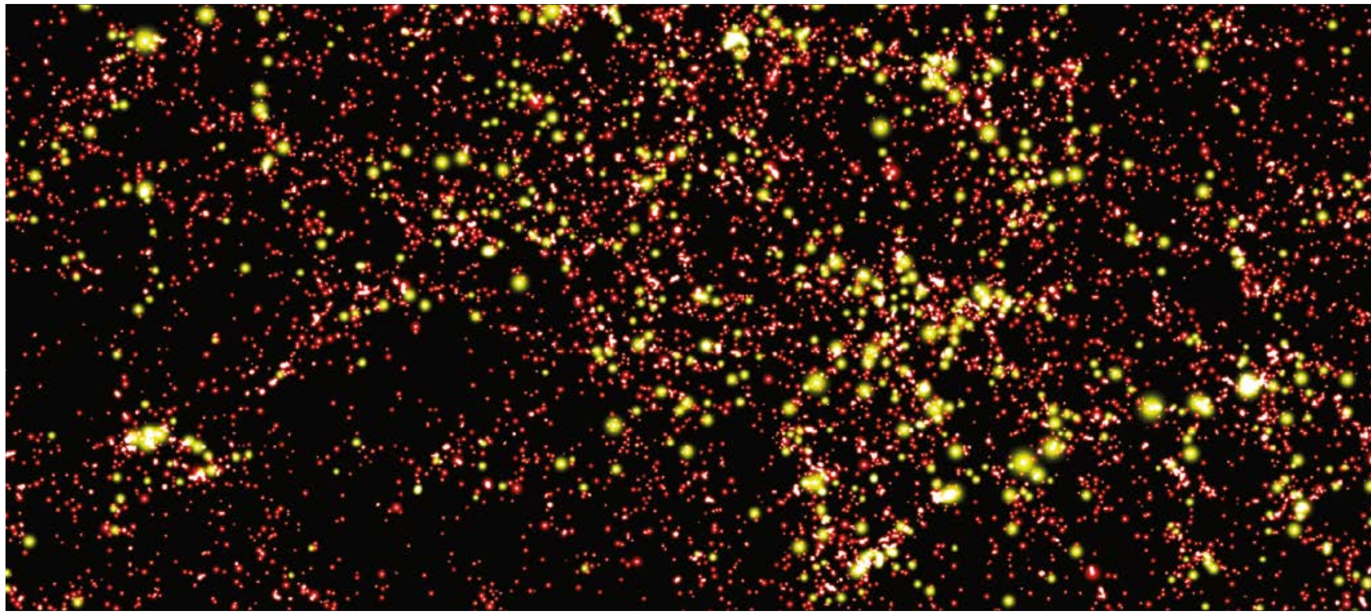
Résumé

Les rayons cosmiques continuent de nous surprendre

Le Spectromètre magnétique alpha (AMS), détecteur arrimé à la Station spatiale internationale, a enregistré pendant ses cinq premières années d'exploitation 85 milliards d'événements avec des rayons cosmiques, à des énergies allant jusqu'à plusieurs TeV, et a transmis ses données au CERN pour leur analyse. AMS détecte à la fois les noyaux et les particules élémentaires, dans le but de comprendre avec précision tant les phénomènes d'astrophysique que la propagation des rayons cosmiques. Les dernières données révèlent des éléments intrigants, qui pourraient faire la lumière sur la matière noire et sur d'autres phénomènes exotiques.

Samuel Ting, CERN and MIT.





A simulation of the distribution of dark matter in the early universe. Clumps of dark matter are shown in red, with yellow indicating clumps weighing more than 300 million solar masses. (Image credit: Virgo consortium/A Amblard/ESA.)

What is AMS telling us?

The latest data from the AMS experiment continue to hold surprises. **John Ellis** explains the implications for particle-physics models of dark matter and other novel phenomena.

In the first half of the 20th century, many of the most important discoveries of new particles were made by cosmic-ray experiments. Examples include antimatter, the muon, pion, kaon and other hadrons, which opened up the field of high-energy physics and set in motion our modern understanding of elementary particles. This came about because cosmic-ray interactions with nuclei in the upper atmosphere are among the highest-energy events known, surpassing anything that could be produced in laboratories at the time – and even in collisions at the LHC today.

However, around the middle of the century the balance of power in particle physics shifted to accelerator experiments. By generating high-energy interactions in the laboratory under controlled conditions, accelerators offered new possibilities for precise measurements and thus for the study of rare particles and phenomena. These experiments helped to flush out the quark model and also the fundamental force-carrying bosons, leading to the establishment of the Standard Model (SM) – whose success was crowned by the discovery of the Higgs boson at the LHC in 2012.

Today, thanks to its unique position on the International Space Station, the AMS experiment combines the best of both worlds as a highly sensitive particle detector that is free from the complicated environment of the atmosphere (see page 26). Collecting data since 2011, AMS has initiated a new epoch of precision cosmic-ray experiments that help to address basic puzzles in particle physics such as the nature of dark matter. The experiment's latest round of data continues to throw up surprises. Arriving at the correct interpretation of events due to particles produced far away in the universe, however, still presents challenges for physicists trying to understand dark matter and the cosmological asymmetry between matter and antimatter.

Best of both worlds

The emphasis in particle physics now is on the search for physics beyond the SM, for which many motivations come from astrophysics and cosmology. Examples include dark matter, which contributes many times more to the overall density of matter in the universe than does the conventional matter described by the SM, ▷

and the origin of matter itself. Many physicists think that dark matter may be composed of particles that could be detected at the LHC, or might reveal themselves in astrophysical experiments such as AMS. As for the origin of matter, the big question has been whether it is due to an intrinsic difference between the properties of matter and antimatter particles, or whether the dominance of matter over antimatter in the universe around us is merely a local phenomenon. Although it is unlikely that there exist other regions of the observable universe where antimatter dominates, there is limited direct experimental evidence against it.

The AMS approach to cosmic-ray physics is based on decades of experience in high-statistics, high-precision accelerator experiments. It has a strong focus on measurements of antiparticle spectra that allows it to search indirectly for possible dark-matter particles, which would produce antiparticles if they annihilated with each other, as well as for possible harbingers of astrophysical concentrations of antimatter. In parallel, AMS is able to make measurements of the energy spectra of many different nuclear species, posing challenges for models of the origin of cosmic rays – a mystery that has stood ever since their discovery in 1912.

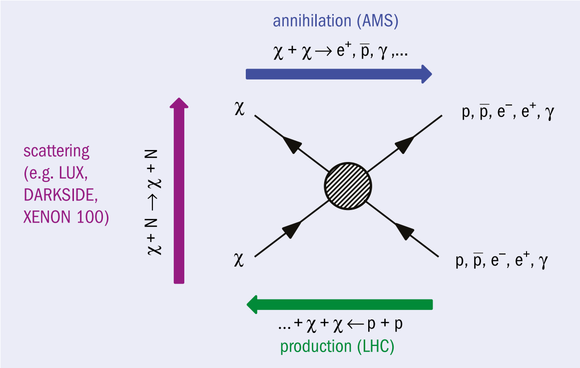
Unconventional physics?

The latest AMS results on the cosmic-ray electron and positron fluxes provide very accurate measurements of the very different spectra of these particles. Numerous previous experiments had discovered an increase in the positron-to-electron ratio at increasing energies, although with considerable scatter. AMS has now confirmed this trend with greater precision, but it also indicates that the positron-to-electron ratio may decrease again at energies above about 300 GeV. The differences between the electron and positron fluxes mean that different mechanisms must be dominating their production. The natural question is whether some exotic mechanism is contributing to positron production.

One possibility is the annihilation of dark-matter particles, but a more conventional possibility is production by electromagnetic processes around one or more nearby pulsars. In both cases, one might expect the positron spectrum to turn down at higher energies, being constrained by either the mass of the dark-matter particle or by the strength of the acceleration mechanism around the pulsar(s). In the latter case, one would also expect the positron flux to be non-isotropic, but no significant effect has been seen so far. It will be interesting to see whether the high-energy decrease in the positron-to-electron ratio is confirmed by future AMS data, and whether this can be used to discriminate between exotic and conventional models for positron production.

One possibility is the annihilation of dark-matter particles.

A more sensitive probe of unconventional physics could be provided by the AMS measurement of the spectrum of antiprotons. These cannot be produced in the electromagnetic processes around pulsars, but would be produced as "secondaries" in the collisions between primary-matter cosmic rays and ordinary-matter particles. It is striking, for instance, that the antiproton-to-proton ratio measured by AMS is almost constant at energies of about 10 GeV. The ratio is significantly higher than some earlier calculations of secondary antiproton production, although recent calculations (which account more completely for the theoretical uncertainties) indicate that the antiproton-to-proton ratio may be somewhat higher – possibly even consistent with the AMS measurements. As with the case for positron production, extending the measurements to higher energies will be crucial for distinguishing between exotic and conventional mechanisms for antiproton production.



By detecting particles produced by dark-matter annihilation, AMS offers one of three independent methods with which to search for dark matter.

AMS has also released interesting data concerning the fluxes of protons, helium and lithium nuclei. Intriguingly, all three spectra show strong indications of breaks in the spectra at rigidities of around 200 GV. The higher-energy portions of the spectra lie significantly above simple power-law extrapolations of the lower-energy data. It seems that some additional acceleration mechanism might be playing a role at higher energies, providing food-for-thought for astrophysical models of cosmic-ray acceleration. In particular, the unexpected shape of the spectrum of primary protons in the cosmic rays may also need to be taken into account when calculating the secondary antiproton spectrum.

The AMS data on the boron-to-carbon ratio also provide interesting information for models of the propagation of cosmic rays. In the most general picture, cosmic rays can be considered as a relativistic gas diffusing through a magnetised plasma. This leads to a boron-to-carbon ratio that decreases as a power, Δ, of the rigidity, with different models yielding values of Δ between $-1/2$ and $-1/3$. The latest AMS data constrain this power law with very high precision: $\Delta = -0.333 \pm 0.015$, in excellent agreement with the simplest Kolmogorov model of diffusion.

The AMS collaboration has already collected data on the production of many heavier nuclei, and it would be interesting if the team could extract information about unstable nuclear isotopes that might have been produced by a recent nearby supernova explosion. Such events might already have had an effect on Earth: analyses of deep-ocean sediments have recently confirmed previous reports of a layer of iron-60 that was presumably deposited by a supernova explosion within about 100 parsecs about 2.5 million years ago, and there is evidence of iron-60 also in lunar rock samples and cosmic rays. Other unstable isotopes of potential interest include beryllium-10, aluminium-26, chlorine-39, manganese-53 and nickel-59.

Promising prospects

What else may we expect from AMS in the future? The prospective gains from measuring the spectra of positrons and antiprotons to higher energies have already been mentioned. Since these antiparticles can also be produced by other processes, such as pulsars and primary-matter cosmic rays, they may not provide smoking guns for antimatter production via dark-matter annihilation, or for concentrations of antimatter in the universe. However, searches for antinuclei in cosmic rays present interesting prospects in either or both of these directions. The production of antideuterons in dark-matter annihilations may be visible above the background of secondary production by primary-matter cosmic rays, for example. On the other hand, the production of heavier antinuclei in both dark-matter annihilations and cosmic-ray collisions is expected to be very small. The search for such antinuclei has always been one of the main scientific objectives of AMS, and the community looks forward to hearing whatever data they may acquire on their possible (non-)appearance.

As this brief survey has indicated, AMS has already provided much information of great interest for particle physicists studying scenarios for dark matter, for astrophysicists and for the cosmic-ray community. Moreover, there are good prospects for further qualitative advances in future years of data-taking. The success of AMS is another example of the fruitful marriage of particle physics and astrophysics, in this case via the deployment in space of a state-of-the-art particle spectrometer. We look forward to seeing the future progeny of this happy marriage.

● Further reading

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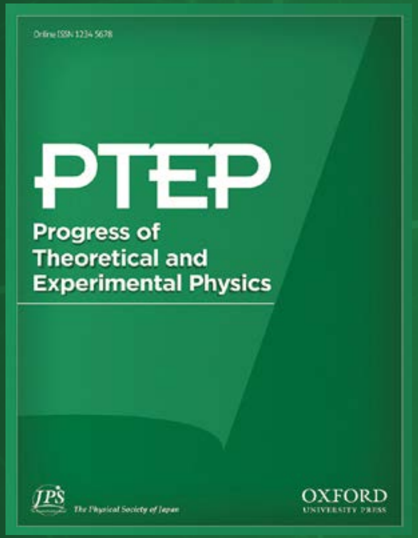
Résumé

Que nous raconte AMS ?

Les dernières données de l'expérience AMS continuent d'apporter leur lot de surprises. Par exemple, les résultats les plus récents d'AMS sur les flux d'électrons et de positons dans les rayons cosmiques confirment des résultats précédents faisant état d'une étonnante augmentation du rapport positons/électrons en fonction de l'énergie. AMS a également observé que les spectres des protons, des noyaux d'hélium et des noyaux de lithium montrent tous des indices importants de déviations à une certaine énergie. Les données sur le rapport bore/carbone fournissent quant à elles des informations intéressantes pour les modèles de la propagation des rayons cosmiques. La compréhension de l'origine de ces caractéristiques pourrait révéler les modèles de la matière noire en physique des particules, ainsi que des phénomènes nouveaux dans l'Univers.

John Ellis, Kings College London.



Faces & Places

AWARDS

APS announces 2017 prize recipients

Top: Michel Della Negra, Peter Jenni and Tejinder Virdee (Panofsky Prize); James Bjorken, Sekazi Mtingwa and Anton Piwinski (Wilson Prize). Bottom: Sally Dawson, Howard Haber, John Gunion and Gordon Kane (J J Sakurai Prize).

The American Physical Society (APS) has awarded its prizes for 2017, several of which are devoted to the fields of high-energy and nuclear physics. The W K H Panofsky Prize in Experimental Particle Physics went to Michel Della Negra and Peter Jenni, CERN, and Tejinder Virdee, Imperial College London, for their "distinguished leadership in the conception, design and construction of the ATLAS and CMS detectors, which were instrumental in the discovery of the Higgs boson". The award recognises and encourages outstanding achievements in experimental particle physics.

The J J Sakurai Prize for Theoretical Particle Physics went to Sally Dawson of Brookhaven National Laboratory, John Gunion of the University of California at Davis, Howard Haber of the University of California at Santa Cruz, and Gordon Kane of the University of Michigan, for their instrumental contributions to the theory of the properties, reactions and signatures of the Higgs boson.

Recognising achievements in the physics of particle accelerators, this year's Robert R Wilson Prize was awarded to James Bjorken, SLAC, Sekazi Mtingwa, Massachusetts Institute of Technology, and Anton Piwinski, DESY, "for the detailed, theoretical description of intrabeam scattering, which has empowered major discoveries in a broad range of disciplines by a wide variety of accelerators, including hadron colliders, damping rings/linear colliders, and low emittance synchrotron light sources".

In the nuclear-physics domain, the APS Herman Feshbach Prize in Theoretical Nuclear Physics went to Joseph Carlson of Los Alamos National Laboratory, "for pioneering the development of quantum Monte Carlo techniques to solve key problems in nuclear-structure physics, cold-atom physics, and dense-matter theory of relevance to neutron stars". The Tom W Bonner Prize in Nuclear Physics, meanwhile, was awarded to Charles Perdrisat of the College of William and Mary, "for groundbreaking measurements of nucleon structure, and discovering the unexpected behaviour of the magnetic and electric nucleon form factors with changing momentum transfer".

Completing the prize tally in the high-energy physics arena, the Dannie Heineman Prize for Mathematical Physics went to Carl Bender of Washington University, for developing the theory of PT symmetry in quantum systems and sustained seminal contributions that have generated profound and creative new mathematics and impacted broad areas of experimental physics.

ANNIVERSARY

Marking 15 years of humanitarian mapping

M Brice/CERN

Members of UNOSAT work on satellite images of Haiti in October to assess the damage of Hurricane Matthew.

On 11 October, a United Nations programme called UNOSAT, which delivers satellite images to regions affected by natural disaster or conflict, celebrated 15 years of success in helping relief and development organisations. UNOSAT has been hosted by CERN's IT department since its inception in 2001, and relies on the laboratory's IT infrastructure – in particular, the Worldwide LHC Computing Grid – to produce maps with a resolution as high as 30 cm. Raw satellite images made available by space agencies and public and private satellite data providers are stored on CERN's servers and then transformed into legible, downloadable maps. The tool has become essential for arranging aid and sustainable reconstruction such as that required in West Africa since 2014 in the fight against the Ebola epidemic, or currently in the context of the Syrian conflict. "CERN's support is essential," says UNOSAT manager Einar Bjorgo. "Without its powerful IT infrastructure, we wouldn't be able to compile the satellite data we receive to make it usable."

EXHIBITION

CERN science on display in Vienna

On 19 October, a new exhibition about particle physics and cosmology, produced in collaboration with the Institute of High Energy Physics of the Austrian Academy of Sciences, opened at the Natural History Museum of Vienna. Called "The beginning of everything", it promises to take visitors on a journey more than 13 billion years into the past, and to communicate the most recent scientific knowledge of particle physics and cosmology from different visual, optical and acoustic angles and perspectives. Part of the exhibition is devoted to CERN, and the exhibition will run until 1 May 2017.

(Top left) CMS featured at the exhibition.

ANNIVERSARY

YITP celebrates 50 years

The C N Yang Institute for Theoretical Physics (YITP) at Stony Brook University in the US celebrated its 50th anniversary with a symposium on 9–10 October. The YITP was founded in 1966, when Chen Ning Yang came to the then almost-unknown Stony Brook University, at the invitation of the university's president John Toll. Together with Tsung-Dao Lee, Yang shared the 1957 Nobel Prize in Physics for his work on parity non-conservation in weak interactions.

The YITP is associated with several advances in the areas of supergravity, gauge-theory renormalisation, neutrinos and QCD collider theory, in addition to statistical mechanics. A video message from Yang saw the 94 year-old theorist refer to his years at Stony Brook as a "second career" after his time at the Institute for Advanced Study. He recalled the earliest days of supergravity and informal lectures from mathematician James Simons, which eventually "contributed to the increasingly close contact between the world communities of physicists and mathematicians".

CONFERENCES

LHC sheds light on extreme cosmic rays

The 19th International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI) took place on 22–27 August in Moscow, Russia, attracting more than 100 physicists. At the core of discussions was the status of our understanding of hadronic particle production as observed in interactions involving cosmic rays, and as measured in accelerator experiments.

The impact of LHC measurements on the interpretation of cosmic-ray data was a central theme. Important general observations of direct relevance to cosmic-ray physics include: the moderate growth of the inelastic cross-section and secondary particle multiplicity; the absence of rapid changes of the particle distributions close to the beamline; and the overall agreement between charm-particle production and perturbative QCD calculations. Thanks to LHC data, the ambiguity in the interpretation of air-shower data of ultra-high-energy cosmic rays has been significantly reduced and a mixed composition of primary elements is now favoured at energies above 10^{19} eV (previously the data were considered compatible with a flux of only protons). Moreover, good agreement is found between the composition data of the two biggest air-shower detectors, the Pierre Auger Observatory and Telescope Array.

Participants of ISVHECRI '16 discussed the implications of LHC data.

Comparing ALICE data relating to atmospheric muons with state-of-the-art simulations, an excess in high-multiplicity muon bundles previously reported by several LEP experiments has not been confirmed. Still, the muonic component of air showers is a source of many puzzles. For example, the Auger collaboration reported that the measured muon number in air showers with energies of 10^{19} eV exceeds the model expectations. In addition, the high-statistics data on muon and electron numbers recorded by the KASCADE air-shower array can still not be consistently interpreted with contemporary interaction models – even after accounting for LHC data, which are taken at an energy higher than that of the famous "knee" in the cosmic-ray spectrum (which corresponds to an energy of around 3×10^{15} eV). On the other hand, at lower energies, the muon data from IceTop (the air-shower array located above IceCube) are still bracketed by expectations for proton and iron particles as primaries. Data relating to pion–nucleus interactions taken with fixed-target experiments, such as NA61 at CERN, are expected to help to resolve these muon puzzles.

The high-energy neutrinos measured by IceCube continue to be a focus of this community. Neutrinos produced in interactions of cosmic rays in the atmosphere constitute the dominant background to those from astrophysical sources. Fortunately, the LHC probes the energy region that is most important for understanding this background, which stems mainly from the production and decay of charm particles. Although the good overall agreement of the charm measurements with predictions is very encouraging, it was reported that the LHC measurements cover only about 12% of the phase space needed for calculating PeV-energy neutrino fluxes.

ISVHECRI participants were also reminded of the early pioneering work on particle physics using cosmic-ray interactions recorded with emulsion chambers, which still harbour phenomena that are yet to be understood. The symposium concluded with a discussion of the most important future accelerator measurements needed for improving our understanding of cosmic-ray data. Studying proton interactions with light nuclei at the LHC is top of the wish list, followed by pion–nucleus interactions in fixed-target experiments at the highest energies possible. The next symposium of the biennial ISVHECRI series will take place in Nagoya, Japan, in spring 2018.

KNOWLEDGE TRANSFER

CERN sets bar for cryogenic safety

CERN is a world leader in cryogenic safety.

Around 120 experts in cryogenic safety met at CERN on 21–23 September for the first cryogenic-safety seminar. In addition to discussions about best practice and regulatory frameworks, a highlight of the event was a new CERN technology called Kryolize developed for the cryomagnets of the LHC and other CERN facilities.

Kryolize is a software tool tailored for sizing cryogenic pressure-relief devices that protect against overpressure, such as that encountered by the LHC shortly after it switched on in 2008. It is based on international and European standards and was originally conceived to respond to the specific needs of CERN to develop valves for use with liquid helium at extremely low temperatures. The LHC uses an unprecedented 120 tonnes of liquid helium to cool 36,000 tonnes of superconducting magnets to just 1.9 K.

Kryolize is supported by CERN's Knowledge Transfer group and currently has 30 users at CERN. Six licences have so far been granted to other research laboratories and it is anticipated that, once the project reaches its conclusion in mid-2017, the tool will have applications in domains ranging from the food industry to medicine.

AWARD

Lifetime achievement

Smits was one of the architects of Horizon 2020.

Robert-Jan Smits, director general for research and innovation at the European Commission, is the first recipient of a new award: Recognition of Lifetime Achievements for European Science and Society. Created by EuroScience, an association of researchers in Europe and founder of the EuroScience Open Forum (ESOF), the award cites Smit's ability to help create new and more effective EU policies and structures, co-ordinate EU tools with national policies and align all of these towards the broader needs of society.

Deep discussions at DIS 2016

The 24th workshop on Deep Inelastic Scattering and related subjects (DIS2016) took place on 11–15 April at DESY in Hamburg, Germany. The event acted as a melting pot for worldwide investigations of the proton structure and strong interactions at the LHC, HERA, Tevatron, RHIC, JLAB, COMPASS and other experiments. It also covered related theory advances, future experiments and results from the high-energy frontier. The workshop was organised into seven separate working groups, and selected highlights from each are given here.

Concerning structure functions and parton densities, the final combined HERA (H1 and ZEUS) inclusive DIS data have had a significant impact on parton-distribution functions (PDFs) and resulting predictions of LHC processes. ATLAS, CMS and LHCb presented the first production measurements of W and Z bosons and of jets made at LHC Run 2, which will help to further constrain the PDFs.

In the electroweak and beyond-the-Standard-Model sector, many final Run 1 results were reported by ATLAS and CMS on the Higgs boson as well as on precision measurements of multiboson production. No deviations from the Standard Model were observed, and it is clear that the community is in need of calculations including next-to-leading order (NLO) electroweak corrections if it is to compete with the LHC's experimental precision.

A wealth of new LHC results concerning QCD and hadronic final states were presented, which often probe the final-state kinematics in great detail. Theorists are attempting to match the improved experimental precision, for example with generators based on full next-to-next-to-leading order (NNLO) calculations. The description of the underlying event and double-parton scattering was another important topic, with many new experimental and theoretical results being debated.

This year's DIS workshop was attended by 327 participants representing 33 countries, presenting 270 talks on a variety of subjects.

In the heavy-flavour community, new CMS top-pair production data from Run 2 have been compared to the first complete NNLO QCD predictions for differential distributions, which have only recently become available. These calculations improve the description of the observed top-quark transverse-momentum spectrum and open a new precision era in top physics. Many new beauty and charm results were presented such as the first Run 2 measurements of open-charm production by LHCb.

Regarding low-x, diffraction and vector mesons, theorists propose to carry out extended studies at the LHC with events containing "Mueller–Navelet" jets (two forward jets with a large rapidity gap between them). Several advances were presented on the phenomenology of diffractive vector-meson production at HERA, where the first measurement of the reaction $\gamma + p \rightarrow \rho^0 \pi^+ n$ was reported by H1. Ultra-peripheral collisions in nuclear collisions at the LHC and RHIC are another hot topic in the low-x community at this time.

Concerning the long-standing spin puzzle – i.e. the question of how the nucleon's spin is distributed among its constituent partons – new spin-asymmetry results were presented by COMPASS as well as by the PHENIX and STAR experiments at RHIC, adding significant constraints on the quark and gluon spin contributions. COMPASS, HERMES and JLAB also presented new studies of semi-inclusive DIS.

Finally, with regard to future experiments, there is much to look forward to. JLAB will continue its 3D-hadron-imaging studies with a second generation of experiments using its 12 GeV electron beam, while COMPASS and STAR will take further data until 2017. Despite the achievements by these facilities, the lack of experimental information for $x \leq 0.01$ remains a severe limitation. As such, there is great hope that the Electron Ion Collider (EIC) project in the US will lead to comprehensive 3D hadron imaging and solve the spin puzzle. On the energy frontier there is also the intriguing opportunity of an electron–ion collider in the envisaged 54 km ring accelerator complex in China. Such machines could provide a unique precision tool for a complete flavour decomposition of the proton structure and would cover a broad spectrum of strong and electroweak physics.

The next DIS workshop will take place in Birmingham, UK, from 3 to 7 April 2017.

LETTERS

Following Blackett's advice

Your review of Antonino Zichichi's tribute to Patrick Blackett (*CERN Courier* September 2016 p59) touched upon Blackett's conviction that physicists should communicate to society the contribution of science to the progress of our civilisation. Never before has this been more pertinent.

You do not have to look very far to find the enemies of fundamental research. First there are those journalists looking for a dramatic storyline and the growing band of unqualified commentators on the internet. Then there are the politicians following an "impact" agenda that favours perceived short-term economic benefits of research over academic excellence. There is also a tendency for research councils, university presidents and learned societies to toe the government line, encouraging some fellow scientists to claim that attention and money should be diverted away from high-energy physics.

The discovery of the Higgs boson in 2012 and gravitational waves in 2016 were triumphs of experimental physics that confirmed theoretical ideas first put forward in 1964 and 1916, respectively. Yet fundamental physics sometimes receives negative publicity because attempts to achieve the much more difficult goals of going beyond the Standard Model and unifying gravity with the other forces have not met some stricter artificial deadlines. Of course we must continually remind the politicians and the media of the economic benefits of fundamental physics: PET scans from the Dirac equation, GPS from general relativity, the Web from CERN, etc. But let us not fall into the trap of boasting only about these populist benefits, lest we be judged on them alone; let us also recall with Zichichi Blackett's exhortation to communicate the progress of civilisation brought about by discovering the laws of nature.

- *Michael Duff, Blackett Lab, Imperial College London.*

Blackett, the UK and CERN

As pointed out in your review of Antonino Zichichi's book about Patrick M S Blackett (*CERN Courier* September 2016 p59), the author offers his personal testimony, from the first time he heard Blackett's name to when he went to work with him, and then about the research he could be involved in. I would like to add one important point, outlined in the book, which was not mentioned in the review: namely the decisive role of Blackett in the foundation of CERN.

The important role of I I Rabi and other scientists, who initiated the foundation of CERN via UNESCO, has been outlined on many occasions. Zichichi's book, however, describes the important role played by Blackett in getting the UK, which had been an observer until then, to ratify the CERN convention on 30 December 1953. Indeed, the influence that Blackett – who was a former chief adviser for operational research in the Admiralty during the Second World War – had at government level allowed him to overcome the initial resistance in the UK government, which was willing to accept expenditure on nuclear projects but reluctant to spend comparable sums on fundamental research in a European organisation.

Hence, in the words of physicist Lew Kowarski written in 1973 (*CERN Courier* September 2016 p62), "important events such as the creation of CERN – only a few years after World War II, with Germany joining and Britain among the signatories of the CERN Convention – do not happen without the engagement of strong personalities".

- *Horst Wenninger, CERN.*

VISITS

S Bennett

Elisabeth Laurin, ambassador and permanent representative of France to the United Nations Office at Geneva and international organisations in Switzerland (right), with CERN Director-General **Fabiola Gianotti** at the 14th edition of France@CERN on 3–4 October. The annual event welcomed representatives from 37 companies covering a wide range of sectors including engineering mechanics, energy, transport and information technology.

S Bennett

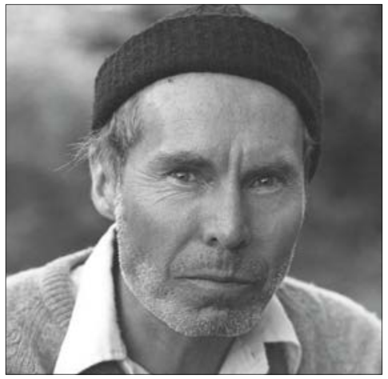
Glenys Beauchamp, secretary, Department of Industry, Innovation and Science, Australian government, visited CERN on 26 October and signed the guestbook in the presence of CERN director for international relations **Charlotte Warakaulle** (left) and Director-General **Fabiola Gianotti**.

P Catapano

Italian actress **Sonia Bergamasco**, who's work includes a role in the 2008 Italian television movie *Einstein*, visited CERN on 13 October, during which she took in the surroundings of the CERN Control Centre.

OBITUARIES

David Jackson 1925–2016


K Gottfried

Jackson is well known for his Classical Electrodynamics *textbook.*

The life of John David Jackson bridged the era of tabletop nuclear-physics experiments and the modern age of large, complex accelerators. Jackson's first professional appointment was in 1949 as assistant professor of mathematics at McGill University in Montreal, Canada, where, half a century earlier, Ernest Rutherford first showed that radioactive matter emits three distinct types of radiation. Shortly after moving to Manchester, UK, Rutherford performed the famous alpha-particle scattering experiment, which demonstrated the existence of the nucleus. When Jackson arrived at McGill, much of Canadian physics was still under the spell of Rutherford: theoretical physicists were often only found in mathematics departments, and quantum mechanics was not even taught. Jackson played a significant role in changing this character of physics in Canada.

Jackson was born in London, Ontario, and obtained his undergraduate education at the University of Western Ontario. In 1946 he was admitted to MIT, where he obtained his doctorate under Victor Weisskopf. His thesis on neutron–proton scattering, published in a widely known paper with John Blatt, led to an offer of a postdoc position from Hans Bethe at Cornell at a time when Feynman was doing his famous work there. Although Cornell was among the hottest destinations in theoretical physics at the time, Jackson felt an obligation to return to Canada. He later wrote that "the foolishness and chauvinism of youth is evident in my acceptance of the [McGill] offer." But it was at McGill that Jackson first displayed his remarkable talents as a teacher of theoretical physics and developed the first draft of what was to become the first (1962) edition of his famous textbook, *Classical Electrodynamics*.

In 1956, Jackson spent a year at Princeton. In that year he produced a brilliant study of the muon-catalysed fusion of protons and deuterons into He^3, and participated actively in the stream of developments unleashed by the discovery of parity violation. In the summer of 1957, Jackson accepted a professorship at the University of Illinois at Urbana, where his research focus began to turn to particle and high-energy physics, and in 1963–1964 he undertook a sabbatical at CERN. In 1967, he accepted a professorship at the University of California in Berkeley, where he remained for the rest of his life. The "November Revolution" of 1974 gave Jackson the opportunity to display his mastery of "simple" nuclear physics and quantum mechanics in his overnight analysis of the amazingly narrow J/ψ resonance discovered in electron–positron collisions at SPEAR. At first his calculation of the J/ψ width was controversial, but before long he was shown to be correct.

Owing to his outstanding personality and superb technical ability, Dave (as he was often known) was in great demand for public service. In addition to membership of the National Academy of Sciences and many important committees, he was acting head of the Fermilab theory department (1972–1973), editor of *Annual Reviews of Particle and Nuclear Physics* (1977–1993), chair of the Berkeley physics department (1978–1981) and deputy director of the central design group for the Superconducting Super Collider (1984–1987). Jackson was also a strong proponent of increasing the participation of women in physics.

David Jackson inspired many because of the character traits he displayed to his colleagues, in his lectures, his publications and even in his infamous homework problems: intellectual rigour, tenacity and self-discipline in the pursuit of demanding goals, strict honesty, and a total absence of vanity.

● *Kurt Gottfried and Maury Tigner, Cornell University.*

Edward J Lofgren 1914–2016

Bevatron pioneer Ed Lofgren.

One of the few remaining physicists who worked on the Manhattan Project, Ed Lofgren passed away peacefully on 6 September at the age of 102. He was a key figure in the development of the Bevatron at Lawrence Berkeley National Laboratory and was its first director during the early days of large-scale particle physics.

Lofgren was born in Chicago as the youngest of seven in a family of Swedish immigrants, and attended Los Angeles Junior College in 1931. He was accepted by Caltech but could not find a job that paid enough to be able to afford it. Later, he transferred to the University of California at Berkeley and received his undergraduate degree in 1938. In 1941, Lofgren interrupted his graduate studies at Berkeley to contribute to the war effort, in which he developed uranium-hexafluoride sources used in the Calutron "farm" at Oak Ridge for uranium enrichment (which would later become the topic of this PhD thesis). In 1944 he moved to Los Alamos and manned a radiation-monitoring site located 9 km from Ground Zero, where the first nuclear test was carried out.

After the war, Lofgren worked on an experimental verification of the McMillan–Veksler "phase-stability" principle by converting the 37″ Cyclotron into the world's first synchro-cyclotron. This led to the redesign of the 184″ Cyclotron, offering a substantially higher accelerating efficiency and a maximum energy almost 10 times higher than the initial design. Following a brief stint at the University of Minnesota investigating cosmic rays with high-altitude balloons, Lofgren returned to the "Rad Lab" at Berkeley in 1948 and served as director of the Bevatron from 1954. He continued his stewardship of this accelerator until his retirement as a laboratory associate director in 1979.

Starting from its first operations in 1954, when the Bevatron was the world's highest-energy machine, seminal experiments contributed to the foundations for particle physics. The antiproton was discovered in 1955, swiftly followed by the antineutron in 1956 and multiple resonances thereafter. The Bevatron era also saw the first industrial-scale physics collaborations, where large groups would systematically analyse millions of photos taken at bubble chambers. The dozens of meson and baryon resonances that were discovered provided the impetus for the introduction of the quark model.

Later, in 1965, Lofgren led the "200 BeV" design study at Berkeley, but after the decision was made to build Fermilab in Illinois he did not take part in the project. By 1970, when the Bevatron's 6 GeV beams had fallen far behind other accelerators, Lofgren and Herman Grunder gave it a new lease of life by converting it into a heavy-ion accelerator: the Bevalac. The Bevalac pioneered the fields of relativistic heavy-ion physics, high-energy calibration of satellite cosmic-ray instrumentation, and medical treatments with heavy-ion beams. Many hundreds of cancer patients were treated with neon and other beams at the facility, laying the foundations for today's hadron-therapy programmes.

His three daughters remember him as a caring father always willing to describe the natural wonders around him to anybody who would listen. Even in his last weeks of life, he was seen explaining the famous San Francisco fog to fellow residents at his Oakland retirement centre. He will be greatly missed.

● *Jose Alonso, Lawrence Berkeley National Laboratory.*

Peter Weilhammer 1938–2016

Peter Weilhammer held many roles at CERN.

Peter Weilhammer passed away on 27 May. He was born in 1938 in Munich and obtained his PhD in physics at the Ludwig Maximilian University in 1969, after which he became a research staff member of the Max Planck Institute and worked with Werner Heisenberg. In 1971 he came to CERN, where his achievements covered the whole spectra of work from particle-physics analysis, detector technology and steering the future of CERN.

Peter's managerial capabilities were recognised very early, and his record is impressive. In the early 1970s he was an official CERN observer at Brookhaven National Laboratory and a member of its scientific council. In the period 1972–1976, he was a physics programme co-ordinator at CERN, a secretary of the nuclear-physics research board and an adviser to the then Director-General. In the periods 1974–1981 and 1984–1989 he was spokesperson of the ACCMOR collaboration; led the WA3 and NA32 experiments; and, later, led the DELPHI micro-vertex team. From 1986–1999 he was head of CERN's solid-state detector group, and also headed two international collaborations on radiation-hard silicon and diamond detectors. Following this, he was chairman of BELLE's silicon-vertex-detector review committee, a member of the CERN technical advisory board to the Director-General and elected spokesman of the CIMA collaboration for the development of novel SPECT and PET instrumentation.

Peter made outstanding contributions to high-precision semiconductor detectors, entering this domain at the beginning of the 1980s with the NA11 experiment. He was one of the main proponents and constructors of high-precision vertex detectors for the NA11, NA32, DELPHI and ATLAS experiments, showing continuous initiative in developing new devices and pursuing systematic studies in heavy-radiation environments and for different applications.

▷

Peter was full of initiative, very energetic and not afraid of taking risks. He worked closely with people from all over the world, helping them as much as he could.

In addition to all of this, Peter was a professional ski instructor and a climber, and many of us have enjoyed trips with him in the mountains. He inspired many of us both in our professional and private lives. Our thoughts go to his family and many friends.

● *His friends and colleagues.*

Wolfhart Zimmermann 1928–2016

Wolfhart Zimmermann, who passed away on 18 September, was one of the outstanding German theoretical physicists of the second part of the 20th century. He made influential discoveries and in 1991 he received the Max Planck medal for contributions to quantum field theory and renormalisation theory.

Zimmermann studied physics and mathematics in Freiburg and Göttingen, completing his thesis in cohomology in 1950. He spent several years in the US, at the Institute for Advanced Study, the Courant Institute of Mathematical Science and the University of Chicago. He then returned to Europe, becoming a fellow at the Max Planck Institute for Physics and Astrophysics in Munich, followed by director in 1991.

Zimmermann (left) with Rolf Hagedorn.

His scientific work concerned perturbative-renormalisation theory, and the development of a general theory of quantised fields. Guided by the experience from renormalised-perturbation theory, Lehmann, Simanzyk and Zimmermann based their “LSZ” theory on a weak-convergence asymptotic condition for the field operators by asymptotic free fields, thus establishing a connection between the physical interpretation in terms of particles and the collision cross-section. The LSZ approach was the starting point of the proof of the experimentally verified dispersion relations and also led to experimentally verifiable predictions that can be extended to cover situations with composite particles.

Zimmermann was closely involved in the physics and physicists of CERN and particularly with Henri Epstein, Yurko Glaser, André Martin and Raymond Stora.

● *Philippe Blanchard, Bielefeld University.*

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LIGO Laser Interferometer Gravitational-Wave Observatory
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Postdoctoral Research Positions
LIGO Laboratory

The Laser Interferometer Gravitational-Wave Observatory (LIGO) has as its goal the development of gravitational wave physics and astronomy. The LIGO Laboratory is managed by Caltech and MIT, and is funded by the National Science Foundation. It operates observatory sites equipped with laser interferometric detectors at Hanford, Washington and Livingston, Louisiana, which recently made the first confirmed detection of gravitational waves. A vigorous LIGO Laboratory R&D program supports the development of enhancements to the LIGO detector as well as astrophysical data analysis, and development of future detectors and detector technologies.

The LIGO Laboratory anticipates having one or possibly more postdoctoral research positions at one or more of the LIGO sites – Caltech, MIT and at the two LIGO Observatories in Hanford, WA and Livingston, LA – beginning in Fall 2017. Hires will be made based on the availability of funding. Successful applicants will be involved in the operation of LIGO itself, analysis of LIGO data, both for diagnostic purposes and astrophysics searches, and/or the R&D program for future detector improvements. We seek candidates across a broad range of disciplines. Expertise related to astrophysics, modeling, data analysis, electronics, laser and quantum optics, vibration isolation and control systems is desirable. Most importantly, candidates should be broadly trained scientists, willing to learn new experimental and analytical techniques, and ready to share in the excitement of building, operating and observing with a gravitational-wave observatory. Appointments at the post- doctoral level will initially be for one-year with the possibility of renewal for up to two subsequent years.

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Call to scientific institutes for collaboration in the context of the Beamline for Schools competition at CERN

beamline for schools

CERN

Call to scientific institutes for collaboration in the context of the Beamline for Schools competition at CERN

In 2017 CERN will, for the fourth time, organize a Beamline for Schools (BL4S) Competition that invites high school students from around the world to make a proposal for an experiment at a beam line of the PS accelerator.

In the framework of this project, CERN invites scientific institutes to participate in the organization of the competition by contributing the expertise of two young researchers (physicist, computer scientist or engineer) for the period from 1 February 2017 to 30 September 2017, subject to a possible extension.

A detailed description of the project and the qualification and skills required from the young researchers can be found at:
http://cern.ch/go/tdD8

The modalities of the proposed collaboration will be set out in a dedicated agreement between CERN and the institute(s) concerned.

For further information, interested institutes may contact:
markus.joos@cern.ch

Details about the competition itself can be found at:
www.cern.ch/bl4s

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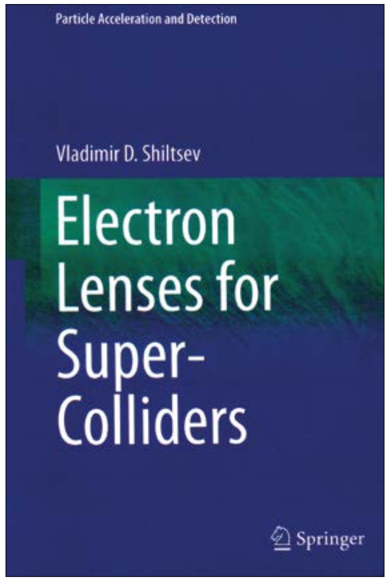
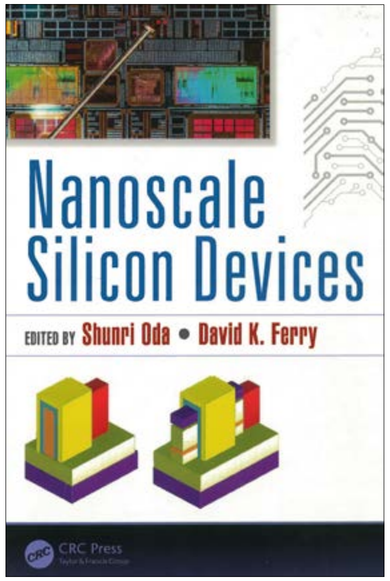
Compiled by Virginia Greco, CERN





Electron Lenses for Super-Colliders

By Vladimir D Shiltsev

Springer

Also available at the CERN bookshop

With an energetic writing style, in this book Vladimir Shiltsev presents a novel device for accelerators and storage rings. These machines employ magnets to bend and focus particle trajectories, and magnets always create forces that increase monotonically with the particle displacement in the magnet. But a particle in a beam also experiences forces from the beam itself and from the other beam in a collider – forces that do not increase monotonically with amplitude. Therefore, magnets are not well suited to correct for beam-generated forces. However, another beam may do the job, and this is most easily realised with a low-energy electron beam stabilised in a solenoidal magnetic field – thus an electron lens is created. The lens offers options for generating amplitude-dependent forces that cannot be realised with magnets, and such forces can also be made time-dependent. The electron lens is in effect a nonlinear lens with a rather flexible profile that can either be static or change with every passing bunch.

D Gabor already proposed the use of electron-generated space-charge forces in 1947 (*Nature* **160** 89–90), and E Tsyganov suggested the use of electron lenses for the SSC (SSCL-Preprint-519 1993). But it was Shiltsev who was the driving force behind the first implementation of electron lenses in a high-energy machine. Two such lenses were installed in the Tevatron in 2001 and 2004, where they routinely removed beam not captured by the radiofrequency (RF) system, and were used for numerous studies of long-range and head-on beam–beam compensation and collimation. In 2014, two electron lenses were also installed in the Relativistic Heavy Ion Collider (RHIC) for head-on beam–beam compensation, and their use for the LHC collimation system is under consideration.

Shiltsev's experience and comprehensive knowledge of the topic make him perhaps the best possible author for an introductory text. The book is divided into five chapters: an introduction, the major pieces of technology, application for beam–beam compensation, halo collimation, and other applications. It draws heavily on published material, and therefore does not have the feel of a textbook. While a consistent notation for symbols is used throughout the book, the figures are taken from other publications, and the units are mostly but not entirely in the International System (SI).

At the heart of the book are descriptions of the major technical components of a working electron lens, and the two main applications to date: beam–beam compensation and halo collimation. Long-range and head-on beam–beam compensation as well as collimation applications are described exhaustively. It is somewhat regrettable that the latest results from RHIC were published too late to be included in the volume (e.g. W Fischer *et al*. 2015 *Phys. Rev. Lett.* **115** 264801; P Thieberger *et al*. 2016 *Phys. Rev. Accel. Beams* **19** 041002). The book names the hollow electron lens a collimator, but it is probably better to describe it as a diffusion enhancer (as suggested on p138) because its strength is at least an order of magnitude smaller than a solid-state collimator, and a hollow lens will not replace either a primary or a secondary collimator jaw.

The last chapter ventures into more speculative territory, with applications that are not all in colliders. Most prominently, space-charge compensation is discussed, largely in terms of tune spread but not resonance driving terms. The latter is only mentioned in the context of multiple electron lenses (up to 24 for a simulated Fermilab Booster example). For this and the other applications mentioned, it is clear that much work remains before these could become reality.

Overall, the book is an excellent entry point for anyone who would like to become familiar with the concepts, technology and possible application of electron lenses. It is also a useful reference for many formulas, allowing for fast estimates, and for the published work on this topic – up to the date of publication.

● *Wolfram Fischer, Brookhaven National Laboratory.*

Nanoscale Silicon Devices

By Shunri Oda and David K Ferry (eds)

CRC Press

The *CRC Handbook of Chemistry and Physics* was first published in 1913 and is a well-known text, at least to older physicists from the time before computers and instant, web-based information. To find relevant data, one had to be familiar with the classification of subjects and tables in the handbook's 2500 or so pages, but virtually everything was covered. Over the years, the CRC Press – while continuing to publish this handbook, for more than 100 years now – has grown into a large publisher that produces hundreds of titles every year in engineering, physics and other fields.

Its recent publication, *Nanoscale Silicon Devices*, describes a variety of investigations that are under way to develop improved and smaller electronic structures for computing, signal processing in general, or memory. Now that transistors approach the dimension of a few

▷

nanometres, less than 100 atoms in a row, methods to account for quantum effects have to be applied, as shown in the first chapter. The second chapter discusses the need to change the shape of transistors as they become smaller. The controlling gate has to extend as much as possible around the conduction channel material and, eventually, silicon may be replaced in the channel by a different semiconductor material.

Another effect due to the small size, as explained in chapter 3, is the increase of variability between devices of identical design. Single-electron devices and the use of electron spin are discussed in several of the following chapters. A major issue today, as highlighted in the book, is the reduction of power for circuits with a large number of transistors, where the leakage current in the OFF state becomes preponderant. In chapter 7, tunnel FET devices are discussed as a way to solve this problem. In chapter 6, a different approach is shown, using nanoelectromechanical ON/OFF switches integrated in the circuit.

This book is not a typical textbook, but rather a collection of 11 articles written by 20 scientists, including the editors Oda and Ferry. Each article centres on the research of its author(s) in a specific area of semiconductor-device development. One of the consequences of this structure is the abundance of internal references. Reading the book does not quite provide a firm idea about the future of electronics, but it could convince readers that much more will be possible, beyond the current state-of-the-art. One has also to keep in mind that the chip industry tends to keep useful findings under wraps and has little incentive to publish its research before products are on the shelves.

The book is a good buy if you want to get a feel about work going on at the interface between pico- and nanoelectronics. For the use of electronics in scientific research, it is essential to understand how devices are constructed and what researchers might be able to gain from them, especially when working in unusual environments such as a vacuum, space, the human body or a particle collider.

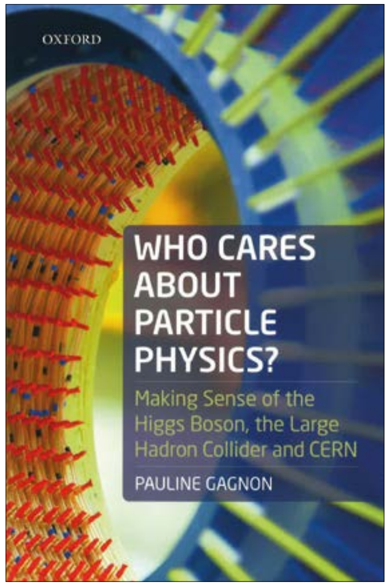
● *Erik Heijne, CERN.*

Who Cares About Particle Physics? Making Sense of the Higgs Boson, the Large Hadron Collider and CERN

By Pauline Gagnon

Oxford

Also available at the CERN bookshop



One of my struggles when I teach at my university, or when I talk to friends about science and technology, is finding inspiring analogies. Without vivid images and metaphors it is extremely hard, or even impossible, to explain the intricacies of particle physics to a public of non-experts. Even for physicists, sometimes it is hard to interpret equations without such aids. Pauline Gagnon has mastered how to explain particle physics to the general public, as she shows in this book full of illustrations but without lack of rigour. She was a senior research scientist at CERN, working with the ATLAS collaboration, until her retirement this year (although she is very active in outreach). Undoubtedly, she knows about particle physics and – more importantly – about its daily practice.

The book is organised into four related areas: particle physics (chapters 1 to 6 and chapter 10), technology spin-offs from particle physics (chapter 7), management in big science (chapter 8) and social issues in the laboratory (chapter 9 on diversity). While the first part was expected, I was positively surprised by the other three. Technology spin-offs are extremely important for society, which in the end is what pays for research. Particle physics is not oriented to economic productivity but driven by a mixture of creativity, perseverance and rigour towards the discovery of how the universe works. On their way to acquiring knowledge, scientists create new tools that can improve our living standards. This book provides a short summary of the technology impact of particle physics in our everyday life and of the effort of CERN to increase the technology spin-off rate by knowledge transfer and workforce training.

Big-science management, especially in the context of a cultural melting pot like CERN, could be very chaotic if it was driven by conventional corporate procedures. The author is clear about this highly non-trivial point: the benefits of the collaborative model we use at CERN in terms of productivity and realising ambitious aims. This organisational model – which she calls the "picnic" model, since each participating institute freely agrees to contribute something – is worth spreading in our modern and interconnected commercial environment, particularly because there are striking similarities with big science when it comes to products and services that are rich in technology and know-how.

As CERN visitors learn, cultural diversity permeates the Organization, and by extension particle physics. Just by taking a seat in any of the CERN restaurants, they can understand that particle physics is a collective and international effort. But they can also easily verify that there is an overwhelming gender imbalance in favour of men. The author, as a woman, addresses the topic of the gender gap in physics and specifically at CERN. She explains why diversity issues, in their overall complexity (not restricted to gender), are very important: our world desperately needs real examples of peaceful and fruitful co-operation between different people with common goals, without gender or cultural barriers.

For what concerns the main part of the book, which is focused on contemporary particle physics, chapters 1, 2, 3 and 6 are undoubtedly very well written, in the overall spirit of explaining things easily but nevertheless with full scientific thoroughness. But I was really impressed by chapter 4, on the experimental discovery of the Higgs boson, and 5, on dark matter, mainly because of the firsthand knowledge they reveal. When you read Gagnon's words you can feel the emotions of the protagonists during that tipping point in modern particle physics. Chapter 5 is an excursion to the dark universe, with wonderful explanations (such as the imaginative comparison between the Bullet Cluster and an American football match). The science in this chapter is up to date and combines particle physics and observational cosmology without apparent effort.

I recommend this book for the general public interested in particle physics but also for particle physicists who want to take a refreshing and general look at the field, even if only to find images to explain physics to family and friends. Because, in the end, everybody cares about particle physics, if you can raise their interest.

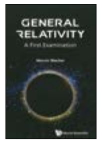
● *Rogelio Palomo, University of Sevilla, Spain.*

Books received

General Relativity: A First Examination

By Marvin Blecher

World Scientific



This book provides a concise treatment of general relativity (GR) ideal for a semester course for undergraduate students or first-year graduate students in physics or engineering. After retiring from a career as an experimentalist in nuclear and particle physics, the author decided to teach an introductory course in GR at Virginia Tech, US. Many books are available on this topic, but they normally go into great detail and include a lot of material that cannot be covered in the short time of a semester. This new text by Blecher aims to cover this gap in the literature and provide just the essential concepts of GR.

The author starts with a review of special relativity and of the basic mathematical instruments, and then moves towards the explanation of the way that gravity affects time. This is discussed first for weak gravity via the conservation of energy using a Newtonian formulation with relativistic mass. Later in the book (chapter 5), it is rigorously treated in a completely GR framework. The Schwarzschild metric is also obtained.

In the following sections, GR is discussed in the context of the solar system (chapter 6) and of black holes (chapter 7). In the latter, an appealing example based on the movie *Interstellar* (Christopher Nolan) is used to discuss why a large gravitational time dilation is possible near a spinning – but not a static – black hole.

Chapter 8 focuses on gravitational waves. The first direct detection of these waves, produced by two black holes that merged into a single one, was announced in February this year, when the book was already going to print. Nevertheless, the author added a discussion on this discovery to the text. The theory of the binary neutron star-system radiation, referred to the binary pulsar discovered by R Hulse and J H Taylor, is also treated, but in the case of elliptical orbits, instead of circular ones as generally done for simplicity in textbooks.

Finally, a chapter is dedicated to cosmology, in which the results of numerical integrations, using the experimental data available for all the energy densities, are discussed.

Raman Spectroscopy: An Intensity Approach

By Wu Guozhen

World Scientific

In this book the author offers an overview of Raman spectroscopy techniques – including Raman optical activity (ROA) and surface-enhanced Raman scattering spectroscopy (SERS) – covering their applications and their theoretical foundations.

The Raman effect is an inelastic two-photon process in which the incident (scattering) photon is absorbed by an atom or molecule (the scatterer) that immediately emits a photon of different energy and frequency than the incident one. This energy difference, which arises because the incident photon vibrationally excites the molecule, is called the Raman shift. Raman shifts provide information on the molecular motion and thus its structure and bond strength. As a consequence, this effect is used for material analysis in Raman spectroscopy.

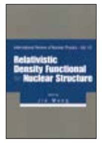
More important than the energy difference are the Raman intensity of the scattered light, which offers insights into the dynamics of the photon-perturbed molecule, and the electronic polarisability of the molecule, which is a measure of how easily the electrons can be affected by the light.

After introducing the Raman effect and the normal mode analysis, the author discusses the bond polarisabilities, the intensity analysis and the Raman virtual states. A group of chapters then cover the extension of the bond polarisability algorithm to the ROA intensity analysis and many findings on ROA mechanism resulting from the work of the author and his collaborators. The last chapter introduces a unified classical theory for ROA and vibrational circular dichroism (another spectroscopic technique).

Relativistic Density Functional for Nuclear Structure

By Jie Meng (ed.)

World Scientific



This book, the 10th volume of the *International Review of Nuclear Physics* series, provides an overview of the current status of relativistic density functional theories and their applications. Written by leading scientists in the field, it is intended both for students and for researchers interested in many-body theory or nuclear physics.

Density functional theory was introduced in 1970s and has since developed in an attempt to find a unified and self-consistent description of the single-particle motion in a nucleus and of the collective motions of the nucleus based on strong interaction theory. Largely applied for heavy and super-heavy nuclei, this description allows mapping the complex quantum-mechanical many-body problem of the structure of these nuclei onto an adequate one-body problem, which is relatively easy to solve.

After explaining the theoretical basics of relativistic (or covariant) density functional theory, the authors discuss different models and the application of the theory to various cases, including the structure of neutron stars. In the last chapter, three variants of the relativistic model and the non-relativistic density model are compared. Possible directions for future developments of energy density functional theory are also outlined.

Readers interested in further details and specific research work can rely on the very rich bibliography that accompanies each chapter.

CERN Courier Archive: 1973

A LOOK BACK TO CERN COURIER VOL. 13, DECEMBER 1973, COMPILED BY PEGGIE RIMMER

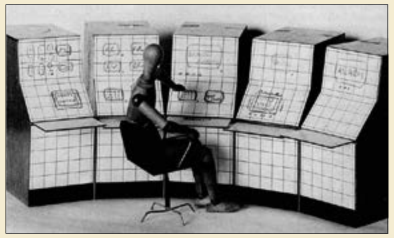
PROGRESS IN CONSTRUCTION OF SPS

Keeping control

It is hard to imagine that only four years ago the use of computers in machine control was still a subject for debate. Now the only debate is how best to use them. The SPS team was able to learn from the work of other laboratories, particularly on the 400 GeV synchrotron at NAL and LAMPF at Los Alamos.

One novelty is that instead of a large, central computer overseeing smaller computers, control tasks will be divided between small or medium sized computers, effectively interchangeable. The number crunching ability of a big computer is lost but this is rarely called upon in machine control, and for the few occasions when it is needed a bicycle ride with a magnetic tape to a link to the CERN central computers will not be too arduous.

Novelty number two is in the mysterious realm of software. A major problem in the past has been the interdependence of programs that have to be "compiled" before they can be run. A system has been adopted in which the programs are kept as statements of a specially developed language called NODAL. These statements are interpreted when the program is run and the "interpreter", resident in each computer, has access to all the information necessary to make the required cross-references and links.


CERN 93.9.73

Not the result of a life test on a machine operator but simply a bit of ergonomics while working out the best layout of the consoles for the SPS control room.

Speed of execution is lost, however for almost all control applications a millisecond is not forever and the speed is entirely adequate.

The computers are linked through a Message Transfer System whereby one computer can ask another to perform some measurement, control function or calculation by using a few simple typed statements.

The "operator interface" will also have its novelties. In addition to conventional control aids, such as black and white television screens and computer input keyboards, there will be colour displays, a programmable knob with feedback from the computer and a new type of touch button screen. The whole gamut of lights, switches, etc, which clutter the control rooms of yesteryear, have to be represented on a single console via the touch panel. Each button has a label written on it by the computer. Pressing a button changes the electrical capacity at that point behind the panel and selects a particular function.

● Compiled from texts on pp363–364.

BROOKHAVEN

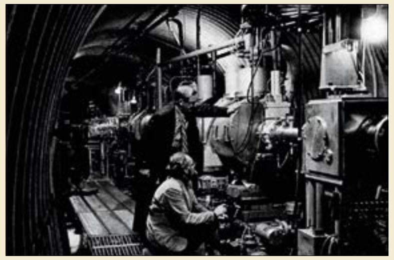
Superconducting magnet operates at AGS

At the beginning of November a large superconducting bending magnet was brought into operation at the Alternating Gradient Synchrotron. It is designed to operate at twice the magnetic field of conventional magnets and has been successfully tested at 4.4 T. The performance seems to have answered several outstanding questions concerning superconducting magnets, an important achievement.

Two magnet sections have been built of standard materials using construction techniques which present no outstanding difficulties. Their magnetic characteristics are identical to 0.01%, in agreement with the design computations, and the mechanical precision compares favourably with the best conventional magnets. This indicates that it should be possible to manufacture such magnets reliably in industry with the expectation that they will be magnetically and mechanically interchangeable.

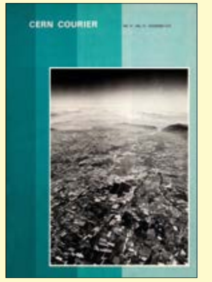
A second question concerns the ability of superconducting magnets to withstand heavy doses of radiation. The AGS magnet absorbed large beam losses without a problem. This is very significant since future superconducting accelerators depend on a reasonable ability to operate under conditions of heating due to sudden beam loss. This is the first experimental evidence on this fundamental question.

● Compiled from texts on pp374–375.

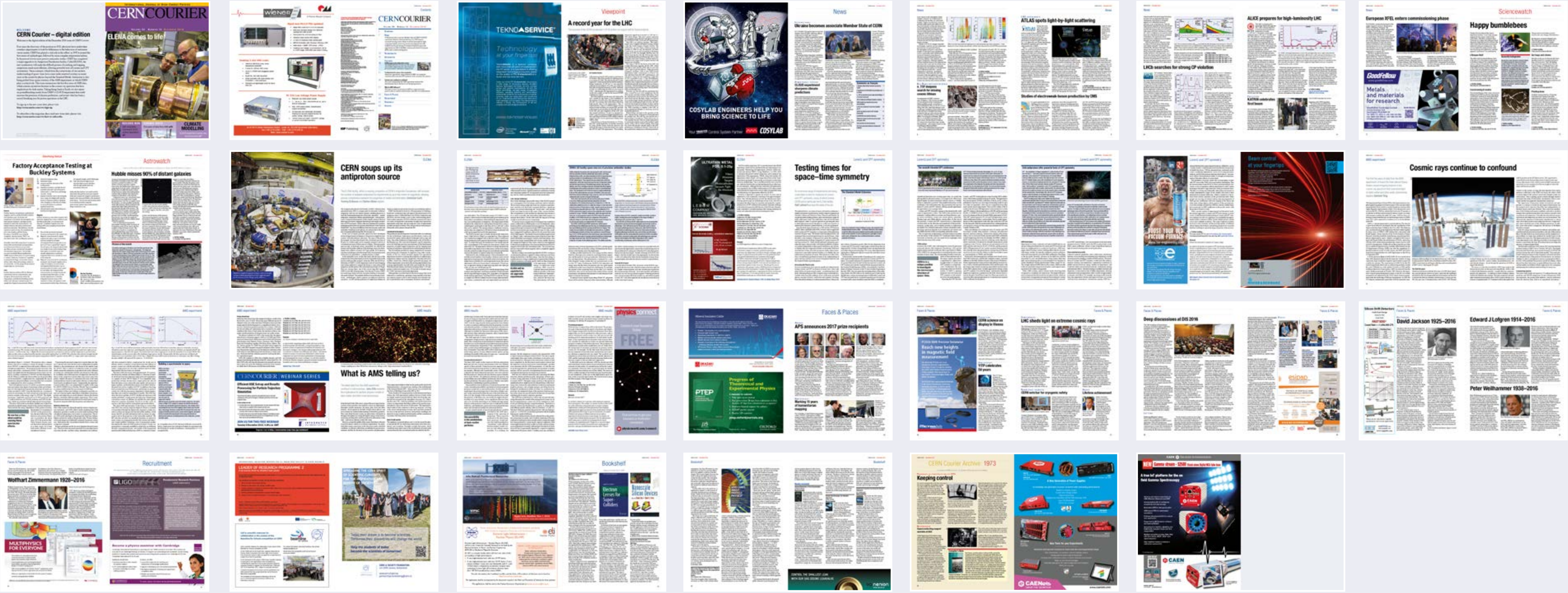

BNL

View of the superconducting magnet installed in the new beamline leading to the seven-foot bubble chamber in the North Area at the AGS.

Compiler's Note



Bent Stumpe, a Danish engineer working at CERN, invented the revolutionary SPS touchscreen. In keeping with CERN's ethos, the technology was immediately transferred to industry but take-up was delayed because the considerable computer power it needed was expensive at the time. Today the technology, further developed and commercialised on a large scale, is found everywhere. Bent also invented a trackerball for the SPS consoles, an x–y pointing device that worked on the same principle as the computer mice developed later by industry in the 1980s. The SPS Message Transfer System was an early instance of client/server inter-processor communication, a type of Remote Procedure Call (RPC). All modern distributed computing systems use this request/response mechanism. Tim Berners-Lee, who worked on RPC at CERN in the1980s, employed this paradigm for the HyperText Transfer Protocol of his invention, the World Wide Web. Today, numberless web clients communicate with billions of web servers across the globe.



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