WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the July/August 2016 issue of *CERN Courier*.

On 20 July 1956, physicists reported in *Science* that they had discovered the neutrino – a quarter of a century after the highly non-reactive particle was postulated. This issue of *CERN Courier* celebrates that discovery and the numerous breakthroughs in neutrino physics that have been made since then, in particular following the 1998 observation that neutrinos oscillate between their three different flavours. Several major neutrino programmes are under way worldwide to further constrain measurements of the masses and mixing parameters of neutrinos, with the CERN Neutrino Platform providing vital support. Sixty years after their discovery, neutrinos have become the most studied of all elementary particles, and are seen by many as our best chance yet to unearth physics beyond the Standard Model.

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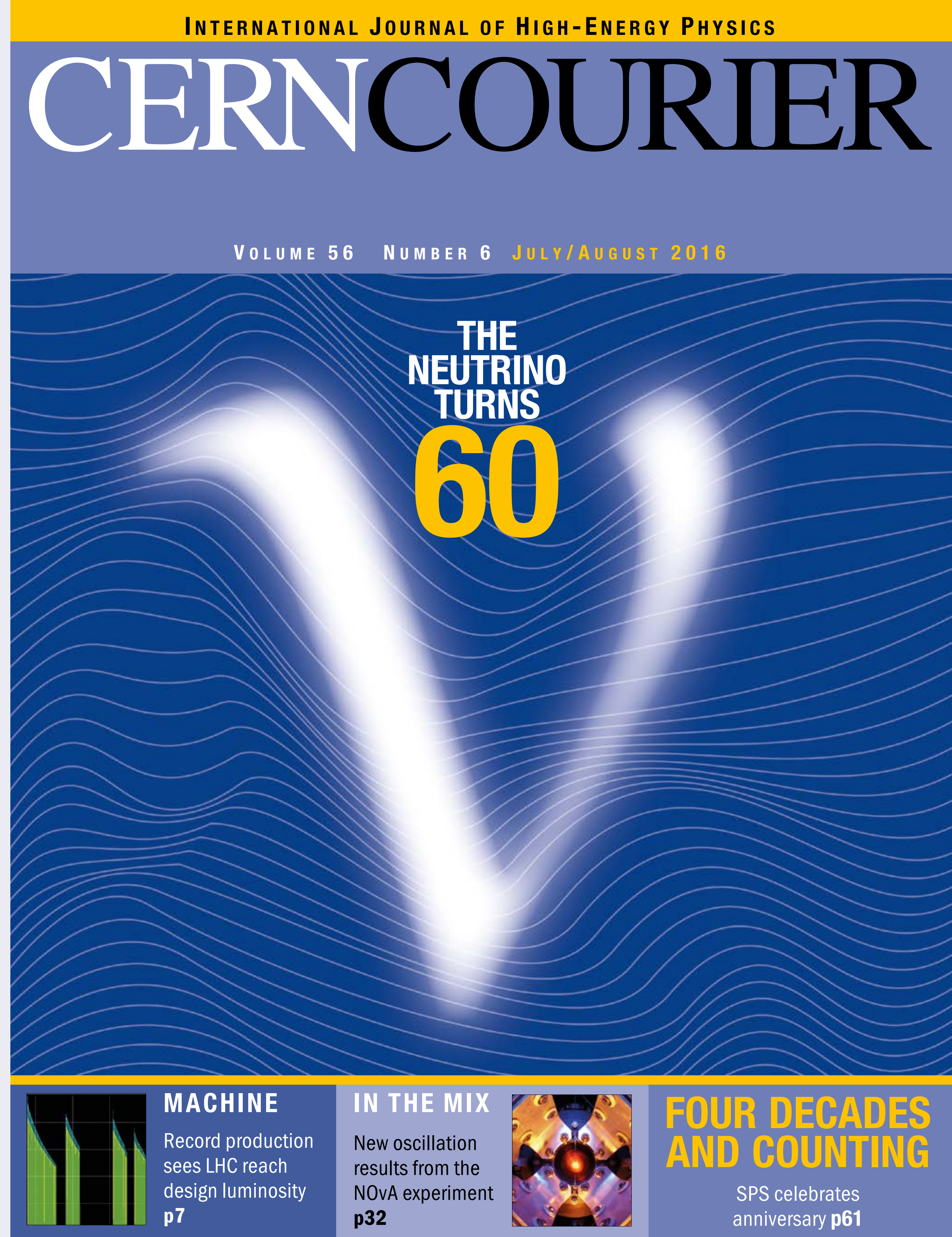

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Covering current developments in high-energy physics and related fields worldwide

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CERN COURIER

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On the cover: 2016 is the 60th anniversary of the neutrino discovery.

Viewpoint

Futures intertwined

Recent agreements between CERN and the US are critical to global particle physics.

CERN

The ICARUS detector, formerly located at Gran Sasso National Laboratory, is being refitted at CERN before being shipped to the US to form part of Fermilab's short-baseline neutrino facility.

By Nigel Lockyer

CERN and Fermilab have a rich history of scientific accomplishment. Fermilab, which is currently the only US laboratory fully devoted to particle physics, tends to favour fermions: the top and bottom quarks were discovered here, as was the tau neutrino. CERN seems to prefer bosons: the W, Z and Higgs bosons were all discovered at the European lab. Both labs also have ambitious plans for the future that build on a history of close collaboration. A recent example is the successful test of a novel high-field quadrupole superconducting magnet made from Nb_3Sn as part of the R&D programme for the High-Luminosity Large Hadron Collider (HL-LHC). The highly successful team behind this technology (the Fermilab-led LHC Accelerator Research Programme, which includes Berkeley and Brookhaven national labs) is also committed to developing 16 T magnets for a high-energy LHC and a possible larger circular collider.

Our laboratories and their global communities are now moving even closer together. At a ceremony held at the White House in Washington, DC in May 2015, representatives from the US Department of Energy (DOE), the US National Science Foundation and CERN signed a co-operation agreement for continued joint research in particle physics and computing, both at CERN and in the US. This was followed by a ceremony at CERN in December, at which the US ambassador to the United Nations and the former CERN Director-General signed five formal agreements that will serve as the framework for future US–CERN collaboration. The new agreements enable US scientists to continue their vital contribution to the LHC and its upgrade programme, while for the first time enabling CERN participation in experiments hosted in the US.

The US physics community and DOE are committed to the success of CERN. Physicists migrated from the US to CERN *en masse* following the 1993 cancellation of the Superconducting Super Collider. In 2008, lack of clarity about the future of US particle physics contributed to budget cuts, which together brought us to a low point for our field. These painful periods taught us that a unified scientific community and strong partnerships are vital to success.

Fortunately, the tides have now turned, in particular thanks to two important planning reports. The first was the 2013 European Strategy Report, which for the first time recommended that CERN supports physics programmes, particularly regarding neutrinos, outside of its laboratory. The following year, this bold proposal led the US Particle Physics Project Prioritisation panel to strongly recommended a continued partnership with CERN on the LHC and to pursue an ambitious long-baseline neutrino programme hosted by Fermilab, for which international participation and contributions are vital.

CERN's support and European leadership are critical to the success of the ambitious Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) being hosted by Fermilab. In partnership with the Italian Institute for Nuclear Physics, CERN is also upgrading the ICARUS detector for our short-baseline neutrino programme. Thanks largely to this partnership with CERN, the US particle-physics community is now enjoying a sense of optimism and increasing budgets.

Fermilab and CERN have always worked together at some level, but the high-level agreements between CERN and the DOE will reach decades into the future. CERN recognises the extensive technical capability of Fermilab and the US community, which are currently working to help upgrade CMS and ATLAS as well as accelerator magnets for the HL-LHC, while the US recognises CERN's leadership in high-energy collider physics, and more than 1000 US physicists call CERN their scientific home.

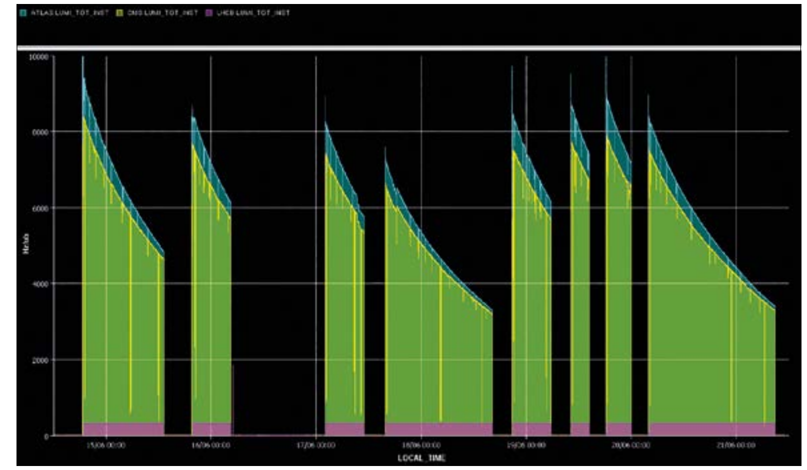
Yet, not everyone agrees that our laboratories should be intertwined. Some in the US think too much money is sent abroad and believe that the funds could be used for particle physics at "home", or for other uses entirely. On the other side of the Atlantic, some might wonder why they should work outside of CERN or, worse, outside of Europe. These views are short-sighted. The best science is best achieved through collaborative global partnerships. For this reason, CERN and Fermilab will be intertwined for a long time to come.

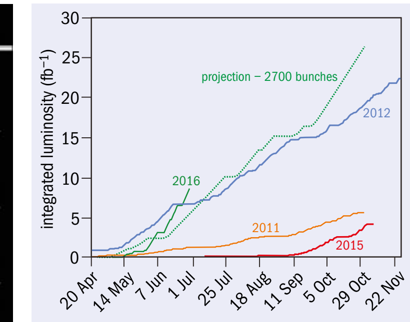
Nigel Lockyer (pictured in the CMS cavern) became director of Fermilab in Batavia, Illinois, in 2013, and has served at the US lab in a variety of roles during the past 25 years. An experimental particle physicist, Lockyer was previously director of TRIUMF in Canada. (Image credit: Fermilab/Sarah Charley.)

News

THE LHC

Record-breaking production at the LHC





(Left) The luminosity delivered to the experiments during a record breaking week in June. (Above) Integrated luminosity versus time, showing how 2016 is already taking the LHC beyond expectations.

The past few weeks have been a record-breaking period for the LHC, with the machine now delivering long fills with unprecedented luminosity. Following the interruption in late May due to problems with the PS main power supply, on 1 June the operations team established collisions with 2040 bunches for the first time this year. This is the maximum number of bunches achievable with the current limitations from the SPS beam dump, which allows the injection of trains of 72 bunches spaced by 25 ns.

The following week saw LHC's previous luminosity record at 6.5 TeV broken by a peak luminosity of just over $8\times10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$, representing 80% of the design luminosity. This was followed by a new record for integrated luminosity in a single fill, with 370 $\mathrm{pb^{-1}}$ delivered in just 18 hours of colliding beams. The availability for collisions during this period was a remarkable 75%, more than double the annual average in 2015. Around 2 $\mathrm{fb^{-1}}$ were delivered during one week, breaking the previous record of 1.4 $\mathrm{fb^{-1}}$ established in June 2012.

These records follow the decision taken at the end of May to focus on delivering the highest possible integrated luminosity for the summer conferences. Following a short technical stop that ended on 9 June, the machine was re-validated from a machine-protection perspective for a sustained period of 2040 bunch operation at high luminosity. Afterwards, new records were set immediately, with one fill on 13–14 June producing more than 0.5 $\mathrm{fb^{-1}}$ in around 27 hours, and the following fill recording a peak luminosity of over $9\times10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. The record integrated luminosity delivered in seven days now stands at 2.4 $\mathrm{fb^{-1}}$. Finally, on 26 June, the team hit the LHC design luminosity ($10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$) for the first time. With such performance, the operations team hopes to deliver over 10 $\mathrm{fb^{-1}}$ to both ATLAS and CMS before the summer conferences.

This is truly a new phase for the LHC and thanks are due to all the teams who have worked tirelessly to make it possible. This year the smaller beam size at the interaction points provides almost double the instantaneous luminosity compared to 2015, yet the machine is behaving impeccably. The stunning and surprising availability is due to a sustained effort over the years by hardware groups such as cryogenics, quench protection, power converters, RF, collimation, injection and others to maximise the reliability of their systems. Of particular note is the major effort co-ordinated by the radiation to electronics team to mitigate the effects of beam-induced radiation on tunnel electronics.

Another case in point concerns cryogenics. With so many bunches circulating, the heat load deposited by the electron cloud on the LHC beam screens in the arcs can reach 150 W per half-cell (a half-cell in an arc includes one quadrupole and three dipole magnets). This is just below the maximum of 160 W that can be sustained by the cryogenics system. With a new cryogenic feed-forward system in place to tune the beam-screen cooling parameters according to the intensity stored in the machine and the beam energy, operation with the high electron cloud currently present in the machine is significantly smoother than in 2015. Of course, the LHC remains a hugely complex machine and the availability is always liable to fluctuations.

Sommaire en français

LHC EXPERIMENTS

CMS highlights from the fourth LHCP conference

The CMS collaboration presented 15 new results at the fourth annual Large Hadron Collider Physics (LHCP) conference on 13–18 June in Lund, Sweden. The results included a mixture of searches for new physics and Standard Model measurements at a centre-of-mass energy of 13 TeV. CMS also summarized its detector and physics-object performance on recently collected 2016 data, demonstrating that the collaboration has emerged from the winter shutdown ready for discovery physics.

The search for new physics in 13 TeV proton collisions continues in earnest, with six new results presented at LHCP. A combined search for high-mass resonances decaying to the Zγ final state, with Z bosons decaying to leptons, in the 8 and 13 TeV datasets yields no significant deviation from background expectations for masses ranging from a few hundred GeV to 2 TeV (EXO-16-021). A similar search in the same channel, but with Z bosons decaying to quarks, produced a similar conclusion (EXO-16-020). CMS has also searched for heavy Z′ bosons that decay preferentially to third-generation fermions, including decays to pairs of top quarks (B2G-15-003) and τ leptons (EXO-16-008), and found no excess above the Standard Model prediction.

The top quark-pair analysis uses special techniques to search the all-hadronic final state, where the highly boosted top quarks are reconstructed as single jets, while the search in the τ lepton channel is carried out in four final states depending on the decay mode. No significant signals are observed in either search, resulting in the exclusion of Z′ bosons up to a mass of 3.3 (3.8) TeV for widths of 10 (30)% relative to the mass in the top search, and 2.1 TeV in the τ lepton search. Another search using the τ lepton looks for heavy neutrinos from right-handed W bosons and third-generation scalar leptoquarks in events containing jets and two hadronically decaying taus. This is the first such search for heavy neutrinos using τ leptons, and CMS finds the data well described by Standard Model backgrounds.

CMS continues to probe for possible dark-matter candidates, most recently in final states that contain top quarks (EXO-16-017) or photons (EXO-16-014) plus missing energy. The data are consistent with Standard Model backgrounds and limits are placed on model parameters associated with the dark matter and graviton hypotheses. A search for supersymmetric particles in the lepton-plus-jets final state was also presented for the first time (SUS-16-011). This analysis targets so-called compressed spectra in which weakly interacting supersymmetric particles can have similar masses, giving rise to muons and electrons with very low transverse momentum. No significant signals are observed and limits are placed on the masses of top squarks and gluinos under various assumptions about the mass splittings of the intermediate states.

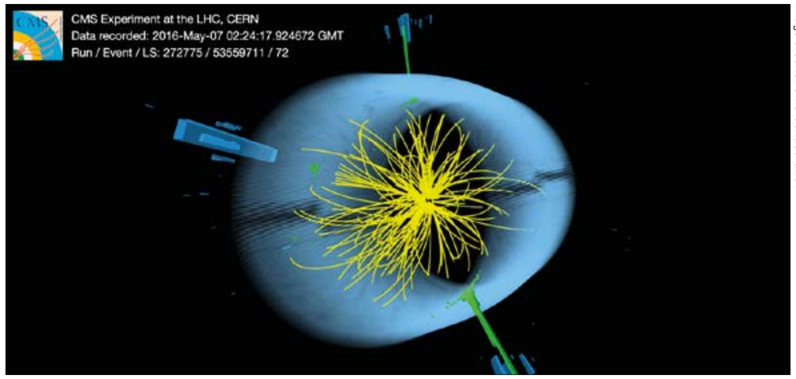


Image credits: CMS Collaboration

A CMS event that was recorded on 7 May showing two high-energy photons (green towers) reconstructed in the electromagnetic calorimeter and many charged particles (yellow curved lines) reconstructed in the tracker.

Finally, a search for a heavy vector-like top quark T decaying to a standard top quark and a Higgs boson (B2G-16-005) was presented for the first time at LHCP. For T masses above 1 TeV, the top quark and Higgs boson are highly boosted and their decay products are reconstructed using similar techniques as in B2G-15-003. Here the data are also consistent with background expectations, allowing CMS to set limits on the product of the cross section and branching fraction for T masses in the range 1.0–1.8 TeV.

Several new Standard Model measurements were shown for the first time at LHCP, including the first measurement of the top-quark cross section at 5 TeV (TOP-16-015) based on data collected during a special proton–proton reference run in 2015 (figure 1). A first measurement by CMS of the WW di-boson cross-section at 13 TeV was also reported (SMP-16-006), where the precision has already reached better than 10%. Finally, three new results on Higgs boson physics were presented for the first time, including the first searches at 13 TeV for vector boson fusion Higgs production in the bottom quark decay channel (HIG-16-003) and a search for Higgs bosons produced in the context of the MSSM model that decay via the τ lepton channel (HIG-16-006). A first look at Higgs lepton-flavor-violating decays in the 13 TeV data (HIG-16-005), using the μτ channel, does not confirm a slight (2.4σ) excess observed in Run 1, although more data is needed to make a definitive conclusion.

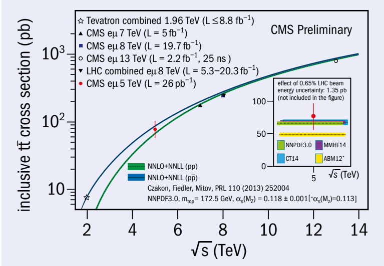


Fig. 1. Top-quark-pair production cross-section in proton–antiproton and proton–proton collisions as a function of the centre-of-mass energy, showing the Tevatron combination at 1.96 TeV in addition to CMS results at 5, 7, 8 and 13 TeV in the dilepton channel. The measurements are compared to the NNLO+NNLL theory predictions.

Further reading

CMS analyses: cms-results.web.cern.ch/cms-results/public-results/preliminary-results/index.html.

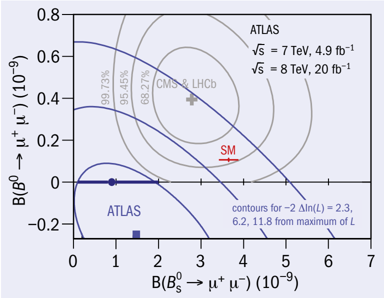
Detector performance: cms-results.web.cern.ch/cms-results/public-results/detector-performance/index.html.

ATLAS clocks rare decay of B mesons into muon pairs

The decays of the B^0_s and B^0 into muon pairs represent an important test of the Standard Model. Such decays take place through a flavour-changing neutral current process, which occurs only through loop diagrams and is further suppressed because the two muons are required to have equal helicity in order to conserve angular momentum.

Although the very small value of the predicted branching fractions (3.7×10^{-9} and 1.1×10^{-10} for the B^0_s and B^0, respectively) opens the possibility to search for new physics, the decays present a challenge for experimental programs. Physicists have been placing upper limits on these processes for more than 30 years, with the values decreasing by roughly two orders of magnitude every decade.

ATLAS recently presented the result of a study based on data collected during LHC Run 1, completing the results obtained by CMS and LHCb (*CERN Courier* September 2013 p19). The new analysis exploits multivariate techniques for the reduction of background events that could mask the small signal from B-meson decays. A first classifier is used to reduce the background due to muons from uncorrelated decays of B hadrons, while a second classifier is used to reduce the fraction of hadrons wrongly identified as muons. Misidentification contributes to the background due to partially reconstructed decays, and is at the origin of the resonant background due to B^0_s decays into pairs of charged mesons when both are mistaken as muons. ATLAS has achieved values of about 0.10% and 0.05% for the probability of a kaon or a pion to be wrongly identified as a muon, pushing the resonant background below the predicted level of the signal.



Likelihood contours of the fit to data in the plane of the B^0_s and B^0 branching fraction. Also shown are the value and uncertainty for $B(B^0_s\to\mu^+\mu^-)$, the upper limits (indicated by dashed areas), the contours corresponding to the combination of the measurements by CMS and LHCb, and the prediction based on the Standard Model.

For the B^0_s meson, the branching fraction measured by ATLAS is $B(B^0_s\to\mu^+\mu^-) = (0.9^{+1.1}_{-0.8})\times10^{-9}$, with an upper limit of 3.0×10^{-9} at a 95% confidence level. The result agrees, within uncertainties, with those of CMS and LHCb. It is lower than the Standard Model prediction but is compatible at the level of two standard deviations. For the B^0 an upper limit $B(B^0\to\mu^+\mu^-) < 4.2\times10^{-10}$ is set at a confidence level of 95%, which again is compatible with previous evidence and predictions.

The new result constrains models for new physics that predict a significant enhancement of these B decays, such as some with an extended Higgs sector. Deviations in the direction of lower branching fractions require further clarification with data collected during LHC Run2.

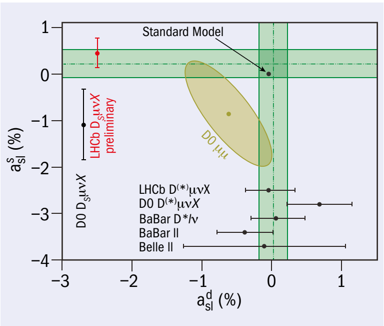
Further reading

ATLAS Collaboration 2016 arXiv:1604.04263.

LHCb updates B_s oscillation measurement

The LHCb experiment has recently made the most precise measurement yet of the asymmetry in oscillations between the matter and antimatter versions of B_s mesons. The measurement exploits the full LHCb dataset recorded during Run 1 of the LHC and is consistent with the Standard Model prediction.

Subtle quantum mechanics effects allow the B_s meson, which contains a strange quark and a beauty antiquark, to spontaneously transform into its own antiparticle, $\bar{B}_s$, in which the quark-antiquark assignment is reversed. Due to quantum interference effects, in the Standard Model this transition occurs at almost exactly the same rate as the reverse process, with the asymmetry between them being predicted to be two parts in a hundred thousand. Finding an asymmetry that is significantly different from this value would suggest that particle-antiparticle oscillations can be indirectly affected by the presence of heavy new particles, as are predicted in new physics models.



The measured asymmetry is shown in red, the horizontal green band is the average of the LHCb and D0 measurements, and the vertical green band the average of measurements of the corresponding asymmetry for B_d mesons (the most precise of which was made by LHCb in 2014 using the Run I dataset). The yellow ellipse depicts a D0 measurement that is closely related to a linear sum of the B_s and B_d asymmetries, and could be interpreted as a hint for new physics. The direct measurements of the two asymmetries from LHCb are still consistent with the Standard Model.

Many of the oscillations can occur within the finite lifetime of the B_s mesons, and an asymmetry would therefore appear as a difference in the numbers of B_s and $\bar{B}_s$ meson decays observed by LHCb. Semi-leptonic decays into a charmed hadron, a muon and a neutrino are particularly suited, and the LHCb data set contains around two million of them. The challenge is to avoid being fooled by fake sources of asymmetry due to small imperfections in the detector. Novel methods have been developed to control these sources based on extensive use of the rich samples of signals with charm and charmonium decays.

The final measured asymmetry is $0.45\pm0.26\pm0.20\%$, which is a factor of two more precise than the next-best measurement from the D0 experiment at Fermilab (see figure). The 13 TeV data that are now being recorded will provide an increased rate of B_s and B_d mesons, which will enable LHCb to probe far smaller asymmetries and enhance its sensitivity to possible new physics effects.

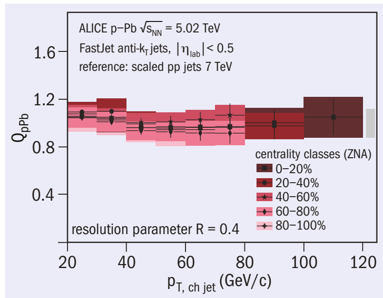
Further reading

LHCb Collaboration LHCB-PAPER-2016-013.

ALICE separates hot and cold nuclear effects

In the early stages of a high-energy collision, high-p_T partons can be created, before producing sprays of hadrons that are measured experimentally as jets. Not only do high-p_T partons carry information about the parton scattering itself, but they also serve as probes for the environment they cross. In nucleus–nucleus collisions, for instance, high-p_T partons probe the strongly interacting medium of quarks and gluons (the quark-gluon plasma, QGP). Due to the interactions of these partons with the QGP, particle production is suppressed at large transverse momentum compared to an incoherent superposition of nucleon–nucleon collisions.

Although this observation is one of the key results in heavy-ion collisions, it is *a priori* not clear to which extent the suppression is caused by hot nuclear-matter effects, such as the jet-medium interaction, and to which extent by cold nuclear-matter effects, such as the presence of the nucleus itself. Unlike in lead–lead collisions, modifications of jet production due to hot nuclear-matter effects are not expected in proton–lead collisions. Therefore, measurements of the nuclear modification of jet spectra in proton–lead collisions can be used to disentangle cold from hot nuclear-matter effects.



The centrality-differential charged-jet nuclear modification factor in proton–lead collisions at a centre-of-mass energy of 5.02 TeV. The nuclear modification factor is defined as the ratio of per-event yields in proton–lead and proton–proton collisions at the same energy, scaled by the number of binary collisions for the particular centrality bin.

ALICE has recently measured charged jet spectra and their nuclear modification in proton–lead collisions for transverse momenta within 20–120 GeV/c. The main corrections include the subtraction of a mean underlying event density and a statistical treatment of within-event fluctuations, as well as an unfolding of the detector response. One of the challenges in analysing proton–lead collisions is to be able to measure the collision geometry (called the event centrality), and also to evaluate the mean number of binary nucleon–nucleon collisions for different centralities. Several methods for centrality determination were tested in ALICE and the least-biased method was used for this measurement.

The measurement produces a clear result: for the probed acceptance, and within the systematic and statistical uncertainties, all nuclear modification factors are compatible with unity. The charged jet spectra measured in proton–lead collisions at an energy of 5.02 TeV do not show any significant centrality dependence and they scale with the jet spectra in proton–proton collisions at the same energy. Therefore, there is no evidence that high transverse momentum jets are modified by the cold nuclear medium, confirming the conclusion drawn from measurements of the nuclear modification factor for single high-transverse momentum hadrons.

Further reading

ALICE Collaboration *Phys. Lett.* B **749** 78.
ALICE Collaboration *Eur. Phys. J. C* **76** 271.
ALICE Collaboration *Phys. Rev. C* **91** 064905.

Telescopes

ESO signs largest ever ground-based astronomy contract

The light-collecting area of the E-ELT will be bigger than all existing optical research telescopes combined, while its adaptive optics system will provide images about 15 times sharper than those from the NASA/ESA Hubble Space Telescope at the same wavelength.

The European Extremely Large Telescope (E-ELT) will be the largest optical/near-infrared telescope in the world, boasting a primary mirror 39 m in diameter. Its aim is to measure the properties of the first stars and galaxies and to probe the nature of dark matter and dark energy, in addition to tracking down Earth-like planets.

At a ceremony in Garching bei München, Germany, on 25 May, the European Southern Observatory (ESO) signed a contract with the ACe Consortium for the construction of the dome and telescope structure of the E-ELT. With an approximate value of €400 million it is the largest contract ever awarded by ESO and the largest contract ever in ground-based astronomy. The occasion also saw the unveiling of the construction design of the E-ELT, which is due to enter operation in 2024.

The construction of the E-ELT dome and telescope structure can now commence, taking telescope engineering into new territory. The contract includes not only the enormous 85 m-diameter rotating dome, with a total mass of around 5000 tonnes, but also the telescope mounting and tube structure, with a total moving mass of more than 3000 tonnes. Both of these structures are by far the largest ever built for an optical/infrared telescope and dwarf all existing ones.

The E-ELT is being built on Cerro Armazones, a 3000 m-high peak about 20 km from ESO's Paranal Observatory. The access road and leveling of the summit have already been completed and work on the dome is expected to start on site in 2017.

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

CERN Courier welcomes contributions from the international particle-physics community. These can be written in English or French, and will be published in the same language. If you have a suggestion for an article, please send proposals to the editor at cern.courier@cern.ch.

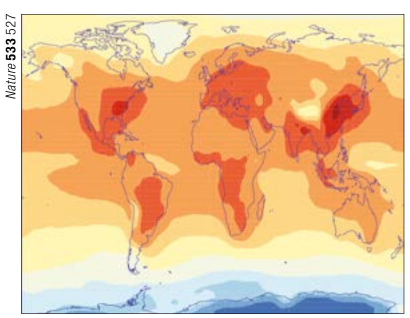
Atmospheric physics

CERN experiment points to a cloudier pre-industrial climate

New results reported in two papers in *Nature* from the CLOUD experiment at CERN imply that the pre-industrial climate may have had brighter and more extensive clouds than previously thought, sharpening our understanding of the impact of human activities on climate. CLOUD (Cosmics Leaving Outdoor Droplets) is designed to understand how aerosol particles form and grow in the atmosphere, and the effect this has on clouds and climate. It comprises a 26 m³ vacuum chamber containing atmospheric particles, into which beams of charged pions are fired from the Proton Synchrotron to mimic the seeding of clouds by galactic cosmic rays.

The increase in aerosols and clouds since pre-industrial times is one of the largest sources of uncertainty in climate change, according to the Intergovernmental Panel on Climate Change. The new CLOUD results show that organic vapours emitted by trees produce abundant aerosol particles in the atmosphere in the absence of sulphuric acid. Previously, it was thought that sulphuric acid – which largely arises from burning fossil fuels – was essential to initiate aerosol particle formation. CLOUD finds that oxidized biogenic vapours dominate particle growth in unpolluted environments, starting just after the first few molecules have stuck together and continuing all the way up to sizes above 50–100 nm, where the particles can seed cloud droplets.

The experiment also finds that ions from galactic cosmic rays enhance the production rate of pure biogenic particles by a factor of 10–100 compared with particles without ions, which suggests that cosmic rays played a more important role in aerosol and cloud formation in pre-industrial times than they do in today's polluted atmosphere.



The annual mean number concentration of soluble particles of at least 100 nm in diameter at cloud-base level.

CLOUD, which has produced a series of high-impact publications following its first results in 2011, is the first experiment to reach the demanding technological performance and ultralow contaminant levels necessary to be able to measure aerosol nucleation and growth under controlled conditions in the laboratory.

Further reading

J Kirkby *et al.* 2016 *Nature* **533** 521.
J Tröstl *et al.* 2016 *Nature* **533** 527.

Accelerators

AWAKE sees first beam

CERN's pioneering AWAKE facility, which aims to drastically reduce the scale of particle accelerators, received its first beam on 16 June. The milestone signals the next stage of commissioning for the novel experiment, which aims to use plasma wakefields driven by a proton beam to accelerate charged particles to high energies over very short distances. The proton beam had to travel around 800 m before entering a 10 m-long plasma cell, which is empty during the current commissioning phase, and then carry on downstream to several detectors. The test was a success, with protons striking the detector straight away, and the team now plans to finalize installation of the experiment, the laser and the full plasma cell. AWAKE hopes to start collecting physics data by the end of the year.

Ans Pardons/CERN

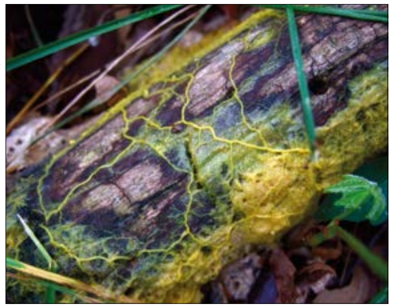
The AWAKE team in the control room as the first beam of particles is sent through the proton beamline to the experiment.

Sciencewatch

Compiled by John Swain, Northeastern University

Learning without neurons

Learning is not only the preserve of multicellular organisms with central nervous systems. According to a new study, much simpler organisms are also up to the task. Audrey Dusstour of Toulouse University in France and colleagues looked at single-celled slime moulds (*Physarum polycephalum*) crossing bridges in a Petri dish. The bridges were treated either with quinine or caffeine as a repellent, or were left untreated. The cells learnt to become accustomed to the chemicals and cross the bridges faster after a period of five days, with their "memory" lasting two days. The learning was also found to be specific: cells that were used to quinine were still averse to caffeine, and vice versa. Simple learning, it seems, does not appear to need neurons.



frankenstoen - flickr, CC BY 2.5

● **Further reading**

R P Boisseau *et al.* 2016 *Proc. R. Soc. B* **283** 20160446.

Learning has hitherto only been seen in multicellular neural organisms, not slime mould.

The longest proof

The largest mathematical proof to date is 200 terabytes in length and unlikely to be checkable by any human being. Marijn Heule of the University of Texas at Austin and colleagues considered the boolean Pythagorean-triples problem, which asks if a set of natural numbers can be divided into two parts such that no part contains three numbers that could be the lengths of the sides of a right-angled triangle. Even with sophisticated "cube-and-conquer" techniques, it took 800 processor cores about two days to complete the proof. The effort returned the answer "no", but the study also raises fundamental questions about the nature and meaning of computer proofs.

● **Further reading**

M J H Heule *et al.* arXiv:1605.00723v1.

Electron–hole collider

Quasiparticles are common in condensed-matter physics, but now it is possible to do collider experiments with them. Fabian Langer of the University of Regensburg in Germany and colleagues used femtosecond optical pulses to create excitonic electron–hole pairs in an insulated tungsten diselenide, and then used a strong terahertz field to accelerate and collide electrons with holes. Emitted photons reveal the details of the collisions, which include annihilation events analogous to those found in high-energy electron–positron collisions.

● **Further reading**

F Langer *et al.* 2016 *Nature* **533** 225.

Sneeze dynamics

High-speed imaging has enabled researchers to directly observe the mechanisms of droplet formation during sneezing. The study reveals that the break up of the fluid into droplets continues to occur outside of the respiratory tract during violent exhalations, involving a complex cascade of events from sheets to bag-bursts to ligaments and, finally, droplets. For violent sneezes, the break up into smaller droplets continues well outside of the nose, the team found. The work is important for controlling the spread of disease and challenges the common belief that respiratory droplets are formed prior to ejection.

A 1000 fps video shows the ejection of saliva and mucus 0.25 s after a sneeze.

● **Further reading**

B E Scharfman *et al.* 2016 *Exp. Fluids* **57** 24.

Imaging with muons

Cosmic muons have been used to image large objects from nuclear reactors to pyramids, thanks to their absorption within thick layers, but until now it has not been possible to image small objects. Now, Istvan Bikit of the University of Novi Sad in Serbia and colleagues have used a muon tracker and a high-purity germanium gamma spectrometer to perform the first cosmic-ray muon imaging of small objects made from low-Z elements. The study, which exploits the greater transparency of low-Z elements to secondary particles, represents a major improvement over absorption-only neutron imaging.

● **Further reading**

I Bikit *et al.* 2016 *EPL* **113** 58001.

Towards a nuclear clock

Our most precise timepieces are atomic clocks, which exploit precise atomic transitions in the microwave and optical bands. Better clocks could come from nuclear transitions, which suffer less from external perturbations, but the only feasible known nuclear state is ^{229m}Th. Now, Lars von der Wense of Ludwig-Maximilians-Universität Munich and colleagues have detected this state directly by searching for α decays in ^{233}U. The half-life was measured to be longer than 60 s and the isomeric energy constrained to be between 6.3 and 18.3 eV, raising hopes that nuclear clocks could become reality.

● **Further reading**

L von der Wense *et al.* 2016 *Nature* **533** 47.

Astrowatch

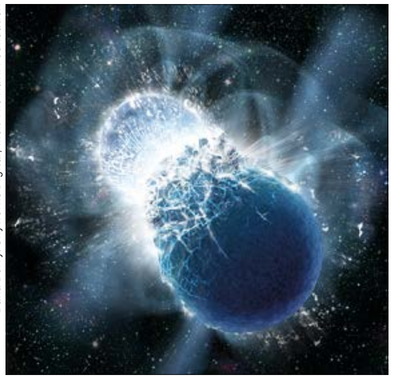
Compiled by Marc Türler, ISDC and Observatory of the University of Geneva, and CHIPP, University of Zurich

Neutron-star mergers create heaviest elements

The origin of some of the heaviest chemical elements is due to rapid neutron capture, but the precise location where this cosmic alchemy takes place has been under debate for several decades. While core-collapse supernovae were thought to be the prime production site, a new study suggests that elements heavier than zinc originate from the merger of two neutron stars. Such a dramatic event would have been responsible for the extreme heavy-element enrichment observed in several stars of an ancient dwarf galaxy called Reticulum II.

Nuclear fusion in the core of massive stars produces elements up to and including iron, which is a stable nucleus with the highest binding energy per nucleon. Building heavier nuclei requires energy to compensate for the loss of nuclear binding and is therefore almost impossible to achieve experimentally. But under certain conditions, stars can produce heavier elements by allowing them to capture protons or neutrons.

Neutron capture, which is unaffected by Coulomb repulsion, occurs either slowly (s) or rapidly (r). Slow neutron captures occur at a pace that allows the nucleus to undergo beta decay prior to a new capture, and therefore to grow following the line of nuclear stability. The r-process, on the other hand, causes a nucleus to accumulate many additional neutrons prior to radioactive decay. The relative abundance of certain elements therefore tells researchers whether nucleosynthesis followed an s- or an r-process. The rare-earth element europium is a typical r-process element, as are gold, lead and uranium.



Dana Berry/Skyworks Digital, Inc./The Kavli Foundation

Artist's impression of two neutron stars colliding – an event found to produce the heaviest elements such as gold, lead and uranium.

For the r-process to work, nuclei need to be under heavy neutron bombardment in conditions that are only found in dramatic events such as a core-collapse supernova or in mergers of two neutron stars. The supernova hypothesis has long been the most probable candidate for the r-process, whereas other scenarios involving rarer events, such as encounters between a neutron star and a black hole, have only been considered since the 1970s. One way to distinguish between the two hypotheses is to study low-metallicity galaxies in which the enrichment of heavy elements is low. This enables astrophysicists to determine if the enrichment is a continuous process or the result of rare events, which would result in stronger differences from one galaxy to the other.

Alexander Ji from the Massachusetts Institute of Technology, US, and colleagues were lucky to find extreme relative abundances of r-process elements in stars located in the ultra-faint dwarf galaxy Reticulum II. Although nearby and in orbit around the Milky Way, this galaxy was only recently discovered and found to be among the most metal-poor galaxies known. This means that Reticulum II formed all of its stars within about the first three-billion years after the Big Bang, and is therefore only enriched in elements heavier than helium by a few generations of stars.

High-resolution spectroscopic measurements of the nine brightest stars in Reticulum II carried out by the team indicate a very strong excess of europium and barium compared with iron in seven of the stars. These abundances exceed by two-to-three orders of magnitude those in any other ultra-faint dwarf galaxy, suggesting that a single rare event produced these r-process elements. The results also show that this event could be a neutron-star merger, but not an ordinary core-collapse supernova. Although it is not possible to conclude that the majority of our gold and uranium comes from neutron-star mergers, the study certainly gives more weight to such a hypothesis in the 60-year-long debate about the origin of r-process elements.

Further reading

A P Ji *et al.* 2016 *Nature* **531** 610.

Picture of the month

This beautiful image, showing an enormous bubble being blown into space by a young star, was chosen to celebrate the 26th anniversary of the Hubble Space Telescope. After so many stunning images captured by this exceptional satellite since its launch on 24 April 1990, it is difficult to surprise us. Like a soap bubble, the delicate Bubble Nebula is being blown into space by a super-hot star 45 times more massive that our Sun (located slightly off-centre on the upper-left side of the bubble). The strong stellar wind racing out at a speed of 6.4 million km/h sweeps up the cold interstellar gas in front of it, forming the outer edge of the bubble much like a snowplough piles up snow. Located in the constellation of Cassiopeia at a distance of 7100 light-years, the nebula has a diameter of seven light-years – which is about one-and-a-half times the distance from our Sun to its nearest stellar neighbour, Alpha Centauri.

NASA/ESA/Hubble Heritage Team (STScI/AURA)

Ghosts in the machine

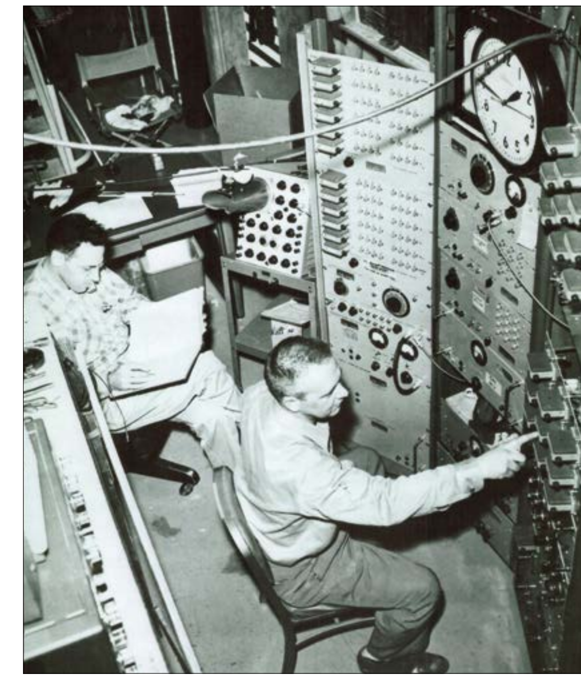
Christine Sutton describes the pioneering 1956 experiment that proved the existence of the neutrino, and how subsequent particle-beam experiments at CERN and elsewhere contributed to unearthing a further two neutrino types.

In July 1956, in a brief paper published in *Science*, a small team based at the Los Alamos National Laboratory in the US presented results from an experiment at a new, powerful fission reactor at the Savannah River Plant, in South Carolina. The work, they wrote, "verifies the neutrino hypothesis suggested by Pauli". Clyde Cowan, Fred Reines, Kiko Harrison, Herald Kruse and Austin McGuire had demonstrated for the first time that it was possible to detect neutrinos, setting in motion the new field of neutrino physics. The key ingredients were an intense source and a big detector, with more than a touch of ingenuity and patience.

More than two decades previously, in 1930, Wolfgang Pauli had proposed that the "energy crisis" in nuclear beta decay – presented by the continuous energy spectrum of the emitted electron – would be solved if the decaying nucleus also emitted a second, undetected particle. This would allow the energy released to be shared between three objects, including the recoiling nucleus, and so yield electrons with a range of energies, just as observed. The new particle had to be neutral and have a relatively small mass. Pauli called his proposal "a desperate remedy", in part because he thought that if such a particle did indeed exist, then it "would probably have long ago been seen".

Nevertheless, Enrico Fermi took the possibility seriously and based his seminal work on beta decay, published in 1934, on a point-contact interaction in which a neutron decays to a proton, electron and (anti)neutrino: $n \rightarrow p\, e^-\, \bar{\nu}$. Soon afterwards, Hans Bethe and Rudolf Peierls calculated the cross-section for the inverse reaction in which a neutrino is absorbed, but when they found a value of about $10^{-44}\,\text{cm}^2$, the pair concluded that no one would be able to detect neutrinos (Bethe and Peierls 1934). What they did not count on was the discovery of nuclear fission – which on a macroscopic scale produces copious numbers of neutrinos – or the ingenuity of experimentalists and, later, accelerator physicists.

Notoriously, nuclear fission was first applied in the atomic bombs used towards the end of the Second World War. A few years later, in 1951, Fred Reines, a physicist who had worked on the Manhattan Project at Los Alamos, began to think about how to harness the neutrinos produced during tests of atomic bombs to make a direct detection of the elusive particle. He was soon joined in this strange pursuit by Clyde Cowan, a fellow researcher at Los Alamos, after they were stranded together at Kansas Airport, where the conversation turned to the "supreme challenge" of detecting neutrinos.



Los Alamos National Laboratory

Fred Reines, left, and Clyde Cowan, at the controls of the Savannah River experiment, which discovered the electron antineutrino in 1956.

Reines had an idea to place a detector close to a bomb-test tower and use the timing of the detonation as a "gate" to minimise background. But what kind of detector? He and Cowan decided on the recently developed medium of liquid scintillator, which could both act as a target for the inverse beta-decay reaction $\bar{\nu}\, p \rightarrow e^+\, n$, and detect the emitted positrons via their annihilation to gamma rays. It was an audacious plan, not only in taking advantage of a bomb test but also in scaling up the use of liquid scintillator, which until then had been used only in quantities of about a litre. Reines and Cowan named it "Project Poltergeist", to reflect the neutrino's ghostly nature.

Remarkably, the Los Alamos director gave approval for the experiment. However, in late 1952, Cowan and Reines were urged to reconsider the more practical idea of using antineutrinos from a nuclear reactor. The challenge was to work out how to reduce the ▷

Los Alamos National Laboratory

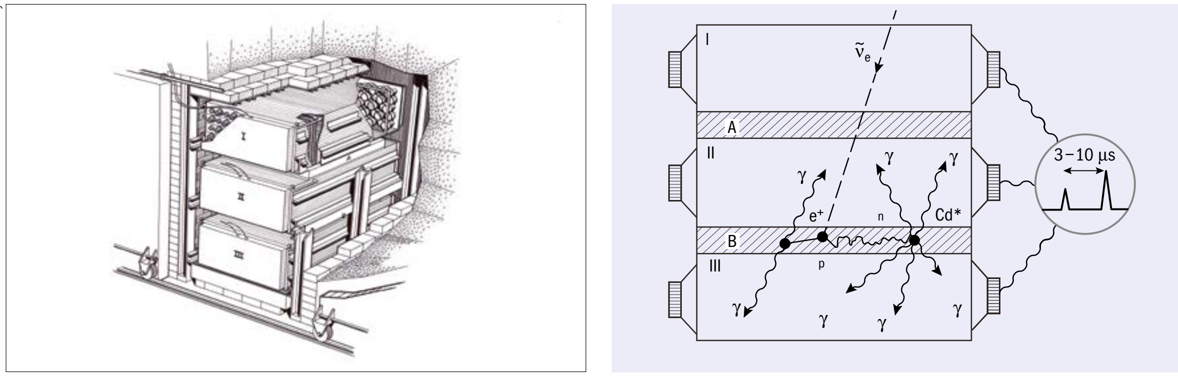


Fig.1. (Left) The detector used at Savannah River consisted of three 1400-litre tanks of liquid scintillator (I, II and III), each viewed by 100 phototubes. The smaller tanks (A and B) contained the targets of 200 litres of water doped with cadmium. (Right) The principle of the delayed-coincidence method for detecting the electron antineutrino in the experiment at Savannah River.

backgrounds, because the antineutrino flux from a reactor would be thousands of times smaller than that from a nuclear explosion. Reines and Cowan realised that in addition to looking for positron annihilation, they could also detect the neutrons through neutron capture – a process that is delayed for several microseconds, thanks to the neutron's random walk through a medium prior to interacting with a nucleus. In particular, the addition of cadmium to the detector would increase the likelihood of capture and lead to the emission of gamma rays. The signature for inverse beta decay would then be a delayed coincidence between two sets of gamma rays: one from the positron's annihilation and the other from the neutron's capture.

The detector for Project Poltergeist contained 300 litres of liquid scintillator with added cadmium chloride, viewed by 90 photomultiplier tubes, and was set up in 1953 at a new reactor at the Hanford Engineering Works in Washington State. This initial experiment showed a small increase in delayed coincidences when the reactor was operating compared with the situation when it was turned off, but it was set against a cosmic-ray background that was more than 10 times higher than the expected signal rate (Reines and Cowan 1953).

This tantalising result encouraged a still more determined effort, with a new detector design that was basically a sandwich with three layers of liquid scintillator and two layers of water with added cadmium chloride to act as the target (figure 1). Positrons produced in a neutrino interaction would be detected almost immediately via two back-to-back gamma rays in the adjacent scintillator tanks, which would be followed a few microseconds later by another burst of gamma rays in the same two scintillator tanks, this time from neutron capture.

On 14 June 1956, Reines and Cowan sent a jubilant telegram to Pauli in Zurich

The second experiment ran at the newly completed Savannah River Plant for a total of 1371 hours in 1956 and, when the reactor was on, it recorded nearly three delayed coincidences per hour (Cowan *et al.* 1956). After completing many checks, on 14 June 1956 Reines and Cowan sent a jubilant telegram to Pauli in Zurich, informing him that they had "definitely detected neutrinos from fission fragments by observing inverse beta decay of protons". At the time, Pauli was in fact at a meeting at CERN, to where the telegram was forwarded, and he reportedly interrupted the meeting to read out the good news, later celebrating with a case of champagne (Reines 1979).

The move to accelerators

At the time of the neutrino's discovery, laboratories such as CERN and Brookhaven were on their way to building proton synchrotrons that would have sufficient energy and intensity to form beams of neutrinos via decays of pions and kaons produced when protons strike a suitable target. The muons produced in the decays could be stopped by large amounts of shielding, allowing only neutrinos to penetrate to experiments beyond. At Brookhaven, this led to the discovery at the Alternating Gradient Synchrotron (AGS) in 1962 that the neutrinos produced in association with electrons (as in beta decay) are different from those produced in association with muons (as in pion decay): a second type of neutrino, the muon neutrino, had been discovered.

In 1963, an ingenious way to produce neutrino beams of greater intensity first came into use at the Proton Synchrotron (PS) at CERN, where Simon van der Meer had described his concept of the neutrino horn a couple of years earlier (van der Meer 1961). Because neutrinos are electrically neutral, they cannot be focused into a beam using magnets, so he devised instead a way to focus the parent pions and kaons using magnetic fields set up by currents circulating in a metallic cone-shaped "horn" (*CERN Courier* June 2011 p24). The device concentrated neutrinos produced as the charged particles decayed in flight into a beam, and because it could focus either positive or negative particles, it produced an almost pure beam of neutrinos (from positive parents) or antineutrinos (negative parents). A second technical innovation at CERN enabled the horn to become a formidable device: the technique of "fast ejection", devised by Berend Kuiper and Günther Plass, could direct all of the protons from one cycle of the PS onto the target at the mouth of the horn (Kuiper and Plass 1959). By mid-1963, thanks to these innovations, CERN had what was at the time the world's most intense neutrino beam.

In the 1970s, the combination of the neutrino beam from the PS and Gargamelle – the large bubble chamber built at the Saclay Laboratory by a team led by André Lagarrigue – led to the discovery of weak neutral currents (*CERN Courier* September 2009 p25), thereby providing crucial experimental support for the unification of the weak and electromagnetic forces. The neutrino experiments with Gargamelle also produced key evidence about the existence of quarks and, in particular, their fractional charges (*CERN Courier* April 2014 p24). Then, in 1977, the Super Proton Synchrotron (SPS) became the source of neutrino beams at higher energies, and for the next 21 years a series of experiments in CERN's West Area used neutrinos in experiments covering a broad range of physics, from neutral currents and the quark structure of matter through quantum chromodynamics to neutrino oscillations (*CERN Courier* December 1998 p28).

Around that time, physicists at Fermilab were closing in on a third neutrino type. The DONUT experiment (Direct Observation of the NU Tau) detected neutrinos produced at the Tevatron, and in 2000, the collaboration announced the discovery of the tau neutrino. Although experiments at CERN's Large Electron–Positron collider had already established from precise measurements of the Z boson that there are three light neutrino types, the observation of the tau neutrino completed the leptonic sector of the Standard Model.

Ten years later, CERN was again setting records for neutrino beams, with the CERN Neutrinos to Gran Sasso (CNGS) project, which directed an intense beam of muon-neutrinos (ν_μ) to two experiments, ICARUS and OPERA, in the Gran Sasso National Laboratory in Italy about 730 km away. CNGS followed the same principle as CERN's early record-breaking beam, this time with protons from the SPS. Following first commissioning in 2006 (*CERN Courier* November 2006 p20), the facility ran for physics from 2008 to the end of 2012, and achieved a maximum beam power of 480 kW – the most powerful at the time. A total of 18.24×10^{19} protons were delivered on target, and the OPERA experiment detected 19,500 neutrino events – with five among them identified as a tau neutrino (ν_τ), thereby firmly establishing the direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations (*CERN Courier* July/August 2015 p6).

A bountiful legacy

Since the first glimpses of antineutrino interactions 60 years ago in reactor experiments, experiments have gone on to detect neutrinos and antineutrinos produced in a variety of ways – both in beams created at particle accelerators and also naturally by reactions in the Sun, interactions of cosmic rays in the Earth's atmosphere and, most recently, astrophysical processes. We now know that neutrinos exist not only in three flavour eigenstates – electron (ν_e), muon (ν_μ) and tau (ν_τ) – but also in different mass eigenstates (ν_1, ν_2 and ν_3) with very small masses, and that they can oscillate from one flavour to another through quantum-mechanical mixing (see p34).

Reactor experiments – in particular Double Chooz in France, the Daya Bay Reactor Neutrino Experiment in China (figure 2) and the Reactor Experiment for Neutrino Oscillation (RENO) in South Korea – are still as relevant now as they were in Cowan and Reines' day. Modern nuclear power plants produce about 10^{20} electron antineutrinos ($\bar{\nu}_e$) per second and experiments based on the same liquid-scintillator concept continue to provide essential contributions to neutrino physics by looking for the "disappearance" of the $\bar{\nu}_e$.

Sixty years after the first detection of the neutrino, and more than 80 years after the particle was tentatively predicted, experiments with neutrinos continue to have a leading role in particle physics. Today, experimentalists around the world are vying to determine precisely the mixing parameters of the neutrino, including the masses. The measurements may prove to hold the answers to some key questions in the field – ensuring that the "supreme challenge" of creating and detecting neutrinos will remain a worthwhile and exciting pursuit for the foreseeable future.

Roy Kaltschmidt/LBNL

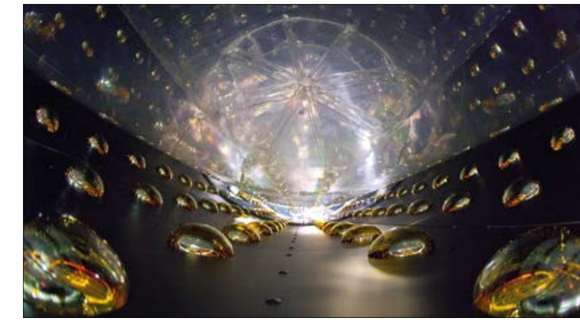


Fig.2. One of eight detectors at the Daya Bay Reactor Neutrino Experiment in China, which are situated within 1.9 km of six nuclear reactors. A larger follow-up experiment called the Jiangmen Underground Neutrino Observatory (JUNO) is currently under development.

● Further reading

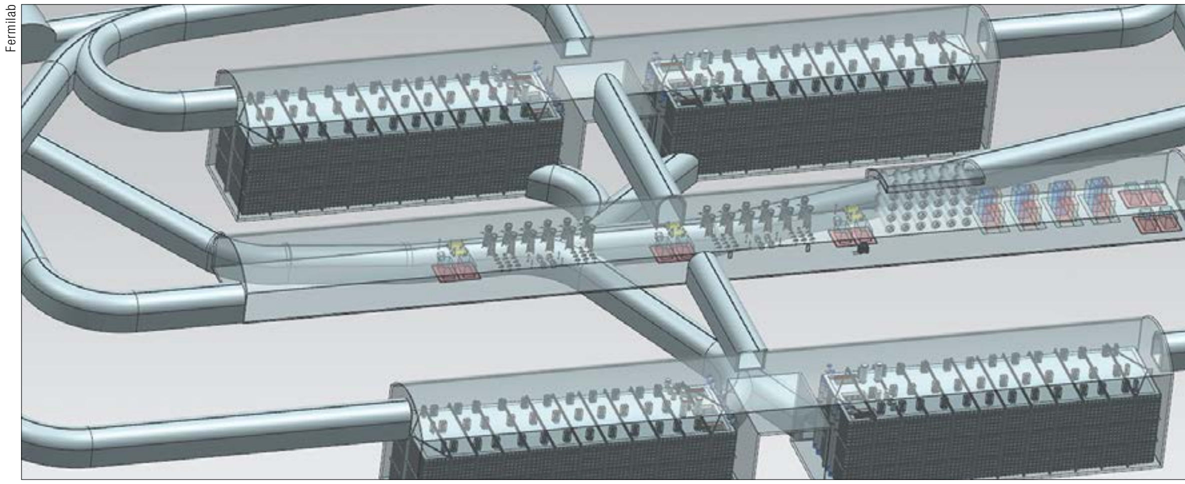
H Bethe and R Peierls 1934 *Nature* **133** 532.
C L Cowan *et al.* 1956 *Science* **124** 103.
F Reines and C L Cowan 1953 *Phys. Rev.* **90** 492.
F Reines 1979 *Science* **203** 16.

Résumé

Des fantômes dans la machine

En 1956, Frederick Reines et Clyde Cowan découvrirent le neutrino en menant une expérience auprès d'un réacteur sur le site de Savannah River (États-Unis), plus de 25 ans après la première prédiction de son existence. Il s'agissait d'une expérience pionnière, dont les principes sont utilisés encore aujourd'hui pour les expériences neutrino modernes auprès de réacteurs. Après cette découverte, les physiciens ont commencé à chercher d'autres manières d'étudier les neutrinos, notamment en utilisant des faisceaux de particules créés à cet effet, développés d'abord au CERN et à Brookhaven (États-Unis). Cette méthode a permis de découvrir le neutrino muonique et le neutrino tauique, respectivement en 1962 et en 2000. Aujourd'hui, divers autres types d'expériences neutrino sondent les propriétés de ces particules si insaisissables.

Christine Sutton, former editor of the *CERN Courier* and author of *Spaceship Neutrino* (CUP 1992).



Fermilab

CERN is collaborating on R&D for the DUNE far detector, which will consist of four cryogenic modules each holding more than 10,000 metric tonnes of active liquid argon. A central utility cavern will house the cryogenics and other systems.

Neutrinos take centre stage

Established in 2013 following recommendations from the European Strategy document, the CERN Neutrino Platform ensures Europe's participation in next-generation long- and short-baseline neutrino experiments in Japan and the US, report **Matthew Chalmers** and **Stefania Pandolfi**.

When CERN was founded in 1954, the neutrino was technically still a figment of theorists' imaginations. Six decades later, neutrinos have become the most studied of all elementary particles. Several new and upgraded neutrino-beam experiments planned in Japan and the US, in addition to the reactor-based JUNO experiment in China, aim to measure vital parameters such as the ordering of the neutrino masses and potential CP-violating effects in the neutrino sector. In support of this effort, CERN is mounting a significant R&D programme called the CERN Neutrino Platform to strengthen European participation in neutrino physics.

CERN has a long tradition in neutrino physics. It was the study of neutrino beams with the Gargamelle detector at CERN in 1973 that provided the first evidence for the weak neutral current, and in the late 1970s, three experiments – BEBC, CDHS and CHARM – used a beam from the SPS to further unveil the neutrino's identity. A milestone came in 1989, when precise measurements at the Large Electron–Positron Collider showed that there are three, and only three, types of light neutrinos that couple to the Z boson. This was followed by searches for neutrino oscillations at NOMAD (also known as WA96) and CHORUS (WA95) during the 1990s, which were eventually established by the Super-Kamiokande collaboration in Japan and the Sudbury Neutrino Observatory in Canada. More recently, from 2006 to 2012, CERN sent a muon-neutrino beam to the ICARUS and OPERA detectors at the Gran Sasso National Laboratory, 732 km away in Italy. The main goal was to observe the transformation of muon neutrinos into tau neutrinos, which was confirmed by the OPERA collaboration in 2015.

Following the recommendations of the European Strategy for Particle Physics in 2013, CERN inaugurated the neutrino platform at the end of 2014. Its aim is to provide a focal point for Europe's contributions to global neutrino research by developing and prototyping the next generation of neutrino detectors. So far, around 50 European institutes have signed up as members of the neutrino platform, which sees CERN shift from its traditional role of providing neutrino beams to one where it shares its expertise in detectors, infrastructure and international collaboration.

"The neutrino platform pulls together a community that is scattered across the world and CERN has committed significant resources to support R&D in all aspects of neutrino research," says project leader Marzio Nessi. Specifically, he explains, ▷

CERN Neutrino Platform: in summary

The CERN Neutrino Platform offers a unique opportunity to build a strong European neutrino community, with immediate physics potential coming from the short-baseline experiments at Fermilab in the US and the new near detector at T2K in Japan. The platform is also making a major contribution to the infrastructure of Fermilab's Long-Baseline Neutrino Facility (LBNF), including the design and construction of a large LBNF cryostat to be placed underground at the Sanford Underground Research Facility, new large detector prototypes and generic R&D on new detectors and data handling. CERN and Europe will therefore participate fully in the construction, commissioning and physics exploitation of the new high-intensity facility. In addition to R&D for the LBNF/DUNE cryostat, the neutrino platform currently has five approved participants:

- WA104, ICARUS far detector for Fermilab's short-baseline programme;
- WA105, the engineering prototype for a double-phase LAr-TPC;
- PLAFOND, a generic R&D framework;
- ProtoDUNE, the engineering prototype for a single-phase LAr-TPC;
- BabyMIND, a muon spectrometer for the WAGASCI experiment.

CERN is using the organisational model of the LHC to help in developing an international project on US soil and to contribute to neutrino programmes in Japan and elsewhere. "This is precisely what CERN is about," says Nessi. "The platform provides a structure at CERN to foster active involvement of Europe and CERN in the US and Japanese facilities."

In December 2014, CERN and the Italian National Institute for Nuclear Physics (INFN) took delivery of the 760 tonne ICARUS detector, which formerly was located at Gran Sasso. The detector is currently being refurbished by the neutrino platform's WA104 team and in 2017 it will be shipped to Fermilab in the US to become part of a dedicated short-baseline neutrino (SBN) programme there. This programme was approved following unexpected results from the LSND experiment at Los Alamos National Laboratory in the 1990s, which hinted at the existence of a fourth – possibly "sterile" – type of neutrino. The result was followed up by the MiniBooNE experiment at Fermilab, which also saw deviations – albeit different again – from the expected signal.

ICARUS will be installed just behind the previous MiniBooNE site, some 600 m downstream from the source of the beam at Fermilab's booster ring. It will be the farthest of three detectors in the line of the beam after the Short Baseline Neutrino Detector (SBND, which is currently under design) and MiniBooNE's successor MicroBooNE (which is already operational). All three detectors employ liquid-argon time projection chambers (LAr-TPCs) to study neutrino oscillations in detail. ICARUS comprises two 270 m^3 modules filled with liquid argon: when an energetic charged particle passes through its volume it ionises the liquid and a uniform electric field causes electrons to drift towards the end plates, where three layers of parallel wire planes oriented at different angles (together with the drift time) allow researchers to reconstruct a 3D image of the event.

The refurbishing campaign at CERN concerns many parts of

CERN

One of two 270 m^3 modules for the ICARUS detector being refurbished by CERN and INFN, which will soon be filled with liquid argon to track neutrinos produced at Fermilab's short-baseline neutrino programme.

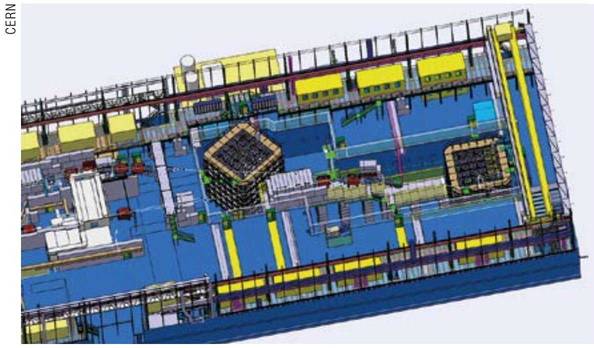
the ICARUS experiment: the photomultipliers, the read-out electronics, the cathode plane and the argon recirculating system. Moreover, it will benefit from European expertise in automatic event reconstruction and the handling of large data sets. Finally, the unique cryostat in which ICARUS will be placed is also being assembled at CERN. "Improving the performances of a detector already successfully operating in the Gran Sasso underground laboratory is extremely challenging in many respects," says ICARUS technical co-ordinator Claudio Montanari. "Indeed, in order to make it fully functional to operate on surface, many different aspects including data acquisition, background rejection, timing and event reconstruction needed to be rethought."

Going deeper

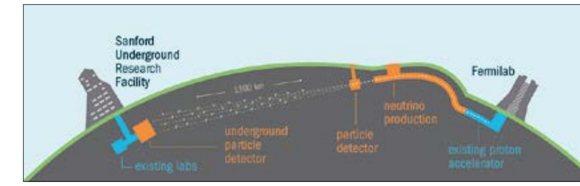
Rapid progress made in understanding neutrino oscillations during the past 15 years has also provided a strong case for long-baseline neutrino programmes. A major new international project called DUNE (Deep Underground Neutrino Experiment), which is estimated to begin operations by approximately 2026 as part of Fermilab's Long Baseline Neutrino Facility (LBNF), will take the form of a near and a far multikiloton detector. The far detector will consist of four 10 kt active LAr-TPC modules sited in a 1.5 km-deep cavern at the Sanford lab in South Dakota, 1300 km away, at which neutrino beams with unprecedented intensities will be fired through the Earth from Fermilab. While the three experiments in the SBN programme will look for the disappearance of electron and muon neutrinos to search for sterile neutrinos, they will also serve as a stepping stone to the large LAr modules required by LBNF. The LBNF/DUNE experiment will allow not just the neutrino-mass hierarchy to be determined but also CP violation to be looked for in the leptonic sector, which could help to explain the missing baryonic matter in the universe.

The neutrino platform pulls together a community that is scattered across the world.

The CERN Neutrino



CERN



Fermilab

(Left) CERN is building a dedicated test facility called ENH1, due to be completed in 2017, which will enable R&D on the DUNE prototype modules and other detector development. (Above) The DUNE experiment will study neutrino beams produced at Fermilab 1300 km away.

Platform is building two large-scale prototypes – single-phase and double-phase ProtoDUNE modules – to enable LAr detectors to be scaled up to the multikiloton level. The cryostat for such giant detectors is a particular challenge, and led physicists to explore a novel technological solution inspired by the liquified-natural-gas (LNG) shipping industry. CERN is currently collaborating with French firm Gaztransport & Technigaz, which owns the patent for a membrane-type containment system with two cryogenic liners that support and insulate the liquid cargo. Although this containment system has the advantage of being modular, the challenge in a particle-physics setting is that the cryostats not only have to contain the liquid argon but also all of the detectors and read-out electronics.

Global connection

While the single-phase ProtoDUNE detector uses technology that is very similar to that in ICARUS, a second neutrino-platform project called WA105 aims to prototype the new concept of a "dual-phase" LAr time projection chamber (DLAr-TPC), which is being considered for one or more of the DUNE far-detector 10 kt modules. In a DLAr chamber, a region of gaseous argon resides above the usual liquid phase. Ionisation electrons drift up through the detector volume and are accelerated into the gaseous region near the top of the cryostat by a strong electric field. Here, large electron multipliers amplify the signals, while the anode collects the charged particles and provides the spatial read-out. "The ProtoDUNE tests foreseen at the CERN Neutrino Platform represent the culmination of more than a decade of R&D towards the feasibility of very large liquid-argon time projection chambers for next-generation long-baseline experiments," says André Rubbia, co-spokesperson of the DUNE collaboration.

ProtoDUNE and WA105 are planned to be ready for test beam by 2018 at a new EHN1 test facility currently under construction in the north area of CERN's Prévessin site. Most of the civil-engineering work to extend the EHN1 building is complete and all components are under procurement or installation, with staff expected to move in towards the end of the year. The test facility was financed by CERN, with two beamlines due to be commissioned in late 2017.

As ICARUS prepares for its voyage across the Atlantic, and the detectors for the next-generation of US neutrino experiments takes shape, the CERN Neutrino Platform is also working on components for Japan's neutrino programme (see p29). The Baby-MIND collaboration aims to construct a muon spectrometer – a state-of-the-art prototype for a would-be Magnetized Iron Neutrino Detector (MIND) – and characterise it in a charged-particle beam at CERN. The system will be assembled at CERN during the winter and tested in May next year, before being shipped to Japan in the summer of 2017. Once there, it will become part of the WAGASCI experiment, where it will contribute to a better understanding of the systematics for the T2K neutrino and antineutrino oscillation analysis. Baby-MIND was approved by the CERN research board in December last year as a Neutrino Platform experiment. "Other projects for the Japanese neutrino programme are also under discussion," says Baby-MIND spokesperson Alain Blondel of the University of Geneva.

Finally, in June it was decided that the CERN Neutrino Platform will also involve a neutrino-theory working group to strengthen the connections between CERN and the worldwide community and help to promote research in theoretical neutrino physics at CERN. "Fundamental questions in neutrino physics, such as the existence of leptonic CP violation, the Majorana nature of neutrinos and the origin of neutrino masses and mixings, will be at the centre of research activities," explains group-convener Pilar Hernández. "The answers to these questions could have essential implications in other areas of high-energy physics, from collider physics to indirect searches, as well as in our understanding of the universe."

- CERN Neutrino Platform: cenf.web.cern.ch.
- Theory working group: th-dep.web.cern.ch/cern-neutrino-platform-theory-working-group-cenf-th.

Résumé

Les neutrinos sur le devant de la scène

Suivant les recommandations de la stratégie européenne 2013 pour la physique des particules, la plateforme neutrino du CERN a été inaugurée fin 2014. Elle vise à servir de pôle pour la participation de l'Europe à la recherche mondiale sur les neutrinos, en vue de développer la prochaine génération de détecteurs de neutrinos. Jusqu'ici, environ 50 instituts européens se sont engagés à participer au projet de plateforme neutrino. Dans ce cadre, le CERN ne fournit pas de faisceaux de neutrinos, mais offre ses compétences en matière de détecteurs, d'infrastructure et de collaboration internationale, au bénéfice notamment de la prochaine génération d'expériences neutrino longue et courte distance au Japon et aux États-Unis.

Matthew Chalmers and **Stefania Pandolfi**, CERN.

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DUMAND and the origins of large neutrino detectors

Forty years ago at a workshop in Hawaii, many of the concepts underlying today's deep-underground and underwater neutrino detectors were formulated. **John Learned** and **Christian Spiering** describe how the event laid the foundations for some of the great discoveries in neutrino physics.

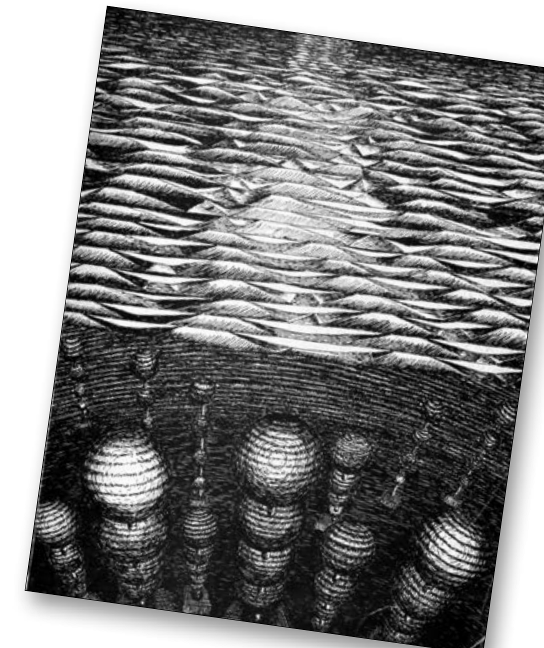
In 1976, neutrinos did not yet have the prominent role in particle physics that they play today. Postulated by Pauli in 1930, they had been said to be undetectable due to their tiny interaction probability, and were only first observed in the mid-1950s by Fred Reines and Clyde Cowan using a detector located close to a military nuclear reactor. In 1962, researchers at Brookhaven National Laboratory discovered a second type of neutrino, the muon neutrino, but the third (tau) neutrino would not be seen directly for a further 38 years. On the other hand, the theory of electroweak interactions mediated by the W and Z bosons was firming up, and measurements of neutrinos played a significant role in this context.

The first naturally generated neutrinos, originating from cosmic-ray collisions in the Earth's atmosphere, were observed in 1965 in deep gold mines located in South Africa and India. Also in the late 1960s, Ray Davis was beginning his famous solar-neutrino observations. The time was right to start thinking seriously about neutrino astronomy.

Enter DUMAND

Plans that ultimately would shape the present-day neutrino industry blossomed in September 1976 at a meeting in Waikiki, Hawaii. It was here that some of the first ideas for large detectors such as the gigaton DUMAND (Deep Underwater Muon and Neutrino Detector) array, which eventually morphed into the present-day IceCube experiment at the South Pole, were envisioned. The technology for smaller water-filled detectors such as IMB (Irvine–Michigan–Brookhaven) and, later, Kamiokande in Japan, were also laid out in detail for the first time. Moreover, totally new concepts such as particle detection via sound waves or radio waves were explored.

The first organised stirrings of what was to become DUMAND took place at a cosmic-ray conference in Denver, Colorado, in 1973, which led to a preliminary workshop at Western Washington University in 1975. It was at this meeting that the detection of Cherenkov radiation in water was chosen as the most viable method to "see" neutrino interactions in a transparent medium, with some deep lakes and the ocean near Hawaii considered to be good locations. This detection principle goes back to Russian physicists Moisey Markov and Igor Zheleznykh in 1960: water provides the target for neutrinos, which create charged particles that generate a flash of light in approximate proportion to the neutrino energy. The water also shields the many downward-moving muons from cosmic-ray interactions in the atmosphere. With light detectors, such as a basketball-sized photomultiplier tube, one could register the light flash over large distances. ▷



Cover art from the DUMAND conference proceedings, showing the basic undersea neutrino-detection principle. (Image credit: Rene Donaldson, Fermilab.)

Anatoly Pethruhkin

Attendees of the 1976 workshop, showing Fred Reines (back, second from left) and one of the present authors, JL (back, third from left). Other attendees included theorist Venyamin Berezinski; cosmic-ray experts Alexander Chudakov, Boris Dolgoshein and Anatolij Petrukhin from Moscow; Saburo Miyake (founder of ICRR in Tokyo, later home of Kamiokande); and astronomer G A Tamman. US particle-physicists Ted Bowen, Sidney Bludman, David Cline, Marshall Crouch, Howard Davis, Richard Davisson, Vernon Jones, Peter Kotzer, Ken Lande, Karnig Mikaeilian, M Lynn Stevenson, Larry Sulak and Dave Yount were joined by astronomers and astrophysicists David Schramm, Ivan Linscott, Rein Silberberg and Craig Wheeler.

The vision of building devices larger than any yet dreamed about, and placing them in the deep ocean to study the cosmos above, attracted many adventurous souls from around the US and elsewhere, a number of whom dedicated years to realising this dream. One of us (JL) joined Reines, along with Howard Blood of the US navy and other ocean-engineering aficionados – in particular, George Wilkins, who was responsible for the first undersea fibre-optic cables. Inventor of the wetsuit and former bubble-chamber developer Hugh Bradner became another driving force behind the project. Theorists, cosmic-ray experts, particle physicists, astronomers and astrophysicists all played important roles (see photograph above). The event captured a spirit of adventure and worldwide co-operation, particularly concerning interactions between US and Soviet colleagues, and the special nature of our unusual international physics collaboration brought a certain level of spice to relations.

Searching the sky

A significant problem of the era was to know what sources of neutrinos the detectors should be looking for. Astrophysicists and astronomers seldom thought about neutrinos at the time, and neutrinos were neglected in calculations of radiation and power in the universe. They were, however, included in studies of solar burning and supernovae, and it was from these efforts that neutrinos began to appear in the astronomer's lexicon. For the first time, a survey of possible astrophysical sources of lower-energy neutrinos (typically 1–100 MeV) was produced at the 1976 meeting, which were organised by Craig Wheeler into seven possible steady sources and eight potential burst sources.

For the steady sources, only solar neutrinos and terrestrial radioactivity appeared practical for detecting neutrinos. For the bursting neutrino sources, galactic gravitational collapses clearly yielded the most available total power for neutrinos. The others – namely type I supernovae, solar flares, gamma- and X-ray bursts and mini-black-hole evaporation – did not seem to have enough power and proximity to be competitive. Even today, these sources have not been observed in terms of neutrinos.

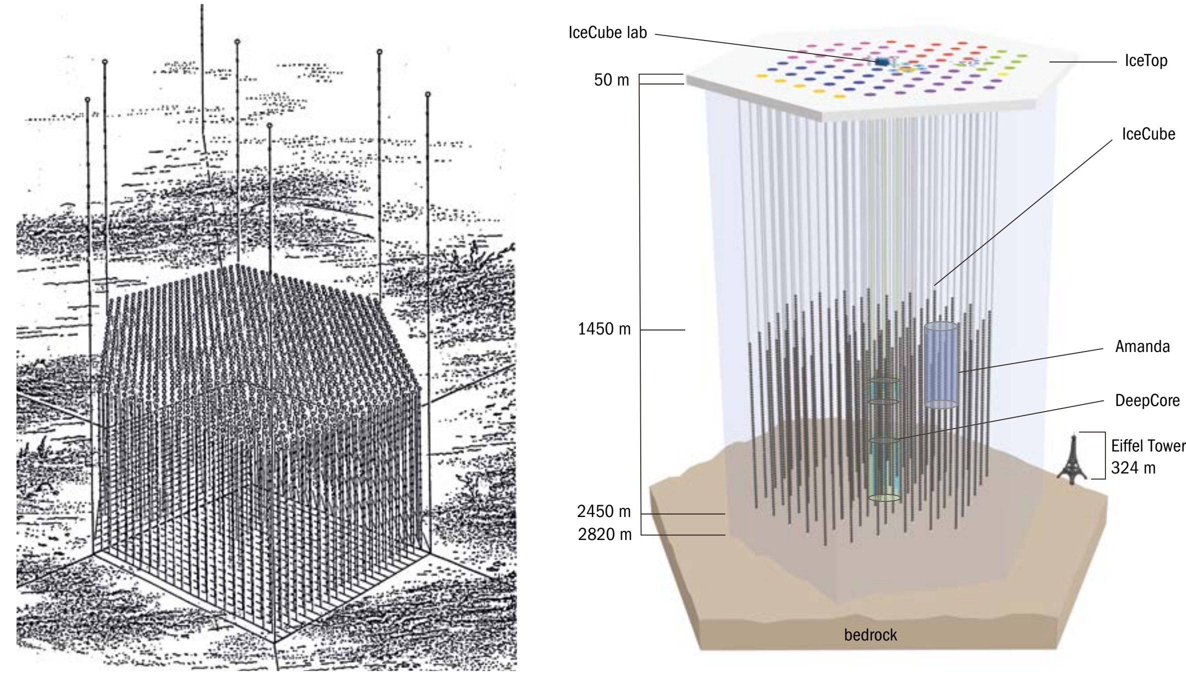
There was also great interest in targeting high-energy (TeV and above) neutrinos, but predictions of the strengths of the potential sources were plagued by huge uncertainties. It was known that the number of cosmic rays impinging upon the Earth decreases as a function of energy up to values of around 10^{20} eV, whereupon the spectrum was predicted to show a cut-off known as the Greisen–Zatsepin–Kuzmin (GZK) limit caused by high-energy protons being degraded by resonant collisions with the cosmic microwave background. Veniamin Berezinsky of the Lebedev Institute in Moscow put forward some prescient models of ultra-high-energy neutrino generation, in particular, those generated in GZK processes, and also gave first estimates of upper bounds on neutrinos from star formation in the early universe. Credible sources of neutrinos with energies far beyond the TeV scale were probably too far ahead of people's visions at the time, while neutrino cross-sections and even the production dynamics were not well defined at the highest energies.

A significant problem was to know what sources of neutrinos the detectors should be looking for.

By the end of the Hawaii workshop, which lasted for two weeks, everyone considered low-energy neutrino detection to be the most worthwhile cosmic-neutrino-detection goal. Aside from solar neutrinos, it was also agreed that neutrinos from supernova collapses were the most likely to be seen (as they later were in 1987, when a burst of neutrinos was observed by the IMB, Kamiokande and Baksan detectors). But it was also realised that this effort requires kiloton detectors with threshold sensitivities of about 10 MeV to guarantee a few supernovae per century. Regarding the detection of high-energy neutrinos in the TeV range, as expected from acceleration processes in galactic and extragalactic objects, everyone understood the necessity of detectors in the megaton to gigaton class. This was so far beyond the reach of technology at the time, however, that people realised they had to start small and work upwards in target mass.

Interestingly, neutrinos generated in the atmosphere with energies in the GeV range were regarded as the least interesting target. Nobody at that time would have expected that precisely these neutrinos, together with solar neutrinos, would demonstrate for neutrino oscillations and lead to the award of the 2015 Nobel Prize in Physics.

IceCube

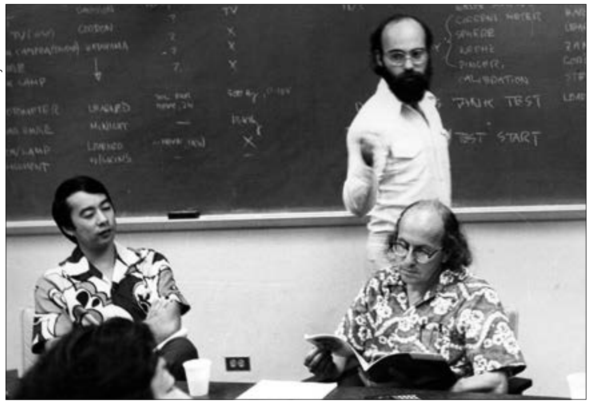


The original DUMAND project (left), which was cancelled in 1995, and the present-day IceCube experiment located at the South Pole (right). Although there are no formal links between the two experiments, their configurations bear strong similarities.

Detector evolution

Considering the vast target volumes required for high-energy neutrino astronomy, it became clear that the most promising – and most affordable – detection method was to register the Cherenkov light in natural water. With the intensity of Cherenkov light being around 30 times weaker than that from a scintillator, however, the design of the optical detectors became paramount. One group of attendees from the 1976 workshop aimed for the use of wavelength shifters that absorb blue light and re-emit green light, allowing the use of modest photodetectors, while another pushed for the development of photomultipliers larger than the 25 cm-diameter versions available at the time – as did in fact transpire. The one serious alternative to optical Cherenkov light detection, building on a concept developed by Gurgen Askaryan in 1957, was to utilise the pulse of sound made by neutrino progeny after neutrino collision with a nucleus of water or another medium such as ice.

Following the 1976 event, annual neutrino workshops were held for about a decade, eventually blending with DUMAND collaboration meetings. The 1978 workshop, held in La Jolla, California, took place in three sessions over a six-week period, and attracted more neutrino converts from physics, astrophysics and ocean engineering. The following year's event, which was held at Khabarovsk and Lake Baikal in Siberia, offered some physicists their first chance to interact with Soviet physicists who had not been able to travel. Indeed, by the end of 1979, international politics and in particular the Soviet–Afghan war had forced the separation of the Russian and US DUMAND efforts. Russian DUMANDers decided to push ahead with a detector array deployed from ice in the world's deepest freshwater lake, Lake Baikal, and one of us (CS) joined the Baikal collaboration in 1988. A few years later, the first underwater neutrino events were identified in Lake Baikal, and the principle of this detection technique was finally proven (followed by more statistics from AMANDA at the South Pole and ANTARES in the Mediterranean Sea). The heroic efforts ▷



Anatoly Pethruhkin

DUMAND'76 was of paramount importance for building personal bonds and stirring ideas. Here: John Learned at the blackboard, with Jed Hirota (left) and Dick Davisson.

of Russian physicists through difficult times have continued for 35 years, and Baikal researchers have just deployed the first subunit of a cubic-kilometre array similar to IceCube.

The formal outcome of the 1976 workshop was a joint resolution and plans for ocean studies and further workshops. The major vision for the high-energy DUMAND detector itself (see diagram, previous page) was an array of bottom-moored strings carrying some 22,000 optical detectors distributed in a volume slightly larger than one cubic kilometre – quite similar to the eventual IceCube array. The DUMAND project carried out many ocean studies and also accomplished some physics offshore in Hawaii, measuring muons and the lack of large bursts.

Alas, DUMAND was cancelled by the US Department of Energy in 1995, prior to starting full deployment. One can debate the causes – the failure of the first deployed string was certainly one aspect. It may be noted, however, that the Superconducting Supercollider had just been cancelled and that the main funding agencies were simply not supportive of non-accelerator research until after SuperKamiokande's discovery of neutrino oscillations in 1998. The DUMAND project was also ahead of its time in terms of its detection scheme, the use of undersea fibre optics and robotic module deployment.

The DUMAND legacy

Attendees of DUMAND'76 realised the importance of the venture, but probably came away with varying levels of belief in its practicality. Perhaps the greatest legacy of the 1976 workshop was bringing natural neutrino studies to the attention of a wide research community, and astrophysicists in particular. The breadth of ideas that this allowed, and the spirit of interdisciplinarity and international co-operation, has continued in the neutrino community. Moreover, initially still-born alternatives for neutrino detection have been revived in the last two decades.

The neutrino-detection method using acoustic signals was taken up in the late 1990s and early 2000s using military hydrophone arrays close to the Bahamas and to Kamchatka, as well as dedicated test set-ups in Lake Baikal, the Mediterranean Sea and in Antarctic ice – namely, the South Pole Acoustic Test Setup (SPATS). More profitably, the radio technique of detecting high-energy neutrino interactions via the negative charge excess in a very-high-energy particle shower induced by a neutrino interaction has allowed stringent upper limits to be placed on neutrino fluxes at the highest energies. The Askaryan Radio Array (ARA), the balloon-borne ANITA project and ARIANNA all focus on radio detection in Antarctic ice. Indeed, ANITA has just reported the first candidate for a super-high-energy neutrino event emerging from the Earth at a large angle.

Probably the most important lineage descending from the 1976 workshop is in the exploitation of the large water Cherenkov detectors located underground: IMB (1983), Kamiokande (1985) and, most notably, SuperKamiokande (1996). Some other experiments can be claimed as at least partial progeny of the early DUMAND enterprises, such as NESTOR in the Mediterranean, the Sudbury Neutrino Observatory (SNO) in Canada and KamLAND in Japan. The links become more tenuous, but the people engaged all owe much stimulation and experience to the explorations of these problems and detector solutions 40 years ago.

As for DUMAND itself, its spirit lives on in present-day neutrino observatories. IceCube at the South Pole is certainly the most extreme realisation of the DUMAND concept, and DUMAND spherical phototube modules are still the archetypal unit for this and many other detectors, such as ANTARES and GVD in Lake Baikal. A further array currently being installed deep in the Mediterranean, KM3NeT, has varied the principle by arranging many small phototubes inside of the glass sphere instead of a single large tube, while IceCube is exploring multiphototube modules as well as wavelength-shifter solutions for its next-generation incarnation.

Following IceCube's discovery of the first extraterrestrial high-energy neutrinos in 2013, we are finally realising the decades-old dream of seeing the universe in neutrinos. Today, with thousands of researchers undertaking neutrino studies, the revelations for particle physics from neutrinos seem to be unending. The experimental road has been full of surprises, and neutrino physics and astronomy remain some of the most exciting games in town.

Résumé

DUMAND et les origines des grands détecteurs de neutrinos

*Plusieurs des concepts sur lesquels reposent les détecteurs de neutrinos souterrains ou sous-marins actuels à grande profondeur ont été formulés il y a quarante ans, lors d'un atelier qui s'est déroulé à Hawaï. C'est là qu'ont émergé certaines des premières idées à l'origine de grands détecteurs tels que DUMAND (*Deep Underwater Muon and Neutrino Detector*), d'une gigatonne, qui a finalement pris la forme de l'actuel IceCube au pôle Sud. Les technologies pour des détecteurs plus petits remplis d'eau, tels que l'IMB (Irvine-Michigan-Brookhaven) et plus tard le Kamiokande (au Japon), y ont aussi été exposées en détail pour la première fois. Des concepts entièrement nouveaux, comme la détection de particules au moyen d'ondes sonores ou radio, ont également été examinés.*

John Learned, University of Hawaii, US, and **Christian Spiering**, DESY Zeuthen, Germany.

Japan eyes up its future

Boosted by recent awards, an ambitious upgrade for T2K and the upcoming Hyper-Kamiokande experiment, Japan's strong neutrino tradition looks set to flourish, describes **Morgan Wascko**.

Kamioka Observatory, ICRR/University of Tokyo

The almost-full water tank at Super-Kamiokande, which is to be upgraded to a megaton-scale detector called Hyper-Kamiokande.

Japan has been a leader in the global neutrino community since the 1980s, breaking ground (both literally and figuratively) with multiple generations of massive underground experiments. These experiments, which although sited in Japan are built and operated by international collaborations, went on to make some of the most surprising discoveries in the history of particle physics. In doing so, they pointed the way to new experiments, and garnered the most prestigious accolades for Japanese physicists and their international partners.

Today, Japan is undertaking two major projects – T2K and Hyper-Kamiokande – to delve deeper into the neutrino's properties. These and other global neutrino projects were the subject of discussions at the Third International Meeting for Large Neutrino Infrastructures, which took place at the KEK laboratory on 30–31 May (see panel overleaf).

From Kamiokande to Super-K

Japan's neutrino odyssey began with the Kamioka Nucleon Decay Experiment (Kamiokande), a 3000 tonne water Cherenkov experiment in the Kamioka mine in Japan's Gifu prefecture, which started collecting data in search of proton decay in 1983. Although the experiment did not observe proton decay, it did make history with novel observations of solar neutrinos and, unexpectedly, 11 neutrino interactions from a supernova (SN1987a). These observations led to the 2002 Nobel Prize in Physics for Masatoshi Koshiba of the University of Tokyo, shared with the late Ray Davis Jr, and paved the way to a second-generation experiment.

Following Kamiokande's success, in the 1990s, the late Yoji Totsuka led the construction of a 50,000 tonne water Cherenkov detector called Super-Kamiokande (Super-K). Like its predecessor, Super-K is also a proton-decay experiment that became famous for its measurements of neutrinos – both solar and atmospheric. Atmospheric neutrinos come from high-energy cosmic-ray interactions in the Earth's atmosphere, predominately from charged-pion decays that result in a two-to-one mix of muon and electron neutrinos that can pass straight through the Earth before interacting in the Super-K detector.

The construction of Hyper-K could start as early as 2018.

Although the cosmic-ray flux impinging on the Earth is isotropic, Super-K data indicated that the flux of atmospheric neutrinos is not. In 1998, the Super-K collaboration showed that muon neutrinos coming from above the detector outnumbered those coming from below. The muon neutrinos that travel from the other side of the Earth transform into tau neutrinos and effectively disappear, because they are not energetic enough to interact and produce charged tau particles. This process, called neutrino oscillation, can only happen if neutrinos have mass – in contradiction to the Standard Model of particles physics. The discovery of atmospheric-neutrino oscillations led to the 2015 Nobel Prize in Physics for Super-K leader Takaaki Kajita and also Arthur McDonald of the Sudbury Neutrino Observatory (SNO) in Canada, for the concurrent observations of solar-neutrino oscillations.

From KEK to Kamioka to T2K

Two new experiments, K2K and KamLAND, were built in Japan to follow up the discovery of neutrino oscillations. The KEK-to-Kamioka (K2K) collaboration built at the KEK laboratory an accelerator-based neutrino beam aimed at Super-K, 250 km away, and also a suite of near-detectors. The collaboration solved several technical difficulties to confirm that nature's most elusive particle was being created in their accelerator beam and was definitely interacting in Super-K, with careful comparisons from the near detectors at ▷

Planning ahead: Third International Meeting for Large Neutrino Infrastructures

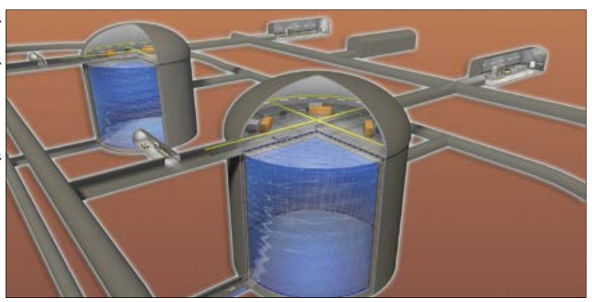
A major upgrade to the T2K experiment and the ongoing design of the Hyper-K detector were among many large neutrino projects discussed at the Third International Meeting for Large Neutrino Infrastructures, which took place at the KEK laboratory on 30–31 May. The event followed the previous instance of the meeting at Fermilab in April 2015 and aims to strengthen global co-ordination on large neutrino infrastructures, not just in Japan but the world over.

The third meeting, which was organised by KEK, ICRR, Fermilab, the Astroparticle Physics European Consortium (APPEC), the ICFA Neutrino Panel and the IUPAP Astroparticle Physics International Committee (APPIC), evaluated progress made since last year, discussed strategy toward the realisation of next-generation large neutrino infrastructures, and reviewed the programme of supporting measurements, prototyping and R&D.

The first day of the event addressed major accelerator-based programmes worldwide, focusing on Hyper-Kamiokande and the DUNE experiment planned in the US. The second day was devoted to examining the non-accelerator physics potential of the various large neutrino infrastructures, for which it was agreed that closer co-ordination is needed.

Participants of the third "Infra" meeting, held at KEK on 30–31 May.

Presenting progress towards its road-map document, the ICFA Neutrino Panel discussed long-term opportunities such as the Neutrino Factory and ESSnuSB. It also identified 2020 as the approximate date when the future of sterile-neutrino searches and cross-section measurement programmes should be defined, and recommended that experiments such as nuSTORM and IsoDAR be evaluated by then. It was proposed that the next "Infra" meeting be held in Europe in 2017.



Kamioka Observatory, ICRR/University of Tokyo

Patrick Dep/J-PARC

(Left) Hyper-K could be constructed from two huge cylindrical tanks each measuring 74 m in diameter and 60 m deep, containing a total of 600 thousand tonnes of highly purified water. (Right) Superconducting magnets at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai village, which bend a 50 GeV proton beam towards the neutrino target. Plans are afoot to excavate Hyper-K a few kilometres from Super-K, so that it receives the existing neutrino beam from J-PARC, which will be upgraded to a higher intensity.

KEK showing that some muon neutrinos were indeed disappearing as they travelled, just as the Super-K collaboration predicted.

The Kamioka Liquid Scintillator AntiNeutrino Detector (KamLAND) experiment was built in the cavern that originally held Kamiokande, and offered sensitivity to electron antineutrinos from Japan's nuclear reactors. KamLAND found that the neutrinos were indeed oscillating in a manner exactly consistent with the solar-neutrino oscillation observed by SNO and Super-K. These two international experiments in Japan, K2K and KamLAND, confirmed that neutrino oscillations were the explanation for the surprising observations of Super-K and SNO. But all of these experiments had seen only the disappearance of neutrinos, and it was therefore time for an experiment to observe the appearance of neutrinos.

In 2009, the Tokai-to-Kamioka (T2K) collaboration, comprising 500 scientists from 11 nations, built an experiment to observe the appearance of electron neutrinos in a muon-neutrino beam. The concept is similar to that of K2K, but with higher beam power and higher precision in the near detectors. To achieve higher beam power, T2K uses the new accelerator complex at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai Village on the east coast of Japan, about 70 km from KEK. The neutrino beam is directed in an off-axis configuration, which allows precise control of the neutrino energy spectrum, towards the Super-K detector 295 km away. In 2011, T2K reported the appearance of electron neutrinos from a muon-neutrino beam, which was the first significant neutrino-flavour appearance signal. For this result, which completed the picture of neutrino oscillations with the three known Standard Model neutrino flavours, T2K and K2K founding spokesperson Koichiro Nishikawa was awarded a share of the 2016 Breakthrough Prize in Fundamental Physics, along with all T2K and K2K collaboration members. The Super-K, KamLAND, SNO and Daya Bay collaborations also shared in the award.

As often happens in particle physics, the previous generation's discovery becomes the current generation's tool to search for new discoveries. In 2014, T2K began to operate with a muon antineutrino beam. By comparing oscillations of antineutrinos with oscillations of neutrinos, it might be possible to find a clue to one of the most profound mysteries in science: why does the universe appear to be composed entirely of matter, when it is believed that equal quantities of matter and antimatter were created in the Big Bang? Differences between the oscillations of neutrinos and antineutrinos could provide the answer to this, and, if they exist, these differences would be an example of CP violation (CPV).

In late June 2016, the T2K collaboration submitted a proposal to J-PARC requesting an extension of its neutrino (and antineutrino) data run that would give the collaboration significant (potentially 3σ) sensitivity to CPV by 2025. The physics reach of this extended run has been boosted by news that MEXT, the Japanese science funding agency, has approved the first step of an upgrade of the main-ring accelerator at J-PARC. This facility will house a new power supply system with which the repetition rate of the main ring will be doubled, resulting in 750 kW beam power for T2K with the potential to exceed 1 MW.

To Hyper-K and beyond

For discovery-level sensitivity to CPV (5σ or above), the next-generation water Cherenkov detector, Hyper-Kamiokande, is currently being designed. To reduce costs while maximising physics potential, the Hyper-K detector design has changed from the original concept of horizontal cylinders to vertical cylinders similar to Super-K, taking advantage of newly developed high-efficiency photo sensors. The international Hyper-K collaboration was formed in 2015, with agreements between the University of Tokyo's Institute for Cosmic Ray Research (ICRR), which runs the Kamioka Observatory, and KEK.

Hyper-K, when exposed to the 1 MW J-PARC neutrino beam, will make precise measurements of neutrino and antineutrino oscillations as it searches for CPV with high significance, as well as perform the most sensitive searches for proton decay yet. Hyper-K construction could start as early as 2018, with physics data-taking in 2026. Combined with long- and short-baseline programmes in the US, Japan's next generation of neutrino observatories should help physicists to answer most of the remaining questions about neutrino oscillations.

Résumé

Le Japon a les yeux rivés sur son futur

Le Japon compte parmi les leaders de la communauté neutrino mondiale depuis les années 1980, et le pays a bâti plusieurs générations d'expériences souterraines de grande taille, qui ont révélé de nombreuses propriétés marquantes du neutrino. Le Japon entreprend aujourd'hui deux projets majeurs, T2K et Hyper-Kamiokande, visant à sonder plus profondément les propriétés des neutrinos. Ces projets et d'autres projets internationaux sur les neutrinos ont été au cœur des discussions lors de la troisième réunion internationale pour les grandes infrastructures neutrino, qui s'est tenue au laboratoire KEK les 30 et 31 mai.

Morgan Wascko, Imperial College London, UK, and KEK, Japan.

CERN Courier July/August 2016

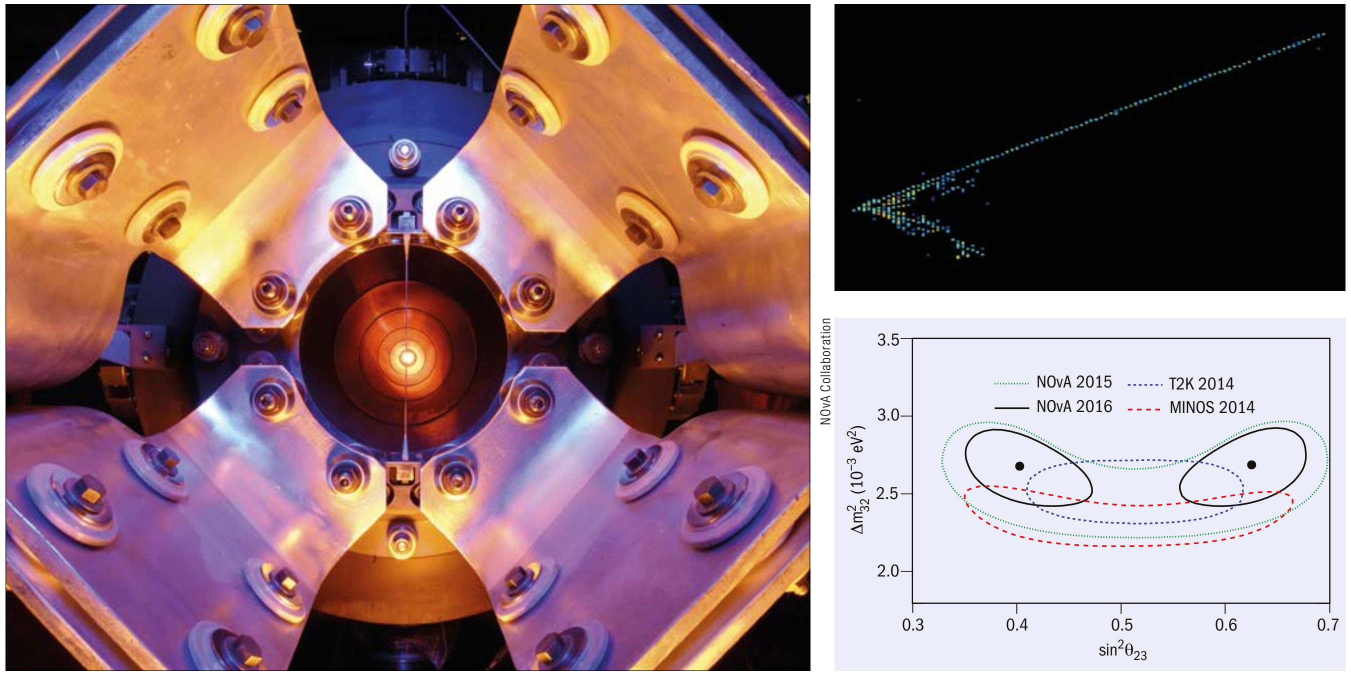
NOvA experiment

NOvA releases new bounds on neutrino mixing parameters

The Neutrino 2016 conference on 4–9 July saw the NOvA experiment in the US present new measurements of neutrino oscillations, report **Ryan Patterson** and **Peter Shanahan**.

The breakthrough results from the Super-Kamiokande and SNO experiments, which showed that neutrinos oscillate between their three flavours, marked the start of nearly two decades of tremendous progress in neutrino physics. The basic features of the three-flavour neutrino oscillation framework have been fleshed out, and the NOvA experiment in the US – which presented its latest results at the Neutrino 2016 conference in London earlier this month – is poised to address many of the remaining unknowns related to neutrino masses and their mixing.

Among these is whether neutrinos obey a "normal" or "inverted" mass hierarchy: that is, whether the mass eigenstate with the least ν_e content (called ν_3) is the heaviest or lightest of the three (see p34). A second set of questions relate to the flavour admixture of the ν_3 state. Past experimental data are consistent with ν_3 being equal parts ν_μ and ν_τ, in addition to a small amount of ν_e. But is there a new symmetry that underlies this apparent ν_μ/ν_τ equality? And if the equality breaks down as measurements improve, which flavour will dominate? A third major unknown is whether neutrinos violate CP symmetry, as allowed by the complex phase δ of the leptonic mixing matrix.



Left: The NuMI horn at Fermilab, which focuses mesons produced in the target into a 675 m-long volume where they can decay to produce neutrinos; top right: a muon-neutrino interaction in the NOvA detector, as viewed by the vertical cells (the neutrino entered from the left); bottom right: 90% CL allowed regions for the dominant "atmospheric" oscillation parameters for the case of the normal mass hierarchy, obtained via the $\nu_\mu \to \nu_\mu$ oscillation channel. NOvA's latest result, which is preliminary, is shown in black, while earlier results from NOvA, T2K and MINOS are also shown.

Addressing the unknown

NOvA was conceived to address these unknowns using two detectors together with the intense beam of muon neutrinos provided by Fermilab's NuMI neutrino source. NOvA's 300 tonne near detector, which is located 1 km downstream of the neutrino source, measures the rate, energy spectrum and flavour composition of the neutrino beam prior to significant flavour oscillations, while the 14,000 tonne far detector is located 810 km downstream in northern Minnesota. The detectors are identical in their structure, consisting of 4 × 6 cm liquid scintillator-filled PVC cells in alternating planes in order to provide two orthogonal 2D views of particle trajectories.

NOvA has been collecting data with the NuMI beam since February 2014, and full operations began the following October upon completion of the far detector (*CERN Courier* July/August 2014 p30). As of May 2016, the experiment has accumulated 16% of its planned total. The results released at Neutrino2016 are based on this data set, and highlighted here are the measurements of $\nu_\mu \to \nu_\mu$ (corresponding to muon-neutrino survival) and $\nu_\mu \to \nu_e$ (electron-neutrino appearance).

To identify the flavour of an interacting neutrino, researchers look for tell-tale signs of a muon or an electron in the recorded event. Muons produced in charged-current ν_μ interactions in NOvA leave long straight tracks of detector activity that can span hundreds of cells (above, top right). Electrons, in contrast, create more compact electromagnetic showers with well-characterised longitudinal and transverse profiles. An important background to both the ν_μ and ν_e charged-current channels comes from neutral-current interactions, whereby the neutrino exits the detector and leaves behind only a hadronic recoil system. Neutral pions in these recoil systems can mimic electrons, while charged pions can mimic muons.

To keep this background at bay in the $\nu_\mu \to \nu_\mu$ measurement, each recorded track is assigned a muon likelihood based on key track features such as overall length and the rate of energy deposition. Additionally, each event must be far enough from the detector edges to ensure that the entire final state has been recorded and that the event is not due to an incoming cosmic ray. For the latest data, the NOvA team predicts 470 selected ν_μ charged current interactions in the far detector if neutrino oscillations do not occur. Only 78 such interactions were observed, in line with the well-established result originally observed by Super-Kamiokande that muon neutrinos are indeed oscillating into other flavours as they travel.

Non-maximal mixing

The real value of these data, though, comes from examining the precise energy dependence and amplitude of the ν_μ disappearance signal, which depends most strongly on the mass splitting $|\Delta m^2_{32}|$ and the mixing angle θ_{23}. The ranges of these parameters allowed by the latest NOvA data are shown above. NOvA's results are consistent with prior measurements but show an intriguing preference for non-maximal mixing – that is, a preference for $\sin^2\theta_{23} \neq 0.5$ and thus a break in the ν_3 state's apparent flavour symmetry. Whether this preference becomes conclusive or fades away will be addressed as NOvA continues to accumulate data.

On the ν_e appearance side, distinguishing signal and background is a trickier affair due to their stronger mutual similarities and to the low probability for $\nu_\mu \to \nu_e$ oscillations. For its latest 2016 ν_e analysis, the NOvA team has developed an event-classification algorithm based on techniques from the image analysis community, notably convolutional neural networks and deep learning. A total of 33 candidate ν_e events were isolated in the latest data, which is far above the expected background of eight, and therefore represents a clear observation of ν_e appearance – in line with data from T2K.

The $\nu_\mu \to \nu_e$ oscillation probability, and therefore this measurement, is a function of several key unknowns that NOvA is pursuing. The probability will be 40–70% higher for a normal mass hierarchy than for an inverted one, with the opposite correspondence holding for antineutrinos. This dependence stems from the so-called matter effect arising from neutrinos scattering off electrons in the Earth, and the effect is intentionally made large in NOvA by choosing the longest-distance baseline possible. Next, the phase δ of the leptonic mixing matrix can either increase or decrease the $\nu_\mu \to \nu_e$ probability by a similar amount, and this effect is also opposite for neutrinos and antineutrinos. Finally, the probability increases or decreases for neutrinos and antineutrinos alike, in step with $\sin^2\theta_{23}$. This last dependence is complementary to the behaviour of the $\nu_\mu \to \nu_\mu$ channel, which is better at detecting non-maximal mixing but cannot on its own distinguish which way the ν_3 flavour mixing breaks.

The present electron-neutrino appearance results, which point to a probability on the higher end of the range, have already started carving up parameter space. But NOvA must collect both neutrino and antineutrino data to disentangle all the above effects, particularly in light of possible non-maximal mixing. The first large antineutrino run for the experiment is slated to begin next spring.

In addition to accruing neutrino and antineutrino exposure for the flagship oscillation measurements, this summer's results also included a first look at the total neutral current rate in the far detector, for which a deficit could suggest mixing with light sterile neutrinos. No deviation is seen thus far, but with both detectors operating smoothly and the NuMI source running at high power, NOvA is set to play a central role in illuminating the neutrino sector in the coming years.

● *CERN Courier* went to press just as Neutrino 2016 got under way. Other expected highlights of the conference include new neutrino oscillation measurements from the T2K experiment in Japan.

Résumé

NOvA lève le voile sur la hiérarchie des masses du neutrino

NOvA est une expérience neutrino longue distance située aux États-Unis, conçue pour chercher les oscillations neutrino muonique-neutrino électronique. Elle détecte les neutrinos issus d'un faisceau produit au Fermilab, à 810 km de distance, arrivant après avoir traversé l'écorce terrestre. En observant combien de neutrinos passent d'un type à l'autre, NOvA espère mesurer l'angle de mélange θ_{13}, la phase δ entraînant la violation de CP, et la hiérarchie des masses du neutrino. La collaboration NOvA a récemment dévoilé les résultats de ses dernières recherches et, au moment de l'impression de ce numéro du CERN Courier*, ceux-ci étaient préparés en vue d'être présentés à la conférence Neutrino 2016.*

Ryan Patterson, California Institute of Technology, and **Peter Shanahan**, Fermilab, US.

A portal to new physics

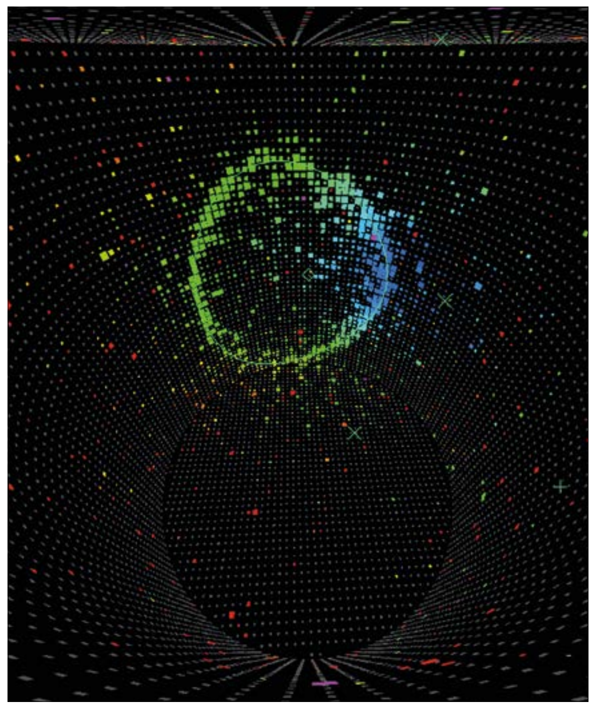
Silvia Pascoli describes how we are closing in on the true nature of the neutrino – thanks to a series of experiments that will help to shed light on the origin of neutrino masses, their mixing and likely impact on physics beyond the Standard Model.

The 1998 discovery that neutrinos can oscillate between different flavours, by the Super-Kamiokande experiment in Japan and subsequently by the SNO experiment in Canada, marked a turning point in our understanding of elementary particles. For many theorists, it represents the first hard particle-physics evidence for the existence of new degrees of freedom (d.o.f.) beyond the known fundamental particles and, most probably, of new physics beyond the Standard Model (SM). The hunt to uncover the new theory is the main focus of the neutrino theoretical community.

First postulated by Pauli in 1930, neutrinos have always played the role of the elusive particle. Their interactions were soon understood thanks to Fermi's beta-decay theory, but searching for them seemed more like science fiction, at the time. In 1946, however, Pontecorvo suggested that nuclear reactors and the Sun are copious sources of neutrinos, and proposed a radiochemical method for the detection of neutrinos.

A decade later, Reines and Cowan established the neutrino's existence by performing a reactor neutrino experiment, and the search for astrophysical neutrinos began soon afterwards. Ray Davis Jr and collaborators later detected solar neutrinos, reporting in 1972 a flux that was significantly smaller than predicted by the most sophisticated solar models developed by John Bahcall. This "solar-neutrino puzzle" was eventually explained in terms of the proposal by Bruno Pontecorvo in 1957 and 1958, applied by him to solar neutrinos in 1967, that neutrinos may oscillate between their different types. Combined with the 1962 proposal by Maki, Nakagawa and Sakata – inspired by the discovery of the muon neutrino in the well-known Brookhaven experiment – that there exists mixing between flavour and massive neutrino states, the stage was set to catch and "see" an oscillating neutrino.

The decade following the discovery of neutrino oscillations did not disappoint.



T2K Collaboration

The ring of Cherenkov light produced by an electron-neutrino candidate in the Super-Kamiokande detector showing that muon neutrinos transform to electron neutrinos, obtained by the T2K collaboration in 2013.

Proving this elegant theoretical picture took a further 36 years of experimental innovation. In the end, it relied on the observation of atmospheric neutrinos produced by collisions of cosmic rays in the upper atmosphere, which produce showers of pions and kaons whose subsequent decays give muon and electron neutrinos. Atmospheric neutrinos were first detected in 1965 by the Kolar Gold Fields experiment in India and another experiment at the East Rand gold mine in South Africa. Then, in 1998, in a momentous discovery, Super-Kamiokande showed that muon neutrinos disappear as a function of distance travelled (see figure 1, overleaf). Just a few years later, thanks to measurements of the total solar-neutrino flux, the SNO experiment confirmed that solar neutrinos can transform from electron neutrinos into muon and tau neutrinos. These two milestones and subsequent results, which have been recognised by a number of prestigious awards, ushered in a mesmerising period of new results that continues to this day.

Neutrino oscillations are the transformation of a neutrino from one flavour into another as it propagates. It is a fundamentally quantum-mechanical process arising from a misalignment of flavour states, ν_e, ν_μ and ν_τ, which describe neutrinos in production and detection, compared with the mass eigenstates, ν_1, ν_2 and ν_3. At the source, a flavour neutrino is the coherent superposition of mass states, which propagate with different phases due to their different masses. As neutrinos travel, the shift in phase results in a different combination of flavour neutrinos. The existence of neutrino oscillations necessarily requires neutrinos to have masses and to mix, which is different from the prediction of the SM (at least in its minimal form). This is why it is widely believed that neutrino oscillations are the first and so far only concrete evidence for physics beyond the SM provided by particle-physics experiments.

The decade following the discovery of neutrino oscillations did not disappoint. In 2002, the KamLAND experiment in Japan reported the first oscillations of man-made neutrinos, produced by nuclear reactors, while the K2K and MINOS experiments detected neutrinos from accelerator-produced beams. Together with the ongoing T2K and NOvA experiments, as well as atmospheric-neutrino observations at Super-Kamiokande, these experiments have established that there are two mass-squared differences that drive different neutrino oscillations and imply the existence of at least three neutrino mass eigenstates. The data also show that neutrino mixing is described by a 3×3 unitary matrix parameterised by three well-measured angles: θ_{12}, θ_{23} and θ_{13}.

We have now an incredibly rich picture of neutrino properties that was unthinkable at the time of the Super-Kamiokande results and that is very different from that of the quarks. But despite these immense achievements, we are still in need of crucial pieces of information to reach a complete understanding of neutrino properties. ▷

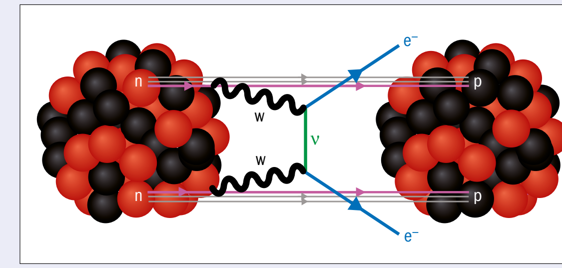
Searching for the neutrino's fundamental nature

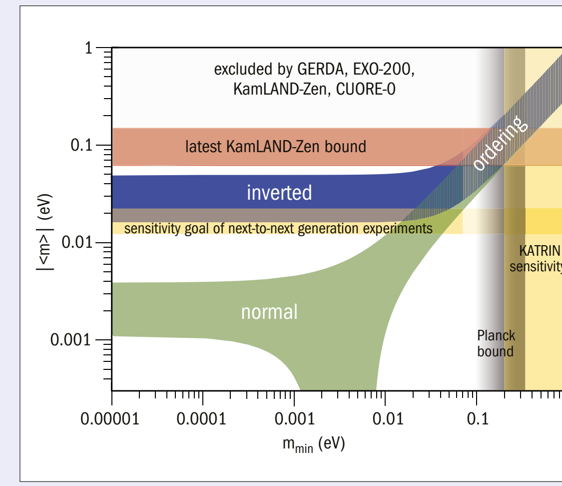
Two-neutrino double beta decay (DBD) is a very rare Standard Model process that causes two neutrons simultaneously to decay into two protons and two electrons, with the emission of two electron antineutrinos. If neutrinos are Majorana particles, however, instead of being emitted, the Majorana neutrinos can mediate a new process called neutrinoless double-beta decay (NDBD), which is not allowed in the Standard Model. Observing this process would be groundbreaking because it would imply that the lepton number is violated and provide crucial information about neutrino masses.

More than a dozen experiments worldwide are searching for NDBD which, like DBD, can be observed in nuclei in which ordinary beta decay is kinematically forbidden. Because NDBD produces no neutrinos to carry off energy, all events will be concentrated at the end point of the two-electron energy spectrum – unlike the case for DBD, in which the spectrum is a continuum. Being an extremely rare process, NDBD searches require sufficiently large detector volumes, very good energy resolution, a location deep underground and extremely low backgrounds.

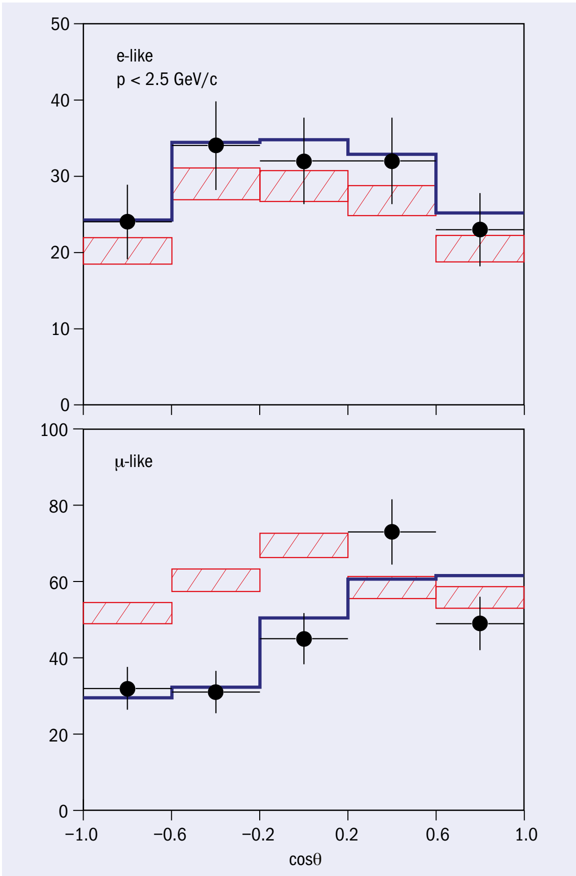
A number of different experimental techniques are being employed. Liquid-scintillator detectors such as KamLAND-Zen in Japan and SNO+ in Canada offer large target masses, and currently KamLAND-Zen provides the strongest bound on NDBD with a half-life greater than 1.1×10^{26} years. Germanium detectors such as GERDA and MAJORANA are more compact and ensure very good energy resolution, while planned experiments such as SuperNEMO and DCBA can track both electrons and could reconstruct their angular distribution. Time projection chambers, such as nEXO in the US and NEXT in Spain, can simultaneously track the electrons and allow large target volumes, while bolometers such as CUORE and AMoRE benefit from very high energy resolution.

Despite this impressive armoury, NDBD hunters are at the mercy of the neutrino masses and mixing parameters (see main text). The NDBD rate depends crucially on the combination of masses and mixing parameters, the so-called effective Majorana mass parameter. If neutrinos exhibit an inverted mass ordering, the predicted lower bound on the decay rate will be just within reach of the next-to-next generation of experiments. If they adopt the normal mass ordering, the decay rate could be anywhere between the current bounds and zero, if a specific cancellation between the three massive neutrinos is at work (see lower figure).





Certain nuclei undergo two beta decays at once without producing any associated antineutrinos (top). The search for such neutrinoless double-beta decay depends critically on the ordering of the neutrino masses, as can be seen in a plot of the predicted two-sigma values of the effective Majorana mass parameter (|<m>|), which controls the decay rate, versus the mass of the lightest neutrino, namely m_1 for normal ordering and m_3 for inverted ordering (bottom).



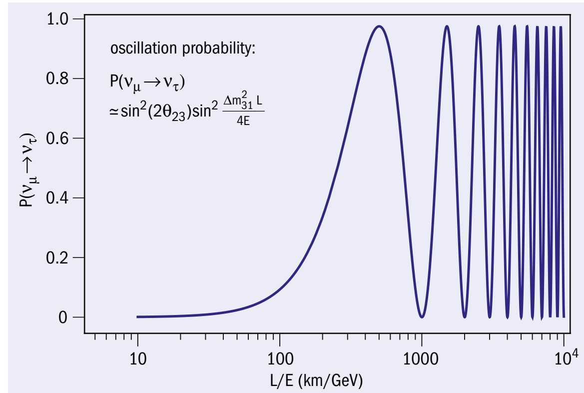


Fig. 1. (Left) Zenith-angle distributions of e-like (top) and μ-like events (bottom) recorded by the Super-Kamiokande experiment in 1998. In the latter, the hatched region shows the Monte Carlo expectation for no oscillations, while the bold line is the best-fit expectation for $\nu_\mu \rightarrow \nu_\tau$ oscillations. For downward-going muon neutrinos ($\cos\theta > 0$), corresponding to neutrinos produced in the atmosphere on average about 20 km above the detector, data and theory are in good agreement. For up-going muon neutrinos ($\cos\theta < 0$) that have travelled through the Earth, however, there is a clear disagreement between data and prediction, signalling $\nu_\mu \rightarrow \nu_\tau$ oscillations. (Above) Starting from basic quantum mechanics and assuming that a neutrino is produced in a superposition of different mass eigenstates (assumed here to be just two for simplicity) with different masses, this equation describes the oscillation probability of a muon neutrino into a tau neutrino, as a function of neutrino energy, E, and distance travelled, L. The current data for the oscillation parameters are used.

The most important question about neutrinos concerns the type of masses they have. So far, all the known fermions are of the Dirac type: their particles and antiparticles have opposite charges and they possess a Dirac mass that arises from the coupling to the Higgs field. Neutrinos could behave in the same way, but because they are electrically neutral it is possible that neutrinos acquire mass via a different mechanism. Indeed, neutrinos and antineutrinos might be indistinguishable, constituting what is called a Majorana particle after Ettore Majorana who proposed the concept in 1937. Unlike Dirac fields, which have four components, Majorana fields have only two d.o.f. Such a particle cannot possess any charge, not even a lepton number.

A matter of conservation

The question of the nature of neutrinos is therefore intrinsically related to the conservation of the lepton number. In the SM, the lepton number is a global accidental symmetry that happens to be preserved thanks to the gauge symmetries and particle content, but it does not have a dynamic role because there are no associated gauge bosons. The question arises whether the ultimate theory of particles and their interactions is lepton-number violating or not. The most promising way to answer this question is to search for neutrinoless double-beta decay, whereby certain nuclei spontaneously undergo two beta decays at once, without producing any neutrinos. This process directly violates lepton-number conservation and would imply that neutrinos are Majorana particles, motivating a broad international experimental programme (see panel on previous page).

A second major question is whether the CP symmetry is violated in the lepton sector, as it is in the quark one. CP violation is one of the three key ingredients in baryogenesis and leptogenesis, which are needed to dynamically explain the observed matter–antimatter asymmetry of the universe (see panel overleaf). There are three possible sources of CP violation in the lepton sector: the Dirac phase, which is the analogue of the one in the quark sector, and two Majorana phases that appear only if neutrinos are Majorana particles. If neutrinos are Dirac particles, the latter can be rotated away as is done in the quark sector.

The first hints of leptonic CP violation came recently from combining data from China's Daya Bay experiment with measurements at long-baseline accelerator facilities, in particular T2K and NOvA. These seem to indicate a preference for a nonzero value of the CP-violating Dirac phase (see figure 2). It is too early to tell, but very ambitious plans – including the proposed Deep Underground Neutrino Experiment (DUNE) in the US and T2HK in Japan – aim to settle the issue by allowing both neutrino and antineutrino oscillations to be studied. The latter behave differently if Dirac CP violation is present, with oscillations that are being enhanced or suppressed, depending on the values of the Dirac phase.

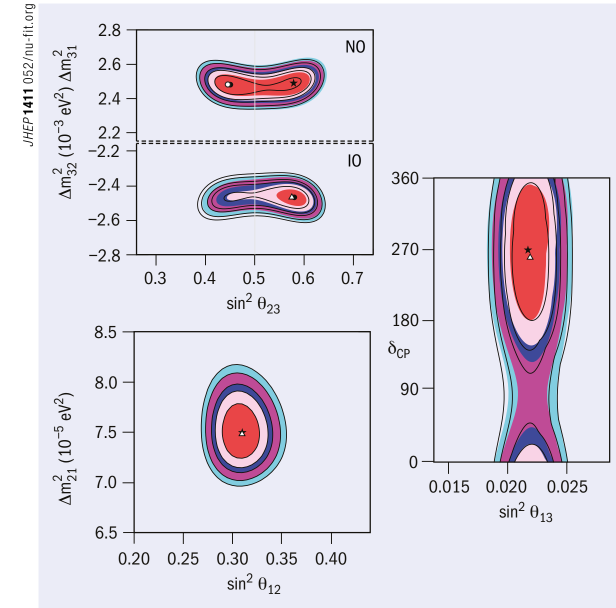


Fig. 2. Current measured values of the oscillation parameters for a global 3ν oscillation analysis. The different contours correspond to the 2D allowed regions at 1σ, 90%, 2σ, 99% and 3σ CL (2 d.o.f.). The coloured region and black lines correspond to two different analyses using the LEM and LID NOvA data. For the atmospheric mass-squared difference, the normal- (NO) and inverted-ordering (IO) allowed regions are shown separately. The allowed region for δ, showing the first possible hints of CP-violation, is shown together with θ_{13}.

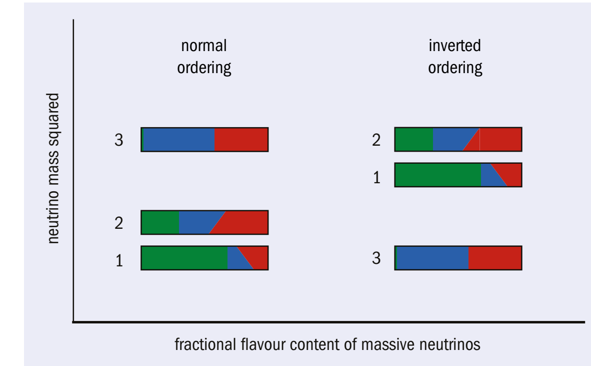


Fig. 3. The flavour content of the three neutrino mass eigenstates, with the mass eigenstates arranged in increasing mass-squared order for the two mass orderings (the overall mass scale is unknown). A mass eigenstate, ν_i, is a superposition of flavour states ν_e (green), ν_μ (blue) and ν_τ (red), with a fraction corresponding to $|U_{\alpha i}|^2$. Varying the Dirac phases, δ, changes this fraction for each mass eigenstate. The figure is similar to that in Phys. Rev. D **69** *117301 and adapted in arXiv:1602.04816.*

The other mixing parameters, namely the three mixing angles, are already quite well-determined. Angle θ_{13} went from being unknown just over four years ago to being the best-measured, thanks to results from the Daya Bay as well as RENO and Double Chooz experiments, while the JUNO experiment in China plans to reach a sub-per-cent accuracy for the θ_{12} angle after a few years of operation. θ_{23} is particularly interesting because it could be exactly maximal, therefore pointing towards a symmetry in the lepton-flavour sector, or could deviate from this by several degrees. Current and future long-baseline oscillation experiments will have the best chance of determining θ_{23}, which will be critical for disentangling the different models proposed to explain the observed mixing pattern.

Massive considerations

As for the values of the neutrino masses themselves, we already have a very precise measurement of the absolute values of the two mass-squared differences – which differ by a factor of about 30 (figure 2 above). But we still lack key pieces of information, namely which neutrino is the lightest, defining the neutrino mass ordering, and what its mass scale is. The sign of the solar mass-squared difference is determined by solar-neutrino oscillations, but that of the atmospheric one is unknown. If it turns out to be positive, corresponding to $m_3 > m_1$, neutrino masses exhibit the so-called "normal" ordering. The alternative scenario, $m_3 < m_1$, implies an "inverted" ordering (figure 3 above).

Knowing the mass ordering and scale is important for theorists because different theoretical models predict different patterns, and also for experimentalists searching for specific signatures. It strongly affects the rate of neutrinoless double-beta decay, substantially impacting on the prospects of discovering the Majorana nature of neutrinos, while in the early universe heavier neutrinos suppress the growth of large-scale structures at small scales. The ordering of the masses also changes the way in which neutrinos propagate over long distances in media such as the Earth, due to weak interactions with the background of electrons, protons and neutrons. This gives neutrinos an effective mass that modifies their energies and the mixing: neutrino oscillations are enhanced for normal mass ordering and suppressed for inverted ordering, with the opposite happening in the case of antineutrinos.

Knowing the neutrino mass ordering still leaves open the question of the overall mass scale.

Experiments such as the long-baseline experiment NOvA, which measures a neutrino beam produced 810 km away at Fermilab, exploit these effects to hunt for the neutrino mass ordering (see p32). With DUNE, which will operate at a distance of 1300 km, and new atmospheric-neutrino observatories such as PINGU, ORCA and INO, as well as JUNO, we expect to resolve this issue in the next 5–10 years. ▷

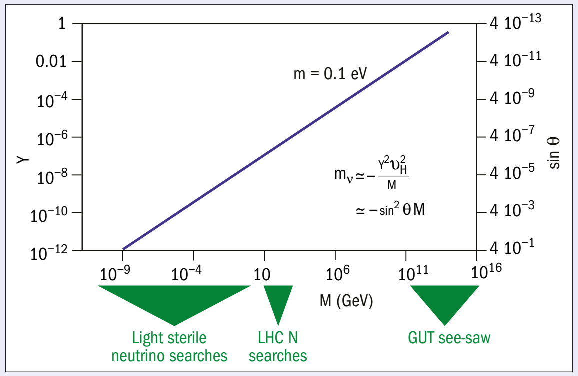
Messengers from beyond the Standard Model

The origin of neutrino masses and mixing is still unresolved, and necessarily requires new degrees of freedom and new interactions. The simplest extension of the Standard Model assumes the existence of right-handed (RH) neutrinos, which behave as singlets with respect to the Standard Model gauge group. Unless specific symmetries are imposed, Yukawa couplings with the lepton doublet and the Higgs will be allowed and the lepton number will be preserved. Dirac masses therefore arise for neutrinos as they do for all the other known fermions, but this mechanism provides no insight as to why neutrino masses are so small (the Yukawa coupling needed would be 12 orders of magnitude smaller than that of the top quark). One could simply accept such extreme fine-tuning as a fact of nature, but this would naively lead one to expect the same mixing in the lepton sector as in the quark one and a similar mass ordering, neither of which is observed.

The alternative option is that neutrinos are Majorana particles. Majorana neutrinos will have a mass term in the Lagrangian that breaks lepton-number conservation. Although this mass term is forbidden by the gauge group of the SM, it could arise as the low-energy realisation of a higher-energy theory. This can explain both the existence of neutrino masses and their smallness, because a strong suppression is induced by the new heavy scale. Theorists are working hard to understand what the new theory at high energy might be. The ultimate theory behind neutrino masses must also explain the observed mixing structure, the presence of CP violation (if observed), and why the lepton sector contains large angles that are different to the quark sector. Many approaches have been proposed, for instance the use of continuous or discrete flavour symmetries, but no unique underlying principle has yet been identified.

The simplest and most studied extension beyond the SM for neutrino masses is the "see-saw type I" mechanism. Because RH neutrinos are completely neutral with respect to the SM gauge symmetries, they could be much heavier than the other known fermions. The Lagrangian would then contain both a Yukawa coupling with the Higgs, as for the quarks, and a Majorana mass term, M, for the RH neutrinos. Once the neutral Higgs boson gets a vacuum expectation value, light masses for the neutrinos arise that are proportional to the square of the Yukawa couplings and suppressed by M. Taking an order-one Yukawa coupling and M of around 10^{14} GeV, we obtain a sub-eV neutrino mass scale as required by the data and, because the lepton number is violated by M, the light neutrinos will be Majorana particles.

This is by no means the only way to give origin to neutrino masses. First of all, since the RH neutrino masses can take any value, the scale of the see-saw mechanism could be lowered even below the electroweak scale, allowing some models to be tested at the LHC. Typical signatures are same-sign dileptons with no missing energy, indicating lepton-number violation, and flavour-violating multi-lepton events. Several searches have been conducted by the LHC's ATLAS and CMS collaborations, but so far no positive hint has been found. The heavy particles responsible for the see-saw mechanism could also be different: a fermion triplet in see-saw type III and a scalar triplet in see-saw type II models. Some models, such as radiative and R-parity-violating supersymmetric models, do not invoke the see-saw mechanism at all.



A log–log plot of the Yukawa coupling versus the RH Majorana mass, M, for a one-generation see-saw mechanism and one light neutrino mass of 0.1 eV. Going to very small masses implies unnaturally small Yukawa couplings, while heavier neutrinos allow large Yukawa couplings but cause the mixing angles to become vanishingly small.

With so many possibilities, clearly one needs to hunt for other beyond-SM signatures to try to identify the origin of neutrino masses. Leptogenesis is a key one. To generate dynamically a baryon asymmetry in the early universe, the three Sakharov conditions need to be satisfied: lepton or baryon number violation, C and CP violation, and an out-of-equilibrium state (satisfied by the expansion of the universe). The see-saw mechanism can satisfy all of these conditions. In the early universe, RH neutrinos got out of equilibrium once the temperature dropped below their mass. Thanks to their decays into leptons and Higgs bosons, a net lepton asymmetry could arise if the rate in one channel and the conjugated one are different due to CP violation. This asymmetry would then be converted into a baryon asymmetry by non-perturbative SM effects. Observing CP violation in future neutrino-oscillation experiments and lepton-number violation in neutrinoless double-beta-decay searches would therefore provide strong hints that leptogenesis is at the origin of the baryon asymmetry of the universe.

However, even knowing the neutrino mass ordering still leaves open the question of the overall neutrino mass scale. So far, we know that neutrino masses cannot be too large. They are restricted to be smaller than 2.2 eV by the Troitsk and Mainz experiments, and well below this limit if one considers cosmological observations, which suggest a conservative bound on the sum of the masses of around 0.7 eV in the standard cosmological model. The KArlsruhe TRItium Neutrino (KATRIN) experiment currently being commissioned in Germany aims to determine the absolute mass scale by searching for a small deformation of the electron energy spectrum in beta decays and will be sensitive to neutrino masses as small as 0.2 eV. It is expected to take data very soon.

The standard neutrino picture comprises three neutrino flavour states and correspondingly three light-mass eigenstates. In many extensions of the SM this is not the case because new degrees of freedom and/or new interactions can be added (see panel above). The simplest extension is that of sterile-neutrinos, which do not experience SM interactions. The corresponding nearly sterile

neutrino mass could take any value, from the very small to the GUT scale, but in many phenomenological studies is around the eV scale and therefore could induce short-baseline oscillations.

Results from the LSND and MiniBooNE experiments in the US, as well as some reactor neutrino ones, have hinted at precisely such a signal. But the results are still controversial, and there is tension with other searches of sterile-neutrinos from short-baseline muon neutrino experiments. New short-baseline reactor and radioactive-source neutrino experiments, in addition to the dedicated short-baseline accelerator programme at Fermilab involving the MicroBooNE, ICARUS and SBND detectors, will shed light on these results and possibly hunt for nearly sterile-neutrinos with even smaller mixing angles. A positive signal would be groundbreaking, forcing us to rethink the theoretical framework for light neutrinos and posing new questions about the nature, masses, mixing and CP-violating properties of the new states.

Indeed, neutrinos remain the most intriguing and elusive of all known fermions and are an ideal portal to explore new physics beyond the Standard Model. Despite impressive progress in the past 20 years, going from not knowing if neutrino oscillations took place to having measured most of the oscillation parameters with great precision, many key phenomenological and theoretical questions remain open and urgently require answers. Fortunately, a broad and exciting experimental programme is under way and, as is often the case in research, the focus of our theoretical work could change in an instant. With the LHC now into its high-energy run, for example, it is possible that we will discover entirely new particles and phenomena beyond the SM. We would then need to establish what connection – if any – exists between this and the already new physics of neutrino masses. Or perhaps neutrino masses come from a secluded sector, possibly at energy scales so high that we cannot test it directly. These and many other questions, informed by the current wealth of new and upcoming experiments, promise to keep neutrino theorists occupied for the foreseeable future.

Résumé

Une porte vers une nouvelle physique

La découverte, en 1998, de la capacité des neutrinos d'osciller entre différentes saveurs a été un pas décisif dans notre connaissance des particules élémentaires. Pour de nombreux théoriciens, cette découverte représente la première preuve tangible, en physique des particules, de l'existence d'une nouvelle physique au-delà du Modèle standard. La quête de cette nouvelle théorie est à présent le sujet d'étude principal de la communauté des théoriciens spécialistes des neutrinos. Fort heureusement, plusieurs nouvelles expériences ou expériences améliorées, dans le monde entier, vont bientôt faire la lumière sur l'origine de la masse du neutrino, ses mélanges et ses possibles propriétés de violation de CP. Les théoriciens pourront ainsi explorer plus facilement le nouveau paysage de la physique.

Silvia Pascoli, Institute for Particle Physics Phenomenology, Durham University, UK.

IceCube seeks to expand

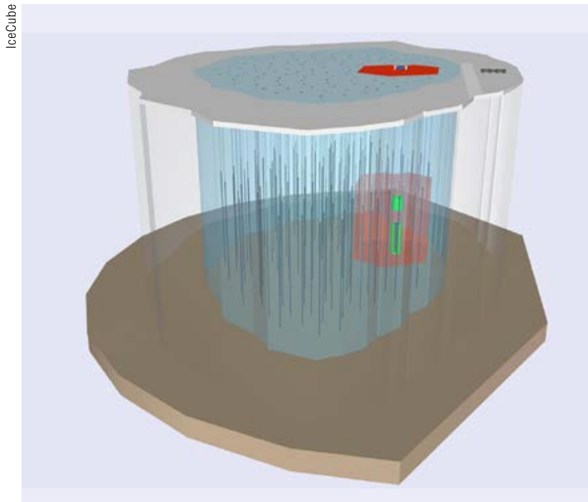
Francis Halzen and **Spencer Klein** set out the case for a next-generation neutrino-detector array that will be able to pinpoint the location of the most energetic events in the universe.

The IceCube experiment at the South Pole has been one of the pioneers of the field of neutrino astronomy. During a seven-year-long construction campaign that ended in 2010, the 325 strong IceCube collaboration transformed a cubic kilometre of ultra-transparent Antarctic ice into a giant Cherenkov detector. Today, 5160 optical sensors are suspended beneath the ice to detect Cherenkov light from charged particles produced when high-energy neutrinos from the cosmos interact with nuclei in the detector. So far, IceCube has detected neutrinos with energies in the range 10^{11}–10^{16} eV, which include the most energetic neutrinos ever recorded (see image opposite). However, we do not yet know where these neutrinos come from. For this reason, the IceCube collaboration is developing designs for an expanded "Gen2" detector.

IceCube observes astrophysical neutrinos in two ways. The first approach selects upgoing events by using the Earth to filter out the large flux of cosmic-ray muons. At low energies (below 100 TeV), the measured flux of muon neutrinos is consistent with an atmospheric origin, whereas at higher energies, a clear excess of events with a significance of 5.6σ is observed. The second approach selects neutrinos that interact inside the detector. A total of 54 cosmic-neutrino events with energies ranging from 30–2000 TeV were detected during four years of operation, excluding a purely atmospheric explanation at the level of 6.5σ. Although there is some tension between the results from the two approaches, a combined analysis finds that the data are consistent with an at-Earth flux equally shared between three neutrino flavours, as is expected for neutrinos originating in cosmic sources.

Towards a new detector

Despite multiple searches for the locations of these sources, however, the IceCube team has yet to find any statistically significant associations. Searches for neutrinos from gamma-ray bursts and some classes of galaxies have also come up empty. Although these observations have disfavoured many promising models of the origin of cosmic rays, the ultimate goal of neutrino astronomy is to detect multiple neutrinos from a single source. This requires many hundreds of events, which would take an array of the scale of IceCube at least 20 years to detect.



IceCube

The proposed Gen2 array surrounds IceCube, incorporating the densely packed PINGU (purple) within DeepCore (green) and the current IceCube (red). The expanded array is shown in blue, along with one possible footprint for a surface array.

To speed up data collection, an expanded IceCube collaboration is planning a greatly enhanced instrument (see above) with multiple elements: an enlarged array to search for high-energy astrophysical neutrinos; a dense infill array to determine the neutrino properties (PINGU); a larger surface air-shower array to veto downgoing atmospheric neutrinos; and possibly an array of radio detectors targeting neutrinos with energies above 10^{17} eV. Most importantly, thanks to the clarity of the Antarctic ice, we would be able to increase the instrumented volume of this next-generation array by a factor of 10 without a corresponding increase in the number of deployed sensors – or in the cost. The Gen2 proposal would therefore see an instrumented volume of approximately 10 km^3 comprising strings of optical modules, but with improved hardware and deployment methods compared with IceCube.

The ultimate goal of neutrino astronomy is to detect multiple neutrinos from a single source.

For the in-ice component PINGU (Precision IceCube Next Generation Upgrade), the Gen2 collaboration is exploring a number of optimised designs for the optical modules, as well as longer strings deployed with improved drilling methods. Photomultipliers (PMTs) with higher quantum efficiency will be used, as is already the case for DeepCore in IceCube, and pressure spheres with improved glass and optical gel will improve sensitivity by transmitting more ultraviolet Cherenkov light. Some designs include more than one phototube per optical module (see below), while more radical concepts envision the addition of long cylindrical wavelength shifters to improve information about the photon arrival direction. Many-PMT designs were pioneered by the KM3NeT collaboration, which is proposing to build a cubic-kilometre-sized European neutrino Cherenkov telescope in the Mediterranean Sea, but are also attractive to IceCube.

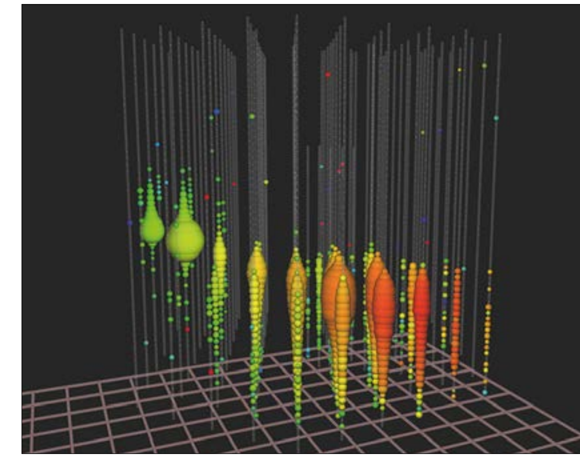
The increased complexity of these approaches would be offset by new electronics, and increased computing power will allow the use of more sophisticated software algorithms that better account for the positional dependence of the optical properties of the ice and the stochastic nature of muon energy loss. This will result in improved pointing and energy resolution of both tracks and showers and better identification of tau neutrinos. IceCube has produced a white paper for the Gen2 proposal (arXiv:1412.5106) that fits well with the US National Science Foundation's recent identification of multi-wavelength astronomy as one of six future priorities, and a formal proposal will be completed in the next few years.

Physics in order

PINGU will build on the success of DeepCore in measuring atmospheric neutrino-oscillation parameters. It consists of a dense infill array in the centre of DeepCore with a threshold of a few GeV, allowing the ordering of the neutrino masses to be determined by matter-induced oscillations of the atmospheric neutrino flux. By precisely measuring the oscillation probability as a function of neutrino energy and zenith angle, PINGU will be able to determine which neutrino is lightest.

Like the present IceTop (a surface air-shower array that covers IceCube's surface), an expanded surface array will tag and veto downgoing atmospheric neutrinos that are accompanied by cosmic-ray air showers. Current Gen2 designs envision a 75 km^2 surface array that would allow IceCube to collect a clean sample of astrophysical neutrinos over a much larger solid angle, including the galactic centre. It will also result in much improved cosmic-ray studies and more sensitive searches for PeV photons from galactic sources. To study the highest-energy (above typically 10^{17} eV) neutrinos, Gen2 may also include an array of radio detectors to observe the coherent radio Cherenkov emission from neutrino-induced showers. Radio detection is now pursued by the ARA (the Askaryan Radio Array at the South Pole) and ARIANNA (located on Antarctica's Ross Ice Shelf) experiments, but coincident observations with IceCube Gen2 would be preferable.

Of course, IceCube is not the only neutrino telescope in town. ANTARES has been taking data in the Mediterranean Sea since 2008 and will be followed by KM3NeT (*CERN Courier* March 2016 p12), while the Gigaton Volume Detector (Baikal-GVD) is currently being built in Lake Baikal, Russia (*CERN Courier* July/August 2015 p23). Seawater, lake water and Antarctic ice present different challenges and advantages to cosmic-neutrino observatories, and sites in the Northern Hemisphere benefit because the galactic centre is below the horizon. While we all benefit from friendly competition and from sharing R&D resources, size has undeniable advantages. IceCube-Gen2, should the project go ahead, will be larger than any of the proposed alternatives, and is therefore well placed to write the next chapter in neutrino astronomy.



IceCube

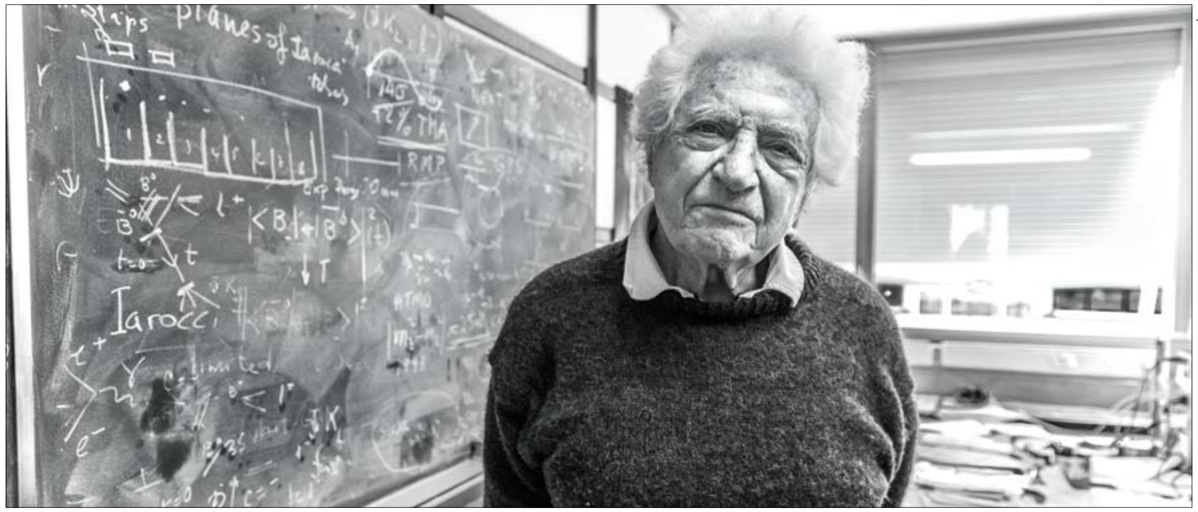
(Above) The highest-energy neutrino event observed by IceCube produced a through-going muon that deposited 2.6±0.3 PeV of energy. The size of each sphere represents the amount of observed light, while the colour indicates the time of the hit, from yellow (earliest) to green. (Below left) Concept for an IceCube-Gen2 multi-PMT digital optical module, motivated by KM3NeT. (Image credit: Alexander Kappes.)

Résumé

IceCube cherche à s'étendre

L'expérience IceCube, au pôle Sud, a été une pionnière dans le domaine de l'astronomie des neutrinos. Elle a transformé un kilomètre cube de glace de l'Antarctique en un immense détecteur Tchérenkov, qui détecte la lumière des particules chargées produites lorsque des neutrinos à haute énergie venus du cosmos interagissent avec des noyaux situés à l'intérieur du détecteur. IceCube a détecté les neutrinos les plus énergétiques jamais observés, mais leur origine reste un mystère. Pour cette raison, la collaboration IceCube élabore des plans pour un détecteur plus grand, « Gen2 », d'un volume instrumenté environ dix fois plus grand que celui d'IceCube, ce qui accélérera considérablement la collecte des données.

Francis Halzen, University Wisconsin-Madison, IceCube principal investigator, and **Spencer Klein**, Lawrence Berkeley National Laboratory and University of California, Berkeley.


Sophia Bennett/CERN

Jack Steinberger photographed in his office at CERN in 2016.

Neutrino pioneer

Jack Steinberger joined CERN in 1968, six years after his seminal discovery of the muon neutrino. **Paola Catapano** spoke to him in May on the occasion of his 95th birthday.

When I meet Jack in his office in Building 2, he has just returned from a "splendid" birthday celebration – a classical-music concert "with a lady conductor", he is quick to add. It had been organised by members of his town of birth, Bad Kissingen in South Germany, and was held at the local gymnasium that bears his name. Steinberger's memories of the town are those of a 13 year-old child in pre-war Germany during the Nazi election propaganda. "Hitler was psychopathic when it came to Jews," he says. "In making me leave, however, he did me a great favour because I had a wonderful education in America."

Talking to this extraordinary man and physicist – who is too modest to dwell on the 1962 discovery of the muon neutrino that won him, Leon Lederman and Melvin Schwartz the 1988 Nobel Prize in Physics – is like taking a trip back in the history of particle physics. With the help of a scholarship from the University of Chicago, Steinberger completed a first degree in chemistry in 1942. He owes his first contact with physics to Ed Purcell and Julian Schwinger, with whom he worked at the MIT radiation laboratory where he had been assigned a military role in 1941 – the year that Japan attacked the US at Pearl Harbour.

"We were making bombsights for bombers, something that could be mounted on airplanes and could see the ground with radar and so you could find military targets," he explains. "The bombsight we succeeded in developing had a very limited accuracy and you couldn't see a military target, but you could see cities." With a heavy heart, Steinberger adds that the radar system was used in the infamous Dresden bombing. "That was my contribution during the war," he states flatly.

The Fermi years

When the war ended, Steinberger went back to Chicago with the intention of completing a thesis in theoretical physics. Then he met Enrico Fermi. "Fermi was the biggest luck I had in my life!" he exclaims, with a spark in his striking blue eyes. "He asked me to look into a problem raised by an experiment by Rossi and Sands on stopping cosmic-ray muons, and suggested that I do an experiment instead of waiting for a theoretical topic to surface," recalls Steinberger. At the time, most experiments required just a handful of Geiger counters and a detector measuring about 20 cm long, he says. "The experiment I wanted to do required 80 of those and was 50 cm long, so it was not trivial to build it."

It was the time before computers, when vacuum tubes were the height of technology, and Fermi had identified the resources required in the physics department of the University of Chicago. Once the experiment was up and running, however, Fermi suggested it would produce results more quickly if it were located on top of a mountain, where there would be more mesons from cosmic rays. "He found a young driver – I didn't know how to drive, it was the beginning of cars – who took me to the only mountain in the US with a road to the top," says Steinberger. "It was almost as high as Mt Blanc, and I could do the experiment faster by being on top of that thing."

The experiment showed that the energy spectrum of the electron in certain meson decays is continuous. It suggested that the muon undergoes a three-body decay, probably into an electron and two neutrinos, and helped to lay the experimental foundation for the concept of a universal weak interaction. What followed is history, leading to the discovery of the muon neutrino (see article on p25). "It is likely that we had no prejudice on the question of whether the neutrino in muon decay is the same as the one in beta decay."

Apart from the discovery of the muon neutrino, Steinberger's pioneering work in physics overlaps 40 years of history of electroweak theory and experiment. At each turn of a decade, Steinberger was the first user of the latest device available for experimentalists, starting with McMillan's electron synchrotron when it had just been completed in 1949, or Columbia's 380 MeV cyclotron in 1950. In 1954, he published the first bubble-chamber paper with Leitner, Samios and Schwartz, making a substantial contribution to the technique itself and achieving important results on the properties of the new unstable (strange) particles.

Lasting legacy

What brought Steinberger to CERN in 1968 was the availability of Charpak's wire chamber, which he realised was a much more powerful way to study K^0 decays – to which he says he had "become addicted". Then he conceived and led the ALPEH experiment at the Large Electron–Positron (LEP) collider. The results of this and the other LEP experiments, he says, "dominated CERN physics, perhaps the world's, for a dozen or more years, with crucial precise measurements that confirmed the Standard Model of the unified electroweak and strong interactions".

These days, Jack still comes to CERN with the same curiosity for the field that he always had. He says he is "trying to learn astrophysics, in spite of my mental deficiencies", and thinks that the most interesting question today is dark matter. "You have a Standard Model which does not predict everything and it does not predict dark matter, but you can conceive of mechanisms for making dark matter in the Standard Model," he says. "You don't know if you really understand it, but you can imagine it. And I am not the only one who doesn't know."

Résumé

Entretien avec Jack Steinberger

Le physicien du CERN Jack Steinberger, qui a récemment fêté ses 95 ans, a partagé le prix Nobel de physique 1988 pour son rôle dans la découverte du neutrino muonique, 26 ans plus tôt, au Laboratoire national de Brookhaven. Il a quitté l'Allemagne en 1934, fuyant les persécutions contre les juifs, et s'est installé aux États-Unis, où il a ensuite étudié sous la direction d'Enrico Fermi, à Chicago. Pendant les années 1950, il a participé au développement des chambres à bulles, et a contribué à la myriade de découvertes et de résultats qui ont mené à l'élaboration du Modèle standard. Aujourd'hui encore, il n'est pas rare de croiser Jack au CERN.

Paola Catapano, CERN.

Faces & Places

Appointments

John Womersley appointed director of ESS

The European Spallation Source (ESS) under construction in Lund, Sweden, has named John Womersley as its next director general. Womersley, who is chief executive of the UK's Science and Technology Facilities Council (STFC), will take over from current ESS director general Jim Yeck on 1 November.

More than 40 institutions from 15 countries are participating in the €1.84bn ESS, which will be the world's most powerful source of neutrons when it enters full operation in 2025. Womersley, a particle physicist who worked at Fermilab and later became a scientific adviser to the US Department of Energy, was directly involved in the UK's decision to join the ESS project in 2014. He has led STFC, which manages the UK's contribution to CERN and other international projects, since 2011 and is also the current chair of the European Strategy Forum on Research Infrastructures.

ESS

John Womersley at the Foundation Stone Ceremony in 2014, which marked the beginning of the construction of the ESS.

"I'm excited to join ESS. It's one of Europe's largest and most visible new research projects. Scientists, staff, partner institutions and countries across Europe have come together to build what will be the world's leading neutron source for research on materials and life sciences," says Womersley. "The impressive progress at ESS can be seen in the construction site in Lund and I am determined to keep up the momentum."

Yeck, who was previously director of the IceCube neutrino telescope project, joined ESS as CEO and director general at the beginning of 2013 and successfully led ESS into construction. The ESS ERIC (European Research Infrastructure Consortium) was established in August 2015.

TRIUMF welcomes new associate director

Oliver Kester has been appointed associate laboratory director for the Accelerator Division at TRIUMF in Canada, succeeding Robert Laxdal. An accomplished accelerator physicist and scientific leader, Kester is currently a professor at Goethe-Universität Frankfurt and director at FAIR (Facility for Antiproton and Ion Research) under construction in Darmstadt, Germany. He has also held faculty and administrative positions at CERN, the University of Munich and Michigan State University.

Gabi Otto/GSI

Oliver Kester will start his new role at TRIUMF in September.

Kester's research interests focus on the production and transport of intense charged-particle beams, the development of accelerator cavities, beam instrumentation and electron targets for heavy-ion storage rings. In his new role, effective from 12 September, he will be responsible for the operation of the accelerator facilities, the construction of the ARIEL project and the advancement of accelerator research at TRIUMF. "I couldn't be more thrilled to join TRIUMF at such an exciting time for accelerator science at the laboratory," said Kester.

Awards

Markov prize for black-hole theory

The Institute for Nuclear Research (INR) of the Russian Academy of Sciences has awarded its 2016 Markov prize to Victor Berezin of INR RAS and Valery Frolov of Alberta University in Canada for their outstanding contributions to the theory of black holes. Berezin is a well-known specialist in the field of gravity theory and cosmology. He contributed much to the theory of quantum and quasi-classical gravitational collapse, and carried out pioneering research in the properties of black holes, the spectra of their masses and radiation parameters. Frolov, who was unable to attend the ceremony due to other commitments, has made advances in our understanding of interior space and black-hole entropy, extra-dimensional models and the interactions between black holes and strings or branes.

INR

Prize winners Victor Berezin of INR RAS (left) and Valery Frolov of Alberta University.

The award was presented at the 14th Markov Readings in Moscow on 13 May. These are a series of international seminars held in commemoration of the prominent Russian scientist Moisey Markov (1908–1994).

Prizes galore for LIGO discovery

Following the discovery of gravitational waves by LIGO (Laser Interferometer Gravitational-Wave Observatory), which was announced in February this year, the breakthrough has been recognized by three major awards.

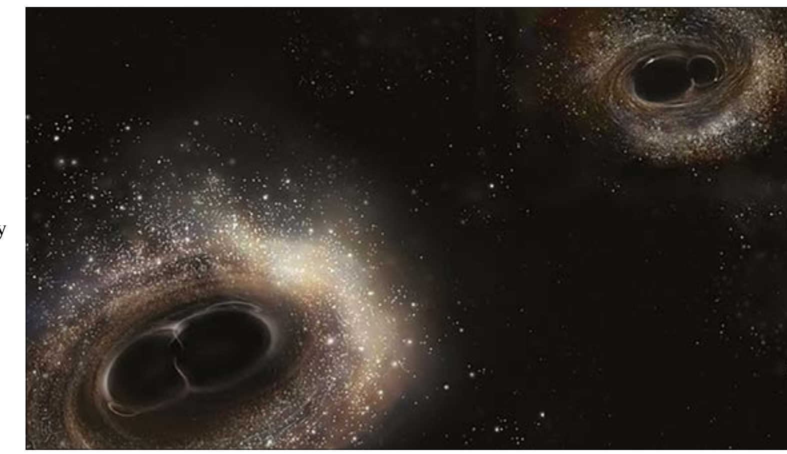
On 2 May, the selection committee of the new $3 million Special Breakthrough Prize in Fundamental Physics announced that LIGO founders Ronald Drever and Kip Thorne of Caltech and Rainer Weiss of MIT would share one third of the award, with the remaining amount being shared equally between LIGO's 1005 authors and seven members of LIGO's sister experiment VIRGO. The laureates will be recognized at the 2016 Breakthrough Prize ceremony in autumn, where the annual Breakthrough Prize in Fundamental Physics (which is distinct from the special prize) will also be presented.

Just two days later, on 4 May, the same founding LIGO members and the LIGO discovery team received the $0.5 million Gruber Cosmology Prize for the detection of gravitational waves, which the prize announcement described as "a technologically herculean and scientifically transcendent achievement". Drever, Thorne and Weiss will also receive a gold medal recognizing their dedication and work. Finally, on 2 June, the pioneering LIGO trio was awarded the 2016 Kavli Prize in Astrophysics. The $1m prize, which is presented once every two years, recognizes their instrumental role in establishing the experiment.

"The lion's share of the credit for LIGO's gravitational-wave discovery belongs to the superb 1000-member LIGO team, who pulled it off," said Thorne. "They have made Weiss, Drever and me look good. And my deep thanks go out, also, to the succession of outstanding LIGO directors who provided the leadership required for success – Robbie Vogt, Stan Whitcomb, Jay Marx, David Reitze, and especially Barry Barish, who designed and led the transformation of LIGO from the small R&D project that Weiss, Drever and I created."

Left to right: Gruber Foundation, Caltech, Bryce Vickmark

LIGO founders Ronald Drever, Kip Thorne and Rainer Weiss.



LIGO/A Simonnet

The recent discovery of a second black-hole merger marks the beginning of gravitational-wave astronomy.

● LIGO's announcement in February was based on the detection of waves from a single cosmic event that arrived at the interferometer sites on 14 September 2015. The waves were generated 1.3 billion years ago by the merger of two orbiting black holes, which caused tiny displacements (on the order of one part in 10^{21}) in LIGO's twin interferometers located on either side of the US.

In June, however, LIGO reported a second event, also from colliding black holes, which was detected on 26 December. Named "GW151226", it marks the beginning of gravitational-wave astronomy, said LIGO spokesperson Gabriela González. "It takes a lot of people, physics and engineering to build these exquisite instruments, and they detected these gravitational waves very clearly."

Winners of the 2016 Beamline for Schools announced

Sixteen students have won the chance to conduct their own experiments at CERN, having been named as the winners of CERN's 2016 Beamline for Schools competition. Two teams of high-school students were selected from a total of 151 teams from 37 countries to come to CERN in September. The "Pyramid Hunters", from Marshal Stanisław Małachowski High School in Poland, propose to measure the muon absorption of limestone to help understand muon-tomography images of the Chephren pyramid recorded many years ago. The other winners, "Relatively Special" from Colchester Royal Grammar School in the UK, aim to test the validity of the Lorentz factor by measuring the effect of time dilation on the decay rate of pions.

Guillaume Jeanneret/CERN

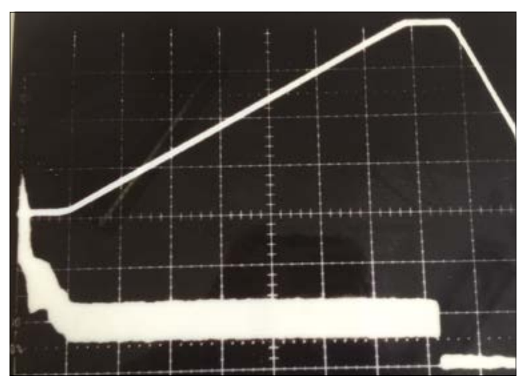
Students undergoing training on the beamline as part of the 2015 competition.

The Beamline for Schools competition enables high-school students to run an experiment in the same way that researchers do at the Large Hadron Collider and other CERN facilities. Students were asked to submit a written proposal and video explaining their experiment's methods and goals. "This competition is very effective in triggering motivation for fundamental physics in young, brilliant students at a moment that is crucial for their future career choices", said Claude Vallee, chairperson of the CERN SPSC committee that chose the winning teams.

The first Beamline for Schools competition was launched two years ago to coincide with CERN's 60th anniversary, and has so far seen winning teams from the Netherlands, Greece, Italy and South Africa perform experiments at CERN. "We are very happy to be able to offer this experience to high-school students, thanks to the support received via donations to the CERN & Society Foundation," said Markus Joos, Beamline for School project leader.

ANNIVERSARIES

Celebration marks 40 years of SPS service



L Evans

Physicists gathered for a barbeque at CERN's Prévessin site on 17 June to celebrate 40 years since the first beam in the SPS (above).

An event at CERN held on 17 June celebrated the 40th anniversary of the Super Proton Synchrotron (SPS), which has been at the centre of some of CERN's most famous discoveries. The 6.9 km-circumference SPS operated as a hadron collider from 1981–1984, flushing out the W and Z bosons, before going on to feed particles to LEP and the LHC. The image (above, right) shows the original scope trace of the first beam accelerated to 300 GeV (the SPS was originally called the "300 GeV Project", although it soon reached higher energies). It was taken during the meeting of the CERN council in June 1976, recalls Lyn Evans, who is director of CERN's Linear Collider collaboration. Aged 30 at the time, Evans was a junior physicist and was sent over to the council chamber to show the trace to the director general, John Adams, so that he could announce the exciting news at the council meeting. When he got there, however, he found the chamber empty. "They had broken for lunch, so I just left it on the DG's desk," says Evans. "The rest is history!" (See p61.)

CERN openlab: supporting the LHC community for 15 years

CERN

Charlotte Warakaulle, CERN director for international relations, presents an award to Peter Gleissner of Intel in recognition of 15 years of fruitful collaboration.

CERN openlab held an event on 8–9 June to showcase CERN's collaboration with leading ICT companies and research institutes, which are a key source of support for the worldwide LHC research community. The event marked 15 years since CERN openlab was established, and more than 100 people attended.

"Since 2001, this unique public-private partnership has worked to ensure that members of CERN's scientific community have access to the very latest ICT solutions to help them carry out their ground-breaking physics research," said Alberto Di Meglio, head of CERN openlab.

Celebrating 40 years of supergravity

With 2016 marking 40 years since the formulation of supergravity (SUGRA), a celebration took place at CERN on 24 June, attended by SUGRA pioneers Sergio Ferrara, Dan Freedman and Peter van Nieuwenhuizen. Supergravity is central to the scientific heritage of the CERN Theory Department, and has inspired and continues to inspire generations of physicists, theorists and experimentalists alike.

Bennett, Sophia

Peter van Nieuwenhuizen, Sergio Ferrara and Dan Freedman at the Council Chamber.

INDUSTRY

Netherlands firms exhibit products at CERN

The biennial Holland@CERN event took place on 30 May – 2 June, attracting 36 firms from the Netherlands to exhibit their products. The Netherlands has been a contributor to big-science projects for 60 years, ranging from major particle accelerators like the LHC and fusion reactors such as ITER to telescopes such as the E-ELT and various light sources.

"The Dutch firms were very happy with the many new contacts they have been able to make with people at CERN, and received many visitors to their stands," said Rob Klöpping, Dutch Industrial Liaison Officer, Netherlands Organisation for Scientific Research (NWO).

Sophia Bennett

CERN Director-General Fabiola Gianotti with Ambassador Roderick van Schreven, Permanent Representative of the Netherlands to the United Nations and the World Trade Organisation (to her right).

Third European Cryogenics Days focuses on HEP

Sophia Bennett

The attendees of June's European Cryogenics Days event in front of the main building.

Cryogenics has contributed widely to the successes of high-energy physics (HEP). Conversely, HEP has pushed cryogenic engineering developments to a high level of technical excellence. The third European Cryogenics days, hosted by CERN on 9–10 June, focused on the latest developments in this area. Organized by the Cryogenics Society of Europe, together with the High-Energy Physics Technology Transfer Network (HEPTech) and CERN, the event attracted 176 participants from industry and academia, mostly from Europe.

Cryogenics are not just crucial for machines such as CERN's LHC and the Wendelstein-7X stellarator in Germany, but also for state-of-the-art light sources such as the European X-ray Free Electron Laser at DESY and also the central solenoid module of the ITER fusion experiment. Lessons learnt from ATLAS and CMS, which both use dedicated cryogenic equipment, addressed noticeable shortfalls such as oil contamination. Cryogenics for the European Spallation Source (ESS) target was also explored, as were the novel membrane cryostats for the large-volume neutrino detectors under development as part of the CERN Neutrino Platform (see p21).

Regarding future cryogenic applications for HEP, efforts will be concentrated on the development of dedicated cryogenic systems for the high-luminosity LHC and the Future Circular Collider (FCC). It is clear already that the FCC cryogenic system will require cryoplants far beyond the present state-of-the-art, with unit capacities of 100 kW at 4.5 K.

The event also addressed instrumentation for cryogenic systems, research in the cryogenic field, and future developments in cryotherapy and space applications. The event was accompanied with an industrial exhibition and bilateral brokerage meetings organised by the Enterprise Europe Network.

CONFERENCES

Beauty on show in the south of France

The Beauty 2016 participants in front of the conference venue in Marseille.

The 16th International Conference on *B*-physics at Frontier Machines, Beauty 2016, was held in Marseille, France, from 2–6 May. The conference, which saw 66 invited talks divided between 18 theoretical and 48 experimental topics, covered a wide range of subjects including studies of CP violation and rare decay properties of beauty and charm hadrons.

Heavy flavour physics, in particular decays of *b*-hadrons, offers a powerful probe of physics beyond the Standard Model because new particles may manifest themselves in observables that can be calculated and measured with high precision. Run 1 of the LHC has resulted in the discovery of the rare decay $B^0_s \rightarrow \mu^+\mu^-$ and new constraints for CP violation in $B^0_s \rightarrow J/\psi\phi$ decays, for instance, and several puzzling patterns in data for rare *b*-hadron decays have emerged.

Highlights of Beauty 2016 include the world's best measurement of the semi-leptonic CP asymmetry in B^0_s–$\bar{B}^0_s$ mixing by the LHCb experiment. The corresponding observable, $a^s_{SL} = [0.39 \pm 0.26\,(\text{stat}) \pm 0.20\,(\text{syst})]\%$, which probes the difference between $B^0_s \rightarrow \bar{B}^0_s$ and $\bar{B}^0_s \rightarrow B^0_s$ transitions, is in agreement with the Standard Model expectation (which predicts a^s_{SL} at the 10^{-5} level) and therefore does not confirm a previous intriguing result by the D0 Collaboration at Fermilab. ATLAS also presented the world's best measurement of the decay-width difference of the B^0_d-meson system, while CMS reported the double upsilon-production result at $\sqrt{s} = 8$ TeV and the BaBar collaboration released the first study of the rare decay $B^+ \rightarrow K^+\tau^+\tau^-$, which is experimentally challenging.

Some of the most interesting current results concern "flavour anomalies". In particular, the ratio $BR(B \rightarrow D^*\tau\nu)/BR(B \rightarrow D^*\ell\nu)$, where $\ell = \mu, e$, is measured to be approximately 4σ away from Standard Model expectations, providing a test of lepton flavour violation. The rare decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$ also shows deviations from expectations, with the angular distribution of its decay products (namely the "P'_5" observable) looking particularly intriguing. In order to interpret these and further data from LHC Run 2, it is crucial that we have a point of reference from the Standard Model. In the case of P'_5, the situation is complicated due to effects from strong interactions, for instance. Impressive progress on lattice QCD has enabled calculations that are crucial inputs for theoretical predictions, such as the decay constant of the B^0_s and hadronic form factors.

LHCb also reported new world-best measurements of the angle γ of the unitarity triangle from pure tree-level decays, which still has a significant uncertainty, $70.9^{+7.1}_{-8.5}$ degrees, and leaves a lot of space for future improvement. Concerning possible CP violating effects in the $B^0_s \rightarrow J/\psi\phi$ decay, the experimental precision has reached a level where effects from so-called penguin topologies have to be included. The pentaquark state observed by LHCb has also put hadron spectroscopy and exotic states under the spotlight, although LHCb data do not confirm the udsb "tetraquark" state recently reported by D0.

Whilst CP violation in the charm sector has not yet been observed, LHCb is close to approaching the Standard Model expectations. Recent theoretical progress has also resulted in new analyses of direct CP violation in the neutral kaon system, which are not in good agreement with experiment, thereby adding yet another flavour anomaly that has to be understood. Finally, the NA62 experiment raises the exciting prospect of testing the Standard Model via the rare decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$.

Beauty 2016 was a great success. The future experimental programme for heavy-flavour physics is very bright, with the super-*B* factory at KEK under construction and further LHC data to come.

● http://beauty2016.in2p3.fr.

Highlights of IPAC 2016 in Korea

The 7th International Particle Accelerator Conference, IPAC16, was held in Busan, Korea, from 8–13 May, attracting more than 1200 participants from 37 countries.

Lepton and hadron colliders continue to push performances to serve research in particle physics. The LHC is back in action after a major shutdown and has successfully restarted operation at the unprecedented energy of 6.5 TeV per beam, while the commissioning of the SuperKEKB collider in Japan is progressing firmly after a major upgrade to increase its luminosity. At RHIC in the US, electron lenses have been used to enhance the collider's performance by compensating for beam–beam effects.

Meanwhile, several upgrade programmes and new storage rings for the synchrotron X-ray community are in full swing, led by MAX IV in Sweden, which is the first synchrotron light source based on a multi-bend achromat cell. Novel optimization techniques based on genetic algorithms are taking the horizontal emittance of storage rings towards the X-ray diffraction limit, which allows smaller and more stable beams for users. More than a dozen contributions at IPAC16 focused on the development of linear optics measurement and correction techniques, ▷

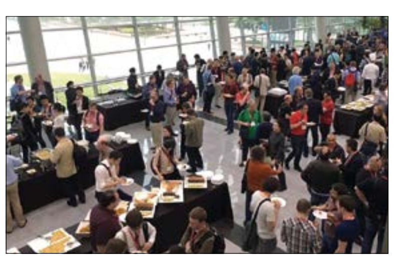
with recent studies of beta functions opening the door for light sources to replace the traditional and lengthy orbit response techniques with fast turn-by-turn-based optics corrections.

At the high beam-power front, the Spallation Neutron Source in the US has reached 1.4 MW and launched a study to double the power at 1.3 GeV. Meanwhile, the European Spallation Source in Sweden, which is based on an unprecedented 5 MW linear accelerator that will reach an energy of 2 GeV using superconducting RF cavities, is well into construction and progressing towards first beam in June 2019. Accelerating superconducting cavities based on Nb$_3$Sn (the same material being explored for the HL-LHC and FCC magnets) have now been shown for the first time to outperform Nb cavities, defining the next generation of superconducting RF technology.

Other highlights from the Korea event included developments at J-PARC in Japan, where the rapid-cycling synchrotron is approaching routine 1 MW operation and the main 50 GeV ring is delivering a 400 kW beam for long-baseline neutrino experiments. There was also a session devoted to engagement with industry, which is crucial for the high-luminosity LHC, and a report from PACMAN – a Marie-Curie network based at CERN that is pushing the limits of technology in component alignment, in addition to training qualified engineers and creating synergies between institutes.

The Xi Jalin Prize for outstanding work in the accelerator field was awarded to Derek Lowenstein from Brookhaven National Laboratory in the US, while the Nishikawa Tetsuji Prize was awarded to Gwo-Huei Luo at the NSRRC in Taiwan. Sam Posen of Fermilab in the US received the Hogil Kim Prize, and the Mark Oliphant Prize was awarded to Spencer Jake Gessner of SLAC for his PhD thesis work on hollow-channel plasma wakefield accelerators.

The eighth IPAC will take place in Copenhagen, Denmark, on 14–19 May 2017.
● www.ipac16.org.



IPAC16 was hosted by Pohang Accelerator Laboratory in Korea.

Visits

Sophia Bennett

Austria's minister for labour, social affairs and consumer protection, **Alois Stöger**, visited CERN on Wednesday 8 June, during which he toured the ATLAS cavern with experiment spokesperson **Dave Charlton** (right).

Sophia Bennett

The **Rt Hon Hugo Swire MP**, minister of state, Foreign and Commonwealth Office, UK, in the LHC superconducting magnet test hall with head of the beams department **Paul Collier** (right) on 9 June.

Maximilien Brice

On 14 June, the Japanese minister for education, culture, sports, science and technology, **Hiroshi Hase**, signed the guestbook with the director for research and computing, **Eckhard Elsen**, and the director for international relations, **Charlotte Warakaulle**, during a visit that took in the ATLAS visitor centre and the LHC magnet test hall.

Sarah Charley

Under secretary for science and energy at the US Department of Energy, **Franklin (Lynn) M Orr**, pictured at CMS on 16 June with CMS scientist **Isobel Ojalvo** from the University of Wisconsin-Madison.

Obituaries

Péter Hasenfratz 1946–2016

Péter Hasenfratz was born in Budapest, Hungary on 22 September 1946. He studied physics at Eötvös University, finishing his PhD in 1973, and in 1975 he took up a postdoc position under Gerard 't Hooft in Utrecht. He then returned to Budapest, before moving to the CERN Theory Division in 1979.

Péter then began to work on field theory regularized on a space–time lattice. In 1980, together with his younger sister Anna, he presented the first correct computation of the scale parameter of QCD on the lattice. In 1982 he organized the first international workshop on lattice field theory at CERN, sending handwritten invitations to each of the participants. He had planted the seed for a new scientific community, and today several hundred people meet annually at the lattice conferences.

In 1984 he went to the University of Bern, and from 1999–2001 he was the director of the Institute for Theoretical Physics there. His lectures, not only in Bern but also at numerous international schools, have been described as a revelation by participants.

Péter was extremely creative and made many original contributions to quantum field theory. He often calculated things analytically that had seemed incalculable before, such as the exact value of the dynamically generated mass gap in several 2D asymptotically free quantum field theories. In addition, he significantly contributed to our understanding of chiral symmetry on the lattice. While cleaning up his office in 1997, he discovered an old preprint by Paul Ginsparg and Kenneth Wilson from 1982 that contained the now famous Ginsparg–Wilson relation, which turned out to hold the key to understanding chiral symmetry. By constructing a novel solution for this relation, Péter breathed new life into this old paper and today, with more than 950 citations, it has become one of the most cited papers in lattice field theory.

Ruth Bestgen

Péter Hasenfratz was a member of the CERN Theory Division from 1979–1984.

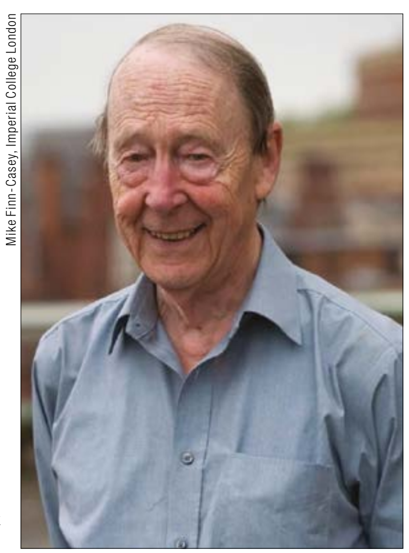
He had always wished that he could witness the discovery of the Higgs boson, since he had a special interest in electroweak symmetry-breaking, and his wish was granted in 2012 – one year after his retirement. Tragically, after this most remarkable scientific career, rapidly advancing Alzheimer's disease probably prevented him from fully appreciating the scientific significance of this discovery.

Péter was an extraordinary scientist and an extremely friendly, kind person. He passed away peacefully at home on 9 April, leaving behind his wife Etelka, their four children, six grandchildren, and his sister Anna.
● *His colleagues.*

Tom Kibble 1932–2016

Tom Kibble, an internationally renowned theoretical physicist whose contributions range from the theory of elementary particles to modern early-universe cosmology, died on 3 June in London, aged 83.

One of Kibble's most important pieces of work in this area was his study of spontaneous symmetry-breaking, whereby vector particles can acquire a mass accompanied by the appearance of a massive scalar boson. This mechanism – which was put forward independently in 1964 by Brout and Englert, by Higgs and by Kibble, Guralnik and Hagen – lies at the heart of the Standard Model and all modern unified theories of fundamental particles. It was finally confirmed in 2012 by the discovery of the Higgs boson at CERN (the associated massive W and Z vector bosons having already been discovered at CERN in the early 1980s), winning Higgs and Englert the 2013 Nobel Prize in Physics.



Mike Firn-Casey, Imperial College London

Tom Kibble, co-inventor of spontaneous symmetry-breaking.

The vindication of spontaneous symmetry-breaking presented a much-debated dilemma for the Nobel Committee, notwithstanding Brout's demise in 2011, because prizes can be awarded to at most three individuals. However, Kibble was also sole author of a 1967 paper that focused on the non-abelian generalization of the mechanism. When the Standard Model came along shortly afterwards, Kibble's paper was seen to explain not only why the W and Z acquire a mass but, equally crucial, why the photon does not. At a celebration of Kibble's 80th birthday at Imperial College in March 2013, Steven Weinberg ended a public lecture by stating "Tom Kibble showed us why light is massless". Indeed, Higgs said that Kibble should have shared the prize awarded to Englert and himself "because of what he ▷

wrote in 1967". Kibble himself maintained a dignified modesty throughout, in keeping with the honesty and integrity for which he was justly famous.

Spontaneous symmetry-breaking also predicted the existence of soliton-like solutions of the field equations of unified field theories. In 1976, Kibble realised that these structures could condense as the universe cooled from the hot conditions prevailing in the Big Bang, and might therefore have striking effects on the development of large-scale structures in the universe called cosmic strings. Kibble's vision has thereby provided an extraordinary link between the macroscopic and microscopic features of our universe – an effect that has been confirmed experimentally in the context of vortex formation in superfluid helium 3.

Kibble was born in Chennai, India, to missionaries Walter and Janet (nee Bannerman) and he attended Edinburgh University in the UK from 1951–58. After spending a year at Caltech in the US he joined the theoretical physics department at Imperial College London, which had recently been founded by Abdus Salam. In 1970 Kibble became professor of theoretical physics at Imperial, and was head of the department of physics there from 1983–1991.

He was an outstanding teacher and his textbook on classical mechanics has become a classic. In 2005 he was awarded the 2005 NESTA/Nature Mentoring lifetime achievement award. Kibble was elected Fellow of the Royal Society in 1980 and served as its vice-president in 1988–89. He was awarded the 1981 Hughes Medal of the Royal Society, jointly with Peter Higgs, "for their international contributions about the spontaneous breaking of fundamental symmetries in elementary-particle theory". Other awards include the 1984 Rutherford Medal and Prize, the 1993 Guthrie Medal and Prize, the 2009 Dirac Medal, the 2010 Sakurai Prize for Theoretical Physics, Honorary Fellowship of the IOP in 1998 and the 2012 Einstein Medal. He received a CBE in 1998 and a knighthood in 2012.

Kibble was also concerned about the nuclear arms race and took leading roles in several organizations promoting the social responsibility of science. These included the British Society for Social Responsibility in Science, Scientists against Nuclear Arms, Scientists for Global Responsibility and the Martin Ryle Trust. Tom Kibble was the personification of stature, dignity and integrity, and will remain so in our memories. His wife, Anne (nee Allan), whom he married in 1957, died in 2005. He is survived by their son, Robert, and two daughters, Helen and Alison.

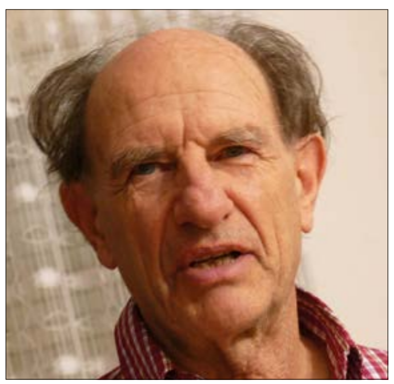
● *Mike Duff, Imperial College London.*

Gérard Mennessier 1943–2016

Gérard Mennessier, a theorist at Laboratoire Charles Coulomb in Montpellier, France, passed away on 8 April. He was much admired by his many colleagues and collaborators, both for his physics achievements and for his human qualities, especially his modesty and cordiality even in adverse circumstances.

After studying at the Ecole Normale Supérieure, Mennessier began his research in Paris before moving to Montpellier. His research in particle physics ranged from phenomenology, experiments and theory to mathematical physics and tended to involve rigorous numerical computations. In phenomenology, he made significant contributions to dispersion relations for photo-production and C-violation in photo-production of pions in proton Compton scattering. He also helped determine total cross-sections for hyperon

Elisabeth Richard



nucleon scattering, three-meson resonances and meson pair production in two-photon processes, and constructed a practical theory of the multi-layered transition radiation detector.

Some of Gérard Mennessier's most important contributions concerned pion–pion scattering.

Mennessier's most enduring contributions are in the field of pion–pion scattering from a rigorous S-matrix framework based on axiomatic field theory, for which he helped improve the bounds by a factor of 40. Another achievement was his role in proving that there are several and even continuous solutions when you try to extract the KM matrix from the moduli of the matrix if there are more than three generations of quarks, contrary to what was believed at the time. More recently, Mennessier's interests moved to the life sciences, in particular genomics.

We send our deep condolences to his daughter Elisabeth and to his many friends and admirers.

● *His friends and colleagues.*

György Vesztergombi 1943–2016

György Vesztergomb, a prominent figure in Hungarian high-energy physics, died on 2 May after a long illness. He was emeritus professor of the Wigner Research Centre for Physics at Eötvös University in Budapest, and a member of several CERN committees as Hungarian delegate or representative. During his career he founded and led several research groups in experimental particle and nuclear physics, including the Hungarian components of the CERN experiments L3, NA49, CMS, ALICE and NA61.

Gyuri, as he was known to his friends, was born in Mohács and studied physics at the Eötvös University. His diploma work concerned neutron-induced reactions at KFKI Research Institute for Particle and Nuclear Physics (RMKI), after which he analyzed bubble-chamber data. He joined the related experiment at the Serpukhov accelerator, where he developed methods and software to enable electronic data to be transferred to magnetic tapes, rather than photographic films. In 1974 Vesztergombi moved to CERN and joined Pierre Darriulat's group at the ISR, where he started to work on phenomena associated with large transverse momentum. From 1976 onwards he contributed to the study of the quark structure of the proton at the SPS experiment NA4 in the group of Carlo Rubbia, and he later worked on the detailed study of W and Z bosons as a member of the L3 Collaboration at LEP.

During the 1980s, while at the Max Planck Institute in Munich, Gyuri joined CERN's NA35 streamer chamber experiment – which was among the first attempts to create the quark–gluon plasma. On returning to Hungary he defended his doctoral thesis titled "Interaction of quarks and gauge bosons" in 1992, and in the same year he played a crucial role in Hungary's accession to CERN. His NA49 group contributed to the assembly, operation and analysis of a grid-geometry time-of-flight wall and, encouraged by the successes at RHIC, he proposed a detailed study of large transverse momentum particles. Vesztergombi was co-spokesman of the successor experiment NA61 and chairman of the collaboration board for several years.

Hungarian Academy of Sciences

György Vesztergombi played an active role in many CERN experiments.

Simultaneously, he started preparatory work for the planned LHC experiments. Under his guidance, KFKI-RMKI built the hadronic forward calorimeter for CMS and his group was partly responsible for the alignment of the CMS tracker. Vesztergombi foresaw that the expected volumes of LHC data could not be handled with classical computing methods, and got involved in highly parallel and associative computer programming and field-programmable gate arrays. He played a pioneering role in the development of new ideas – among them a proposal to use the waters of Lake Geneva as a gigantic detector for a neutrino beam fired from CERN. In Hungary, he was also the first to recognize the potential of plasma-wakefield acceleration, and hoped that it would one day take us into the PeV energy regime to reveal the internal structure of quarks.

In recognition of his work, Vesztergombi received the Academy Award of the Hungarian Academy of Sciences in 1992 and the Officer's Cross of the Order of Merit of the Hungarian Republic in 2009. He taught experimental particle physics at Eötvös University for more than two decades, and was dedicated to educating young researchers. In Gyuri we have lost an energetic, highly versatile and imaginative scientist. But his activities and enthusiasm have launched the careers of a new generation of physicists.

● *Ferenc Siklér, Wigner Research Centre for Physics, Budapest, and colleagues.*

Irene Vichou 1964–2016

Our ATLAS colleague Irene Vichou passed away in April, after a long career working on CERN experiments, including many years as a member of the ATLAS collaboration.

Irene started to work at CERN's West Area Omega experiment while a PhD student at the University of Athens. From 1993, she worked with the ATLAS liquid-argon calorimeter group from LAL Orsay, during which time she participated in calorimeter-prototype beam tests and carried out the first full simulation of photon and electron identification for the ATLAS calorimeters. In 1996 Irene joined the ATLAS Tile Calorimeter community, initially working with the IFAE Barcelona team, and was involved in the first prototypes of the caesium radioactive source calibration system.

One of the important results of Irene's work was the identification of the long-term degradation of the photomultiplier performance, which led the manufacturer to modify the design.

In 2000, Irene joined the ATLAS team at Athens University and brought into operation an important test bench to qualify the 10 000 photomultiplier blocks assembled for the ATLAS Tile Calorimeter.

Ilias Efthymiopoulos

Irene Vichou led the ATLAS Tile Calorimeter group.

Then, in 2004, she joined the University of Illinois at Urbana-Champaign, where she helped prepare the calorimeter for sub-detector operation within ATLAS. She was responsible for many crucial activities including the implementation of services, the commissioning and refurbishment of electronics, data preparation and detector performance, and at a broader level coordinated several activities within the Jet/EtMiss group. Irene was also the supervisor of several PhD students and was a highly regarded mentor.

Irene was appointed project leader of the ATLAS Tile Calorimeter system in 2014. Under her leadership, the project saw a major consolidation and repair campaign for the front-end electronics during the long shutdown after the LHC Run 1, enabling the collaboration to start Run 2 with a fully working detector that was more robust against failures. R&D for the Tile Calorimeter upgrade for the high-luminosity LHC also took a large step forward under her supervision.

Irene was a calm and thoughtful colleague and a good friend to many of us in ATLAS. She always looked carefully and deeply into every topic, earning her the appreciation and respect of all. We came to rely on her calmness, quiet wisdom and authority in all Tile Calorimeter matters and beyond.

Our thoughts are with Irene's husband Ilias, and their daughters Paulina and Natalia.

● *Her friends and colleagues in ATLAS.*

Vadim Volkov 1923–2016

Vadim Volkov, a physicist at the Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research (JINR), Russia, passed away on 22 April aged of 93. Volkov entered Moscow State University in 1940. The following year he volunteered for military service at the front, and his crusade with the Soviet Army from Moscow to Koenigsberg saw him receive several medals. He fought in the Battle of Moscow near Volokolamsk and in the Battle of Kursk, in addition to battles for the liberation of Belarus and in fighting in East Prussia. When the war was over, Volkov resumed his studies at Moscow State University. In 1946 he married his high-school sweetheart Anna Guskova, and the pair were married for 70 years.

JINR

Vadim Volkov served in World War II just one year after beginning his studies.

Volkov's PhD focused on studies of the deuterium–deuterium reaction. From 1956 he began working in Georgy Flerov's group at the Laboratory of Measuring Instruments of the Academy of Sciences, and from 1960 until his final days he worked in the Flerov Laboratory of Nuclear Reactions at JINR. As head of the group, he achieved a number of important scientific results that are cited to this day. He carried out pioneering studies on the transfer of a considerable number of nucleons from one nucleus to the other, leading to the discovery of a new type of nuclear reaction between complex nuclei. These multi-nucleon transfer reactions were then used to produce new neutron-rich isotopes for the first time, with nearly 30 new isotopes synthesized.

Volkov coined several terms that entered scientific literature: Q ground-ground (Qgg) systematics, double-nuclear system and deep inelastic transfer reactions. He also developed a model of competition between complete fusion and quasi-fission, which was crucial for the later synthesis of heavy and super-heavy elements. Volkov published more than 200 publications and two monographs, and in 1975 was honoured with the USSR State Prize for his groundbreaking research into the synthesis and study of new nuclei. He became the first Flerov Prize laureate in 1993 and was awarded the Russian Order of Honour in 2006.

He was always keen to share his valuable life and scientific experience with young scientists, and his poise, self-discipline and optimism were highly appreciated by his colleagues. Vadim Volkov's life is a vivid example of the contribution to the service of science, and we feel blessed to have known and worked with such a remarkable person and outstanding scientist.

● *His friends, colleagues and the FLNR staff.*

Event

Swedish MAX IV light source inaugurated

Maxlab

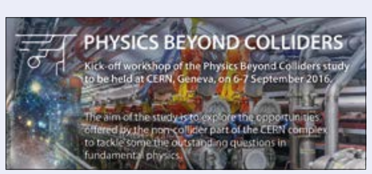
MAX IV will produce some of the brightest X-ray beams in the world.

On 20 June, coinciding with the Northern Hemisphere's brightest day, the new MAX IV light source in Lund, Sweden, was inaugurated by Swedish prime minister Stefan Löfven, in the presence of the King of Sweden. This state-of-the-art synchrotron light source will deliver narrow beams of intense X-rays towards samples placed in numerous beamlines fanning out tangentially from the ring. The 3 GeV storage ring has a circumference of 528 m, the 1.5 GeV booster a circumference of 9 m and the injector is a 300 m-long linac.

Construction started in 2010 and the project has received several prizes and awards for its environmental credentials. When fully operational, the facility, which marks Sweden's largest single investment in research, will be able to receive about 2000 researchers a year working across 25 beamlines. Two beamlines are already operational, with a further three experimental stations to be connected to the large ring in the autumn.

Event spotlight

CERN management has launched a Beyond Collider Physics study, a kick-off workshop for which will take place at CERN on 6–7 September 2016. The aim of the study is to explore the opportunities offered by CERN's accelerator complex and infrastructure via projects complementary to high-energy colliders. Although the scientific focus is on fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, the goal of the Beyond Collider Physics study is to survey the possibilities and stimulate new ideas that might require different types of experiment. Details about the programme, registration and abstract submission, as well as the mandate of the group, can be found on the workshop website at: indico.cern.ch/event/523655/.



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DESY

PARTICLE PHYSICS.

DESY, Hamburg location, is seeking:
Scientist (f/m)

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DESY is one of the world's leading research centres for photon science, particle and astroparticle physics as well as accelerator physics.

The particle physics programme of DESY consists of strong contributions to the LHC experiments ATLAS and CMS and to the preparation of future experiments. The experimental programme is enhanced by collaboration with a strong theory group. DESY is searching an experienced experimental physicist (f/m), who will take a leading role in the physics analysis of ATLAS data and in the upgrade of the silicon strip detector for HL-LHC.

The position

- Active role in the ATLAS experiment
- Leading role in ATLAS data analysis
- Strong participation in ATLAS silicon detector upgrade (hardware and/or software aspects)
- Participation in the supervision of students and postdocs

Requirements

- PhD in experimental Particle Physics
- Extensive knowledge and experience in data analysis
- Experience in detector operations and/or development
- Experience in software development
- Outstanding teamwork abilities and excellent communication skills and knowledge of English

For further information please contact Prof.Dr. Beate Heinemann, beate.heinemann@desy.de.

Please submit your application including a motivation letter, research interests, curriculum vitae and copies of University degrees to the DESY human resources department (recruitment@desy.de). Make sure that you indicate the position identifier (FHMA022/2016) on all communications. Please also arrange for at least three letters of reference to be sent to the DESY human resource department, clearly stating your name and the position identifier (see above).

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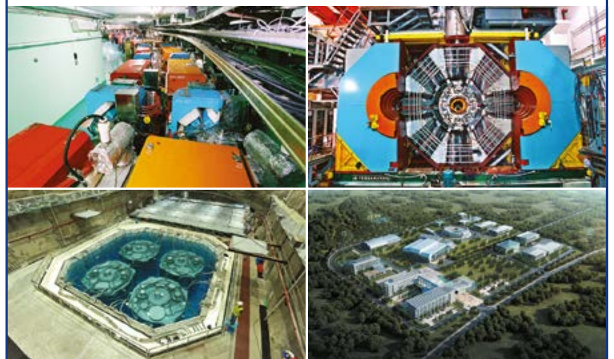

IHEP Recruitment of Overseas High-level Talents

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Tel: (86)010-88235879, Fax: (86)010-88233102
Address: No. 19 (B), Yuquan Road, Shijingshan District, Beijing, (Postcode: 100049)

Applications should include a CV, an outline of academic accomplishments, description of current research and plan for future research, 3 – 5 published papers representative of your work, and a record of citations for your work. You should arrange for 3 letters of reference from experts in your field to be sent by post or email (established scientists are not requested).

For detailed information please visit
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DIRECTOR

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Jefferson Science Associates, LLC (JSA) invites nominations and applications for the position of Lab Director for the Department of Energy's Thomas Jefferson National Accelerator Facility (Jefferson Lab) in Newport News, Virginia. The JSA Board seeks a strong and visionary scientific leader with effective management skills and who enjoys stature among peers in the scientific and lab communities.

The successful candidate will be responsible for leading and managing all Lab initiatives and activities in support of a world-class research facility, including its strategic and long-range planning and its building of a comprehensive external relations program to serve and promote the interests of the lab and its users. Reporting to the JSA Board, the Director is the Chief Executive Officer of Jefferson Lab and is responsible for the Lab's 700-plus staff and total annual budget of approximately $100 million.

Jefferson Lab (www.jlab.org) is a national laboratory for nuclear physics research. As a user facility for scientists worldwide, its primary mission is to conduct basic research to advance the understanding of the fundamental constituents of the atomic nucleus and their interactions. The tools for probing the structure of the nucleus are the Lab's Continuous Electron Beam Accelerator Facility (CEBAF) and the advanced particle-detection and ultra-high-speed data-acquisition equipment in four experimental halls. The lab is now completing a major, $338 million upgrade of the electron accelerator from 6 GeV to 12 GeV with addition of the fourth experimental hall to specifically investigate exotic structures. The international user community includes over 1,500 scientists over half of whom are actively involved in the Lab's experimental program.

JSA (www.jsallc.org) is a joint venture comprised of the Southeastern Universities Research Association (SURA) and Pacific Architects and Engineers (PAE). JSA was created specifically to manage and operate Jefferson Lab for the Nuclear Physics User Community, so its members can continue to conduct innovative research. SURA is the university consortium that propelled Jefferson Lab into the forefront of nuclear and hadronic physics as well as in superconducting radiofrequency technologies. PAE is a global leader in providing enduring support for the essential missions of the U.S. government, its allied partners and international organizations.

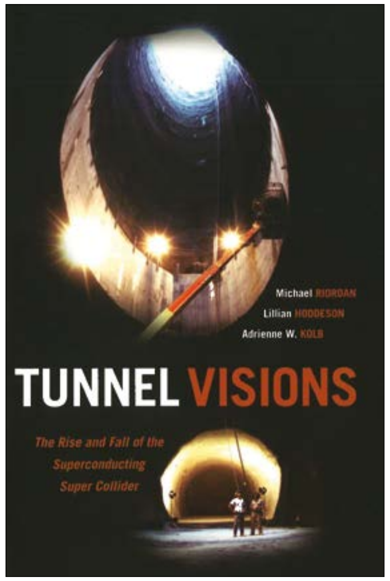
Nominations, applications, and inquiries should be directed to: **Donald Geesaman, Chair; Director Search Committee; c/o SURA; 1201 New York Avenue, NW; Suite 430; Washington, DC 20005** or to **directorsearch@sura.org**. For timely consideration, submit an outline of qualifications and accomplishments and a curriculum vita by **15 August 2016**. Candidate must be willing and able to obtain a federal security clearance. Hugh Montgomery will continue to lead the lab until a suitable candidate is identified. JSA is an Equal Opportunity, Affirmative Action Employer.

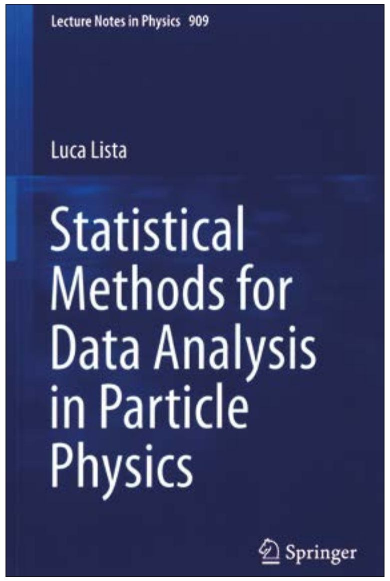
Bookshelf

Compiled by Virginia Greco, CERN

Tunnel Visions

By M Riordan, L Hoddeson and A W Kolb
University of Chicago Press
Also available at the CERN bookshop





The Superconducting Super Collider (SSC), a huge accelerator to be built in Texas in the US, was expected by the physicists who supported it to be the place where the Higgs boson would be discovered. Instead, the remnants of the SSC facilities at Waxahachie are now property of the chemical company Magnablend, Inc. What happened in between? What did go wrong? What are the lessons to be learnt?

Tunnel Visions responds to these historical questions in a very precise and exhaustive way. Contrary to my expectations, it is not a doom and gloom narration but a down to earth story of the national pride, good physics and bad economics of one of the biggest collider projects in history.

The book depicts the political panorama during the 10 years (~1983–1993) of life of the SSC project. It started during the Reaganomics, hand in hand with the International Space Station (ISS), and concluded during the first Clinton presidency after the 1990s recession and the end of the Cold War. The ISS survived, possibly because political justifications for space adventure are easier to find, but most probably because from the beginning it was an international project. The book explains the management intricacies of such a large project, the partisan support and disregard, until the final SSC demise in the US congress. For the particle-physics community this is a well-known tale, but the historical details are welcome.

However, the book is more than that, because it also sheds light on the lessons learnt. The final woes of the SSC signed the definitive opening of the US particle-physics community to full international collaboration. For 50 years, without doubt, the US had been the place to go for any particle physicist. Fermilab, SLAC and Brookhaven were, and still are, great stars in the physics firmament. Even if the SSC project had not been cut, those three had to keep working in order to maintain the progress in the field. But that was too much for essentially a zero-sum budget game. The show must go on, so Fermilab got the main injector, SLAC the BaBar factory, and Brookhaven the RHIC collider. Thanks to these upgrades, the three laboratories made important progress in particle physics: top quark discovery; W and Z boson precision measurements; Higgs boson mass hunt narrowing between 113 and 170 GeV; detection of possible discrepancies in the Standard Model associated with b-meson decay; and the discovery of the liquid-like quark–gluon plasma.

Why did the SSC project collapse? The authors explain the real reasons, not related to technical problems but to poor management in the first years and the clash of cultures between the US particle-physics community and the US military-industrial system. But there are also reasons of opportunity. The SSC was several steps beyond its time. To put it into context: during the years of the SSC project, at CERN the conversion of the SPS into a collider took place, along with the whole LEP programme and the beginning of the LHC project. That effort prevented any possible European contribution to the SSC. The last-ditch attempt to internationalize the SSC into a trans-Pacific partnership with Japan was also unsuccessful. The lessons from history, the authors conclude, are that at the beginning of the 1990s the costs of frontier experimental particle physics had grown too much, even for a country like the US. Multilateral international collaboration was the only way out, as the ISS showed.

The Higgs boson discovery was possible at CERN. The book avoids any "hare and tortoise" comparison here, however, since in the dawning of the new century, the US became a CERN observer state with a very important in-kind contribution. In my opinion, this is where the book grows in interest as it explains how the US particle-physics community took part in the LHC programme, becoming decisive. In particular, the US technological effort in developing superconducting magnets was not wasted. The book also talks about the suspense around the Higgs search when the Tevatron was the only one still in the game during the LHC shutdown after the infamous incident in September 2008.

Useful appendices providing notes, a bibliography and even a short explanation of the Standard Model complete the text.

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

Statistical Methods for Data Analysis in Particle Physics

By Luca Lista
Springer
Also available at the CERN bookshop

Particle-physics experiments are very expensive, not only in terms of the cost of building accelerators and detectors, but also due to the time spent by physicists and engineers in designing, building and running them. With the statistical analysis of the resulting data being relatively inexpensive, it is worth trying to use it optimally to extract the maximum information about the topic of interest, whilst avoiding claiming more than is justified. Thus, lectures on statistics have become regular in graduate courses, and workshops have been devoted to statistical issues in high-energy physics analysis. This also explains the number of books written by particle physicists on the practical applications of statistics to their field.

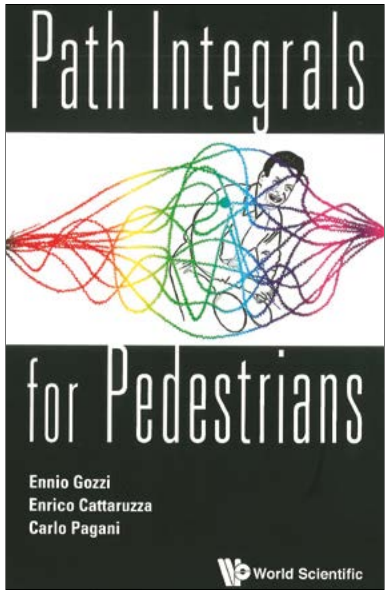
This latest book by Lista is based on the lectures that he has given at his home university in Naples, and elsewhere. As part of the Springer series of "Lecture Notes in Particle Physics", it has the attractive feature of being short – a mere 172 pages. The disadvantage of this is that some of the explanations of statistical concepts would have benefited from a somewhat fuller treatment.

The range of topics covered is remarkably wide. The book starts with definitions of probability, while the final chapter is about discovery criteria and upper limits in searches for new phenomena, and benefits from Lista's direct involvement in one of the large experiments at CERN's LHC. It mentions such topics as the Feldman–Cousins method for confidence intervals, the CLs approach for upper limits, and the "look elsewhere effect", which is relevant for discovery claims. However, there seems to be no mention of the fact that a motivation for the Feldman–Cousins method was to avoid empty intervals; the CLs method was introduced to protect against the possibility of excluding the signal plus background hypothesis when the analysis had little or no sensitivity to the presence or absence of the signal.

The book has no index, nor problems for readers to solve. The latter is unfortunate. In common with learning to swim, play the violin and many other activities, it is virtually impossible to become proficient at statistics by merely reading about it: some practical exercise is also required. However, many worked examples are included.

There are several minor typos that the editorial system failed to notice; and in addition, figure 2.17, in which the uncertainty region for a pair of parameters is compared to the uncertainties in each of them separately, is confusing.

There are places where I disagree with Lista's emphasis (although statistics is a subject that often does produce interesting discussions). For example, Lista claims it is counter-intuitive that, for a given observed number of events, an experiment that has a larger than expected number of background events (b) provides a tighter upper limit than one with a smaller background (i.e. a better experiment). However, if there are 10 observed events, it is reasonable that the upper limit on any possible signal is better if $b = 10$ than if $b = 0$. What is true is that the expected limit is better for the experiment with smaller backgrounds.



Finally, the last three chapters could be useful to graduate students and postdocs entering the exciting field of searching for signs of new physics in high energy or non-accelerator experiments, provided that they have other resources to expand on some of Lista's shorter explanations.

● *Louis Lyons, University of Oxford, UK.*

Path Integrals for Pedestrians

By E Gozzi, E Cattaruzza and C Pagani
World Scientific

The path integral formulation of quantum mechanics is one the basic tools used to construct quantum field theories, especially gauge-invariant theories. It is the bread and butter of modern field theory. Feynman's original formulation developed and extended some of the work of Dirac in the early 1930s, and provided an elegant and insightful solution to a generic Schrödinger equation.

This short book provides a clear, pedagogical and insightful presentation of the subject. The derivations of the basic results are crystal clear, and the applications worked out to be rather original. It includes a nice presentation of the WKB approximation within this context, including the Van Vleck and functional determinant, the connections formulae and the semiclassical propagator.

An interesting innovation in this book is that the authors provide a clear presentation of the path integral formulation of the Wigner functions, which are fundamental in the study of quantum statistical mechanics; and, for the first time in an elementary book, the work of Koopman and von Neumann on classical and statistical mechanics.

The book closes with a well selected set of appendices, where some further technical details and clarifications are presented. Some of the more mathematical details in the basic derivations can be found there, as well as aspects of operator ordering as seen from the path integral point formulation, the formulation in momentum space, and the use of Grassmann variables, etc.

It will be difficult to find a better and more compact introduction to this fundamental subject.

● *Luis Álvarez-Gaumé, CERN.*

Books received

Bananaworld: Quantum Mechanics for Primates

By Jeffrey Bub
Oxford University Press

This is not another "quantum mechanics for dummies" book, as the author himself states. Nevertheless, it is a text that talks about quantum mechanics but is not meant for experts in the field. It explains complex concepts of theoretical physics almost without bringing up formulas, and makes no reference to a specialist background.

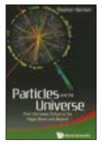
The book focuses on an intriguing issue of present-day physics: nonlocality and the associated phenomenon of entanglement. Thinking in macroscopic terms, we know that what happens here affects only the surrounding environment. But going down to the microscopic level where quantum mechanics applies, we see that things work in a different way. Scientists discovered that in this case, besides the local effects, there are less evident effects that reveal themselves in strange correlations that occur instantaneously between remote locations. Even stronger nonlocal correlations, still consistent with relativity, have been theoretically supposed, but have not been observed up to now.

This complex subject is treated by the author using a particular metaphor, which is actually more than just that: he draws a metaphoric world made of magic bananas, and simple actions that can be performed on them. Thanks to this, he is able to explain nonlocality and other difficult physics concepts in a relatively easy and comprehensive way.

Even if it requires some general knowledge of mathematics and familiarity with science, this book will be accessible and interesting to a wide range of readers, as well as being an entertaining read.

Bookshelf

Particles and the Universe: From the Ionian School to the Higgs Boson and Beyond
By Stephan Narison
World Scientific



This book aims to present the history of particle physics, from the introduction of the concept of particles by Greek philosophers, to the discovery of the last tile of the Standard Model, the Higgs boson particle, which took place at CERN in 2012. Chronologically following the development of this field of science, the author gives an overview of the most important notions and theories of particle physics.

The text is divided into seven sections. The first part provides the basics concepts and a summary of the history of physics, arriving at the modern theory of forces, which are the subject of the second part. It carries on with the Higgs boson discovery and the description of some of the experimental apparatus used to study particles (from the LHC at CERN to cosmic rays and neutrino experiments). The author also provides a brief treatment of general relativity, the Big Bang model and the evolution of the universe, and discusses the future developments of particle physics.

In the main body of the book, the topics are presented in a non-technical fashion, in order to be accessible to non-experts. Nevertheless, a rich appendix provides demonstrations and further details for advanced readers. The text is accompanied by plenty of images, including paintings and photographs of many of the protagonists of particle physics.

Beyond the Galaxy: How Humanity Looked Beyond our Milky Way and Discovered the Entire Universe
By Ethan Siegel
World Scientific

This book provides an introduction to astrophysics and cosmology for absolute beginners, as well as for any reader looking for a general overview of the subject and an account of its latest developments.

Besides presenting what we know about the history of the universe and the marvellous objects that populate it, the author is interested in explaining how we came to such knowledge. He traces a trajectory through the various theories and the discoveries that defined what we know about our universe, as well as the boundary of what is still to be understood.

The first six chapters deal with the state-of-the-art of our knowledge about the structure of the universe, its origin and evolution, general relativity and the life of stars. The following five address the most important open problems, such as: why there is more matter than antimatter, what dark matter and dark energy are, what there was before the Big Bang, and what the fate of the universe is.

Written in plain English, without formulas and equations, and characterized by a clear and fluid prose, this book is suitable for a wide range of readers.

Modern Physics Letters A: Special Issue on Hadrontherapy
By Saverio Braccini (ed.)
World Scientific

The applications of nuclear and particle physics to medicine have seen extraordinary development since the discovery of X-rays by Röntgen at the end of the 19th century. Medical imaging and oncologic therapy with photons and charged particles (specifically hadrons) are currently hot research topics.

This special issue of *Modern Physics Letters* is dedicated to hadron therapy, which is the frontier of cancer radiation therapy, and aims at filling a gap in the current literature on medical physics. Through 10 invited review papers, the volume presents the basics of hadron therapy, along with the most recent scientific and technological developments in the field. The first part covers topics such as the history of hadron therapy, radiation biophysics, particle accelerators, dose-delivery systems and treatment planning. In the second part, more specific topics are treated, including dose and beam monitoring, proton computer tomography, innoacustics and microdosimetry.

This volume will be very useful to students, researchers approaching medical physics, and scientists interested in this interdisciplinary and fast-moving field.

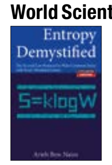
The Penultimate Curiosity: How Science Swims in the Slipstream of Ultimate Questions
By R Wagner and A Briggs
Oxford University Press

This book uses an original perspective to trace the history of the human quest for making sense of the world we live in. Written in collaboration by a painter specialising in religious subjects and a physical scientist who is a professor in the UK and also the director of a centre for research in quantum information processing, it starts from the assumption that both religion and science are manifestations of human curiosity.

Science and its methods, based on reproducible experiments and evidence-based conclusions, are able to find answers to the "how" questions, to explain how nature works. This is what the authors call the "penultimate curiosity". But the "ultimate curiosity" is "why" the world is like it is. Science doesn't necessarily have the answer to such a question. Religions were born to try and give an answer to this.

In the book, science and religion are not placed in opposition to one another. On the contrary, it is shown how they can live in a mutually enriching relationship. The authors sweep human history from caveman times to the present day, explaining the nature and evolution of the entanglement between the two. The text is also accompanied by many beautiful illustrations that are an integral part of the argument.

Entropy Demystified: The Second Law Reduced to Plain Common Sense (2nd edition)
By Arieh Ben-Naim
World Scientific



In this book, the author explains entropy and the second law of thermodynamics in a clear and easy way, and with the help of many examples. He intends, in particular, to show that these physics laws are not intrinsically incomprehensible, as they appear at first. The fact that entropy, which is defined in terms of heat and temperature, can be also expressed in terms of order and disorder, which are intangible concepts, together with the evidence that entropy (or, in other words, disorder) increases perpetually, can puzzle students. Some mystery seems to be inevitably associated with these concepts. The author asserts that, looking at the second law from the molecular point of view, everything clears up. What a student needs to know is the atomistic formulation of entropy, which comes from statistical mechanics.

The aim of the book is to clarify these concepts to readers who haven't studied statistical mechanics. Many dice games and examples from everyday life are used to make readers familiar with the subject. They are guided along a path that allows them to discover by themselves what entropy is, how it changes, and why it always changes in one direction in a spontaneous process.

In this second edition, seven simulated games are also included, so that the reader can experiment with and appreciate the joy of understanding the second law of thermodynamics.

Inside Story

Super Proton Synchrotron turns 40

The workhorse of CERN's accelerator complex continues to drive discoveries.

L Evans

Piotr Traczyk

Left: The occasion of the first beam accelerated in the Super Proton Synchrotron on 17 June 1976, showing (back row, left to right): Claudio Aramatea, machine operator; H P Kindermann, radio-frequency system; Bas de Raad, beam transport; Michael Crowly-Milling, who built the control system; and the present author Lyn Evans, then a junior physicist. Front row: Simon van der Meer (left) and J D Pahud, who were responsible for the SPS power supplies. Right: Inside the 7 km-circumference SPS tunnel.

The Super Proton Synchrotron (SPS) was approved by CERN Council in December 1970. By mid-May 1976 a beam circulated for the first time, although it took another month to get the radio-frequency system to operate correctly. The first beam was accelerated to 300 GeV on 17 June (the SPS was originally approved as a lower energy machine called the 300 GeV Project), which happened to be the day of the Council meeting. John Adams formally asked the Council for permission to accelerate the beam further to 400 GeV, and 10 minutes later we were there!

The approval of the SPS was a long process that began in the early 1960s. Initially it was supposed to be a completely new laboratory located in the south of France, but there was deadlock in the Council when it was realised that the additional infrastructure would add considerable extra cost to the project. Adams broke the deadlock when he proposed to build the machine deep underground across the road from the Meyrin site.

Even during the construction of the SPS, events were taking place elsewhere at CERN that would prove to be pivotal in turning CERN into the world's greatest particle-physics laboratory. The first was the demonstration of stochastic cooling, already proposed in 1968 by Simon van der Meer as a method of increasing the density of particle beams in the Intersecting Storage Rings. The second was the discovery of weak neutral currents at the Gargamelle bubble chamber fed with a neutrino beam from the smaller Proton Synchrotron (PS). The existence of neutral currents had been predicted by the nascent electroweak theory, which also predicted the existence of two vector bosons with a rough estimate of their masses.

Carlo Rubbia was the first to realise that the SPS could be converted into a storage ring with a sufficient energy to create these W and Z bosons. Since the SPS was a single ring, he proposed that the protons were collided with the counter-rotating antiprotons produced by the PS and then stored in a special ring where they could be cooled using stochastic cooling. Once a sufficient number of antiprotons had been accumulated and cooled, they would be transferred to the SPS and accelerated, together with protons, to the maximum energy that the SPS could muster (initially 270 GeV). In 1978, work started on building the Antiproton Accumulator and to convert the SPS into a part-time storage ring. In 1983 the first W and Z particles were observed, winning Rubbia and van der Meer the Nobel prize the following year.

Initially it was planned to site the 300 GeV Project in the south of France.

Although the SPS is not a superconducting machine, the proton–antiproton collider was also an essential step towards the design of the LHC, for instance by elucidating the physics of bunched-beam hadron colliders. The SPS has proven to be an extremely versatile machine, mainly because of the quality of its design and construction. It has provided particle beams, protons and heavy ions to fixed-target experiments for 40 years, including a neutrino beam for the detectors in the Gran Sasso laboratory 800 km away. The SPS has also served as the injector to LEP, where it accelerated electrons and positrons to 22 GeV, and today it accelerates protons to its maximum energy of 450 GeV for injection into the LHC. Yet thanks to the care with which it has been maintained, the core of the machine is still the same as it was 40 years ago.

The SPS, together with the PS, continues to be the workhorse of CERN today. It serves thousands of users, both for the LHC experiments and the fixed-target community, in addition to providing test beams for high-energy physics and also for a new plasma wake-field experiment called AWAKE. Thank you SPS. We look forward to another 40 years!

● *Lyn Evans, former LHC-project leader and director of the Linear Collider collaboration.*

CERN Courier Archive: 1973

A look back to CERN Courier vol. 13, July/August 1973, compiled by Peggie Rimmer

CERN NEWS

Storm hits CERN

Late in the afternoon of 12 June, a cloudburst lasting an abnormally long time (over an hour) swept down on CERN and left behind flood damage amounting to millions of Swiss francs. Preceded by a violent wind of nearly 50 miles [80 km] an hour, the storm began with hail that fell for 15 minutes. Drains, choked with hailstones and leaves, were unable to cope with the subsequent torrent of rain. Hardly a building or installation, surface or underground, went unscathed, but three areas were hit very hard: installations of the Nuclear Physics Division, Track Chambers Division and Health Physics Group.

In NP Division, water and mud inundated Hall 1-1 of the Intersecting Storage Rings to a depth of a metre and the delicate equipment there – mainly electronic counters and spark chambers – can be considered a write-off. In the basement of Laboratory 3, spark chambers, vacuum pumps, detectors, recorders and stabilized power supplies were for the most part destroyed.

A wave of water passing down the road from the ISR penetrated the electricity substation and by underground tunnels reached the basements of Laboratory 13, where there was a large quantity of apparatus belonging to TC Division – counters, scalers, power supplies, spares for measurement tables, etc. Many reels of unexposed film were completely submerged, together with 400 km of exposed film.

The 2 m hydrogen bubble chamber was the scene of much activity when water was seen infiltrating under the chamber building in the tunnels housing the 10 kA power supplies and the power, monitoring and safety lines of the entire installation. The refrigeration plant had to be shut down and it was decided to evacuate the liquid hydrogen from the chamber.

The most serious damage in the Health Physics Group building was the complete destruction of the low-level counting laboratory. The laboratory is in the basement to reduce the influence of environmental radiation and its specialised equipment is a total write-off.

● Compiled from texts on pp217–219.

Much of the exposed bubble-chamber film was damaged by mud and water. Boxes of film were stacked in the open air while their usual home was cleaned.

CERN 91.6.73

This swimming pool in the basement of the Main Building illustrates how the unusual volume of water far exceeded the capability of the drainage system.

Vacation courses

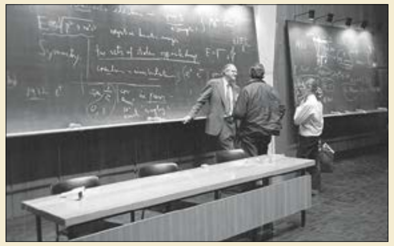
During the season when many CERN employees are off on holiday, vacation students have arrived to follow a two to four month course.

At the end of every year, circulars on the courses [which began in 1962] are sent by the Fellows and Associates Service to the universities and technical colleges in all the Member States. Students reading physics, electrical and electronic engineering, mathematics and information science are invited to submit applications before the following March.

This year there were some 350 applicants, of whom 148 were invited to follow the courses. They are distributed over the various scientific and technical divisions – joining groups working on experimental and applied physics, data handling, accelerators, technical services or health physics. As well as taking part in the daily work of the groups, the students are offered a series of lectures on elementary particle physics, accelerators, detectors and computer science, through which they can become familiar with the various facets of particle physics research.

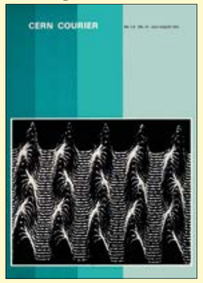
● Compiled from texts on p219.

CERN 146.7.73



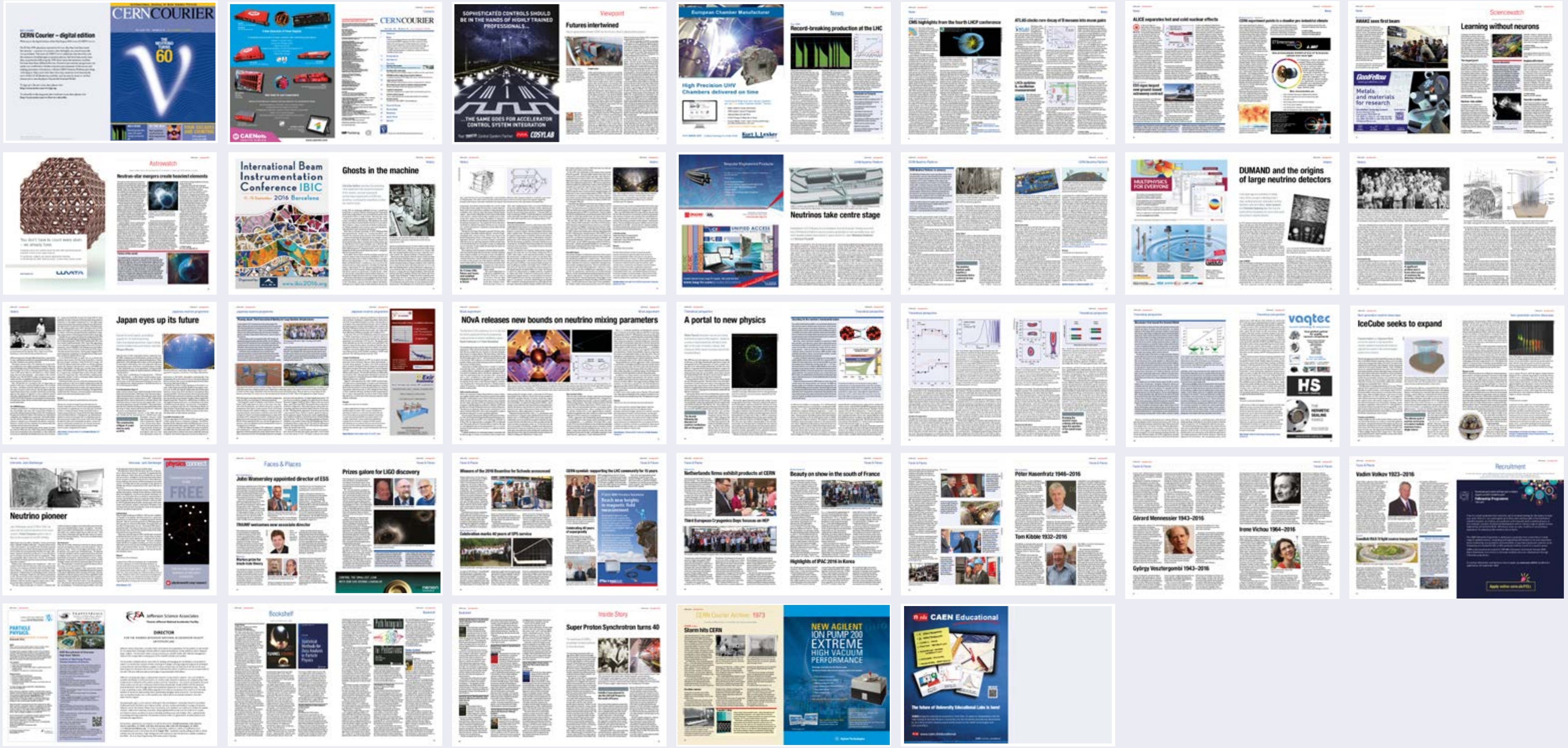
V F Weisskopf (former Director-General of CERN, who is also a summer visitor) continues discussions after one of his, by now traditional, introductory lectures on high energy physics for the summer students.

Compiler's Note



Climate change? Extreme weather events – destructive hailstorms and increasingly high temperatures – are a regular feature of summer in western Switzerland. The highest temperature ever reached north of the Swiss Alps, 39.7 °C, was recorded in Geneva in July 2015.

Wild weather notwithstanding, the number of applications for CERN's hugely popular summer student programme continues to grow. It is presently around 1000, with some 150 candidates selected each year. In 1998, the programme was extended to include high-school teachers, and for the past 15 years or so, non-Member-State participants have joined their European colleagues, thanks to complementary funding. Many a successful career in physics followed a summer as a student at CERN.



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