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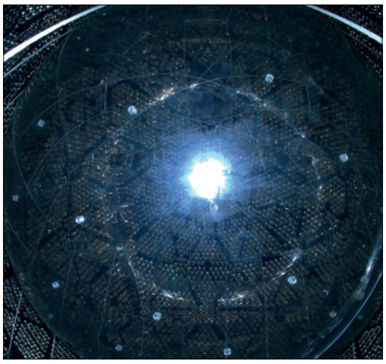
SNO+ Collaboration



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Focus on: Big science

Welcome to this focus issue of *Physics World*, which tackles some of the challenges in building upcoming "big science" facilities. We kick off by looking at CERN's Large Hadron Collider (LHC), which is set to restart next year following an upgrade and maintenance programme (p7). Once back online, the LHC will be generating even more data than in its previous run – in fact, dealing with huge volumes of information is a problem for many upcoming facilities (p19), as is training enough scientists to use them (p15). The issue also examines how two neutrino experiments are set for a boost (p9 and p23) and looks at novel technologies for tackling dark energy (p16) and high-energy cosmic rays (p12).

Michael Banks, Contributing Editor

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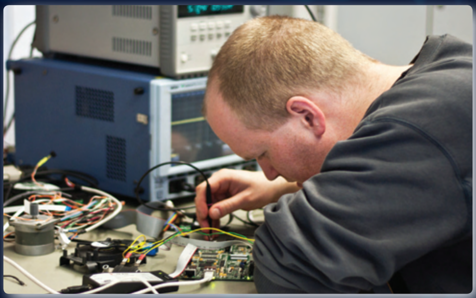
(*Matthew Kapust/South Dakota Science and Technology Authority*)



Works starts on ESS neutron source

Ready for action Sofie Carsten Nielsen, Danish science minister, and Swedish education minister Jan Björklund, break ground for construction of the European Spallation Source.

Construction has finally begun on the long-awaited €1.84bn ($2.4bn) European Spallation Source (ESS), which will take five years to build and will be the most powerful neutron source in the world. Initially envisioned almost two decades ago, the ESS buildings will be complete by 2019 with experiments set to begin four years later. “We are thrilled to be able to move ahead,” says Jim Yeck, ESS director-general. “Many people have been working hard for several years already to get to this point.”

The facility will include a 600 m underground linear proton accelerator that will create a beam of protons with an energy of 2 GeV and a power of 5 MW. These protons will then be sent to a heavy-metal target station to produce neutrons, which will in turn travel to 22 instruments where researchers will use them to investigate a range of materials from superconductors to proteins. The ESS will also feature sample-preparation labs as well as a supercomputing hub and a software-development centre.

“This is a very important project for materials scientists in Europe, especially for those using neutrons to study matter,” says ESS science director Dimitri Argyriou. With existing European facilities aging and competition in the field growing in Asia and North America, Argyriou adds that “the ESS is a must for European researchers”.

Some 13 nations have already committed about 97% of the total construction costs, with Sweden paying 35%, Denmark 12.5%, Germany 11%, the UK 10% and France 8%. Talks are currently ongoing with the Netherlands, Latvia and Lithuania to cover the remaining 2.5%. Yeck says that other factors were important in ensuring construction could begin, including securing approvals from the Swedish Environmental Court and the Swedish Radiation Safety Authority (SSM), which came during the summer. The SSM approval is, however, conditional, meaning that additional permits will be necessary as construction progresses.

Yeck adds that all partner countries will be involved in the construction of the ESS facility with a large part of the accelerator being built in France and Italy, while Germany, Spain and the UK will contribute to the target station. Meanwhile, Czech, Hungarian and Swiss partners will contribute instruments, and universities and institutes in Sweden and Denmark will make “significant contributions”.

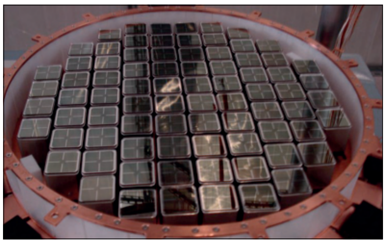
The ESS has also announced that Roland Garoby, who has spent more than 35 years at the CERN particle-physics lab, will become its technical director this month. Garoby recently led the upgrade of CERN’s injector complex for the Large Hadron Collider and is also currently chair of the ESS’s technical advisory committee. “The opportunity to play a leading role in the ESS project is incredibly attractive,” he says, adding that the next five years will be “a multi-facetted challenge”.

A foundation-laying ceremony for the ESS is set for 9 October with more than 600 people from the European scientific community expected to attend.

Ned Stafford

Particle physics

Upgrade set for dark-matter detector



Bigger and better Physicists are planning to upgrade the current XENON detector at the Gran Sasso National Laboratory in Italy so that it can hold one tonne of xenon.

A vast upgrade to the XENON dark-matter experiment at the Gran Sasso National Laboratory in Italy is set to provide a significant increase in sensitivity by being able to better spot cosmic rays masquerading as dark-matter particles. Costing $11m and expected to start taking data in 2015, XENON1T will contain one tonne of xenon to hunt for weakly interacting massive particles (WIMPs) – a leading dark-matter contender.

Installed in 2008, the current XENON detector contains 100 kg of xenon and has provided the world’s best limits on the collisional cross-sections between WIMPs and xenon atoms within the detector. But despite the laboratory being situated deep underground to block out most other particles, stray neutrons produced by the decay of cosmic-ray muons can still enter the detector and produce “false positives”. Because the signal from the WIMPs, if they exist, will be weak, these false positives could obscure the real signal.

In a conceptual design report published in June, the XENON team has now laid out the design of its new Cerenkov detector, half of which will be funded by the US. In order to eliminate unwanted neutrons and improve sensitivity, XENON1T will be housed in a 10.5 m-high cylindrical water tank. Whenever a relativistic neutron passes though, it will produce Cerenkov radiation that will be detected by photomultipliers. Should a signal be recorded at the same time as one from a neutron, it will be a false positive that can be ignored as WIMPs do not interact with the electromagnetic force so cannot produce light of their own.

XENON1T could be followed by an even bigger detector in around 2021, dubbed XENONnT, which will have more than seven tonnes of xenon. This would increase the opportunities for scattering events resulting in a stronger WIMP signal, possibly to the point where firm conclusions about the nature of dark matter can be made.

Gemma Lavender

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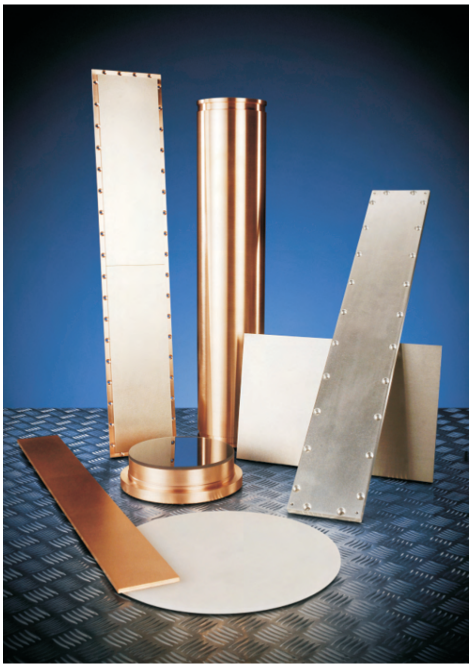

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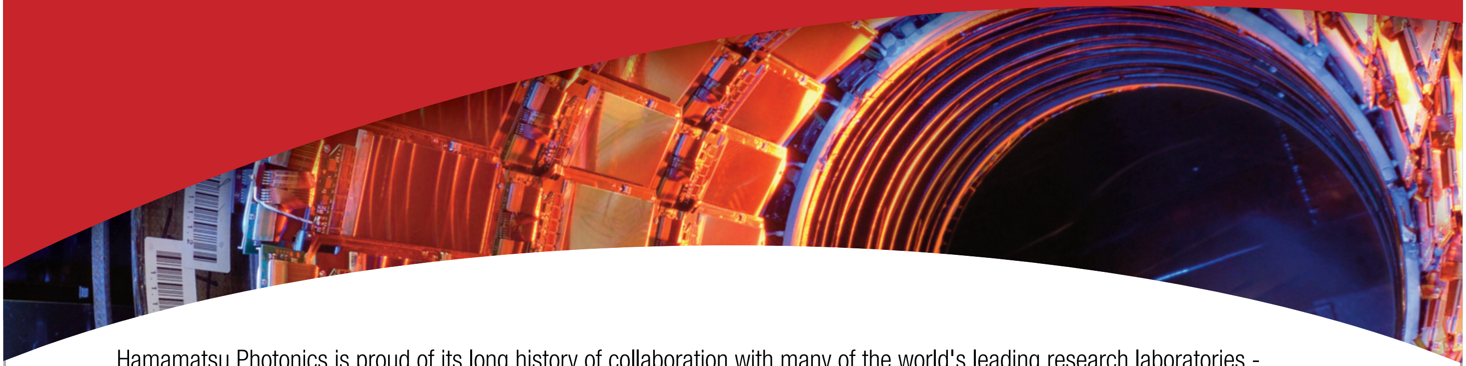

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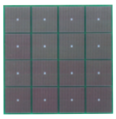
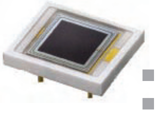


- T2K Experiment

Large Area APDs and Arrays



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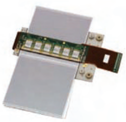

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Particle physics

CERN celebrates 60 years of science

This year holds a particular significance for the CERN particle-physics lab near Geneva. On 29 September, the lab celebrated 60 years since it was conceived by holding an official ceremony at the lab's Globe of Science and Innovation. Earlier last month a special symposium, entitled "Science and Peace", was also attended by representatives of CERN's member states at which speakers presented highlights from the lab's first 60 years and told their own personal stories of life at CERN.

CERN was established in the aftermath of the Second World War by a handful of Europe's leading scientists who saw an opportunity to construct an international laboratory for fundamental research that would bring nations together through science. CERN itself came into being in September 1954 by the 12 founding states: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the UK and Yugoslavia. CERN now has 21 member states with many other countries from around the world – including the US, Japan and India – participating in its research programme.

Earlier this year, a separate event was held in July at UNESCO's headquarters in Paris to mark the signature of the CERN convention, which established the lab. On 19 September, CERN also celebrated the anniversary of its first council session, which was actually held in Geneva on 7–8 October 1954, with a concert by the United Nations Orchestra held at the Globe.

"With its discoveries and innovations, CERN has been bringing the world together through science for 60 years," says Rolf-Dieter Heuer, CERN's director-general.

Michael Banks

- See "CERN gears up for LHC switch on", p7

Facilities

Diamond secures materials analysis facility

The Diamond Light Source in Oxfordshire, UK, is set for a £10m ($16m) microscopy complex that will focus on biology and the physical sciences. To be complete in 2015, the Materials Characterisation Facility will provide researchers with high-resolution electron microscopes to investigate a range of materials and their chemical interactions at the atomic level. The facility will include a hard X-ray nanoprobe beamline, called I14, which will extend out 175 m from the main storage ring.

Completed in 2007, Diamond is the UK's largest synchrotron facility that provides high-intensity X-rays to 25 beamlines – a number that is set to increase to 33 by 2018. These are used by researchers in a wide range of areas from studying Neolithic paintings to gaining a better understanding of superconductivity.

Diamond Light Source

I14 can see clearly now A new facility at the Diamond synchrotron will provide researchers with a range of tools with which to study their materials.

The new venture is a partnership between Oxford University, the UK chemical firm Johnson Matthey, and Diamond, which is funded by the UK Science and Technology Facilities Council and the Wellcome Trust. The new facility will have 12 staff in total, with some drawn from Diamond's existing team of 500 and others recruited into new posts.

Diamond spokesperson Mary Cruse calls the new facility a "significant development", adding that the first scientists to use the electron microscopes are expected to arrive late next year. "Housing the beamline and the electron microscopes in one building near the synchrotron will make it easy for the researchers to study their samples using different techniques." says Cruse. "Co-location in one building is also very efficient from a construction point of view."

Kulvinder Singh Chadha

Briefs

DESY gets a handle on big data

The DESY lab in Hamburg is teaming up with IBM to speed up the handling and storage of the massive volumes of X-ray data that are generated by the lab's PETRA III synchrotron. The 14 beamlines at PETRA III have a range of detectors that can each generate about 5 Gbit of data every second – enough to fill one CD-ROM. IBM's "elastic storage" architecture, which will be used at DESY, can handle more than 20 Gbyte/s of data and will also provide researchers with high-speed access to their research results. There are also plans to use a similar data storage and retrieval system for the lab's upcoming European X-ray Free Electron Laser, which is expected to produce around 100 petabyte of data each year when up and running in the coming decade.

- See "Surviving the flood", p19

First electrons at MAX IV

The first electrons have been generated at the €300m ($390m) synchrotron-radiation facility in Sweden dubbed MAX IV. When open in 2016, MAX IV will use a 250 m-long linear accelerator to inject electrons into two storage rings with a circumference of 96 m and 528 m. The larger ring will hold electron beams at 3 GeV, while the 96 m ring will operate at 1.5 GeV. The electrons in the storage rings will then be made to emit X-rays by being sent through "undulators", which force the electrons to travel along a sinusoidal path. Having two storage rings will allow researchers to produce a range of photon energies – the small ring will produce long-wavelength light, while the other will produce higher-energy photons. The large storage ring is expected to be installed in July 2015 and the small storage ring in January 2016, with the inauguration of MAX IV taking place in June 2016.

Namibian telescope sees first pulsar

The High Energy Stereoscopic System (HESS-II) in Namibia – consisting of four 12 m and one 28 m reflecting telescopes – has detected its first pulsar. HESS-II is based near the Gamsberg Mountain in Namibia in southwest Africa and is a system of Imaging Atmospheric Cherenkov Telescopes that investigates cosmic gamma rays in the energy range from about 10 GeV to 10 TeV. HESS-II picked up gamma rays of around 30 GeV from the Vela pulsar, making it the first detection of pulsed emission using a ground-based gamma-ray instrument sited in the southern hemisphere.

Capacitive sensors to achieve sub-nanometre resolution and stability

Queensgate sensors in outer space.

Capacitive micrometry is a sensitive technique for detecting small displacements. It works by detecting the change in impedance of a parallel plate capacitor as the spacing or area changes. Displacements as small as 10^{-14} m, about the diameter of an electron, or 10,000 times smaller than an atom, have been measured using this technique.

NX/NZ Nanosensors

The Nanosensor is a non-contact measuring system based on the principle of capacitance micrometry to enable highly accurate displacement measurement.

The two Nanosensor plates (Probe and Target) are mounted facing each other with an air gap (G) equal to the measurement range. The probe is secured to a fixed reference and target to the moving part.

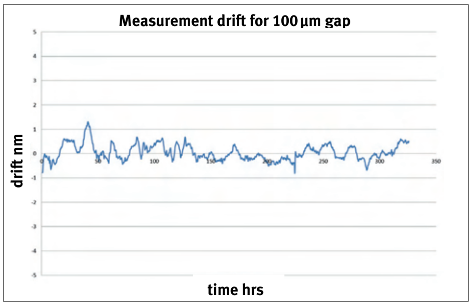
They are available for ranges from 20 microns to 15 mm in a variety of materials including aluminium, Super Invar, gold on Zerodur and gold-coated alumina.

Measurement stability

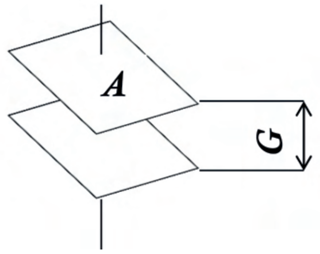
Choice of material is important due to the impact of the thermal property of the material. For example 10 mm of material will expand by 230 nm per degree for aluminium compared to 3 nm for Super Invar.

Queensgate Instruments pioneered the use of capacitance sensors in nano positioning and micrometry. Many industries require measurements that reliably and accurately measure sub-nm displacements but also require stability over several days.

The combination of advanced sensor and control electronics design allow Queensgate to offer exceptional levels of long-term measurement stability.



The capacitance (C) is given by: **$C\hat{}\,\acute{}=C(1+\acute{\eta})+C_s=\varepsilon A/G$**



ε = relative permittivity of medium between plates (typically 8.85)

A = the plate area

G = plate separation

C = function of electrode finish, flatness and tilt

$\acute{\eta}$ = correction based on guard ring configuration

C_s = stray capacitance in parallel with the sensor capacitance and could be due to unshielded wiring or edge effects

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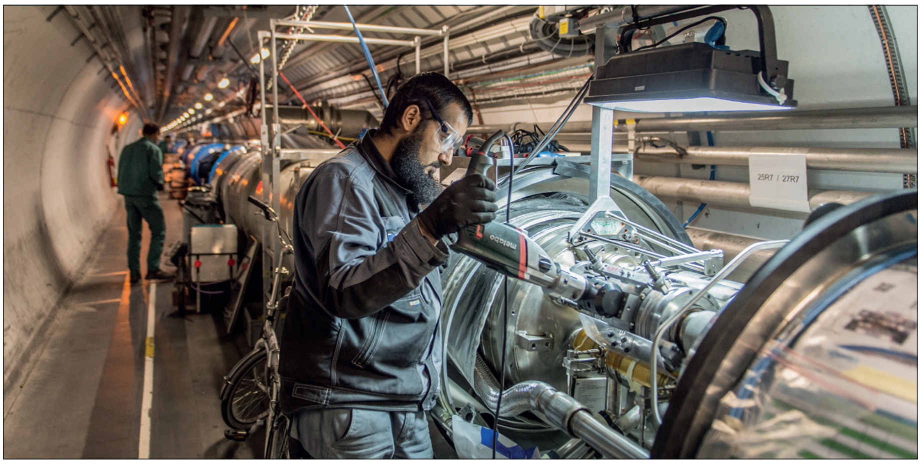
CERN gears up for LHC switch on

Following a two-year shutdown for maintenance and upgrades, **Ned Stafford** looks at how the LHC has been improved to allow researchers to hunt for new particles


Anna Pantelia/CERN

Power boost The upgrade and maintenance job at CERN's Large Hadron Collider has involved the consolidation of 10 170 splices between superconducting magnets.

CERN's 27 km-circumference Large Hadron Collider (LHC) – the world's most powerful particle accelerator – is expected to be fully operational once again next year, allowing physicists to resume experiments after a two-year shutdown for maintenance and upgrading. CERN scientists hope that the upgrade will enable the LHC to operate with collision energies of 13 TeV, just short of its design energy of 14 TeV. This would open a new window for discoveries, including studying the Higgs boson in greater detail and hunting for "supersymmetric" particles. Indeed, the upgrade is expected to improve the LHC's ability to detect heavy new particles by a factor of two, while the number of Higgs bosons produced will increase by an order of magnitude in total.

The LHC upgrade – costing SwFr 150m ($160m) – was completed in June, and is being followed by a step-by-step restarting and testing process that will last into early 2015. The upgrade will allow the LHC to operate at higher energies and with beams that are squeezed into a smaller area as they pass through the detectors to increase the collision rate. "There is a general sense of anticipation – the excitement is building," says theoretical physicist John Ellis of King's College London, who is also based at CERN. "I am personally looking forward to a lot of fun in the next two to three years and, as data come out, raking through the coals and seeing if there are any gems."

Following a hugely successful run lasting three years, the LHC, which accelerates and collides protons with antiprotons, was shut down for maintenance in February 2013. The LHC had been operating with collision energies of around 7 TeV – or 3.5 TeV per beam. Despite not reaching its full design energy during that first run, in July 2012 scientists were still able to announce that they had detected the Higgs boson, which was first theorized in 1964. CERN's successful detection was capped last year when François Englert and Peter Higgs were awarded the 2013 Nobel Prize for Physics.

But the rest of CERN's accelerator complex has been receiving plenty of attention too during the current shutdown, with maintenance and upgrading work also being carried out on the "injector complex" – the chain of smaller accelerators that feed the LHC with particles. The starting point for protons at CERN is linear accelerator 2, or "Linac 2", which sends protons into the Proton Synchrotron Booster (PSB) that in turn injects protons into the Proton Synchrotron (PS). The next and final step before delivery of protons to the LHC is the 7 km Super Proton Synchrotron (SPS), which was first switched on in 1976. "I like to compare it to changing gears on a car," says Ellis.

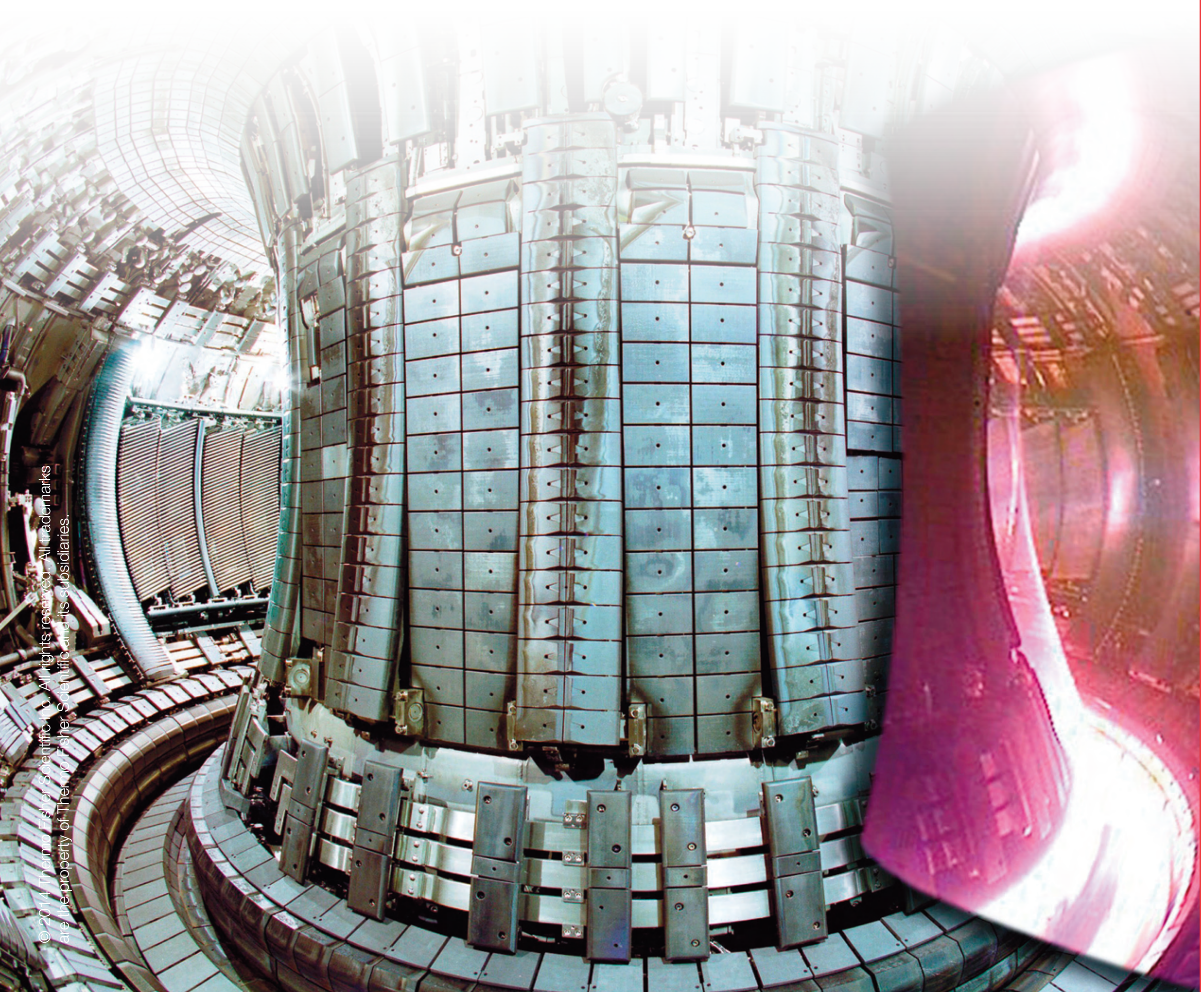
The long list of maintenance and upgrading tasks that CERN completed during the 16-month shutdown include making 1695 openings and re-closures of the vacuum enclosure in between the LHC magnets that include the vacuum and helium pipes. Engineers made 400 000 electrical-resistance measurements as well as improving the 13 kA circuits in the 16 main electrical-feed boxes. These circuits connect the warm current leads from the power supplies with the superconducting leads that feed the current to the magnets. The upgrade also involved completely replacing four quadrupole magnets and 15 dipole magnets that looked suspect during testing.

But the biggest portion of work, according to Mike Lamont, head of the accelerator operation group at CERN, was the consolidation of more than 10 000 "splices" between superconducting magnets. These splices are essentially "superconducting cable joints" with six splices per interconnect. "This was a huge job," Lamont says, pointing out that the consolidation included soldering shunts on the splices to ensure electrical continuity and installing improved electrical insulation, which also acts as a mechanical restraint to limit stresses and deformations.

The maintenance work was complete in June, with the restarting process for the LHC beginning shortly afterwards. At the time, Frédérick Bordry, CERN's director for accelerators and technology, described the LHC as "coming out of a long sleep after undergoing an important surgical operation". On 2 June, the PSB was restarted followed by the PS on 18 June. In July, powering tests began at the SPS and the physics programme covering CERN's antimatter experiments is expected to resume in October.

Lamont says that the LHC is having to undergo months of intensive testing to ensure that the upgrade was successful before the full physics programme at the LHC can resume next year. Testing includes putting a current through each of the LHC's eight sections and Lamont adds that all eight sections of the LHC should be cooled down by October to the operating temperature of around 2 K.

Lamont, however, hesitates to describe the LHC as new, but agrees that the LHC will have enhanced capabilities. "From a physics viewpoint, we are entering new ground," he says. "It is a new frontier."



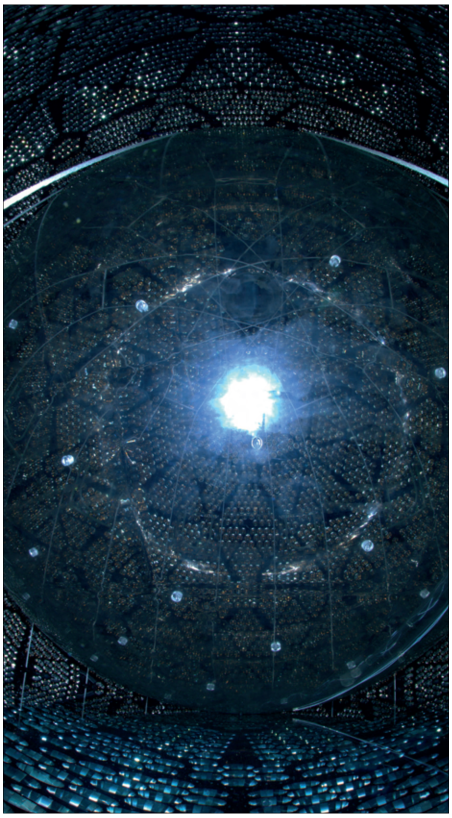
Doubling up for double-beta decay

Physicists are refilling a huge plastic sphere 2 km underground with a liquid containing ultra-pure tellurium in the hope of detecting an exceptionally rare form of nuclear decay, as **Edwin Cartlidge** reports

The Creighton nickel mine in Sudbury, northern Ontario, Canada, is no stranger to neutrino physics. Inside the mine, at the end of a tunnel 2000 m below ground, is a 30 m-high cavity containing a hollow acrylic sphere surrounded by thousands of photomultiplier tubes. During the first half of the last decade that 12 m-diameter sphere contained heavy water, which was monitored for the Cerenkov light generated when incoming solar neutrinos occasionally collided with its molecules. Data from the Sudbury Neutrino Observatory (SNO), as the facility was then called, showed neutrinos "oscillating" from one type to another as they pass through the Sun – a result that implied neutrinos have mass and propagate as bizarre "mixed states," contrary to the Standard Model of particle physics.

That apparatus is now being adapted to carry out a quite different kind of neutrino experiment, known as SNO+, which, rather paradoxically, is on the look-out for nuclear reactions that do not give off any neutrinos. The acrylic sphere will be filled with a liquid scintillator – an organic substance that emits light when charged particles pass through it – containing the isotope tellurium-130, which is thought to undergo a process known as "neutrinoless double-beta decay". This decay – if it exists at all – is extraordinarily rare: on average at least 10^{25} years will elapse before any given nucleus experiences the transformation. Its detection, however, would be a major discovery in physics, since it would mean that the neutrino – uniquely – is its own antiparticle, as well as providing a value for the mass that SNO showed neutrinos do possess.

In trying to observe this ultra-rare decay for the first time, SNO+ is not alone. Around a dozen different research groups around the world are operating, or will shortly start up, experiments searching for neutrinoless double-beta decay (see p23). Each tries to minimize the time needed to see the putative decay, by striking a balance between several, often competing, factors: the propensity of a given isotope to decay; the amount of that isotope that can realistically be obtained; the background radioactivity associated with that isotope; as well as the energy resolution and efficiency of the detector used to monitor the decay.


SNO+ Collaboration

Double or nothing The SNO+ experiment, based at SNOLAB in Canada, will be filled with a liquid scintillator containing the isotope tellurium-130 in order to hunt for neutrinoless double-beta decay.

In the case of SNO+, which forms part of the larger "SNOLAB" facility at Creighton that also carries out measurements on neutrinos from the Sun and nuclear reactors, the collaboration initially decided to use neodymium-150. This is because it is thought to have the highest decay rate of any of the 35 double-beta decay isotopes, as well as one of the lowest associated backgrounds. However, neodymium-150 makes up a fairly small fraction of naturally occurring neodymium – about 6% – and so (like other isotopes) has to be enriched. The collaboration had hoped that it could carry out this enrichment in a special facility in France but in the end it was unsuccessful.

Faced with this problem, the collaboration took the radical step of ditching neodymium-150 in favour of tellurium-130, which makes up 34% of naturally occurring tellurium – the highest proportion of any of the candidate isotopes. The researchers made this decision last year, some eight years into their project, having developed new techniques to purify the tellurium-130 and load it into the scintillator. A year-and-a-half on, the group appears happy with its choice. "We made the decision to gamble," says Oxford University's Steve Biller, spokesperson for the UK contingent within SNO+, "and we have since made enormous progress."

Background check

As its name suggests, neutrinoless double-beta decay is related to beta decay, the phenomenon in which a neutron inside a nucleus converts into a proton, accompanied by the emission of an electron and an antineutrino. Some nuclei containing even numbers of protons and neutrons can also undergo the much rarer double-beta decay, which sees two neutrons being simultaneously transformed into protons together with the emission of two electrons and two antineutrinos. This reaction was first observed experimentally in 1987, but theorists are pretty sure that the neutrinoless version of it exists too, despite being much rarer still. In this case, the two antineutrinos, by virtue of being their own antiparticles, annihilate one another before they can escape from the nucleus.

Physicists are looking for evidence of this decay by measuring the energy of the electrons given off. In normal double-beta decay the energy liberated by the reaction is carried off by both the electrons and the neutrinos. Since the divvying up of energy is not fixed but varies randomly from one decay to the next, the electrons' energy spectrum forms a curve spanning a wide range of values. In neutrinoless double-beta decay, on the other hand, all of the energy – a well-defined quantity – is taken up exclusively by the electrons, resulting in a spike at that energy value.

One group has in fact claimed to have seen such a spike – the Heidelberg–Moscow collaboration, which operated a germanium detector at the Gran Sasso laboratory in Italy between 1990 and 2003. However, many other physicists working in the field believe that what that collaboration actually saw were commonplace radioactive processes. Indeed, much of the work that goes into these experiments is dedicated to keeping background radioactivity to a minimum, which is why the detectors are

Neutrinos

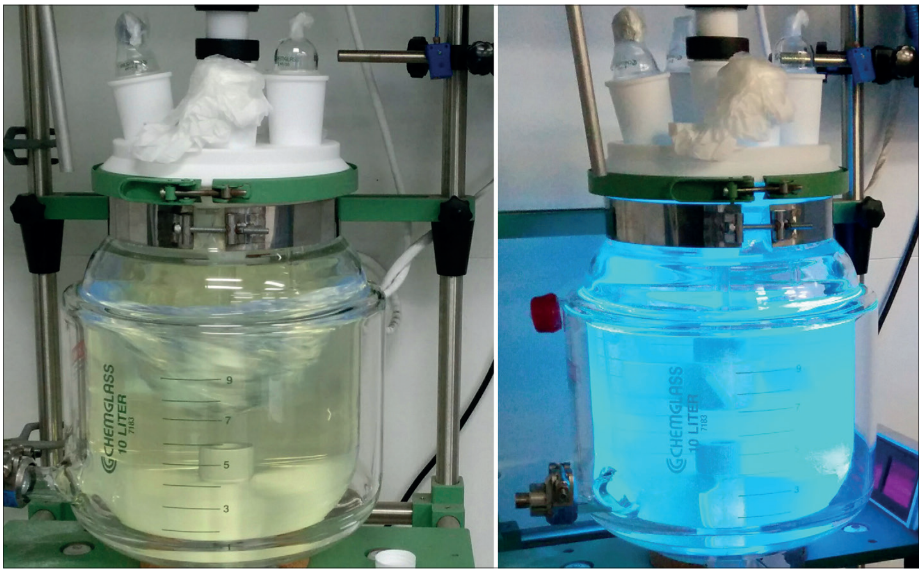
placed deep underground – locating them there minimizes radioactivity produced by interactions with cosmic rays. The detectors are also heavily shielded – in the case of SNO+, by filling the underground cavity with ordinary water – and use components that are themselves as free of radioactive isotopes as possible.

Part of the reason neodymium-150 looked attractive to the SNO+ team is that the position of its would-be decay peak is at about 3.4 MeV, putting it beyond the 3 MeV upper limit of most polluting background. (The tellurium-130 peak, in contrast, would lie at about 2.5 MeV.) However, Biller and SNO+ spokesperson Mark Chen realized that the most serious potential troublemaker – bismuth-214 – could be dealt with. Produced during the decay of the uranium that is naturally present in almost all materials, bismuth-214 gives off 3.2 MeV when it subsequently undergoes beta decay. But just a fraction of a second after it does so, the new decay product, polonium-214, gives off an alpha particle with a known amount of energy, allowing the researchers to identify the former event as background and so remove it.

Good numbers

Things came together for the two physicists when Chen was on sabbatical at Oxford in the autumn of 2011. Biller was thinking about the choice of isotope, having become frustrated with the shortcomings of neodymium, and then over tea one day he and Chen thrashed out a calculation for the potential sensitivity of the experiment using tellurium. They realized the numbers looked "really good". However, they also realized that these headline figures needed substantiating, so kept the calculations to themselves while their colleague Minfang Yeh and others at the Brookhaven National Laboratory in the US worked out how to load and purify the tellurium-130.

Initially, Yeh and co-workers tried loading the tellurium using an organic material, just as they had with neodymium (an intermediary being required to dissolve metals in an organic liquid). However, the results were disappointing: a browny-yellowy liquid that would not let light through. Undeterred, Yeh then decided to first dissolve telluric acid in water, before adding that mixture to the scintillator – linear alkyl benzene – using a surfactant. The result was a clear liquid that remains stable. Unlike the organic alternative, water is not a scintillator, which limits the amount of tellurium that can be loaded if light levels are to be kept above a certain minimum. However, the researchers found in fact that a decent light yield could be maintained even with concentrations of tellurium of several per cent – a result that suggested the experiment could reach very high sensitivities in the future.



SNO+ Collaboration

Fully loaded A container of a liquid scintillator containing the isotope tellurium-130 (left). The same container is then shone with ultraviolet light to simulate scintillation.

The Brookhaven researchers also developed a new purification technique to reduce levels of radioactive impurities "activated" by cosmic rays. The technique involves dissolving telluric acid in water, re-crystallizing it using nitric acid and then rinsing off contaminants with ethanol. The telluric acid can then be transported underground, dissolved in water at 80 °C and cooled so that it can re-crystallize a second time.

With this work under their belt, Biller and Chen presented their proposal to the rest of the collaboration in March 2012. A year later – following additional R&D and independent scrutiny by some of their colleagues – the collaboration held a vote on whether or not to switch isotope. The result of the vote, says Chen, was a near unanimous yes. "We didn't know at first whether this was a crazy idea, so we kept a lid on it," adds Biller. "But now we are confident that this new approach will work."

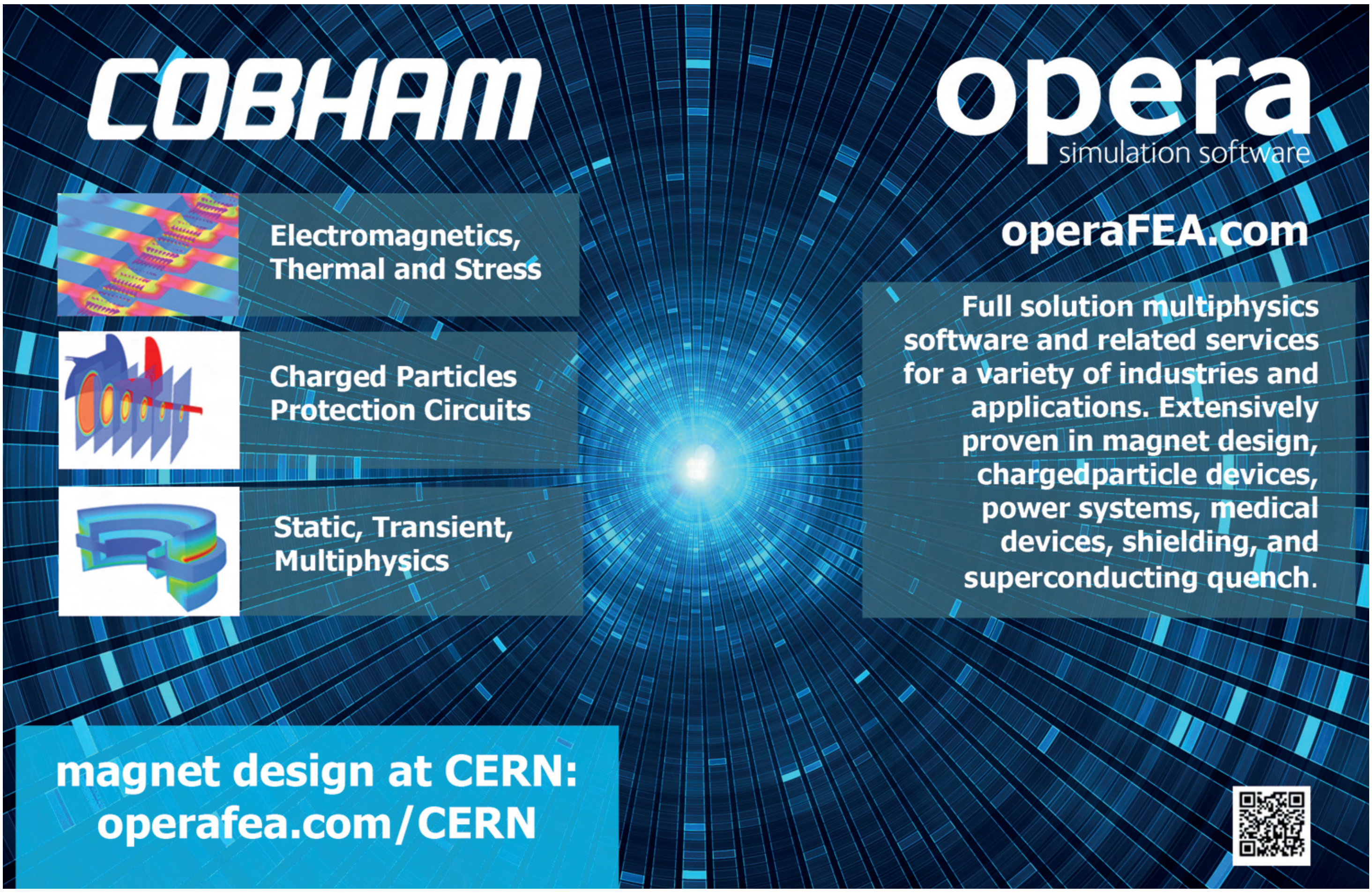
Massive sensitivity

Since the decision was taken to switch to tellurium, Chen, Biller and colleagues have not been wasting any time. This year they are filling the acrylic sphere with ordinary water in order to make basic tests of the experimental apparatus, and were also due to receive the first shipments of telluric acid from China. Then next year they should gradually replace the water with the scintillator, which they will purify and to which they will then add the 800 kg of tellurium-130 foreseen for the first phase of the experiment by the end of 2016.

According to Chen and Biller, between three and five years running with the 800 kg ought to bring SNO+ to within sight of the "inverted-hierarchy region" – a range of neutrino masses that oscillation data show might be favoured in nature (the size of neutrino mass that can be probed by neutrinoless double-beta decay experiments being inversely proportional to the square root of the attainable decay half-life). Increasing the detector mass to eight tonnes – which, they estimate, could be achieved by roughly doubling the $15–$20m needed to implement the first phase – should then allow for a "high sensitivity" search of most of the inverted-hierarchy region.

Giorgio Gratta, spokesperson for the EXO-200 xenon experiment in the US, cautions that the relatively poor energy resolution of SNO+ and the "non-specific nature" of any potential signal would make it hard for Chen and colleagues to convince others that they are seeing the neutrinoless decay. In fact, argues Ettore Fiorini, former spokesperson of the crystal-based tellurium-130 CUORE detector in Gran Sasso, it is essential that peaks are seen in two or preferably three types of isotope. He believes that SNO+ and its closest rivals ought to reach the inverse-hierarchy region "at about the same time".

Future projections aside, for the moment the SNO+ researchers are concentrating on simply making sure that the first stage of their experiment works as planned. Biller points out that higher-than-expected trace radioactive contamination, for example, or unexpected optical behaviour on the metre-scale might diminish the experiment's sensitivity below predicted values. "Our desktop measurements have given us about as much confidence as we can have in our experiment," he says. "But getting such a detector up and running is almost invariably more difficult than you think."



Astronomy

Drilling down to catch cosmic rays

A huge neutrino detector is currently being built at the South Pole to understand the origins of high-energy cosmic rays. **Jude Dineley** looks at the challenges in constructing the Askaryan Radio Array


T Benson

Testing ground The $8m Askaryan Radio Array will aim to detect ultra-high-energy neutrinos.

Ultra-high-energy cosmic rays are an enigma. They bombard the Earth with energies of more than 10^{20} eV – over 10 million times greater than the energies generated at CERN's Large Hadron Collider. And yet, where ultra-high-energy cosmic rays originate and what accelerates them is still a mystery. Astrophysicists are hoping such questions will be answered by the $8m Askaryan Radio Array (ARA) that, if funded, will come fully online at the South Pole in the coming decade. Consisting of 37 nodes or "stations", the ARA will sit on the 3 km-high Antarctic plateau and eventually span an area of 200 km^2.

The ARA is a large international collaboration consisting of 50 researchers from some 11 institutions, including the University of Wisconsin-Madison in the US and the National Taiwan University (NTU) in Taipei. All the ARA partners are involved in existing Antarctic cosmic-neutrino detectors: IceCube – a 1 km^3 detector embedded 2.5 km deep in the ice that reported its first detection of neutrinos with energies up to 10^{15} eV in 2013 – and the balloon-borne ANITA detector. ANITA, which is yet to make a confirmed detection, surveys around 1.5 million square kilometres of ice from 37 km up in the atmosphere and is sensitive to neutrinos with energies above 10^{19} eV.

The ARA will explore the so-far uncharted energies between IceCube and ANITA. Its main goal is to detect ultra-high-energy neutrinos that are predicted to result from interactions between high-energy cosmic rays and the cosmic microwave background in the vicinity of the unknown cosmic accelerators. Unlike the particles that make up cosmic rays, such as protons, neutrinos have no charge and next to no mass, meaning that those emitted from the edge of the universe can, in principle, reach Earth undeflected by fields and matter in the cosmos.

Spotting neutrinos

Building a detector at the South Pole might seem a perverse thing to do, but the beauty of Antarctica is that it has the largest expanse of ice in the world. And ice – being a dense, radio-transparent dielectric – is ideal for glimpsing neutrinos, which are notoriously hard to spot. Moreover, the ability to detect neutrinos improves the deeper you go. "We found that if we deployed the sensors at a depth of 200 m, then we have a factor of three times higher sensitivity than if we leave them at the surface," says Albrecht Karle of the University of Wisconsin-Madison, who is managing the ARA's deployment.

Each of the ARA's 37 stations will detect radio waves over 50 km^3 of ice and will be placed around 2 km apart on a hexagonal grid. Stations have been designed as standalone interferometers, enabling the three stations already deployed to start observing. Working over two intense summer seasons, each lasting six to eight weeks, the collaboration installed the prototype testbed station at the surface of the ice in late 2010 as well as the three full stations – one at 100 m and two at 200 m below the surface of the ice – in 2011 and 2012. The telescope will become more sensitive as each new station gets added – an approach that leaves the door open for the total number of stations to eventually expand beyond just 37.

Chosen for reliability and cost-efficiency, the 37 stations will be powered by the generators that supply the Amundsen-Scott South Pole Station with electricity. They will be connected by cables, which, along with data links, will run as far as 15 km across the ice to reach the most remote stations. It is estimated that the ARA will draw under 5 kW – less than 1% of the total power consumption at the South Pole Station.

Each ARA station will have 16 receiver antennas, divided into eight pairs spread across four detector "strings" suspended vertically in the ice to a depth of 200 m. Each pair comprises one horizontally and one vertically polarized antenna. The antennas will detect neutrinos by looking for the radio waves emitted when these tiny neutral particles collide with nuclei in the ice – a phenomenon called the Askaryan effect. By measuring the sequential arrival of the pulse at the antennas, the direction and the curvature of the wavefront can be deduced. From this information, the distance of the neutrino–ice interaction from the station can be calculated, which when combined with the pulse magnitude, can be used to determine the energy of the interaction.

Fine-tuned to maximize sensitivity, Karle estimates that the ARA will detect up to 10 events per year. Frequency and polarization characteristics detected by the antennas will also help improve the location of the events in the ice – a step towards locating neutrino sources in the sky. "By knowing their incoming energy and angle, we can point back to certain suspect astrophysical objects," says Pisin Chen of the NTU, which is funding one quarter of the stations. These could include supermassive black holes found in active galaxies and gamma-ray bursts. However, the ARA's primary goal, as Karle stresses, is to detect the particles in the first place. "Our priority is to detect events reliably," he says. "Once we have nailed that, then it will be a different game."

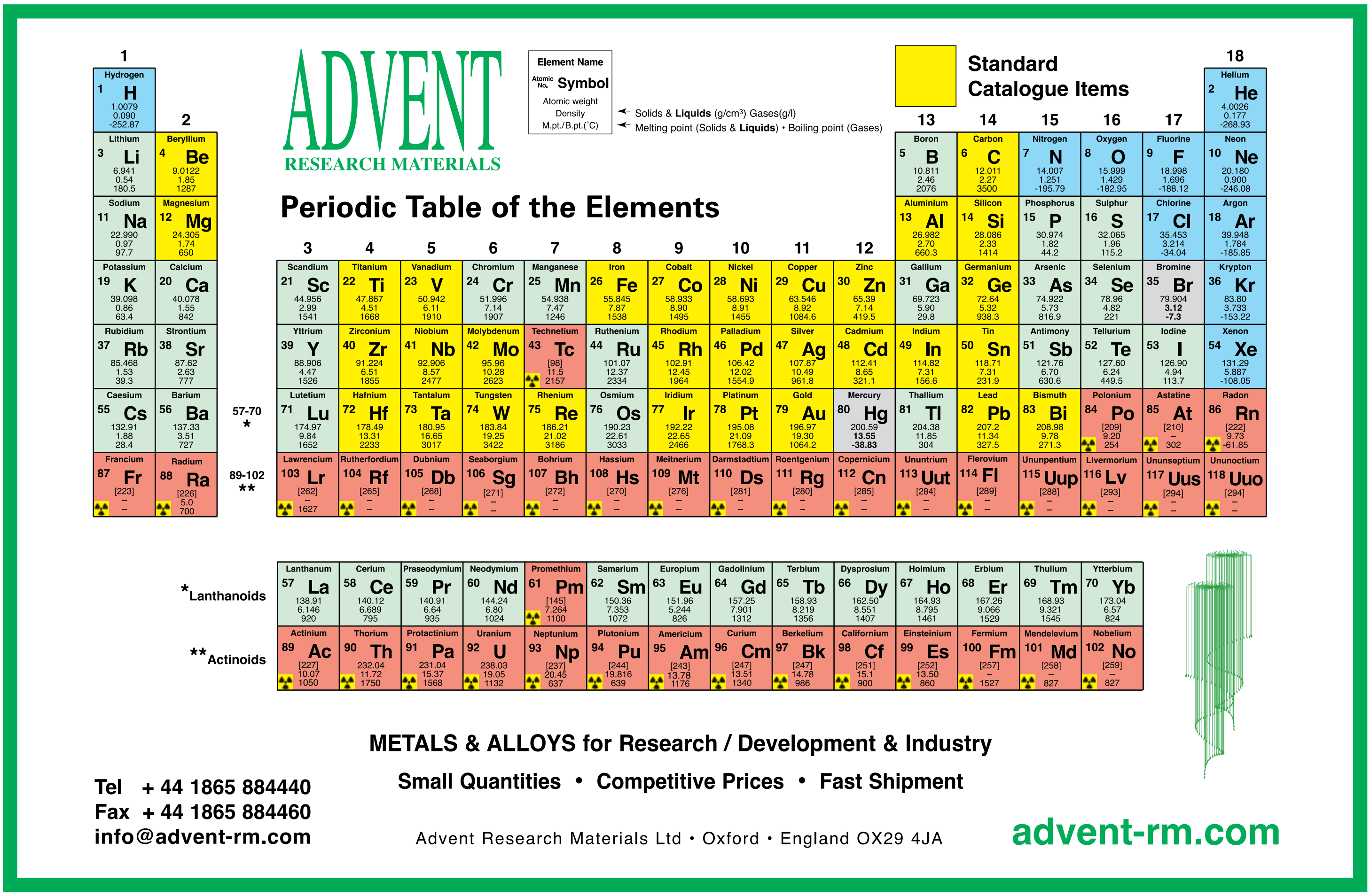
Drilling down under

Members of the collaboration are facing some significant challenges in building the ARA. As mechanical engineer Terry Benson of the University of Wisconsin-Madison points out, one particular problem is that the harsh conditions, remote location and associated logistics mean that the drills that are used to bore holes in the ice must be robust, easy to repair and fuel-efficient. In fact, Benson and colleagues have pioneered drilling technology with these criteria in mind. Their approach melts the ice with pressurized water at a temperature of 85 °C and then rapidly pumps it to the surface, leaving a dry hole. This means that the detectors do not need to be waterproofed from the melted ice or shielded as it refreezes and expands.

Yet, the technique carries a risk that equipment can get damaged and lost in the ice. "Keeping water liquid at the South Pole is hard to do," explains Benson, who has worked eight summers in Antarctica since 2004. "If you have delays when the drill equipment is sitting in the hole, it can freeze in and you can't get it out." But in addition to good design, meticulous preparation and instruments that can monitor the holes during drilling, Benson singles out experience as the most important factor. Safety is another top priority, with hazards including the hot, pressurized drill water and high-voltage power, not to mention the harsh environment. Indeed, crews are equipped with survival packs in case they get injured or exposed to poor weather conditions that could stop them returning quickly to the South Pole Station.

Chen's NTU group, which built the second and third stations, is now assembling additional ones in Taipei. However, for now, their installation is on hold. While money from Taiwan and other non-US states is in place, it is unclear if or when the National Science Foundation (NSF) will provide the ARA's US partners with the funding needed for deployment. "It's the US that has the capability of transporting all of the equipment to the pole. Most other countries are not able to do it, so that's becoming a bottleneck," says Chen, who adds that the US contribution is "very crucial". If funding is secured in time for construction over the 2016–17 Antarctic summer, Karle estimates the array will be completed by 2022. Yet the ARA is not the only neutrino experiment being built at the South Pole: the ARIANNA facility, which will be located on the Ross Ice Shelf, is in the early stages of construction and will search more than 500 km^3 of ice at the same energies.

Amy Connolly – a physicist at Ohio State University who is working with colleagues on simulations of neutrino detections by the ARA and analysing its first data – says that the prototype testbed has provided a successful proof of principle and made the first observations of background noise, proving that it will not overwhelm signals from true neutrino events. By feeding the data into simulations of a full station, the collaboration is also developing techniques to maximize sensitivity. "Based on our experience with the testbed, we can say more definitely that with a full ARA, we can really dig deep into the expected flux of cosmogenic neutrinos and begin to do real physics and astrophysics," says Connolly. Funding permitting, it would seem that the ARA has a bright future. "It's going to be a very powerful experiment," says Connolly. "If the NSF will only just allow us to build it."



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Periodic Table of the Elements

Element Name
Atomic No. **Symbol**
Atomic weight
Density ← Solids & **Liquids** (g/cm³) Gases(g/l)
M.pt./B.pt.(°C) ← Melting point (Solids & **Liquids**) • Boiling point (Gases)

🟨 **Standard Catalogue Items**

1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hydrogen 1 H 1.0079 0.090 -252.87																		Helium 2 He 4.0026 0.177 -268.93
Lithium 3 Li 6.941 0.54 180.5	🟨 Beryllium 4 Be 9.0122 1.85 1287												Boron 5 B 10.811 2.46 2076	🟨 Carbon 6 C 12.011 2.27 3500	Nitrogen 7 N 14.007 1.251 -195.79	Oxygen 8 O 15.999 1.429 -182.95	Fluorine 9 F 18.998 1.696 -188.12	Neon 10 Ne 20.180 0.900 -246.08
Sodium 11 Na 22.990 0.97 97.7	🟨 Magnesium 12 Mg 24.305 1.74 650												🟨 Aluminium 13 Al 26.982 2.70 660.3	🟨 Silicon 14 Si 28.086 2.33 1414	Phosphorus 15 P 30.974 1.82 44.2	Sulphur 16 S 32.065 1.96 115.2	Chlorine 17 Cl 35.453 3.214 -34.04	Argon 18 Ar 39.948 1.784 -185.85
Potassium 19 K 39.098 0.86 63.4	Calcium 20 Ca 40.078 1.55 842		Scandium 21 Sc 44.956 2.99 1541	🟨 Titanium 22 Ti 47.867 4.51 1668	🟨 Vanadium 23 V 50.942 6.11 1910	Chromium 24 Cr 51.996 7.14 1907	Manganese 25 Mn 54.938 7.47 1246	🟨 Iron 26 Fe 55.845 7.87 1538	🟨 Cobalt 27 Co 58.933 8.90 1495	🟨 Nickel 28 Ni 58.693 8.91 1455	🟨 Copper 29 Cu 63.546 8.92 1084.6	🟨 Zinc 30 Zn 65.39 7.14 419.5	Gallium 31 Ga 69.723 5.90 29.8	🟨 Germanium 32 Ge 72.64 5.32 938.3	Arsenic 33 As 74.922 5.73 816.9	Selenium 34 Se 78.96 4.82 221	Bromine 35 Br 79.904 **3.12** **-7.3**	Krypton 36 Kr 83.80 3.733 -153.22
Rubidium 37 Rb 85.468 1.53 39.3	Strontium 38 Sr 87.62 2.63 777		Yttrium 39 Y 88.906 4.47 1526	🟨 Zirconium 40 Zr 91.224 6.51 1855	🟨 Niobium 41 Nb 92.906 8.57 2477	🟨 Molybdenum 42 Mo 95.96 10.28 2623	Technetium 43 Tc [98] 11.5 ☢ 2157	Ruthenium 44 Ru 101.07 12.37 2334	🟨 Rhodium 45 Rh 102.91 12.45 1964	🟨 Palladium 46 Pd 106.42 12.02 1554.9	🟨 Silver 47 Ag 107.87 10.49 961.8	🟨 Cadmium 48 Cd 112.41 8.65 321.1	🟨 Indium 49 In 114.82 7.31 156.6	🟨 Tin 50 Sn 118.71 7.31 231.9	Antimony 51 Sb 121.76 6.70 630.6	Tellurium 52 Te 127.60 6.24 449.5	Iodine 53 I 126.90 4.94 113.7	Xenon 54 Xe 131.29 5.887 -108.05
Caesium 55 Cs 132.91 1.88 28.4	Barium 56 Ba 137.33 3.51 727	57-70 *	Lutetium 71 Lu 174.97 9.84 1652	🟨 Hafnium 72 Hf 178.49 13.31 2233	🟨 Tantalum 73 Ta 180.95 16.65 3017	🟨 Tungsten 74 W 183.84 19.25 3422	🟨 Rhenium 75 Re 186.21 21.02 3186	Osmium 76 Os 190.23 22.61 3033	🟨 Iridium 77 Ir 192.22 22.65 2466	🟨 Platinum 78 Pt 195.08 21.09 1768.3	🟨 Gold 79 Au 196.97 19.30 1064.2	Mercury 80 Hg 200.59 **13.55** **-38.83**	Thallium 81 Tl 204.38 11.85 304	🟨 Lead 82 Pb 207.2 11.34 327.5	🟨 Bismuth 83 Bi 208.98 9.78 271.3	Polonium 84 Po [209] 9.20 ☢ 254	Astatine 85 At [210] – ☢ 302	Radon 86 Rn [222] 9.73 ☢ -61.85
Francium 87 Fr [223] – ☢ –	Radium 88 Ra [226] 5.0 ☢ 700	89-102 **	Lawrencium 103 Lr [262] – ☢ 1627	Rutherfordium 104 Rf [265] – ☢ –	Dubnium 105 Db [268] – ☢ –	Seaborgium 106 Sg [271] – ☢ –	Bohrium 107 Bh [272] – ☢ –	Hassium 108 Hs [270] – ☢ –	Meitnerium 109 Mt [276] – ☢ –	Darmstadtium 110 Ds [281] – ☢ –	Roentgenium 111 Rg [280] – ☢ –	Copernicium 112 Cn [285] – ☢ –	Ununtrium 113 Uut [284] – ☢ –	Flerovium 114 Fl [289] – ☢ –	Ununpentium 115 Uup [288] – ☢ –	Livermorium 116 Lv [293] – ☢ –	Ununseptium 117 Uus [294] – ☢ –	Ununoctium 118 Uuo [294] – ☢ –

*Lanthanoids	Lanthanum 57 La 138.91 6.146 920	Cerium 58 Ce 140.12 6.689 795	Praseodymium 59 Pr 140.91 6.64 935	Neodymium 60 Nd 144.24 6.80 1024	Promethium 61 Pm [145] 7.264 ☢ 1100	Samarium 62 Sm 150.36 7.353 1072	Europium 63 Eu 151.96 5.244 826	Gadolinium 64 Gd 157.25 7.901 1312	Terbium 65 Tb 158.93 8.219 1356	Dysprosium 66 Dy 162.50 8.551 1407	Holmium 67 Ho 164.93 8.795 1461	Erbium 68 Er 167.26 9.066 1529	Thulium 69 Tm 168.93 9.321 1545	Ytterbium 70 Yb 173.04 6.57 824
**Actinoids	Actinium 89 Ac [227] 10.07 ☢ 1050	Thorium 90 Th 232.04 11.72 ☢ 1750	Protactinium 91 Pa 231.04 15.37 ☢ 1568	Uranium 92 U 238.03 19.05 ☢ 1132	Neptunium 93 Np [237] 20.45 ☢ 637	Plutonium 94 Pu [244] 19.816 ☢ 639	Americium 95 Am [243] 13.78 ☢ 1176	Curium 96 Cm [247] 13.51 ☢ 1340	Berkelium 97 Bk [247] 14.78 ☢ 986	Californium 98 Cf [251] 15.1 ☢ 900	Einsteinium 99 Es [252] 13.50 ☢ 860	Fermium 100 Fm [257] – ☢ 1527	Mendelevium 101 Md [258] – ☢ 827	Nobelium 102 No [259] – ☢ 827

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Opinion: Bill Stirling

Supporting the next generation

With Europe building a whole host of world-class facilities in the coming decade, **Bill Stirling** warns of a possible shortage of scientists that are able to use them

Career concerns Bill Stirling says big facilities need a strong supply of talented scientists.

ILL

Europe has a long tradition of constructing world-class laboratories and forging international partnerships. Collaboration has been a cornerstone of Europe's historical scientific success leading to one of the great accomplishments of modern science in Europe – the discovery of the Higgs boson at CERN's Large Hadron Collider in 2012. Today, countries across Europe are jointly funding the next generation of facilities – such as the European Extremely Large Telescope (E-ELT) to be built in Chile and the European Spallation Source (ESS) in Lund, Sweden – that any country would find difficult to fund alone.

As well as being the world's primary laboratory for particle physics, CERN is a remarkable demonstration of European countries working and investing together to achieve a globally leading position in science. France and Germany also came together in 1967 to found the Institut Laue-Langevin (ILL) in Grenoble – one of the first multinational laboratories to be built in postwar Europe. The UK joined in 1973, further strengthening their shared scientific interests. Today, the ILL is the world's leading centre for neutron science, with about 1500 researchers from more than 40 countries visiting each year. One of the reasons for its success has been the consistent programme of re-investment made possible by pan-European support.

While a single country might baulk at investing on its own in a multi-million-euro research instrument or infrastructure, spreading the cost across multiple countries has made this a more realistic prospect. Such collaborations are to be found in virtually every area of science. For example, European Space Agency (ESA) missions and the international fusion-based energy project ITER.

"Big science" ultimately depends on the work of us "little" scientists. So as facilities and projects keep getting bigger, it is important that we do not lose sight of the human component. We must not forget the individual scientists who make this research possible. For these multinational collaborations to succeed we must support a new generation of scientific talent, and address any challenges that they face in taking advantage of our world-class instrumentation. If we cannot ensure a continued stream of enthusiastic scientists, free and able to pursue their studies around Europe and work at such world-class facilities, there is little point in having these at all.

The human element

When I left the UK in 1972 to do a postdoc in Germany, I gave very little thought to my long-term career. But I have always believed that working at an international facility can be tremendously valuable for early-career researchers. Apart from the benefits associated with a change of environment, working in an international, multicultural group is a highly stimulating experience. As a young scientist, I worked in teams from half a dozen countries, where the mix of educational backgrounds made for a richer working relationship.

Today's researchers, however, are more aware of the potential personal difficulties associated with a change of country. Unfortunately, basic issues such as childcare and transferable pension plans have yet to be resolved in a satisfactory way in Europe, which only further complicates the prospect of prolonged stays abroad. While some steps are being taken – the European Commission, for example, is considering a pan-European pension fund for researchers – the future remains unclear. If we are to ensure the long-term health of our European science community based on exciting collaborations, more needs to be done to ensure that researchers can travel around as freely as their scientific ideas.

These concerns are shared by the eight members of the EIROforum, the partnership of Europe's largest intergovernmental research organizations that includes CERN, ESA and the ILL. A survey carried out by the European Research Area in 2012 found that almost 60% of researchers required access to research infrastructures of pan-European interest. Of the 60%, around 37% had experienced access problems – whether in terms of financial barriers, complex regulations or the poor communication of information.

Whatever the UK's future role within the European Union, it will remain a significant partner in facilities such as the ILL and the European Synchrotron Radiation Facility. This imposes a duty on the UK to attract more researchers to such facilities, yet UK staff numbers have been decreasing at the ILL over recent years, with researchers increasingly preferring to take jobs at home. The competitive salaries offered in the UK are clearly contributing to this trend, as is the rise of powerful national facilities such as the ISIS neutron source and the Diamond synchrotron, both based at the Rutherford Appleton Laboratory in Oxfordshire. These problems are clearly not limited to the UK. Of the more than 10 000 researchers in the European synchrotron community, only a small number make a significant trans-European move each year.

Nevertheless, PhD and postdoc programmes across Europe's universities and laboratories do allow people to move between countries and benefit from world-class facilities. In addition to facilitating the free flow of scientific talent, we must also address the issue of scientific training. If we do not maintain a pool of scientific talent to draw on in the future, we will find ourselves increasingly side-lined from the great discoveries of tomorrow. International collaborations are not without their challenges, but when they work, they can be very positive for science and for the individuals concerned.

Bill Stirling is director of the Institut Laue-Langevin in Grenoble, France

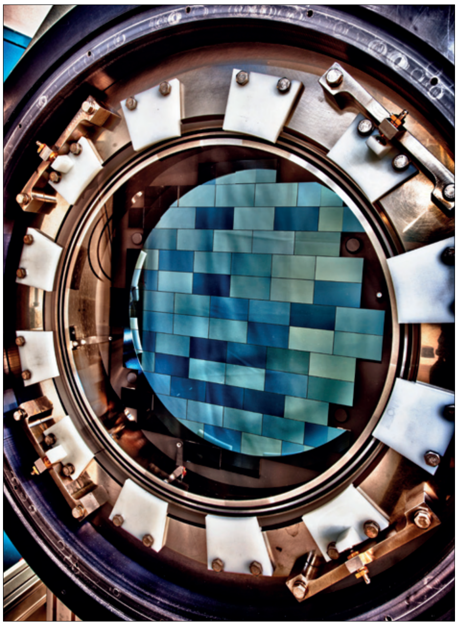
The new MKID on the block

Imaging devices based on superconductors rather than semiconductors could provide the data needed to understand what is speeding up the universe's expansion, as **Edwin Cartlidge** reports

In 1998 two groups of researchers made an announcement that shocked the scientific world: the expansion of the universe is accelerating. For most of the 20th century scientists had known, or at least strongly suspected, that the universe was expanding, but they thought that the gravitational attraction of all the mass in the cosmos was causing the expansion to slow down. Having observed the light from a number of very distant supernovae, the two groups found this not to be the case. Many other groups have since confirmed their findings and have shown that the apparent repulsive force thought to be driving the acceleration – known as dark energy – accounts for about three quarters of the energy density of the universe. To date, however, no-one has been able to explain what dark energy actually is.

Various theories about the nature of dark energy have been proposed, but putting these to the test requires detailed information about exactly how the universe has expanded and how dark matter has brought mass together in the 14 billion years since the Big Bang. One way to do this is to measure the properties of large numbers of galaxies and use those data to establish whether matter has tended to clump together or move apart over cosmic time. This involves wide-field imaging of the night sky in order to obtain the angular co-ordinates of each galaxy and then measuring the galaxies' spectra to pin down their distance along the line-of-sight (the redshift of their spectral lines revealing how quickly they are moving away from us, and so, via the Hubble relation, how far they are from us). The result is a 3D map charting the evolution of the universe.

One current facility that is being used to draw such a map is the Dark Energy Camera, a 570-megapixel device mounted on the 4 m Victor M Blanco telescope in Chile. The camera started up last year and surveys 5000 square degrees, or one-eighth of the sky, in minute detail. More ambitious still is the Large Synoptic Survey Telescope (LSST), due to see first light in Chile in about 2020, which will use an 8.4 m primary mirror and a camera with three billion pixels to survey the whole sky every week for 10 years. In terms of imaging, the output of the two facilities will be extraordinarily high – some 300 million galaxies should be observed by the former and a whopping 10 billion by the latter. The galaxies' spectra, however, will be obtained simply by capturing the images through a handful of filters of varying colours. While more distant objects tend to be redder, the redshift measurements obtained in this way will not be precise enough to record the universe's expansion history in detail.


Fermilab

Eye on the sky The Dark Energy Camera – a 570-megapixel device mounted on the 4 m Victor M Blanco telescope in Chile – uses charge-coupled devices to take images.

The solution to this problem, according to astrophysicist Ben Mazin of the University of California, Santa Barbara, is to carry out spectroscopic measurements not with the conventional charge-coupled devices (CCDs) used in the Dark Energy Camera, LSST and almost every other major telescope in the world, but with a new kind of sensor known as a microwave kinetic inductance detector (MKID). Rather than using semiconductors to convert incoming photons into single electrons, as is the case in CCDs, MKIDs instead employ a superconductor, typically titanium nitride. Each photon breaks Cooper-paired electrons in a pixel of superconductor to produce thousands of excitations known as quasiparticles, with the resulting change in the material's inductance then measured using a microwave resonator.

These devices are ideal for carrying out redshift measurements, explains Mazin, as the number of quasiparticles produced by a photon depends on the energy, and hence frequency, of that photon. In other words, an MKID pixel array can both image and measure the spectra of many objects – potentially as many as tens or even hundreds of thousands – in the sky at the same time. "I think it is the only way that people have thought of so far of getting low-resolution spectroscopic follow-up for the large numbers of galaxies imaged in sky surveys," says Mazin, who has been developing MKID technology since 2000. "It is a very powerful technique for studying dark energy."

Speeding up spectroscopy

To accurately record spectra from celestial objects, astronomers use devices known as spectrographs. These instruments are placed at a telescope's focus and typically use a diffraction grating to split up the incoming light into its component wavelengths, with an object's redshift then obtained by measuring the displacement of well-known absorption or emission lines. Historically, all the light arriving at a telescope was focused on a single long slit in front of the spectrograph, which meant that only one spectrum at a time could be obtained and the process was therefore very slow. In recent years, the technique has been speeded up through the use of multi-object spectrographs, in which a mask with multiple slits or a fibre-optic plug plate directs the light to the spectrograph. Pre-existing imaging data from wide-field surveys are used to precisely position the slits or fibres so that each one captures the light from a specific object in the sky.

Multi-object spectrographs can currently analyse hundreds of objects at the same time, while the Dark Energy Spectroscopic Instrument (DESI), being built by scientists at the Lawrence Berkeley National Laboratory in California to attach to the Mayall 4 m telescope in Arizona in about 2018, will have 5000 of these channels. However, even this huge ramping up of spectroscopic measurements will not be enough to keep pace with the biggest surveys, according to Juan Estrada, a physicist at Fermilab near Chicago, who says that a spectrograph like DESI would be capable of following up on a few tens of millions of the galaxies imaged by the LSST. (DESI itself will be looking at the northern sky whereas the LSST will be imaging the southern.) "You would have to mount existing spectrographs on lots of different telescopes," he says, "but the numbers make that impossible to do."

Enter MKIDs. Estrada points out that the highest energy resolution (energy divided by uncertainty in the energy) that could be achieved with MKIDs – about 150 – is far lower than that of the best spectrographs, which can reach as high as 40 000. That lower energy resolution then translates into a poorer distance resolution. But, he says, it is perfectly good for doing cosmology, which is mostly concerned with the furthest reaches of space and time. "Low resolution is enough to measure objects in the sky to 10 or 15 megaparsecs," he says. "A smaller distance than that is not interesting."

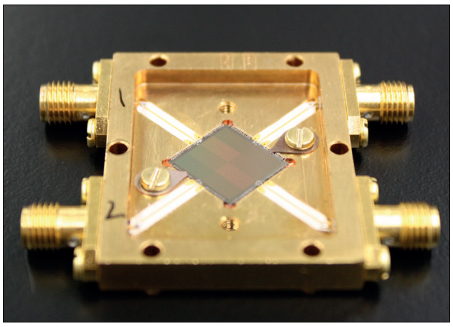
Estrada's group at Fermilab is currently building an MKID array with 20 000 pixels, based on the technology developed by Mazin. It hopes to mount the device on the Southern Astrophysical Research telescope in Chile within the next couple of years in order to obtain redshifts from objects imaged by the Dark Energy Camera.

Looking further into the future, Mazin and colleagues at Santa Barbara are hoping to have a 100 000-pixel array, known as Giga-z, ready by about 2023. Like multi-object spectrographs, Giga-z will take the spectra of individual sources by splitting up the incoming light from a telescope using a mask created with pre-existing survey data. In this case, however, the number of holes in that mask will be 100 000 – each one illuminating a 10 × 10 arcsecond pixel in the MKID array behind. According to Mazin, Giga-z should acquire about 2.5 million spectra a night on a dedicated 4 m telescope, allowing it to produce redshift data for around two billion of the galaxies imaged by the LSST.

Mazin has already put the basic MKID technology – optimized for near-infrared and optical wavelengths – to the test in a 2000-pixel camera installed at the Palomar 200-inch telescope in California in 2011. He says that he and his colleagues "got skunked" last year when the telescope's dome did not open for five nights because of bad weather, but adds that they got good results the year before, allowing them to publish research on the Crab pulsar and white dwarfs.

Cool challenges

Despite these early achievements, however, Mazin admits that there is still plenty of room for improvement. In particular, he notes, MKIDs' energy resolution is some way below the (fairly modest) theoretical maximum. That maximum at optical wavelengths (0.4 μm) is about 100, but the best that his group has achieved so far is around 10, a figure, he says, that will need to improve by a factor of three to five before the technology can be used in Giga-z. To do so, he and his colleague are working to improve the materials used to make the MKIDs, as well as reducing noise from the detectors' electronic components. "MKIDs are a very new technology," he adds, "and there is tremendous headroom to improve the performance."

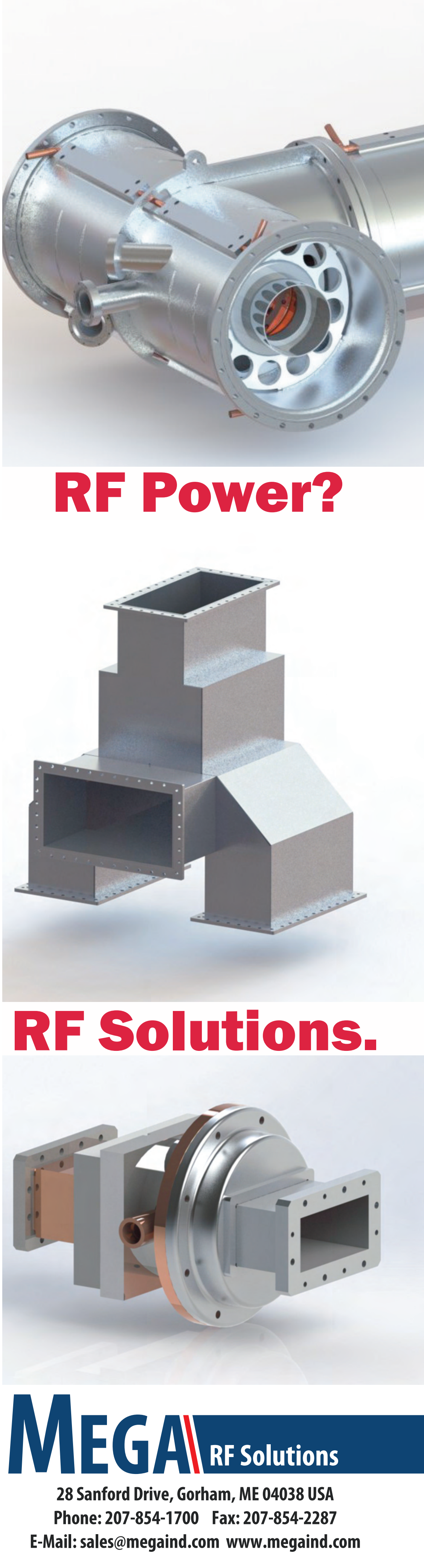

Ben Mazin

Seeing clearer Future telescopes hunting for dark energy could use microwave kinetic inductance detectors instead of the conventional charge-coupled devices currently used.

Another challenge is refrigeration, as pointed out by LSST chief scientist Tony Tyson of the University of California, Davis. Astronomical instruments are generally kept chilled, at temperatures of around 100 K, in order to limit interference produced by thermal noise. But MKIDs need to be much cooler still – having an operating temperature of around 100 mK – in order to be fully superconducting. That will be tricky when using large MKID arrays, according to Tyson, because the focal plane over which the light is collected can be up to 1 m across. Mazin, however, says that Giga-z might only need a 20 cm-diameter focal plane, which, he believes, "should be trivial to cool".

Challenges notwithstanding, Estrada believes that MKIDs have a bright future and that the technology has the "promise of a revolution for the way that we look at the sky". Indeed, he draws a parallel with the early development of CCDs in the 1980s, a technology, he says, that was regarded as having "a lot of promise but not producing much science".

Tyson cautions that the physical size of an MKID pixel – a square with sides about 0.2 mm long – means that they would not replace CCDs in imaging cameras (the more established technology now having pixels as small as 0.01 mm on a side). But he believes that MKIDs's ability to combine imaging with spectral analysis makes them ideal for studying dark energy and the large-scale structure of the universe more generally. "For moderate-precision spectroscopic information on billions of galaxies there is simply no other way," he says.

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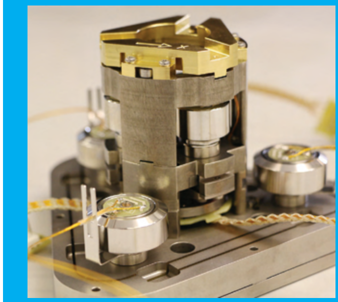


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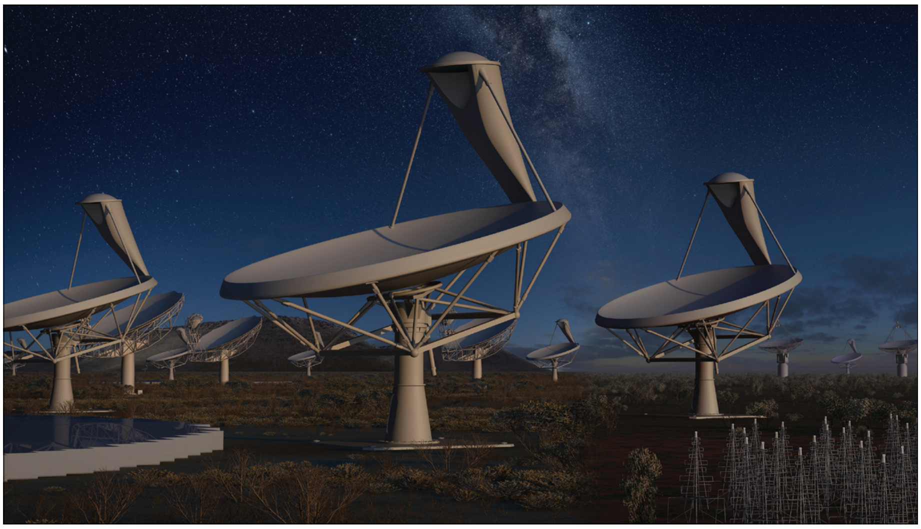
Surviving the flood

Planned big-science facilities are set to generate more data than all the global Internet traffic combined. **Jon Cartwright** finds out how scientists will deal with the data deluge


SKA Organisation

Data hungry The Square Kilometre Array, currently being built in southern Africa and Australasia, will produce more than 250 000 petabytes of data every year – enough to fill 36 million DVDs.

When the €2bn ($2.6bn) Square Kilometre Array (SKA) sees first light in the 2020s, astronomers will have an unprecedented window into the early universe. Quite what the world's biggest radio telescope will discover is of course an open question – but with hundreds of thousands of dishes and antennas spread out across Africa and Australasia, you might think the science will be limited only by the enormous extent of the telescope's sensitivity, or its field of view.

But you would be wrong. "It's the electricity bill," says Tim Cornwell, the SKA's head of computing. "While we have the capital cost to build the computer system, actually running it at full capacity is looking to be a problem." The reason SKA bosses are concerned about electricity bills is that the telescope will require the operation of three supercomputers, each with an electricity consumption of up to 10 MW. And the reason that the telescope needs three energy-hungry supercomputers is that it will be churning out more than 250 000 petabytes of data every year – enough to fill 36 million DVDs. (One petabyte is approximately 10^{15} bytes.) When you consider that uploads to *Facebook* amount to 180 petabytes a year, you begin to see why handling data at the SKA could be a bottleneck.

This is the "data deluge" – and it is not just confined to the SKA. The CERN particle-physics lab, for example, stores around 30 petabytes of data every year (and discards about 100 times that amount) while the European Synchrotron Radiation Facility (ESRF) has been annually generating upwards of one petabyte. Experimental physics is drowning in data, and without big changes in the way data are managed, the science could fall far short of its potential.

Data drizzle

Cornwell says that he can remember the start of his astrophysics career at the UK's Jodrell Bank Observatory in the late 1970s, when staff could print out every data point from an experimental run on a sheet of paper six metres long. As sample sizes have inflated, however, experimental groups have been forced to overcome problems associated with taking the data – whether storing it, processing it or transferring it from one place to another. "Over 30 years, each of those has been a factor at some point," Cornwell says.

At the SKA today, being able to process data without blowing the energy budget is the key concern. While the actual number of data falls with each processing step, Cornwell and his colleagues still have to perform careful computer modelling in order to determine exactly which experiments will be possible. Some will not – and electricity costs will be to blame. "This is what people predicted five years ago – that capital costs would be exceeded by the running costs," Cornwell notes.

The problem at the SKA is not simply down to the number of data being generated. Unlike many other experimental facilities, the SKA's data will be coming from disparate sources – dishes and antennas – that are spread over much of the southern hemisphere. As a result, the data must be collated before anything else can be done with them. If the data originated at roughly the same place, on the other hand, other possibilities for streamlining would have opened up. That is true at CERN, which in 2006 launched a special computing network to farm out data from its Large Hadron Collider (LHC) to labs around the world for processing, thereby avoiding the need for costly, on-site number crunching. Today, the Worldwide LHC Computing Grid consists of more than 170 computing centres in 40 countries and played a vital role in the discovery in 2012 of the Higgs boson.

Despite the success of the Grid, CERN is concerned about what the future holds for data-intensive computing. In May, a public–private partnership between CERN and various computing companies called CERN openlab produced a white paper, "Future IT Challenges in Scientific Research". The paper outlined six main challenges: how to extract data, and how to initially filter them; the best types of computing platforms and software to handle the data; how to store the data; where to find the computing infrastructure, whether it is on-site, over a CERN-type grid, or in a Internet-shared "cloud"; how to transmit data; and how to analyse them efficiently.

Physics institutions feel the pressure of these challenges differently. At the ESRF, where X-ray data must be recorded within a confined region around a sample, engineers have to extract one gigabyte of data per second – a tiny fraction of what is possible at CERN or the SKA. However, even that relatively small amount is tricky to handle. The synchrotron was originally mandated to give visiting scientists all the raw data that they generate during their experimental runs, but Andy Grotz, the group leader of software at the ESRF, says that aim is no longer realistic, and that they must reduce it. “We suffer from the data deluge, in that we almost cannot keep up,” he adds. “We have to change the way we work radically.”

Often little is lost by reducing raw data. For instance, thousands of X-ray images may be needed to define a crystal according to the most common parameters – orientation, strain and so on – but, once those parameters have been calculated, the raw data are, for many visiting scientists, superfluous. The trouble is how to reduce the raw data when the requirements of visiting scientists can be so varied. Grotz says the ESRF has in the past allowed its computer scientists to help visiting scientists reduce data “on a goodwill basis” so that the files are small enough to be taken home on a USB stick or any other convenient medium. Now, he says, the lab is looking at ways of formalizing the process because the raw data sets are always too unwieldy.

One option – which Grotz and others have submitted as a research and innovation project to the European Commission (EC) under its Horizon 2020 funding programme – is to set up a cloud-computing facility with other European science institutions for the express purpose of data reduction. The key requirement of such a system would be that it is easy to use, even for those scientists who are not computer-savvy. “More and more users want to be able to use this as a turnkey system, where they can provide a sample and get out data that they understand,” says Grotz.

Different requirements

If it goes ahead, Grotz and colleagues’ Horizon 2020 project would follow on from Cluster of Research Infrastructures for Synergies in Physics (CRISP). This project, which has run for three years under backing from the EC, brought together 11 European research facilities, including the SKA, the ESRF and CERN, to tackle all aspects of the data deluge. CRISP has had some successes, such as finding new ways to extract data quickly from detectors, but Grotz says other targets – such as automatically storing the contextual data (or “metadata”) from experiments – has proved difficult because of the innate differences between research institutions.

Differences between hosting institutions may not only be practical. Bob Jones, the head of CERN openlab, believes the recent scandals of how governments can tap into private data have galvanized people into thinking about who should have access to what data. Science is competitive, he says, and groups that have helped fund an experiment may be concerned if that experiment’s data are farmed somewhere else for processing, because it might allow non-participating groups to sneak access. Some data could even carry a political or security risk, he says – a satellite’s image of a war zone, for instance.

Legislative answers to such problems could hinder collaborative computing efforts or they could streamline it, says Jones. But whatever happens, he says, there needs to be a collective decision. “There are a number of interests, but really it boils down to Europe deciding what the rules are for accessing data, rather than having them imposed on it by a third party.”

When it comes to the data deluge, it seems, staying above water will not be easy. Grotz says that a more general problem is financial, in the sense that computing is often bottom of the list for managers who are budgeting experimental infrastructure. “By the time we get to the software and computing infrastructure, the money has usually run out,” he says. A change of mindset is needed, but Grotz thinks that we are still in that antediluvian world where just generating the data is the priority. “It’s like we’re still working with slide rules,” he says.

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Opportunities exist to contribute to large scale national and international accelerator activities such as the development of the long-baseline neutrino facility at Fermilab and TeV-scale collider developments world-wide as well as cutting edge innovative research in laboratory –scale experiments to investigate the “dark” sector of the vacuum and other precision experiments e.g. “g-2” and “mu-to-e”.

Working seamlessly with the outstanding accelerator research staff at Fermilab, NIU physics and engineering departments and its Northern Illinois Centre for Accelerator and Detector Development (NICADD) and the consortium of mid-western universities and laboratories, with access to advanced accelerator test facilities at Fermilab, ANL and other international laboratories such as CERN (Switzerland), DESY (Germany), ESS (Sweden), John Adams Institute and Cockcroft Institute (UK), the cluster will offer unique collaborative research opportunities. Details of specific opportunities and recruitment will be announced in near future.

Prospective Masters- and PhD-level students, postdoctoral fellows, research scientists and aspiring academic faculty members should contact **Professor Swapan Chattopadhyay** (**schaterji@niu.edu** or **swapan@fnal.gov**) for further details and send early expressions of interest and professional background information in advance.

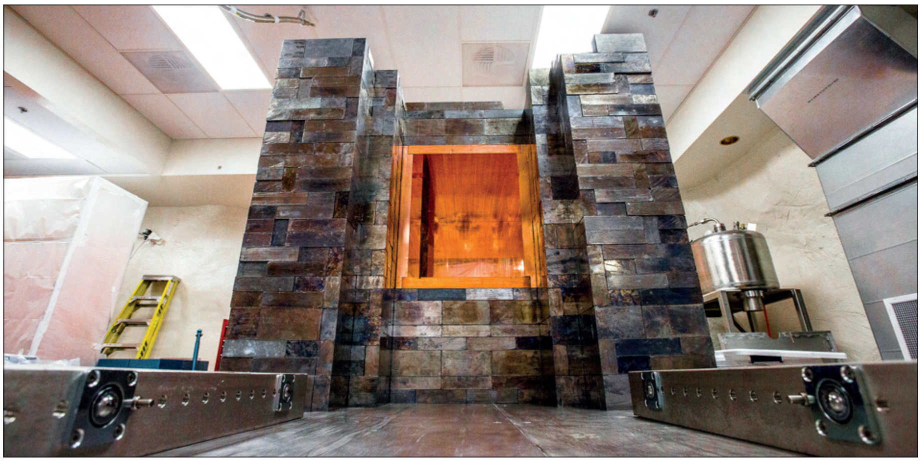
Reducing cosmic rays to a trickle

Michael Schirber travels to South Dakota to a neutrino experiment that is seeking to eliminate stray signals from cosmic rays by machining copper a mile underground

Cosmic rays are a nuisance when searching for very rare particle events. Not only can they produce background noise that mimics a real signal, but long before an experiment has even started they can also induce unwanted reactions in detector materials by producing radioactive nuclei that interfere with the ultra-sensitive measurements. So to combat this, physicists take experiments deep underground where the cosmic-ray downpour is greatly diminished.

One such example is the Sanford Underground Research Facility (SURF) in South Dakota, which extends nearly a mile underground. Physicists at the lab are currently building an experiment called the Majorana Demonstrator (MJD), which will use enriched germanium to search for an extremely rare process called neutrinoless double-beta decay. Determining if this hypothetical decay occurs requires lowering the background to unprecedented levels. The MJD researchers are therefore pioneering new techniques to reduce the background from ionizing radiation so that it is a factor of 100 below previous experiments.

To pull off this feat, the Majorana team is forming the world's purest copper and fabricating it into components in the world's deepest clean machine shop. These steps and others should make this experiment the most free from cosmic rays ever.



Matthew Kapust, Sanford Underground Research Facility

Below the surface The Majorana Demonstrator will use enriched germanium to search for neutrinoless double-beta decay.

Nuclear issues

The overall scientific goal of the MJD is to test whether neutrinos are their own antiparticle. This idea – first formulated by the Italian physicist Ettore Majorana in 1937 – offers an explanation for why the neutrino's mass is many orders of magnitude less than that of the electron and the other fundamental particles. A neutrino–antineutrino equivalence could also help explain how matter came to dominate antimatter in the early universe.

The most direct way to see if neutrinos are "Majorana" particles would be to scrunch them into a small volume and look for annihilations. But physicists simply do not have the means to concentrate neutrinos tightly enough to overcome the enormously low probability of two neutrinos interacting. A much more feasible approach is to search for neutrinoless double-beta decay, even if it is highly elusive, see p9.

Double-beta decay is a process experienced by 35 isotopes, including germanium-76 and xenon-136, and it involves two neutrons in the nucleus simultaneously decaying into two protons, emitting two electrons and two antineutrinos in the process. If the neutrino is a Majorana particle, however, then the two antineutrinos would in essence annihilate each other before leaving the nucleus – the net result being neutrinoless double-beta decay.

Several experiments have looked for neutrinoless double-beta decay in germanium-76 and xenon-136. But except for one controversial claim a few years ago, all these efforts have come up empty. Based on such non-detections, physicists estimate that the lifetime for neutrinoless double-beta decay is more than 10^{25} years, which in terms of a decay rate is less than one decay per year in 10 kg of germanium. To probe smaller decay rates (longer lifetimes), experiments need to not only get larger with more nuclei, but they also need to better suppress noise.

A castle for germanium

Protecting MJD's germanium detectors from cosmic rays is an effort that starts well before the experiment is even switched on. As cosmic rays can react with germanium to produce unwanted radioactive nuclei such as germanium-78 and cobalt-60, the team had 30 kg of germanium, which is enriched with germanium-76, shipped by sea from Russia in a special steel container that limited its exposure to cosmic rays. "Flying is out of the question, and when we transport anything by car, we worry about the altitude along the route," says John Wilkerson of the University of North Carolina, who is the principal investigator on MJD.

Once in the US, the germanium is formed into single-crystal detectors, measuring about 60 mm across and weighing about a kilogram. If a neutrino-less double-beta decay were to occur in one of these crystals, the energy from the two emitted electrons – around 2 MeV – would produce multiple ionizations that would be detectable as a current pulse in the contact pin placed at the base of each detector. In total, the project plans to have 30 kg of enriched-germanium detectors and 10 kg of natural-germanium detectors, which will be stacked in strings inside liquid-nitrogen cryostats.

When fully up and running, the whole assembly will be tucked into six layers of shielding. The outer three layers will consist of an aluminum box to keep out radon, "veto panels" that identify any residual cosmic-ray muons, and polyethylene sheets to slow any incoming neutrons. Inside will be a 45 cm-thick "castle" made of carefully stacked lead bricks that block gamma rays, while the final two layers are 5 cm-thick copper shields. Being so close to the detectors, the innermost copper shield – as well as detector mounts and cryostat containers – are being made with ultrapure copper that is grown underground in a separate clean room at SURF. The project's special electroforming process – in which dissolved copper ions deposit on a large stainless-steel electrode – reduces radioactive contaminants, such as uranium and thorium, to one-tenth of the levels in conventionally formed copper.

It takes about 14 months to grow the 14 mm-thick cylindrical copper sheets used to make the shield walls. But rather than cart the copper back up above ground for machining, the project has built an underground clean-room machine shop next to the main lab to avoid any stray cosmic rays hitting the copper to produce radioactive cobalt-60. "Our effort to manufacture such a large fraction of our parts underground is a first," says MJD spokesman Steve Elliott of the Los Alamos National Laboratory.

A prototype of the MJD – without enriched germanium or electroformed copper – started taking data at the end of June. The team plans to install the first set of enriched detectors at the end of this year, and the rest towards the end of 2015. The eventual goal is to cut radiation backgrounds to a level of one count per tonne per year in the energy region of interest. Such a demonstration would then help justify building the next-generation experiment – a one-tonne germanium detector that would be large enough to test a viable model for the neutrino mass distribution.

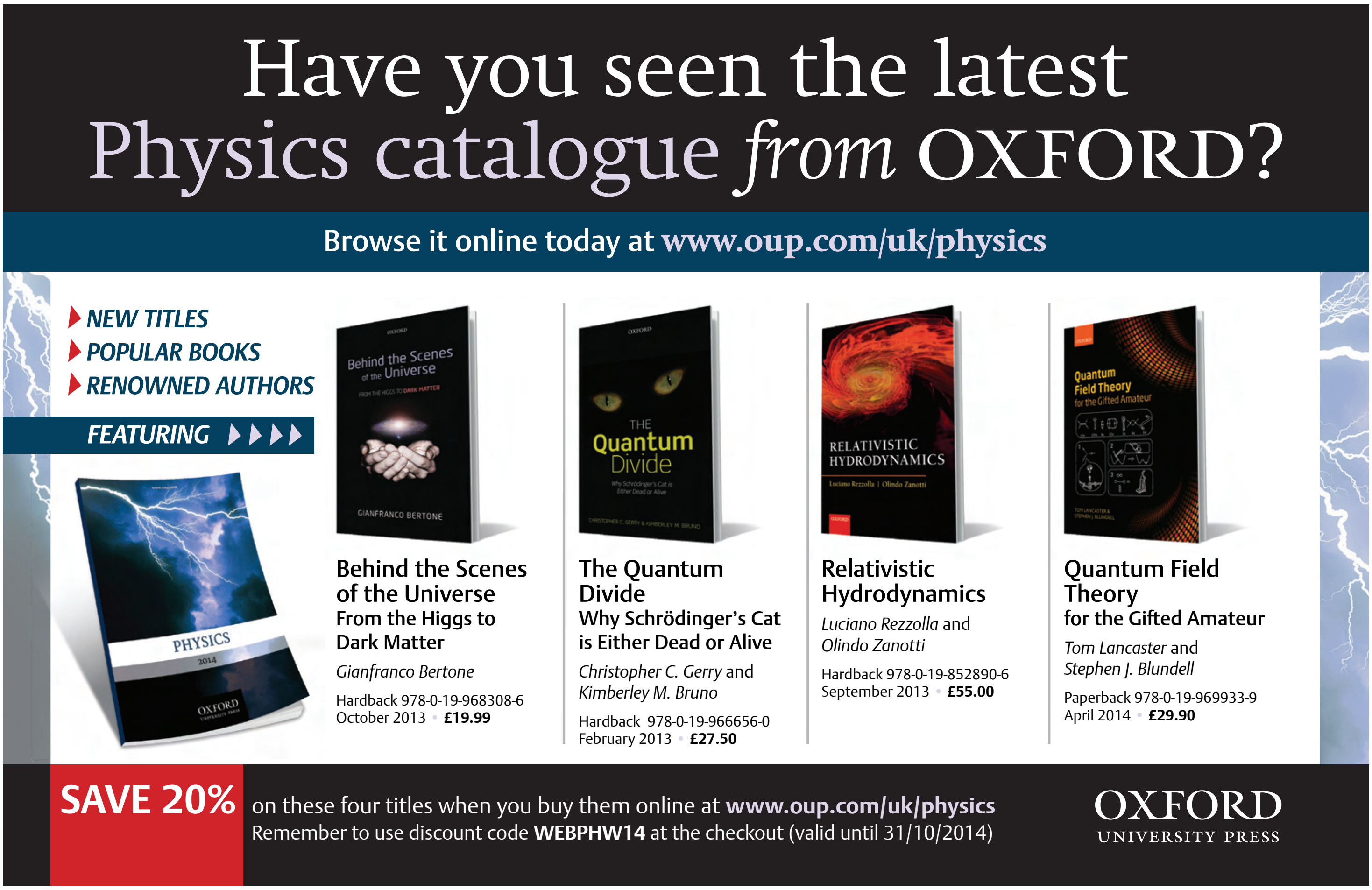
It might seem strange to build detectors that will likely remain silent for months or even years but then again no signal would be a result in itself. "We learn about the science questions that we are interested in regardless of whether we see a signal," Elliott says. "So we don't get bored."

Heading deep underground in search of neutrinos

The Majorana Demonstrator (MJD) is located 1478 m underground at level 4850 in the Sanford Underground Research Facility, which is in the old Homestake mine of the Black Hills in South Dakota. A visit to the experiment requires donning a hard hat and overalls, and then climbing into one of the "cages" that miners previously used to get to work. The 10-minute descent down the 70-year-old shaft is cold and dark, with the only light coming from a few headlamps. The cage is also open, allowing water flowing down the shaft wall to splash on the dozen or so occupants.

At the bottom, the mining gear is traded in for a clean-room suit, and all electronic equipment is swabbed to remove any possible contaminants. The detector room, which is 10 m × 12 m and roughly 3 m high, has three interconnected glove boxes that are used to assemble the detector strings. To avoid any contamination when handling sensitive components in the glove box, the team members put a pair of latex gloves on top of the rubber gloves in the box. "Maintaining cleanliness underground is much harder than at the surface," says Cabot-Ann Christofferson, a chemist from the South Dakota School of Mines and Technology.

Clean and tidy Researchers work hard to avoid any kind of contaminant that could interfere with the sensitive measurements.

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