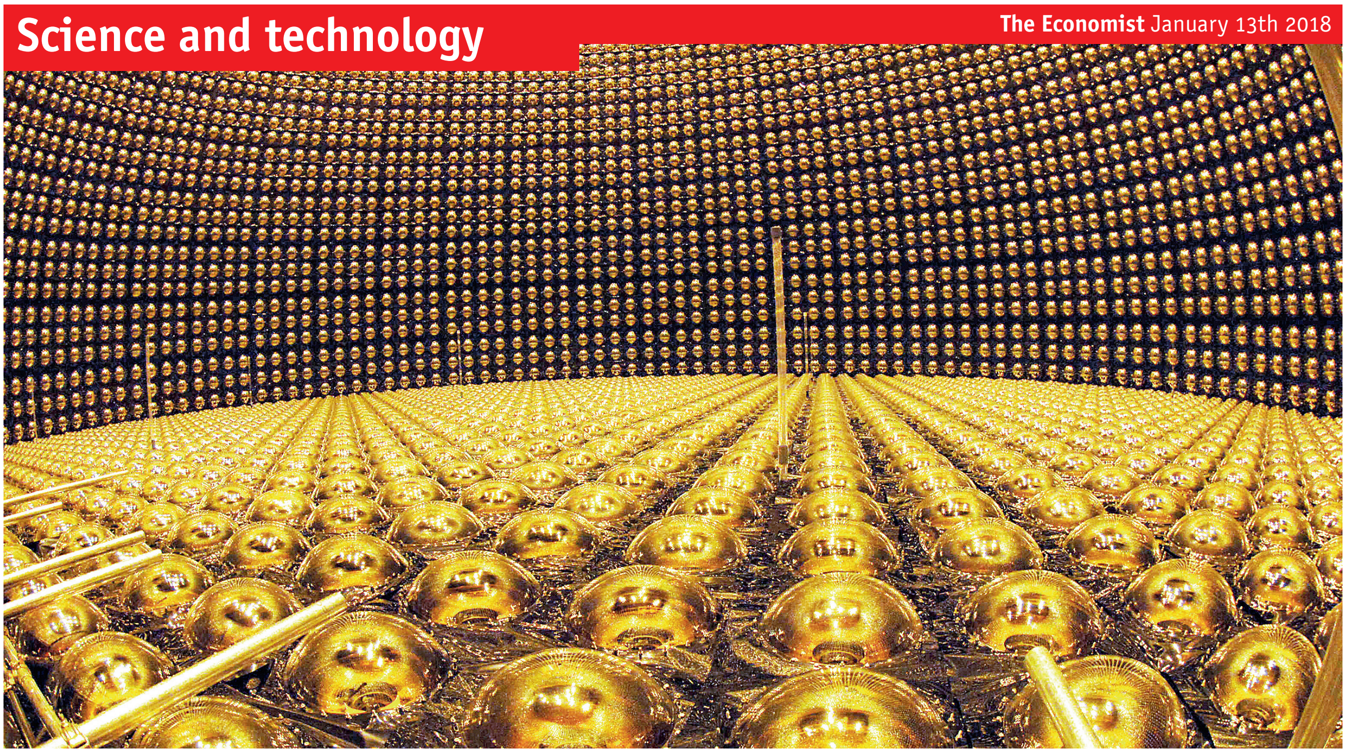

Particle physics

No GUTs, no glory

Fundamental physics is frustrating physicists

DEEP in a disused zinc mine in Japan, 50,000 tonnes of purified water held in a vast cylindrical stainless-steel tank are quietly killing theories long cherished by physicists. Since 1996, the photomultiplier-tube detectors (pictured above) at Super-Kamiokande, an experiment under way a kilometre beneath Mount Ikeno, near Hida, have been looking for signs that one of the decillion (10^{33}) or so protons and neutrons within it (of which a water molecule contains ten and eight respectively) has decayed into lighter subatomic particles.

That those tubes have, in the more than 20 years the experiment has been running, failed to do so is a conundrum for physics, and one that is becoming more urgent with every passing month. Grand unified theories (GUTs), thought since their genesis in the 1970s to be the most promising route to understanding the fundamental forces that bind matter together, predict that protons and neutrons should occasionally disintegrate in a way that breaks what was previously regarded as an iron law of physics—namely that the number of baryons (a class of particle that includes both protons and neutrons) in the universe is constant.

The crucial word, though, is "occasionally". If the GUT approach is right, the average decay time in question is far longer than the age of the universe itself. But by corralling huge numbers of baryons together, the people behind Super-Kamiokande hoped to spot one decaying much sooner, in just a few years. Those hopes have been dashed. The detector's most recent estimate, published in January 2017, now pegs the lifetime of a proton at more than 1.6 x 10^{34} years—and rising. That rules out simpler GUTs (including the first, called SU(5), proposed by Howard Georgi and Sheldon Glashow in 1974). It also encroaches on the predictions of more recent, and more complex, varieties such as "flipped SU(5)".

In the dark

GUTs are among several long-established theories that remain stubbornly unsupported by the big, costly experiments testing them. Supersymmetry, which posits that all known fundamental particles have a heavier supersymmetric partner, called a sparticle, is another creature of the seventies that remains in limbo. ADD, a relative newcomer (it is barely 20 years old), proposes the existence of extra dimensions beyond the familiar four: the three of space and the one of time. These other dimensions, if they exist, remain hidden from those searching for them.

Finally, theories that touch on the composition of dark matter (of which supersymmetry is one, but not the only one) have also suffered blows in the past few years. The existence of this mysterious stuff, which is thought to make up almost 85% of the matter in the universe, can be inferred from its gravitational effects on the motion of galaxies. Yet no experiment has glimpsed any of the menagerie of hypothetical particles physicists have speculated might compose it.

Despite the dearth of data, the answers that all these theories offer to some of the most vexing questions in physics are so elegant that they populate postgraduate textbooks. As Peter Woit of Columbia University observes, "Over time, these ideas became institutionalised. People stopped thinking of them as speculative." That is understandable, for they appear to have great explanatory power. GUTs, for example, seek to merge three of the four known fundamental forces: the strong, weak and electromagnetic interactions (gravity is the fourth). In the process, they explain, among other things, the overwhelming preponderance of matter over antimatter in the universe, a puzzling observation called matter-antimatter asymmetry.

The Standard Model, the current best theory in particle physics, cannot do this. GUTs, on the other hand, posit various mechanisms by which subatomic particles (of both matter and antimatter) can fall apart and thus, in some way, allow matter to gain the upper hand. Unfortunately, most of these are untestable with current technology. Recreating the incredibly high energies at which the fundamental forces are thought to merge (those encountered during the early moments of the Big Bang) would require a particle collider larger than the solar system. Of GUTs' predic-

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tions, only the proton and neutron decay being sought by Super-Kamiokande seems testable. And, so far, the tests are negative.

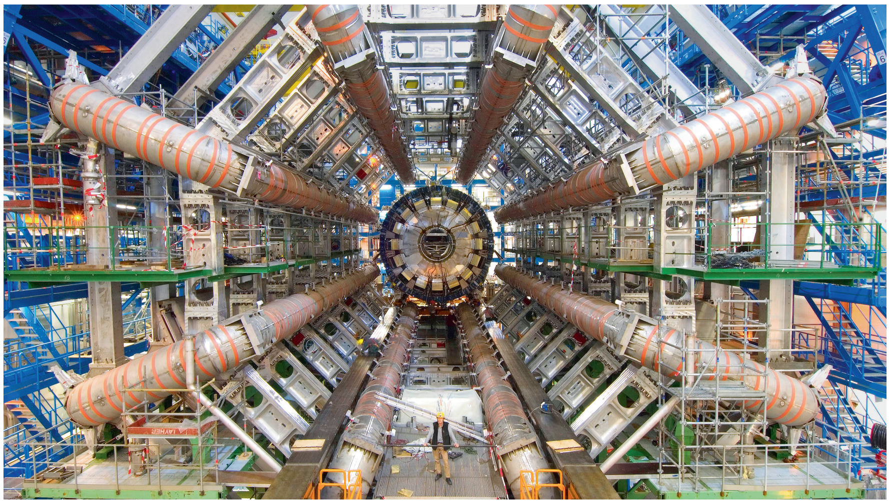
A similar story can be told for supersymmetry. This theory can, among other things, account for the value of the mass of the Higgs boson (a recently discovered particle that is responsible for imbuing other particles with mass) in a way that the Standard Model cannot. Nothing in that model gives a precise value for the Higgs's own mass, and calculations from first principles, based on quantum theory, suggest it should be enormous—roughly a hundred million billion times higher than its measured value. Physicists have therefore introduced an ugly fudge factor into their equations (a process called "fine-tuning") to sidestep the problem. Supersymmetry resolves it more neatly.

The problem arises because as a Higgs boson moves through space, it encounters "virtual" versions of Standard Model particles (like photons and electrons) that are constantly popping in and out of existence. According to the Standard Model, these interactions drive the mass of the Higgs up to improbable values. In supersymmetry, however, they are cancelled out by interactions with their sparticle equivalents.

Various flavours of supersymmetry predict that one or other of the sparticles should have popped up by now in the Large Hadron Collider. The LHC (one of the detectors of which is pictured above, under construction) is the principal machine at CERN, the world's biggest particle-physics laboratory, near Geneva. But of sparticles it has seen no sign.

The mass of the Higgs is one aspect of what is known as the hierarchy problem in physics. This is the riddle of why gravity is so much weaker than the other three fundamental interactions—as demonstrated by the fact that a fridge magnet can pick up a paper clip, and in so doing easily overcome the gravitational force of a whole planet. The connection with the Higgs-mass problem is that if the Higgs really was huge, that would also make other particles (protons, neutrons and so on) more massive, thus giving them much stronger gravitational fields. Whereas supersymmetry resolves the problem via sparticles, theories with extra dimensions (such as ADD) do so by allowing gravity, but not the other three fundamental forces, to spread through these dimensions. That dissipates gravity's strength in comparison with that of the other three.

This happens because gravitons (the hypothetical particles that carry the gravitational force) leak into those dimensions. If gravitons were created in the LHC, which some theories suggest is possible, then signs of such leakage could be sought. So far, though, no LHC-generated gravitons have turned up.



Watching the detectors

The dark-matter picture is more complex still. There are plenty of lines of evidence indicating the stuff exists, and many theories that propose this or that particle to explain what it might actually be. As its name suggests, dark matter is difficult to spot. Though it participates in gravitational interactions, it does not interact electromagnetically. This means it neither emits nor absorbs light. Nor does it get involved with the strong force—the one that holds atomic nuclei together. One class of hypothetical objects that might be dark matter do interact via the weak force, a phenomenon that also controls some sorts of radioactive decay. These objects are called WIMPS (weakly interacting massive particles). Exactly what they are remains obscure. Some sparticles would fit the bill, but there are other candidates. Several possible WIMPS, though, should be detectable by experiments that, like Super-Kamiokande, involve large tanks of liquid.

Tank warfare

In those experiments the preferred fluid is not water but liquid xenon, and the phenomenon being sought is not a spontaneous decay but an interaction between a WIMP and an atomic nucleus, which will generate a flash of light that can be detected by arrays of photomultiplier tubes at the top and bottom of the tank. Xenon is the darling of dark-matter hunters because it is a heavy element with a large nucleus. It is thus more likely to get hit than lighter atoms. It is also reasonably cheap, unreactive and easy to purify. So far, however, the xenon-filled vats have remained as dark as the matter they hope to find. Two of the world's three most sensitive xenon-tank experiments reported their latest results in October 2017. Searches by XENON1T, under Gran Sasso, a mountain in Italy, and PandaX-II at China Jinping Underground Laboratory, in Sichuan, which contain 3,500kg and 500kg of xenon respectively, came up empty-handed. The third of the trio, 368kg of xenon in an experiment called LUX, in a former gold mine in the Black Hills of South Dakota, also failed to find WIMPS before it was shut down in May 2016.

These WIMP searches have become progressively larger over the past two decades. XENON1T, for instance, was preceded by two detectors, XENON10 (15kg) and XENON100 (165kg), the first of which started work in 2006. LUX will be followed by LUX-ZEPLIN, which will use 7,000kg of the stuff. In China, PandaX-4T (4,000kg) is already being built and there are tentative plans for a whopping 30,000kg detector (PandaX-30T). Even something of that size, though, would not altogether rule out WIMP-based hypotheses were it to find no evidence of WIMPS. The nature of the models means that they can be tweaked almost endlessly.

The history of the search for proton decay, meanwhile, goes back even further. The first experiment to be built to look for it in the mine that now hosts Super-Kamiokande was called KamiokaNDE, and used a piddling 3,000 tonnes of water for the purposes of detection. That was in 1983. Hyper-Kamiokande, Super-Kamiokande's successor, should be ready to go in 2026. It will survey an astonishing 500,000 tonnes of water (ten times that of its predecessor) for 20 years or more, pushing the minimum average lifetime of a proton up to 10^{35} years if it fails to find one.

Persistence in the face of adversity is a virtue, of course. And, as all this effort shows, physicists have been nothing if not

The Richard Casement internship

We invite applications for the 2018 Richard Casement internship. We are looking for a would-be journalist to spend three months of the summer working on the newspaper in London, writing about science and technology. Applicants should write a letter introducing themselves and an article of about 600 words that they think would be suitable for publication in the Science and Technology section. They should be prepared to come for an interview in London or New York. A stipend of £2,000 a month will be paid to the successful candidate. Applications must reach us by January 26th. These should be sent to: casement2018@economist.com persistent. Yet it is an uncomfortable fact that the relentless pursuit of ever bigger and better experiments in their field is driven as much by belief as by evidence.

The core of this belief is that Nature's rules should be mathematically elegant. So far, they have been, so it is not a belief without foundation. But the conviction that the truth must be mathematically elegant can easily lead to a false obverse: that what is mathematically elegant must be true. Hence the unwillingness to give up on GUTs and supersymmetry. New theories have been made by weaving together aspects of older ones. Flipped SU(5), for example, combines GUT with supersymmetry to explain the Higgs mass, the hierarchy problem and matter-antimatter asymmetry—and provides dark-matter candidates to boot. With every fudge applied, though, what were once elegant theories get less so. Some researchers are therefore becoming open to the possibility that the truth-is-beauty argument is a trap, and that the universe is, in fact, fundamentally messy.

The beauty myth

One such is Sabine Hossenfelder of the Frankfurt Institute for Advanced Studies, in Germany. She argues that the appeal of GUTs, supersymmetry and the like rests on their ability to explain "numerological coincidences" that do not need to be explained. Perhaps, to take one example, the universe simply started out with more matter than antimatter in it, rather than this being a consequence of its subsequent evolution. As she points out, no theory precludes this possibility—it is just that it is not very elegant. Similarly, she says, "It's not like anybody actually needs supersymmetry to explain anything. It's an idea widely praised for its aesthetic appeal. Well, that's nice, but it's not science."

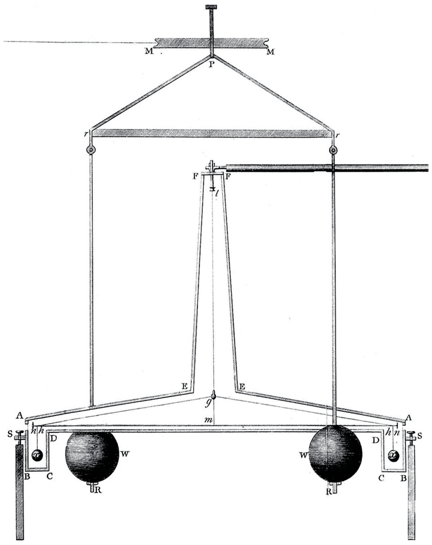
Dr Hossenfelder's remains a minority opinion, but other heterodox approaches, perhaps because they offer the possibility of experimental testing, are also gaining ground. Surjeet Rajendran of the University of California, Berkeley, for example, is using a "suck it and see" method that would have been familiar to 19th-century physicists, who did not yet have a huge body of theory to guide and constrain their experiments. He is searching for dark-matter particles outside the range of masses that conventional theories of what WIMPs are predict.

That he and his colleagues are able to do so is, in part, because their apparatus is small and cheap—and thus worth a punt by a grant committee. At its core lies a sensitive magnetometer, known as a SQUID. This should pick up the tiny magnetic fields that dark-matter particles would be expected to generate indirectly by weak-force interactions with atomic nuclei as they fly through the apparatus. As Dr Rajendran's experiments are carefully shielded, only such particles, with their extraordinarily weak interactions with normal matter, would be expected to enter the apparatus and be detected.

Other teams, working within the limits of conventional-but-as-yet-unproven theory, have similarly economical, collider-eschewing ideas. ADD and other, related, ideas predict that extra dimensions are populated by non-Standard Model particles. Tiny objects, held less than a tenth of a millimetre apart, should experience forces transmitted by these particles in ways detectable by bench-top apparatus. Such forces would, for instance, cause the gravitational attraction between the objects in question to deviate from Newton's inverse-square law, which states that the gravitational force between two bodies is inversely proportional to the square of the distance between them.

Andrew Geraci and his team at the University of Nevada, in Reno, hope to find such deviations by tracking the movement of a glass bead just 300 billionths of a metre across, cradled in a network of laser light. Similarly, Eric Adelberger of the University of Washington, in Seattle, is employing a torsion balance, a piece of kit invented over 200 years ago for the purpose of measuring weak forces (Henry Cavendish, a British natural philosopher of the 18th century, used one, illustrated below, to work out the density, and therefore the mass, of Earth). A number of other groups are searching for the effects of these forces within molecules that consist of just two atoms. Any extradimensional forces experienced by the atoms will translate into minute differences between the energy levels of their electrons. Such differences can, in turn, be probed spectroscopically by using a laser to excite the electrons and measuring the wavelengths at which they then emit light.

Advances in laser physics of this sort are also behind ACME, an experiment occupying about 100 square metres of laboratory space at Harvard University. ACME is looking for the sparticles of supersymmetry. But it is doing so indirectly, by monitoring their putative effects on the properties of single electrons with incredible accuracy. The electrons being looked at are inside molecules of thorium monoxide, which has some unique properties that make it suited to the search.



How they used to do it

According to the Standard Model, an electron's charge is spherically distributed. Interactions with sparticles, however, would deform this sphere in a way that would create a slight positive charge in one place and an equal, negative charge opposite it. When placed in an electric field, this deformed electron would experience a force called a torque that would cause it to rotate. The stronger the field, the more torque there would be. There is a particular electron in a molecule of thorium monoxide that is exposed, by its location between the thorium and oxygen atoms, to an electric field of 100 gigavolts per centimetre—a million times greater than anything that can be produced in a laboratory. That would magnify the torque on a distorted electron to the point where it should be detectable with lasers.

In 2014 the group behind ACME published work showing that the electrons they were looking at had properties in line with those predicted by the Standard Model. At the sensitivities they were able to achieve, that ruled out interactions with the sorts of sparticles that might have been created at the LHC. ACME has been souped up since. David DeMille of Yale University, one of the physicists behind the project, says the collaboration will be publishing its next round of measurements within months, pushing into territory the LHC is not powerful enough to explore.

So far, though, the small-is-beautiful approach has been no more successful than the big colliders in coming up with new phenomena. Most physicists therefore want to double down, construct an even bigger collider and hope something interesting emerges from that. Whether politicians and taxpayers will be up for this remains to be seen. That fundamental physics has got as far as it has is, essentially, a legacy of its delivery to political leaders of the mid-20th century of the atom and hydrogen bombs. The consequence of this was that physicists were able to ask for expensive toys—for who knew what else they might come up with. That legacy has now been spent, though, and any privilege physics once had has evaporated. This risks leaving in permanent limbo not only the GUTs and their brethren, but also the sceptical idea of Dr Hossenfelder that the Standard Model really is all there is. And that would surely be the most depressing result of all. ■