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Physics

We may be about to solve the greatest riddle of electromagnetism

Physicists have long wondered why particles can only have an electric charge of +1, -2 or any whole number. Now we increasingly suspect that, actually, that's not true after all

By Jacklin Kwan

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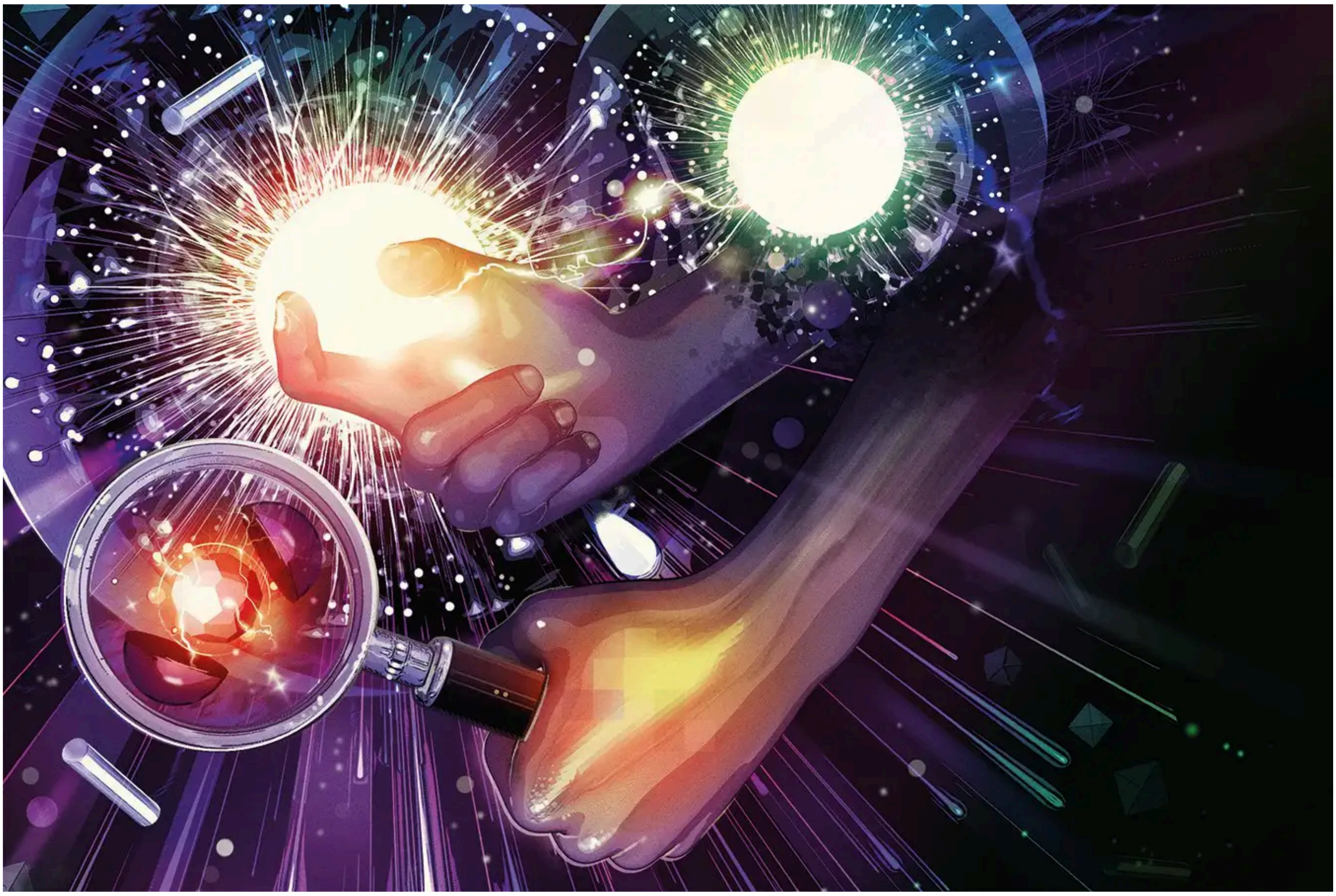
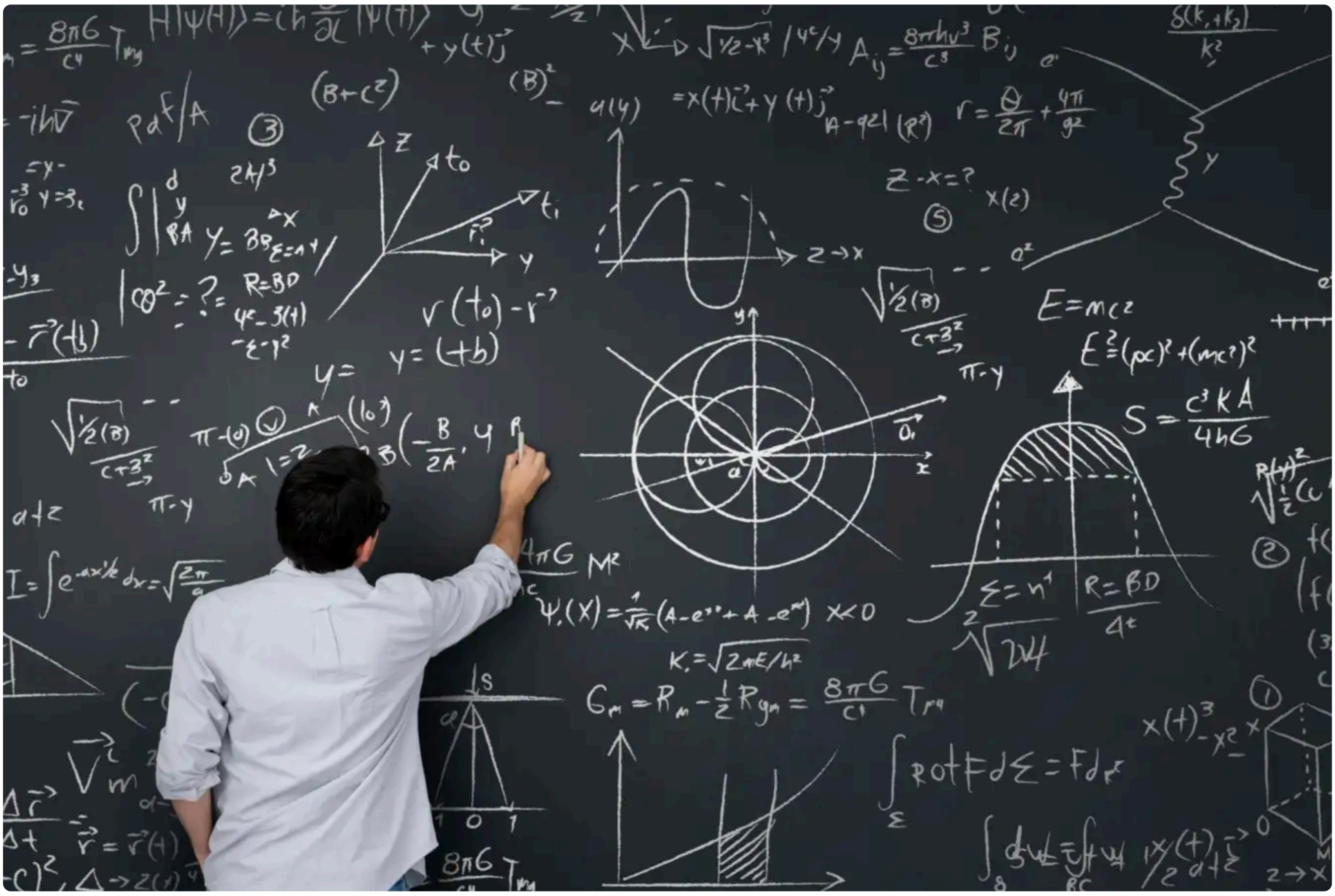


Chris Malbon

Most of us don't think much about electric charge, apart from in those annoying moments when our phones run out of it. But for physicists, it is a big deal. In every atom, negatively charged electrons orbit a nucleus containing positively charged protons, with the whole dance sustained by their mutual attraction. It would be fair to say, then, that charge is about as fundamental as it gets.

This explains why physicists have long been at such pains to understand its nature, and for the most part they have been successful. But there is one question that has always hung in the air, unanswered. It seems that the smallest possible unit of charge is that of an electron – all other naturally occurring particles only have multiples of this. In nature, you can find charges of −1 or +3 or −2, but never 0.25. Why is this?

You might shrug and say that is just how the universe is. But in truth, there have always been good reasons to suspect that fractional charges do exist, even if we haven't caught one yet. And it is a particularly live issue today thanks to fresh insights from string theory, one candidate for a theory of everything.



The laws of physics appear to follow a mysterious mathematical pattern

The symbols and mathematical operations used in the laws of physics follow a pattern that could reveal something fundamental about the universe

🔗 /article/2452341-the-laws-of-physics-appear-to-follow-a-mysterious-mathematical-pattern/

Now, experiments are beginning at the CERN particle physics lab near Geneva, Switzerland, to hunt for particles that could have charges just thousandths that of an electron. If they can find them, it would be an Earth-shattering discovery. "It is no exaggeration to say that observing millicharges would be like the Copernican revolution all over again," says theoretical physicist Jonathan Feng 🔗 http://www.ps.uci.edu/~jlf/ at the University of California, Irvine.

When physicists say that molecules, atoms and particles can only have charges that come in integer values, they mean whole multiples of the elementary charge (1.6×10^{-19} coulombs, for those taking notes). This is the charge attached to two of the basic constituents of atoms: electrons and protons (the former being negative, the latter positive). So naturally, when atoms or molecules gain or lose electrons in chemical reactions, they build up charge in correspondingly discrete quantities.

But these waters run much deeper than that. The standard model of particle physics 🔗 /article/mg25934553-600-a-brief-history-of-the-standard-model-our-theory-of-almost-everything/ sets out our best account of the particles that make up reality. Glance at this and you see that, although not all particles have an electric charge, those that do tend to follow the same pattern. For instance, the muon and tau have a -1 charge and the W boson can be +1 or -1.

Yet there are three reasons to think this isn't the end of the story. First, we know for a fact that the standard model doesn't cover everything, not least because it is silent on the topic of dark matter, a substance we are pretty sure exists, but can't identify.

Second, there is a caveat to all the above in that quarks, another fundamental particle of matter, buck the trend. They have a charge of either +2/3 or -1/3, but are never found in isolation, only in pairs or triplets arranged so that their cumulative charge is always a whole number. This shows that fractional charge isn't strictly impossible – which prompts the question of whether there could be other examples out there.

Magnetic monopoles

Third, there is the work of theoretical physicist Paul Dirac 🔗 /article/mg20126905-400-review-the-hidden-life-of-paul-dirac-by-graham-farmelo/ nearly 100 years ago, which provides a further hint that there is something strange going on with charges. To get your head around it, you need to know that physics paints electric charge and magnetic "charge" as two intimately related phenomena – indeed, electricity and magnetism both arise from the same force, electromagnetism. In nature, electric charges always occur separately, as positive and negative, but magnetic charges – what we call north and south – apparently always appear together.

Or do they? In 1931, Dirac was thinking about a hypothetical object, a so-called magnetic monopole, which is like a north magnetic charge without its south counterpart (or vice versa). He started by assuming these existed in the form of a particle and, using the newly invented framework of quantum mechanics, he explored how such a particle would behave 🔗

https://royalsocietypublishing.org/doi/10.1098/rspa.1931.0130 in the presence of an electric field. He found that, for the maths to work properly, electric charge would have to come in certain fixed quantities. In other words, if magnetic monopoles were to exist, they would offer a mathematical rationale for why electric charge must come in certain fixed quantities. Crucially, the strength of the magnetic charge of the monopole matters: the stronger it is, then the smaller the fundamental unit of electrical charge would be.

The FORMOSA experiment during installation at CERN
FORMOSA Collaboration

To be clear, we have never found a monopole, despite decades of searching, /gallery/monopoles/ involving everything from antennas in Antarctica to meteorites. And that leaves us with a puzzle. Either monopoles really don't exist, in which case we are back to square one and we don't know why electric charge should come in fundamental units, or perhaps they do exist, but they are just so rare or so massive that they are only produced in the most energetic particle collisions, making them devilishly hard to detect. In any case, there remains the possibility that particles with extremely tiny charges are out there, waiting to be discovered.

Where string theory comes in

One idea that has long pointed in this direction is string theory, the hypothetical framework that sees the fundamental ingredients of reality as one-dimensional "strings" that vibrate in 10 or more dimensions. These extra dimensions would be "compactified", or scrunched up very small, and this could happen in many different ways. Back in 1985, theorists Edward Witten and Xiao-Gang Wen repeated Dirac's analysis in the context of string theory. What they found was surprising. Depending on the specific flavour of string theory, the strength of a magnetic monopole could be five times larger than that originally predicted by Dirac when he assumed that electrons were the most elementary electric charge.

Remember the relationship between electric charges and monopoles? The bigger the monopole, the smaller the fundamental charge. On further inspection, Witten and Wen found that charges five times smaller than that of the electron could be stable. They would exist as strings wrapped around a "hole" in all these extra dimensions of space and time. "Magnetic monopoles, if we could find them, would be very informative about fundamental physics, and I think most theoretical physicists who have thought about it seriously believe they do exist," says Witten. He reckons we may not see them today because of the way the universe expanded rapidly after they were created at the beginning of time, drastically diluting the concentration of monopoles in space.

Stephen Hawking's final theorem turns time and causality inside out

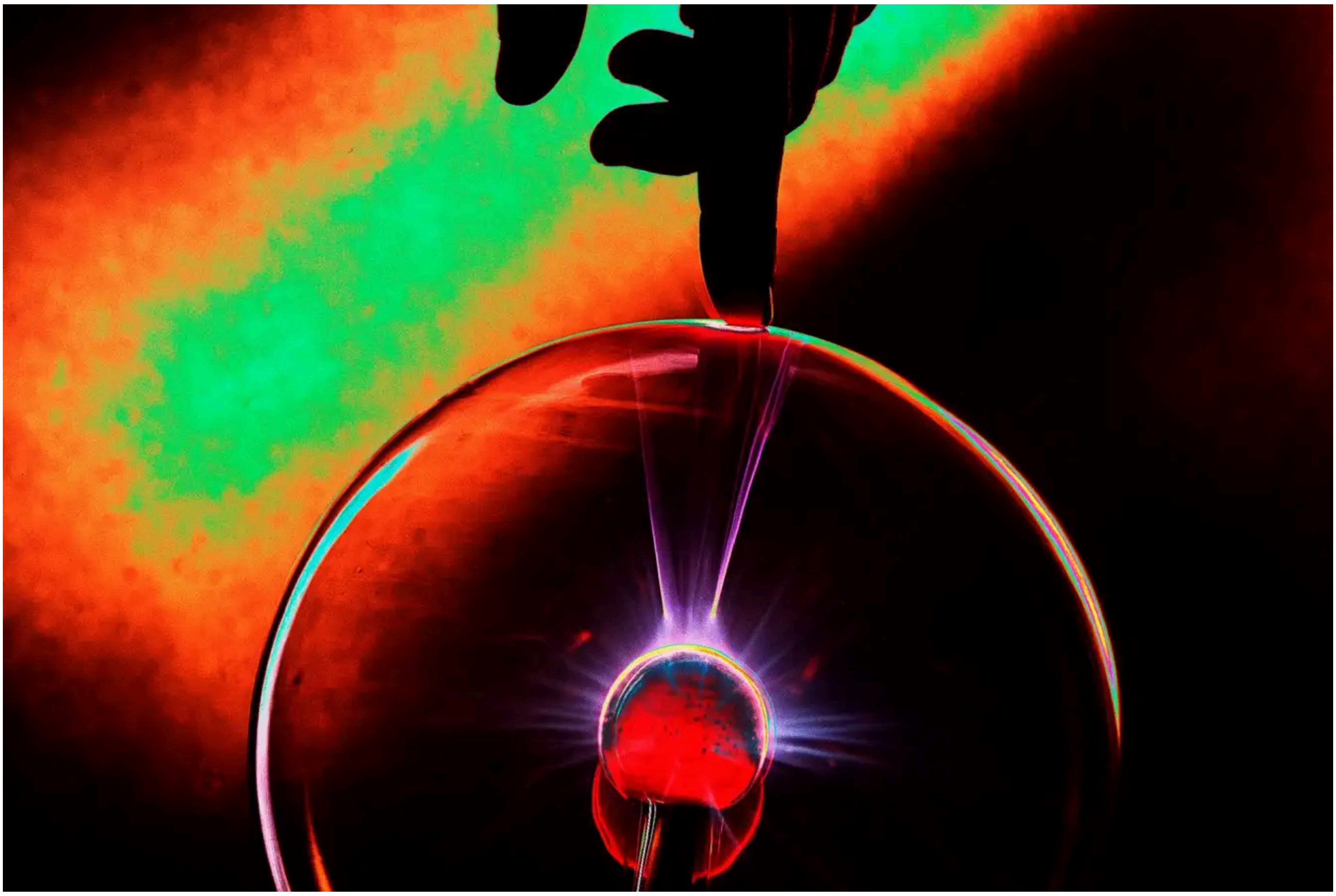
In his final years, Stephen Hawking tackled the question of why the universe appears fine-tuned for life. His collaborator Thomas Hertog explains the radical solution they came up with

🔗 /article/mg25734310-200-stephen-hawkings-final-theorem-turns-time-and-causality-inside-out/

More recently, other string theorists have been exploring the possibility of particles with even smaller charges. These "millicharged" particles would have an electric charge equal to perhaps thousandths or even millionths of an electron's. This idea originates from a new way of thinking about dark matter. Years ago, physicists hypothesised that this mysterious substance might be made of a single type of new particle, often nicknamed a WIMP, for weakly interacting massive particle. But since searches for these have come up empty-handed, many physicists now suspect dark matter might be composed of a whole suite of different particles – a "dark sector" – much as regular matter is.

What could these dark sector particles consist of? Well, according to a handful of recent simulations 🔗 https://journals.aps.org/prd/pdf/10.1103/PhysRevD.100.123011, some of them could be millicharged particles. "The amazing thing is that if you put in particles that are not as heavy as the Higgs boson, but are more like the proton or something lighter, and, at the same time, you make them millicharged, you also get the right amount of dark matter," says Feng.

Experimental hunts for fractionally charged particles date back 30 years, for example at the Stanford Linear Accelerator Center in California. But the new theoretical developments have reignited the chase and a clutch of new detectors are being built and tested, many aiming to snare particles with even the slightest whiff of charge. "Searches have gained a lot of steam recently because there's now this connection to new ideas in string theory: dark sector theories," says Feng.



Electric charge is even more mysterious than it looks
Creative collection tolbert photo/Alamy

If millicharged particles do exist, it should be possible to conjure them up using the tried and tested method that yielded the Higgs boson. That involves smashing protons together at incredible speed and hoping that millicharged particles are produced in the debris. This explains why most of the new detectors are being built at CERN, with its Large Hadron Collider (LHC) particle accelerator. These detectors use various arrays of supersensitive scintillators, materials that give off light when hit by charged particles.

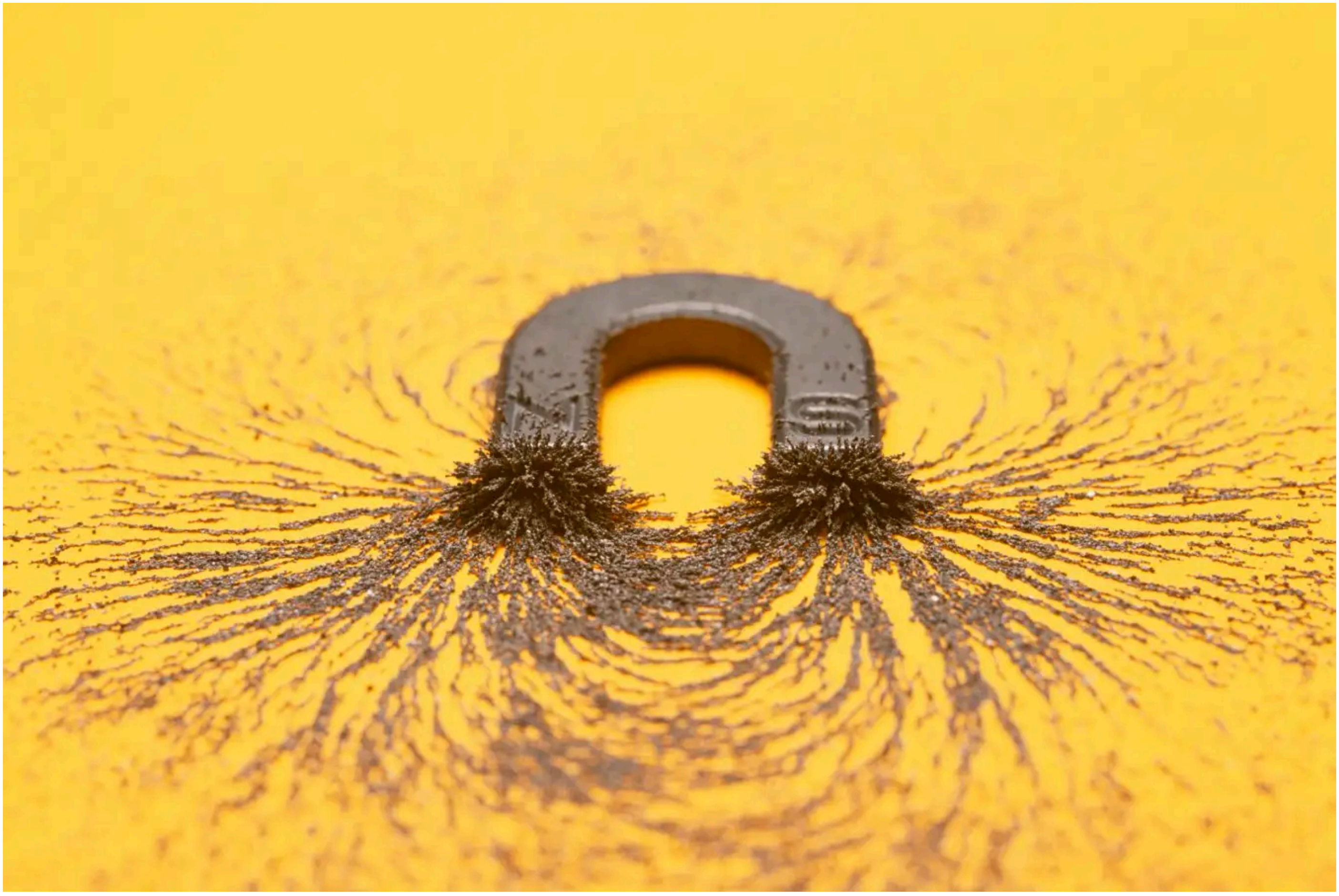
The first detector to be constructed at CERN sprang from an experiment called MoEDAL, originally designed to hunt magnetic monopoles. An extension to this experiment capable of spotting millicharged particles, called the MoEDAL Apparatus for Penetrating Particles (MAPP 🔗 https://home.cern/science/experiments/moedal-mapp), was installed in 2023 and it began taking data earlier this year. James Pinfold, spokesperson for the experiment, says: "If you sort of buy the argument that there should be monopoles, then, in a sense, you're going to buy the argument for millicharges."

Hunting 'millicharges at CERN'

Hot on its heels is another detector called milliQan 🔗 https://u.osu.edu/milliqan/, which has just finished a set of upgrades in 2024, after it first began taking data in

2018. It is above ground, unlike MAPP, which is shielded from interfering cosmic rays by being 100 metres underground. Because of this, milliQan relies on artificial shielding made of concrete and lead. The two experiments are tuned to search for millicharged particles in different mass ranges and with different lifetimes, with milliQan able to detect particles with charges as small as a few per cent that of an electron. MilliQan had a few test runs that prove its parts were working, and improved data runs are continuing at the moment.

Then there is the FORMOSA experiment 🔗 https://fpf.web.cern.ch/node/79, which has just begun prototyping its CERN detector this year. Physicist Yu-Dai Tsai at the University of California, Irvine, who proposed FORMOSA, says it is also complementary with milliQan and MAPP, searching for particles with different masses and at different electric charge ranges. All use techniques to screen out the noise made by other charged particles that we know of, such as muons.



Magnetism is deeply linked with electricity
Cordelia Molloy/Science Photo Library

CERN doesn't have a monopoly on these hunts, though. Other scintillator-based experiments include LANSCE-mQ at the Los Alamos National Laboratory, New Mexico, which is due to begin construction in 2025, and the SUB-Millicharge ExperimenT (SUBMET) at the Japan Proton Accelerator Complex, which has recently begun taking data. Compared with the experiments that Feng witnessed while he did his PhD decades ago, the recent efforts have improved sensitivities by a factor of 10 or more. "These new searches are a very different kind than the ones that have been going on for decades," says Feng.

Millicharges would give us a vital clue to the temperature of the early universe

We haven't found any millicharges or fractionally charged particles yet, but doing so could have ramifications that go way beyond particle physics, and indeed back to a mysterious phase of the early universe. We think that, very shortly after the big bang, the universe blew up in size at an astonishing speed, through a process called inflation. However, this would have left it far emptier than it is now, so theorists reckon some of the energy causing the inflation must have been converted into a flood of particles. This energy-to-particles period is known as "the reheating epoch" and, in line with that name, it would have had a characteristic temperature. According to some dark sector models and string theory, the particles that sprang from this event would have included all the familiar ones from the standard model, plus millicharges and monopoles.

Can we solve quantum theory's biggest problem by redefining reality?

With its particles in two places at once, quantum theory strains our common sense notions of how the universe should work. But one group of physicists says we can get reality back if we just redefine its foundations

🔗 /article/mg26335070-700-can-we-solve-quantum-theorys-biggest-problem-by-redefining-reality/

Despite it being a critical period in cosmological history, there is no experimental benchmark for what this reheating temperature ought to be, which is a big problem. The temperature at which the universe reheated determines how hot and dense conditions were right after inflation and how much energy was available to create the particles around us. The reheating temperature, therefore, affects the very abundance of matter and radiation that eventually evolved into galaxies, stars and planets. That, according to Tsai and his colleague Xucheng Gan at New York University 🔗 https://arxiv.org/abs/2308.07951, is where these millicharges could give scientists a vital clue – their masses would be dependent on the reheating temperature, so finding them would give us a way of looking back at that temperature.

There may – if we are very lucky – be a sneaky shortcut in the hunt for fractionally charged particles. Thanks to the subtle connection between millicharges and monopoles, if we were to find the latter, that might enable us to infer something about the existence of the former. True, we have already been searching unsuccessfully for monopoles for decades – but there is now a surprising new way to seek them.

Conjuring up a virtual monopole

Nick Mavromatos 🔗 https://www.kcl.ac.uk/people/nick-mavromatos at King's College London and several colleagues working on the MoEDAL experiment recently came up with this new tactic. Instead of using MoEDAL to hunt for monopoles produced in particle collisions, the team would conjure one of these lonely poles from thin air. The idea quite isn't as wild as it might sound. Quantum physics teaches us that empty space is fizzing with pairs of virtual particles and antiparticles, which fleetingly pop into existence before mutually annihilating. But pump enough energy into a vacuum and these particles can be forced apart and made real through what is known as the Schwinger mechanism.

To produce a monopole in this way, "pumping in enough energy" means applying an extremely strong magnetic field. And the team realised that they already have exactly this at their fingertips: particular collisions at CERN's accelerators involving lead ions produce very large fields. "These are the strongest magnetic fields in the known universe," says Mavromatos. He and the team reasoned they might be powerful enough to coax a virtual monopole from out of the void.

Earlier this year, Mavromatos and his colleagues published a report on just such an experiment 🔗 https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.133.071803. By this point, you will hardly be surprised to hear that they didn't snare a monopole. But the team plans to try again when the LHC gets a planned upgrade, hopefully by 2030, which would make the approach sensitive to even tinier charges. It may seem disappointing, but then again, what is another few years when we have already been hunting these strange charges for a century?