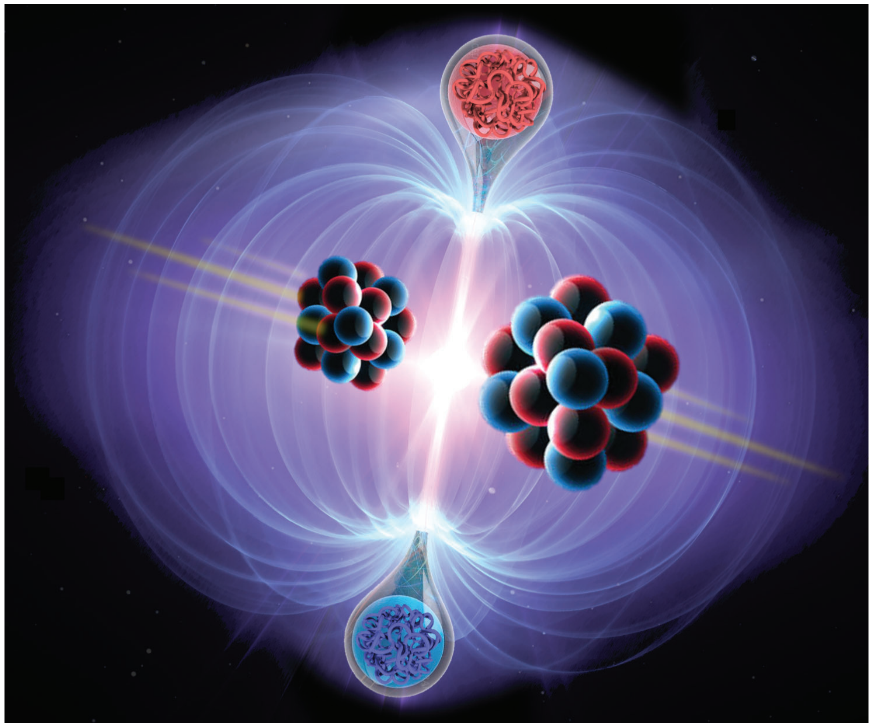
A new search for magnetic monopoles

The latest results from CERN's Large Hadron Collider have established a lower mass limit for the elusive hypothesized particle.



THE COLLISION of two lead nuclei generates an exceptionally strong magnetic field. Magnetic monopoles and their antiparticles are theorized to be produced from the decay of that magnetic field, although they have yet to be observed. (Courtesy of James Pinfold, MoEDAL collaboration.)

A magnet always has a north and a south pole. But nothing in classical electrodynamic theory or quantum mechanics says that magnetic monopoles can't exist. They're the hypothetical analogues to electric charges in Maxwell's equations. In fact, their existence would make the equations more symmetrical: Electric terms could be transformed to magnetic ones, and vice versa (see the article by Arttu Rajantie, PHYSICS TODAY, October 2016, page 40).

Magnetic monopoles could be point-like fundamental particles that carry magnetic charge, similar to electrons and described in 1931 by Paul Dirac.[1] Or they could be composite particles with a substructure, similar to neutrons or protons, as predicted by string theory, grand unified theories, and other explanations for physics beyond the standard model. Observing magnetic monopoles would provide evidence in support of such theories. And unlike the Higgs boson and other particles generated in collider facilities, monopoles are thought to be stable. Experimentalists could, therefore, track and manipulate them, potentially for specialized technologies.

The search for magnetic monopoles has so far come up empty. Although the now-defunct Tevatron, the Large Hadron Collider (LHC), and other particle accelerators were built mostly to study short-lived particles, researchers have used those facilities to search for magnetic monopoles. Elementary-particle collisions produce energies that are, theoretically, sufficient to produce monopoles with masses as high as a few trillion electron volts.

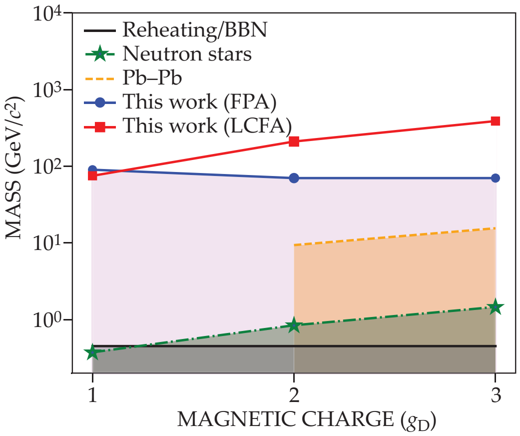
At collider facilities, the search has focused predominantly on monopole production via photon fusion or the Drell–Yan mechanism, in which the energy from the annihilation of a quark–antiquark pair is transformed to produce a point-like monopole and its antiparticle. Researchers might then detect a monopole by measuring the current it would generate in a superconducting ring, observing its strongly ionizing damage on a detector plate, or identifying signs of nucleon decay that would occur if a neutron or proton were to make contact with a monopole.

To make sense of collider measurements, researchers must have accurate estimates of the theoretical monopole production rate and momentum distribution. Otherwise, there's no concrete way to interpret whether the absence of a monopole signal is because of a low production rate or because monopoles don't exist.

The problem, however, is that point-like and composite monopoles are expected to strongly couple to photons. That interaction has prevented researchers from using perturbation theory to reliably calculate their production cross sections, a measure of the likelihood of two particles interacting and subsequently generating the hypothesized monopoles (see PHYSICS TODAY, July 2006, page 16).

Another difficulty for detecting composite monopoles produced from elementary-particle collisions is that they're exponentially suppressed by a factor of $e^{-4/\alpha}$, where α is the electromagnetic fine-structure constant and has a value of about $1/137$. The suppression effectively makes monopoles unobservable and can be explained by an entropy argument: The probability of generating a coherent composite particle decreases dramatically as the number of objects in the system increases.

In 2018 the collaboration known as MoEDAL—the Monopole and Exotics Detector at the LHC—pursued a different detection strategy. The collaboration looked for the production of monopoles from heavy-ion collisions. That mechanism isn't exponentially suppressed, and the theoretical calculations of the monopole production rate are reliable. The team has now published its results.[2] Al-



MASS LIMITS have been placed for magnetic monopoles after the latest search at the Large Hadron Collider (LHC). Researchers used observations and two theoretical approximations of monopole production—free-particle approximation (FPA) and locally constant field approximation (LCFA)—to confirm at the 95% confidence level that they must have masses greater than 75 GeV. The new mass-exclusion region exceeds that from a previous LHC experiment (dashed orange line) and theoretical efforts that have considered cosmic monopole production from neutron stars (dashed green line) and Big Bang nucleosynthesis, or BBN (solid black line). (Adapted from ref. 2.)

though no magnetic monopoles were observed, the collaboration excluded the possibility of monopoles with masses smaller than 75 GeV, roughly 80 times as large as the mass of the proton.

Heavy ions

Smashing particles into one another at a collider facility isn't the only way to produce magnetic monopoles. The Big Bang would have had the conditions necessary to produce a lot of them. But if that's the case, where did they all go? If they exist, the question seems to be answered by cosmic inflation: The exponential expansion of space that occurred during the 10^{-36} of a second after the Big Bang would have greatly diluted their density and prevented them and their antiparticles from annihilating each other.

But so-called intermediate-mass monopoles could have conceivably been produced at the end of or shortly after cosmic inflation. That possibility has motivated researchers to look for monopoles among regular cosmic rays. Many observatories have hunted for evidence of cosmic monopoles in particle tracks and electric current fluctuations for the past few decades[3] (for more on those observatories, see the letters by Ken Frankel and Christopher Harrison, PHYSICS TODAY, June 2017, page 13, and references therein). But those searches rely, of course, on a monopole traveling serendipitously through the facility's detector. The effort is akin to searching for a needle in a haystack.

Instead of elementary-particle collisions or astrophysical searches, the MoEDAL collaboration pursued a heavy-ion approach. The exceptionally strong magnetic fields created when heavy ions collide can give rise to the magnetic counterpart of the Schwinger mechanism, a vacuum-decay effect that produces electron–positron pairs in a decaying electric field.[4] Rather than electron–positron pairs, the decaying magnetic fields may create magnetic monopoles and their antiparticles. The particle production in both cases can be interpreted as quantum tunneling through the Coulomb-potential barrier. That mechanism, crucially, isn't limited by the exponential suppression of monopole production that plagues the elementary-particle-collision mechanism.

The second operational run of the LHC included a period of heavy-ion collisions in 2018. In anticipation of the MoEDAL experiment, Oliver Gould (now at the University of Nottingham), Arttu Rajantie (Imperial College London), and David Ho (now at MathWorks in Cambridge) developed a quantitative description of the production cross section and momentum distribution of monopoles that could be generated in lead–lead collisions at the LHC.[5]

Looking for monopoles produced via the Schwinger mechanism, rather than from elementary-particle collisions, meant that researchers could finally place mass limits on the hypothesized monopoles. Rajantie says that "the most important thing is that it's theoretically much easier to describe and to calculate how many monopoles you would actually expect."

Narrowing the search

In November 2018 a Pb–Pb collision at the LHC produced a magnetic field with a strength of 10^{16} T, the strongest ever observed in the universe. That's about 10 000 times as strong as magnetic fields found on the surfaces of neutron stars. To look for magnetic monopoles, the collaboration designed detector traps made from one ton of aluminum. The exceptionally large magnetic dipole moment of aluminum nuclei allows them to catch particles carrying a magnetic charge.

A DC superconducting quantum interference device (SQUID) then scanned the trapping volumes for the presence of magnetic charges. The signal for a monopole would be marked by the start of a steady current, whose value would depend on the magnetic charge of the monopole as it passed through the SQUID's coil. The current would continue to flow after the monopole had passed.

The researchers used two complementary methods with uncorrelated uncertainties to estimate the production cross section of magnetic monopoles in the LHC run. The first approach—free-particle approximation—calculates the spacetime dependence of the electromagnetic field produced in the heavy-ion collision but neglects self-interactions between monopoles. The second approach—locally constant field approximation—derives an exact solution for the magnetic monopole self-interactions but ignores the spacetime dependence of the magnetic field.

The work, however, wasn't finished with the newly calculated production cross sections. "We still had to translate them into the expected number of monopoles seen by the MoEDAL detectors," says Igor Ostrovskiy, a professor at the University of Alabama and a member of the collaboration. Ostrovskiy's graduate student Aditya Upreti worked on the challenging task of incorporating the new theoretical inputs into MoEDAL's Monte Carlo simulations that estimated the number of expected monopoles.

"At some point we were not sure if we would be able to calculate the trapping efficiency for all cases we needed—as simulations, ran with the help of the CERN's powerful computing infrastructure, were already taking weeks with no end in sight," says Ostrovskiy. After he, Upreti, and their colleagues carefully optimized the simulations, the calculations were completed for magnetic monopoles with Dirac charge of 1–3 g_D. (g_D is the minimum allowed magnetic charge and is equal to one-half the elementary charge e.)

The figure on this page shows the

estimated mass-exclusion region at the 95% confidence level for monopoles as a function of magnetic charge. Ostrovskiy says, "I, for one, was hoping to find monopoles! But we were still happy to produce the exclusion limits, as reliable limits help guide the theoretical development."

Complementary detectors

Although the MoEDAL collaboration didn't discover magnetic monopoles, the study's approach produced the most reliable calculation to date of the probable production rate of monopoles in strong magnetic fields. Furthermore, the negative result narrows the range in which future experiments will look for magnetic monopoles.

The search continues this spring: The LHC's third run will harness a beam with higher energy and five times the luminosity of that in the 2018 run. The MoEDAL experiment will use an updated detector to look for magnetic monopoles with higher mass and magnetic charge. Joining the aluminum trapping detectors will be nuclear tracking detectors consisting of stacked plastic sheets. When a highly ionizing particle rips through the sheets, the damage zone it leaves behind can be etched with a hot sodium hydroxide solution. Then an optical microscope identifies the precise path the particle traversed.

Other highly ionizing particles from beyond the standard model can emerge from heavy-ion collisions and may have strong electrical charges too. "If we do see something, it's going to be a real battle getting people to believe it," says James Pinfold, a physics professor at the University of Alberta and the MoEDAL spokesperson. "That's why we have the two methods."

The double-detector approach would use the nuclear tracker to reveal a monopole's path, and the trap would unambiguously identify the magnetic charge. Pinfold says, "If we do discover a monopole, it will be one of the most revolutionary discoveries of the century."

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Lawrence Livermore achieves a burning plasma in the lab

In that regime, fusion reactions are the plasma's primary source of heating.

Inertial fusion requires a thousand-fold compression of matter to ultrahigh densities and temperatures. The Sun and other stars use gravity to do the job and fuse hydrogen into helium. To mimic the effect on Earth, scientists at Lawrence Livermore National Laboratory's National Ignition Facility (NIF) use the world's most powerful bank of lasers to squeeze isotopes of hydrogen—deuterium and tritium—in a 2-mm-wide capsule.

The facility trains 192 laser beams into a 1-cm-tall, hollow, gold-lined cylinder known as a hohlraum, shown in figure 1, that suspends the capsule inside it. After absorbing UV-laser light, the hohlraum's interior wall reradiates a flux of soft x rays. Within 8 ns, those x rays accelerate and compress the hydrogen isotopes into a hot spot half the width of a human hair at a temperature of 60 million kelvin and a pressure of 350 GPa.

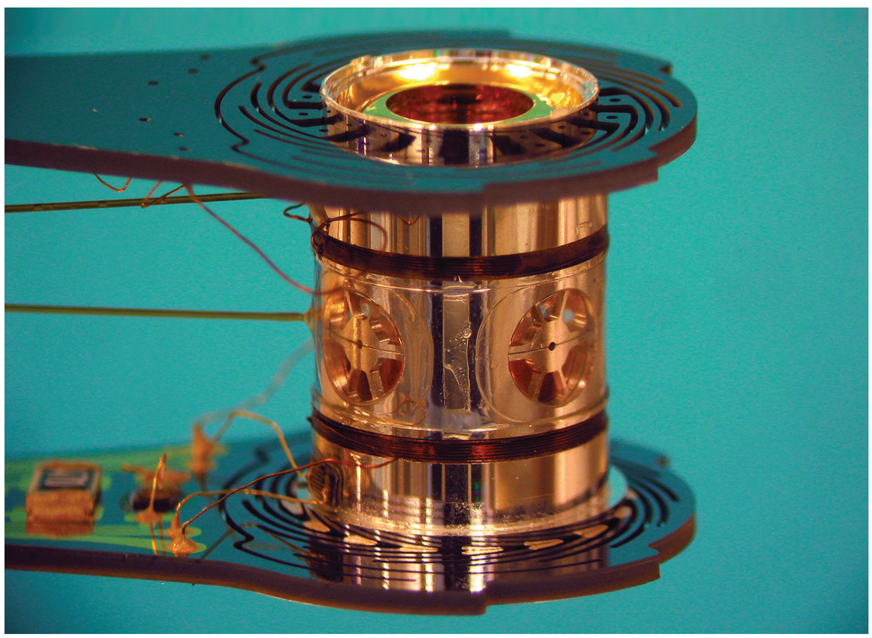

FIGURE 1. A GOLD CYLINDER known as a hohlraum holds a fuel capsule at its center for fusion experiments at the National Ignition Facility. Target-handling systems precisely position the capsule and cool it to cryogenic temperatures. (Courtesy of Lawrence Livermore National Laboratory.)

Under the capsule's surface the hydrogen fuel resides as a thin shell, cooled to 18 K prior to compression. The colder the fuel is initially, the more compressible it is—and hence the hotter and denser it becomes. The fuel's own inertia provides enough delay between the implosion and its sudden deceleration for the strong nuclear force to convert a small fraction of isotope pairs into neutrons and helium nuclei, or alpha particles.

Controlling those conditions is far from easy. Whenever a light fluid presses against a heavier one, the interface suffers Rayleigh–Taylor instabilities. Any imperfections on the capsule surface give rise to hydrodynamic fluctuations that rob the implosion of efficiency. Once the capsule starts to collapse, it can lose spherical symmetry and morph into a bumpy blob. Even worse, the imperfections can destabilize the implosion enough to mix compressed fuel with capsule material. Impurities in the fuel mixture radiate x rays away from