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."

Alex Lopatka

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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 billion atmospheres.

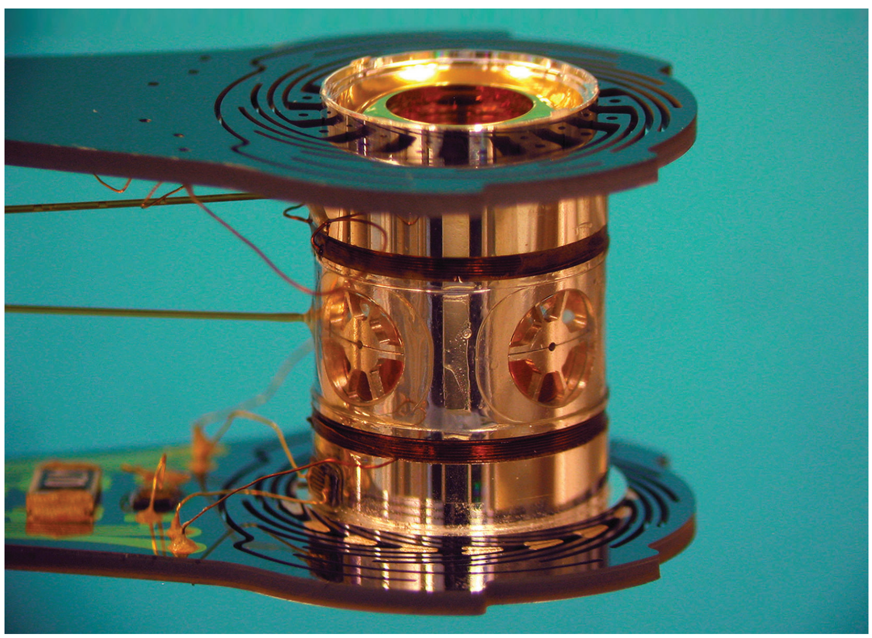

FIGURE 1. A GOLD CYLINDER known as a hohlraum holds a fuel capsule at its center for fusion experiments at the National Ignition Facility. Target-handling systems precisely position the capsule and cool it to cryogenic temperatures. (Courtesy of Lawrence Livermore National Laboratory.)

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 the hot spot and rapidly cool it.

Nonetheless, researchers have been fusing hydrogen into helium, albeit inefficiently, for decades. Since 2009, NIF scientists have been striving to manage the Rayleigh–Taylor instabilities in the lab. The challenge is to heat the plasma hot spot faster than any cooling process, such as thermal conduction or bremsstrahlung radiation, can quench the fusion. That's been an elusive goal.

In three papers—one in *Nature*, one in *Nature Physics*, and a third on the arXiv eprint server—the NIF collaboration reports a more modest achievement: creating a burning plasma in four experiments that it conducted between late 2020 and early 2021.[1–3] In burning plasmas, the fusion reactions themselves—not the compression—are the primary source of heat for the plasma. Alpha particles produced by the reactions collide with electrons in the hot spot. Those electrons then thermalize and heat the fuel further.

Prelude to ignition

The process is an essential precursor to the ultimate goal of ignition, a regime in which the heat from those alpha particles exceeds all the heat losses from the system. The resulting thermal instability then triggers a nonlinear rise in temperature that sustains and propagates the burn deeper into surrounding fuel. The higher the temperature, the greater the fusion, the more alpha particles that collide in the hot spot, and the higher the temperature.

Reaching a burning-plasma state at NIF came from iterative optimization. No single measurement discloses the state's presence. Rather, a comprehensive suite of optical, x-ray, and nuclear diagnostics reveal key aspects of the implosion. Among the data is the neutron yield as a function of time and the size, volume, and energy of the hot spot. A simple metric for assessing the presence of a burning plasma is to evaluate whether the time integral of the fusion power—effectively, the energy gained by the hot spot from alpha particle heating—exceeds the total compressional work done on the hot spot. All the recent experiments satisfied that metric and other more rigorous ones.

"Having reached that regime," says Omar Hurricane, chief scientist of Lawrence Livermore's Inertial Confinement Fusion program, "we are now on

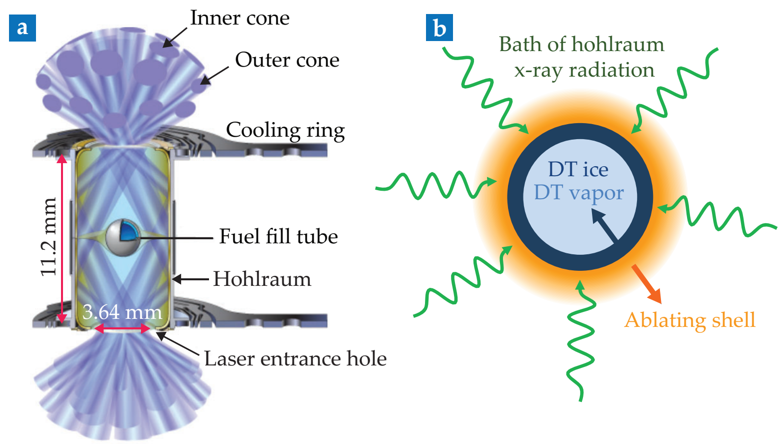

FIGURE 2. INERTIAL CONFINEMENT FUSION uses indirect laser excitation to spark a burning plasma. **(a)** Laser beams enter the hohlraum at various angles through top and bottom holes and heat its interior wall. **(b)** The flux of soft x rays reradiated by that wall expels the capsule's outer shell. By conservation of momentum, its inner shell of frozen and gaseous deuterium and tritium (DT) fuel is driven inward. (Adapted from ref. 1.)

the verge of ignition. The achievement not only opens access to interesting new physics, it fulfills NIF's central mission—supporting stockpile stewardship." As new data emerge, researchers there will be able to tune their computer codes to more accurately simulate what happens in a thermonuclear explosion.

Experiments and simulations have always worked hand in hand at Lawrence Livermore and NIF, and the inertial fusion program was an immense collaboration that took most of the past decade. More than 150 coauthors were involved in each of the three papers.

Holding a bomb

In the four experiments, the lasers unleashed 1.9 MJ in the form of an 8 ns pulse. Each shot roughly tripled the fusion energy achieved in previous record experiments—up to a maximum of 170 kJ. The collaboration stopped short of claiming ignition from those shots or from a fifth, record-making 1.3-MJ-yield shot it conducted a few months later in August. (See "Lawrence Livermore claims a milestone in laser fusion," PHYSICS TODAY online, 17 August 2021.)

To appreciate those numbers, keep in mind that 1 MJ is roughly the caloric energy of a candy bar. It's also the amount of explosive energy in a hand grenade. The difference lies in the amount of time each takes to release its energy. The 1.9 MJ energy of NIF's laser is fixed. So, to generate more powerful implosions the researchers had to increase the size of the fuel capsule by about 15% while keeping the hohlraum's dimensions nearly fixed.

That approach was complicated by the dynamics of the experiment. As the hohlraum heats up under irradiation, less room becomes available for the beams to propagate inside it. As shown in figure 2, an "outer cone" of laser beams reaches the hohlraum's wall close to its ends. Those beams produce a bubble of gold plasma that expands and can clip the inner beams aimed deeper, near the hohlraum's waist. The resulting nonuniformity in radiation temperature drives an aspheric implosion.

Years earlier, NIF scientists had partly resolved that problem by introducing helium gas to slow the expansion and forestall the clipping. The mere presence of gas, however, causes its own problems: laser–plasma instabilities that backscatter the beams and carry their energy out of the hohlraum. When scientists reduced the gas density, they found that those instabilities became much more manageable. But the reduction also increased the speed at which the plasma bubble expanded. Circumventing the problem, they realized, would take a faster implosion and hence more power to drive it.

The NIF scientists built a larger capsule to absorb more radiation and provide that extra power. Fortunately, beforehand they had also changed its composition—swapping out the capsule's plastic hydrocarbon shell for one made of microcrystalline diamond. Initially, the diamond capsules had many flaws that required some difficult engineering to solve, but eventually the replacements' outer surfaces were smoother and largely free of the pits and voids that had seeded instabilities and ruined implosions in earlier experiments.

With diamond's density triple that of plastic, the capsule became a better absorber of x rays and thus a more efficient compressor. Its shell was also thinner, which meant researchers could use a shorter laser pulse—down to 8 ns from 20 ns—to compress the capsule. That too sped the implosion.

Energy exchange

The new capsule design didn't entirely prevent the interception of the laser beams by an expanding plasma. To restore the uniformity of laser heating, the team tested two additional design tactics. One of them, an already well-established technique known as cross-beam energy transfer, was to shift the wavelength of the inner laser beams by just 1.5 Å relative to the outer ones. As the beams cross each other on entering the hohlraum, they scatter through an effective diffraction grating set up by laser–plasma interactions. The scattering transfers energy from the outer beams to the inner beams. And that transfer, in turn, delivers more heat to the hohlraum's waist and equalizes the x-ray flux on the capsule.

The second tactic was to add two pockets in the hohlraum near its poles. Those pockets provide space into which plasma may expand and thus delay the extent to which it occludes the inner beams. They were found to be insufficient for controlling the radiation symmetry. But they did reduce the wavelength shift needed to maintain that symmetry around the capsule.

Even if ignition is right around the corner, Hurricane cautions that converting the NIF experiment or any other fusion project into a clean, sustainable commercial energy source is a long way off. Still, "the House Science Committee seems keen on soon launching a federal fusion-based energy program," says Steven Cowley, director of the Princeton Plasma Physics Laboratory. The House-passed version of the Build Back Better bill includes $140 million over five years for the Department of Energy to carry out an inertial fusion R&D program. But the bill stalled in the Senate, where it doesn't have the votes required for passage.

Existing nuclear power plants use fission, the release of energy when uranium or other heavy elements are broken up into smaller nuclei. They also produce radioactive waste. Fusion, by contrast, produces only short-lived radioactivity induced in reactor components by the reactions' intense high-energy neutron flux. It's also safer because the reactions can be switched off by simply reducing the temperature.

As for what fusion approach—an upgraded and modified NIF reactor, tokamak, or some other system— eventually receives support, the jury is out. Cowley says, "When the time comes for a decision, it will be hard to choose."

R. Mark Wilson

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Diamond-defect NMR monitors a surface reaction

Few other techniques can track adsorbed molecules in real time under ambient conditions.

The study of surface chemistry has always involved a bit of a paradox. Chemical processes at solid–liquid and solid–gas interfaces are ubiquitous in batteries, industrial reactors, biomedical devices, and many other systems. But despite some research at moderate pressures (see the article by Gabor Somorjai and Jeong Young Park, PHYSICS TODAY, October 2007, page 48), most surface-science research tools, such as x-ray photoelectron spectroscopy and secondary-ion mass spectroscopy, work only under ultrahigh vacuum. Not only do they require bulky and expensive pumps and vacuum chambers, but they can't even access the conditions of greatest chemical and biological interest.

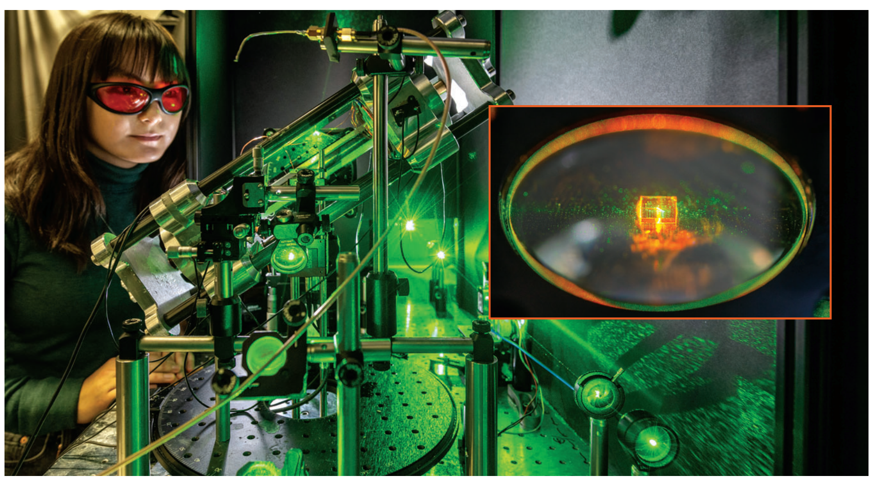

FIGURE 1. NO VACUUM CHAMBERS are needed to study surface chemistry using diamond NV-center NMR. Here, Kristina Liu of the Technical University of Munich operates the relatively simple experiment, which uses green light from an inexpensive solid-state laser to read the NV centers' spin states. The 2-mm-square diamond, not visible in the main image, is shown in the inset. (Photos by Andreas Heddergott, Technical University of Munich.)

NMR spectroscopy is a time-honored tool for chemical analysis that works on bulk liquids, solids, and solid-like biomolecular systems. By measuring the precession frequency of spin-½ nuclei—for example, hydrogen-1, carbon-13, or fluorine-19—in a magnetic field, researchers can extract exquisite chemical information and even reaction dynamics. (See, for example, PHYSICS TODAY, October 2019, page 21.) But because a two-dimensional surface contains fewer molecules than the three-dimensional bulk, conventional NMR isn't usually sensitive enough to study surface chemistry.