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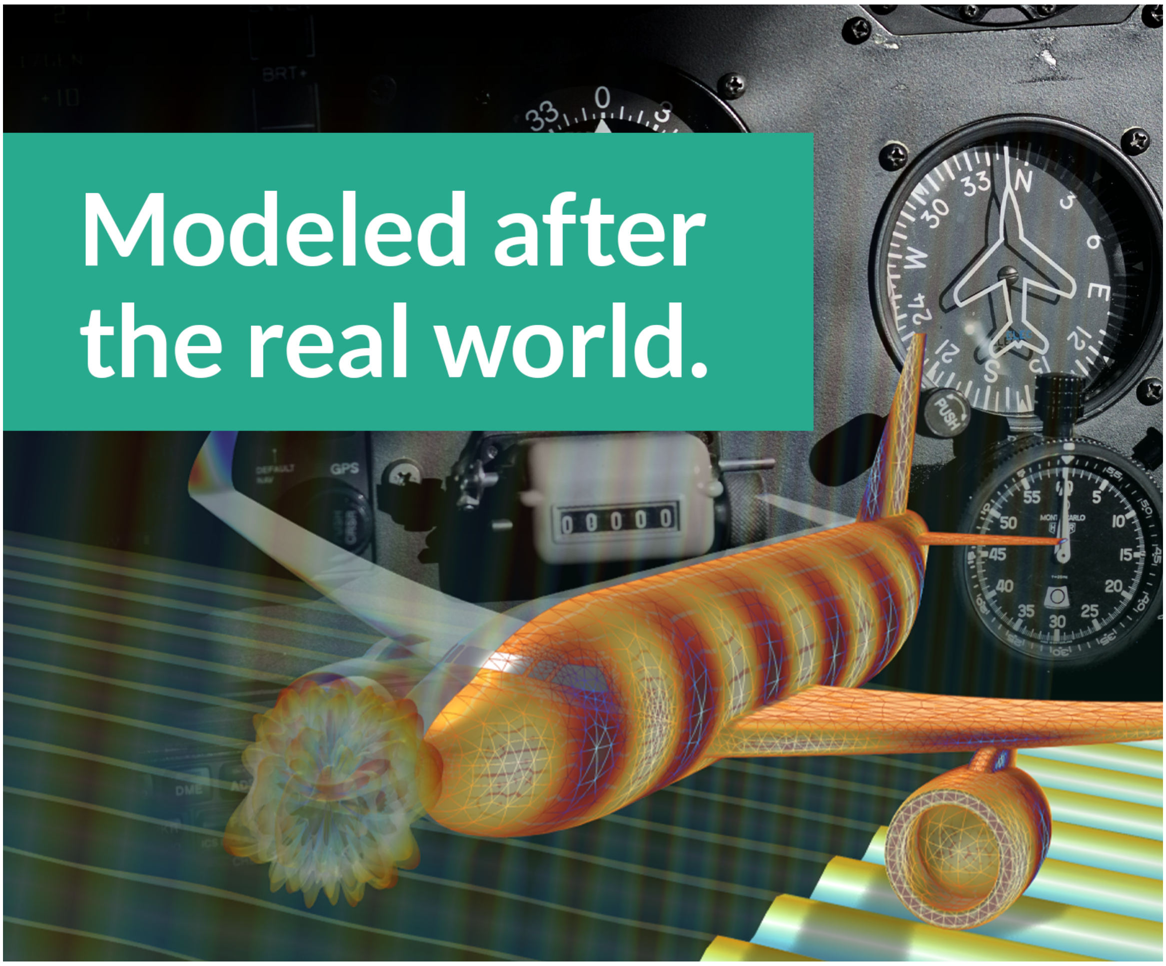

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Precision measurements bring the search for new physics to the table

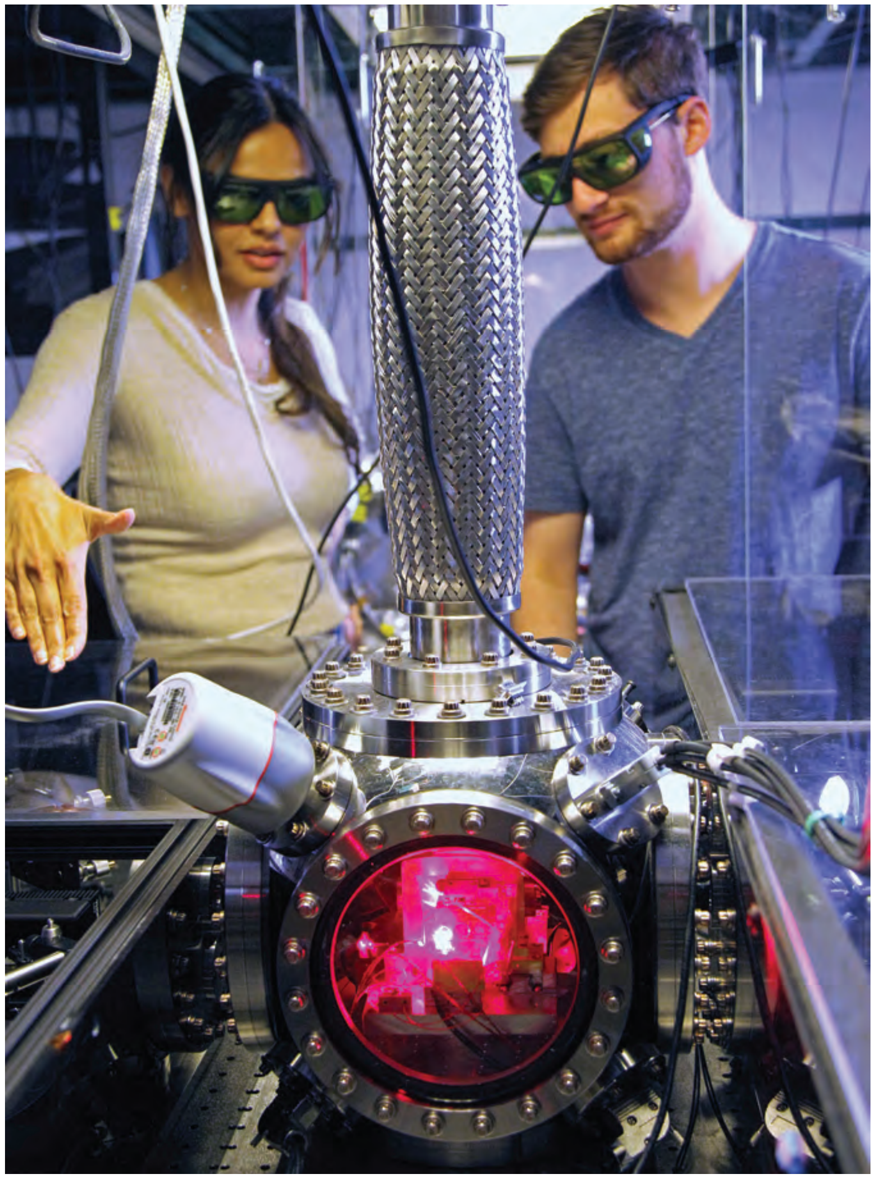
Targeted small-scale experiments look to find smoking guns—or at least to rule out possibilities.

Practitioners of atomic, molecular, and optical (AMO) physics are increasingly applying their tools to the search for physics beyond the standard model, thanks largely to advances in precision-measurement techniques. Particle colliders have dominated the search for new physics in recent decades. But the growth in small-scale studies coincides with two realities: the Large Hadron Collider (LHC) has not found hoped-for new physics and a higher-energy particle collider is likely to be far in the future.

Much evidence exists that the standard model is insufficient in explaining the universe. The preponderance of dark matter and dark energy, which make up roughly 95% of the universe but remain unidentified, is a prime example. Others include the excess of matter over antimatter, the fact that neutrinos have mass, the unexpectedly low mass of the Higgs boson, and the relationship between gravity and the other fundamental forces.

Whereas colliders can detect a wide range of particles and events, tabletop experiments are typically designed to target specific interactions. “You pick what you want to look for and then design the experiment accordingly,” says Daniel Carney, a theoretical physicist at Lawrence Berkeley National Laboratory. The search could be for evidence of dark matter, a fifth force, or changing values of fundamental constants. “The space of possible experiments is vast and unexplored,” says Carney, who started working on tabletop searches for new physics when he “got obsessed with the idea of testing quantum gravity. Tabletop searches are the Wild West.”

“We don’t know how close we are to finding new physics, because we don’t know where it is,” says David DeMille of the University of Chicago. He is one of three principal investigators on ACME, an experiment that seeks to measure the electron’s electric dipole moment using beams of molecules. (See “Diatomic molecules, a window onto fundamental physics,” by David DeMille, PHYSICS TODAY, December 2015, page 34, and “The implications of a precise electron measurement,” by Yuichiro Nakai



TOM PENNY/YALE WRIGHT LABORATORY

MOLLY WATTS AND BEN SIEGEL, graduate students at Yale University, with a vacuum chamber containing trapped microparticles. They use the apparatus to look for recoils of the microparticles when an implanted nucleus decays. It is sensitive to forces as small as zeptonewtons (10^{-21}N).

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and Matthew Reece, Physics Today online, 14 November 2018.)

Cool tools

Over the past 15 or so years, experimenters in AMO physics have advanced techniques to cool, trap, and quantum control systems—from atoms to electrical circuits to macroscopic objects. Many of the advances were made to improve atomic clocks. More recently, "spectroscopic tricks" that were developed for atoms have been extended to molecules, notes Eric Cornell at JILA, a joint institute of NIST and the University of Colorado Boulder.

Cornell is a principal investigator on a trapped-ion experiment that currently puts the tightest constraint on the electron's electric dipole moment. The constraint is about seven orders of magnitude greater than the standard model prediction; a dipole moment larger than predicted by the standard model would be new physics. "If you want to see the electron wobble, you want to apply the biggest honking electric field possible," says Cornell. "Where is that? Inside molecules! They are like a mini high-field physics lab, but with long coherence times that you would not find in a high-energy collision."

Once a new technique exists, says Cornell, people look around and wonder, "I have this cool tool, what can I use it for?" Atomic clocks can be accurate to 18 digits, he says. It's natural to ask, "How can I turn that precision in timekeeping into precision for physical measurements?"

Amar Vutha is trying a different approach to measure the electron's electric dipole moment in his lab at the University of Toronto: He freezes molecules into neon ice. The ice orients the molecules, says Vutha. "Then you apply a magnetic field and look for anomalous spin precession that depends on the orientation of the electron relative to the axis of the molecules."

The approach could search a wide range of parameter space, Vutha says. Any "smoking gun" signals could be followed up with colliders or other experiments, he says. Null results could rule out theories.

At Columbia University, Tanya Zelevinsky and her group are studying transitions between vibrational levels in molecules to learn about interatomic forces; they have characterized a transition in the strontium dimer to parts in 10^{14}. "What does gravity look like at the nanometer scale?" she asks. "If a force is found that modifies the Newtonian gravitational force, it would be a signature of a new physics."

MIRA LITTMANN

A VAN transports the Broadband Reflector Experiment for Axion Detection from the University of Chicago to its new home inside a large magnet at Argonne National Laboratory, roughly 45 kilometers away.

Dark matter could exist over a huge parameter space, covering tens of orders of magnitude. GNOME, the Global Network of Optical Magnetometers to Search for Exotic Physics, is one of many dark-matter searches. It consists of a dozen widely separated stations that collect time-synchronized data on atomic spins to look for transient effects induced by dark-matter collisions or other exotic interactions. And many groups are looking for axions, a proposed ultralight dark-matter particle. Theorists cooked up axions to explain a lack of observed violation of *CP* (combined charge conjugation and parity) symmetry in strong interactions, but axions double as a dark-matter candidate.

Gerald Gabrielse has been working on small-scale precision measurements for 30 years. Until a decade or so ago, he says, "it was lonely." His focus—looking for magnetic and electric dipole moments of electrons, protons, and neutrons—was not mainstream. Now the field is abuzz. After three decades at Harvard University, Gabrielse was wooed by Northwestern University to found and run a center devoted to tabletop precision measurements—where "tabletops" come in various sizes. The ACME experiment, for example, fills a room there. Similar centers, including one created last year at Caltech, are popping up around the world.

Experimental cultures

AMO experiments are typically small, involving just a few people, a few years, and a few hundred thousand to a few million dollars. They may be done by a single group or a small collaboration on a professor's startup funds or grant. And scientists can try things and take risks that would be impossible with an expensive, 20-year high-energy program. The style of work is different, says Zelevinsky. "In AMO culture, experiments are flexible. A couple of students can redesign an experiment to try something new."

Some tabletop precision experiments expand to larger scales. For example, Zelevinsky, DeMille, and collaborators recently moved their apparatus for mea-

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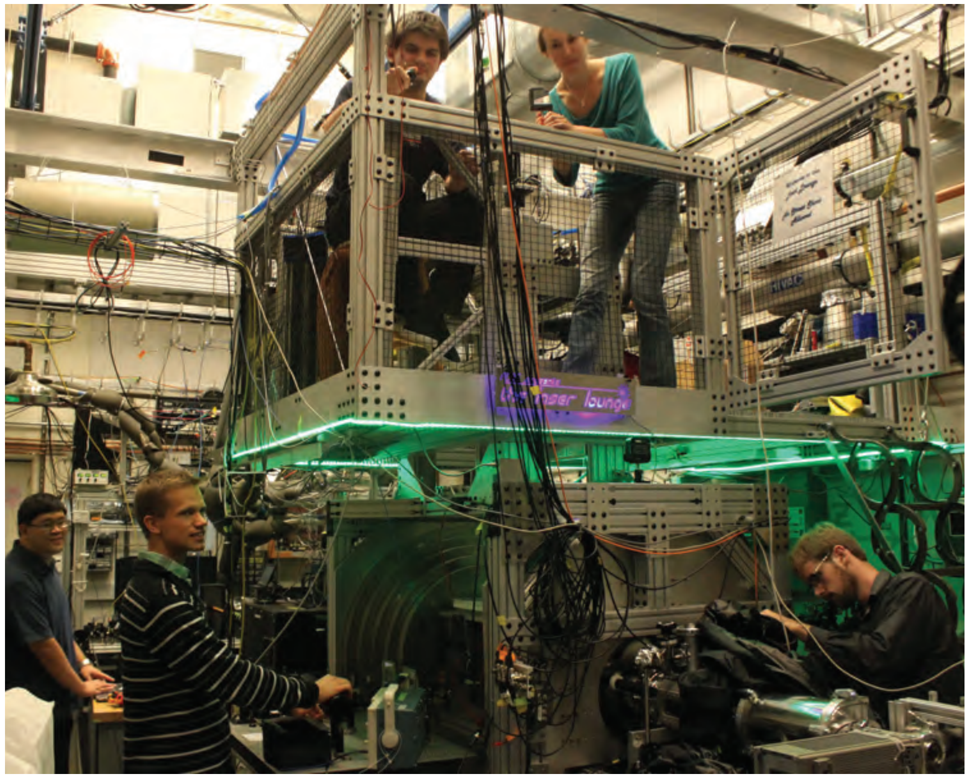

ACME IS AN EXPERIMENT to set limits on the electron's electric dipole moment. Here, collaboration members work on an earlier incarnation of the room-sized apparatus when it was housed at Harvard University. The current generation of the experiment is at Northwestern University.

suring the proton's electric dipole moment to Argonne National Laboratory. A permanent electric dipole moment would violate time-reversal symmetry and could give hints about the asymmetry of matter and antimatter, says Zelevinsky.

A tabletop experiment that measures nuclear recoil during beta decay to look for sterile neutrinos—hypothetical particles that interact only via gravity—has led to a follow-on, the Superconducting Array for Low-Energy Radiation. SALER, which is setting up shop at the Facility for Rare Isotope Beams at Michigan State University (see Physics Today, June 2023, page 21), expands the use of rare-isotope-doped superconductors to search for a wide range of exotic new physics, says Kyle Leach, a nuclear physicist at the Colorado School of Mines.

David Miller, a physicist at the University of Chicago, is a member of the 3000-strong ATLAS experiment on the LHC at CERN and also works on the tabletop Broadband Reflector Experiment for Axion Detection (BREAD). He interacts on a daily basis with about 10 ATLAS colleagues, he says. A large collaboration like ATLAS requires different subgroups to coordinate with each other and to have formalized procedures in a way that a small collaboration doesn't need. Another difference, says Miller, is that contributions from any one individual tend to be more "end-to-end" in a small collaboration and more specialized in a large one.

For precision measurements that grow in scale, says JILA's Cornell, "some of the skills of people who manage big collaborations could be merged with atomic physics."

Interplay of approaches

Should collider physicists feel threatened by the low-cost approaches to seeking new physics? Might those approaches be seen as a better investment than a next-generation collider, which would come with a multibillion-dollar price tag? The consensus seems to be no.

"Collider people debate which collider. The rest of us debate, 'Is a collider worth it?' " quips Berkeley Lab's Carney. "But the search for new physics needs a broad approach."

Precision measurements and high-energy experiments are not in direct competition, says Andrew Geraci, an experimental physicist at Northwestern. If a fifth force is observed, there will be an associated boson, "and you can go look for it with a collider." The discovery of an electron electric dipole moment "would motivate the high-energy-physics strategy," says Gabrielse. "The size of a magnetic moment that we see, or fail to see, places limits on where new physics could be discovered. There is interplay."

For the field as a whole it's good to have studies of different sizes and time scales, says Juan Estrada, a scientist at Fermilab who works on dark-matter and dark-energy experiments. The shorter time scales and lower costs of tabletop experiments "can be attractive for young people to get results," he says, and can provide an opportunity for graduate students to learn instrument building.

"I see colliders and precision measurements as complementary," says DeMille. The LHC is a general-purpose machine, he says. "It's capable of seeing directly—or sometimes indirectly—many different types of particles and fields." In contrast, the electric-dipole-moment experiments, for example, are sensitive only to particles and forces that violate *CP* symmetry, and there is no guarantee that new particles will have that property.

What's most exciting, says DeMille, is that electric-dipole-moment experiments are probing mass scales higher than the LHC will ever be able to do. "If we see clear evidence for an electron electric dipole moment, that would set an upper limit on the mass at which new particles have to appear. That would be healthy for collider physics."

Or, if precision measurements discover axions, says Miller, then it would be "perfectly reasonable" to hypothesize the existence of related particles. "We could detect fundamental properties at BREAD and constrain the parameter space, which could help the LHC look for evidence of particle cousins, like the supersymmetric axino."

"It's an open question as to whether anyone will build the next collider," says Holger Müller, a University of California, Berkeley, physicist who uses atom interferometry to measure the fine-structure constant. "If the LHC had delivered a large number of physics discoveries," he says, "there would be no question. It didn't, so I think it's unclear what will happen. But if the next collider isn't built, it won't be because of precision physics."

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