emanating out in all directions.

The flowers aren't just nice to look at. Because the MXene sheets are oriented perpendicular to the outer surface, they're also ideal for applications in energy storage. To store and release energy quickly, batteries and electrochemical capacitors need high-surface-area electrodes that can hold large numbers of lithium and other ions. (See the article by Héctor Abruña, Yasuyuki Kiya, and Jay Henderson, PHYSICS TODAY, December 2008, page 43.) With the help of Chong Liu and her electrochemistry research group (also at the University of Chicago), Talapin and colleagues showed that the CVD-synthesized MXenes worked well.

Strength in diversity

The sheer number of MXene structures is often touted as one of the family's greatest advantages.[5] Between all the possible M elements, X elements, sheet thicknesses, and surface terminations, there are hundreds of possible MXenes. For MXenes that are solid solutions of two or more metal elements, there are countless more options.

The titanium–carbon MXenes are by far the most studied, so that's what Talapin and colleagues focused on for their demonstration. But the researchers also showed that their synthesis schemes can produce many more MXene types, including several that have never been seen before, such as nitride MXenes that can't survive the HF etching method.

What does the world need with so many MXenes? One answer that's already been explored has to do with MXenes' use as solid-state catalysts. When a surface facilitates a chemical reaction between atoms or molecules adsorbed onto it, the specific surface properties, such as the spacing between atoms and the availability of electron states, matter a lot. The more MXenes there are, the more reactions they can possibly catalyze.

Beyond that, both Talapin and Gogotsi opine that a large part of MXenes' potential remains undiscovered, and the exploration could benefit from new scientific perspectives. In particular, the role of the surface terminations in tuning MXene properties creates an unusual interface between solid-state physics and molecular chemistry, with room for input from researchers in both fields.

"MXenes are metals that behave like semiconductors," says Gogotsi, referring to their combination of conductivity and tunability. "By chemically modifying the surface, you can modulate the optical and electronic properties. There's an exciting demand for the physics community to come explore, to check the existing predictions and make new predictions."

"The engineering side is well on track," says Talapin. "There are brilliant people working in this space, with lots of ideas of what MXenes can be used for. But as the field switches from simpler applications to more complicated ones, the diversity of properties will be more important. The next wave of discoveries will surely come from making MXenes more familiar to physicists and chemists, who can add chemical and physical rigor and deep physical insights. I see huge opportunities here."

Johanna Miller

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Theory and experiment disagree on alpha particles

Electron-scattering experiments on excited helium nuclei open questions about the accuracy and sensitivity of state-of-the-art nuclear models.

Although the helium nucleus has just four nucleons—two neutrons and two protons—theoretical models fail to replicate some of its properties. Or so Sonia Bacca, now at the Johannes Gutenberg University Mainz in Germany, and her colleagues discovered in their 2013 calculations.[1] Helium nuclei, also known as alpha particles, are a popular testing ground for nuclear models because they are relatively simple while still capturing essential nuclear phenomena, and theory replicates their ground state pretty well.

But excited states were another matter. The researchers' calculations of a quantity related to how the nucleons are arranged in the alpha particle's first excited state didn't match the values inferred from electron-scattering experiments. The experiments were primarily from the 1970s, however, and the uncertainties were large.[2] In the intervening decades, the techniques and technologies—particularly detector sensitivity—had improved dramatically, but that property of the humble helium nucleus hadn't been explored experimentally since 1983.

"There are many things which experimentalists can look at," says Concettina Sfienti, a fellow faculty member of Bacca's at Johannes Gutenberg University Mainz, "and if you don't have a theory available or a hint that it might be interesting to look again, then you don't." But in light of the 2013 calculations that seemed to show a disagreement between theory and experiment, Sfienti and her colleagues decided that a new and improved experimental investigation was warranted. Now they and their theory collaborators have confirmed the disagreement and charted theoretical and experimental paths to suss out its origin.[3]

An effective method

The bulk of a nucleus's properties, including size and binding energy, arise from interactions among nucleons, which are themselves derived from the complicated web of strong interactions between constituent quarks and gluons. Early nuclear models were phenomenological, and their uncertainties were hard to assess. But that changed with the introduction of effective field theories.

Effective field theories show up in many topics—including particle physics, statistical mechanics, condensed-matter physics, and general relativity—and are written to capture the given system's behaviors at a certain length or energy scale while ignoring or approximating those at other scales. Such theories transform burdensome calculations into expansions in a set of dimensionless parameters. Many of those expansions are perturbative and can be truncated reasonably at some point.

Introduced in the early 1990s, chiral effective field theory (ChEFT) deals with low-energy quantum chromodynamics, the theory behind the strong interaction. ChEFT creates a hierarchy of nuclear interactions in which those between two nucleons are stronger than those between three, which are stronger than those between four, and so on. In their 2013 paper, Bacca and her colleagues applied a ChEFT that included two-body and three-body interactions to the alpha particle's first excited state, which had been calculated just once before about a decade earlier using a phenomenological Hamiltonian.[4]

ChEFT correctly predicted the helium nucleus's ground-state properties to within 1%, but the theory team realized that wasn't the case for the excited state. The transition from the ground state to an excited state is described by what's known as a transition form factor, which captures information about the shape of the nucleus. The alpha particle's form factor turned out to be highly dependent on the choice of Hamiltonian, and although the older, phenomenological Hamiltonian's form factor nearly fell within the wide error bars of the measured ones, the state-of-the-art ChEFT didn't come close. The form factor could thus serve to distinguish the quality and accuracy of different models—if the experimental uncertainties could be reduced.

Scattered results

Shortly after Bacca's paper was published, Sfienti and her colleagues in the Mainz Microtron's A1 collaboration decided to tackle the experimental problem using the equipment shown in figure 1. "The issue was to develop the target" for the electron-scattering measurement, says Sfienti. Helium is a gas, so holding it requires a container. But adding another material introduces many other nuclei for electrons to bounce off. The researchers crafted an aluminum cell

FIGURE 1. THE MAINZ MICROTRON, a particle accelerator at the Johannes Gutenberg University Mainz in Germany, includes this experimental hall that features a trio of high-precision spectrometers in red, blue, and green. The setup recently provided improved electron-scattering measurements of the alpha particle's cross section when in its excited state. Those results disagree with theoretical calculations, which opens questions for the nuclear-physics community. (Photo by Alexander Sell, JGU.)

with walls that were as thin as possible while still able to handle the pressure difference between the cryogenic gas inside and the surrounding vacuum.

Day and night for three weeks about five years ago, the A1 team shot electrons at the helium target. At a range of angles, they detected the number of scattered electrons, as shown in figure 2a, as a function of the so-called missing mass, a quantity that captures the electron's change in energy and momentum relative to elastic scattering from a helium nucleus. As indicated by the large left peak, many of the measured electrons ricocheted off the aluminum container. And many elastically scattered off helium nuclei to produce the large peak around 0 MeV.

Only one in every 10 000 electrons that hit helium excited the nucleus, and that signal, near 20 MeV in figure 2a, needed to be distinguished from the large background—a difficult task. To measure the background signal on its own, the researchers shot electrons at a nearly empty aluminum cell. (There had to be some helium gas, or else the thermal stress on its walls would've broken the cell.) Those measurements were paired with simulations and phenomenological models for elastic and inelastic scattering off aluminum nuclei. Over several years, Sfienti and her

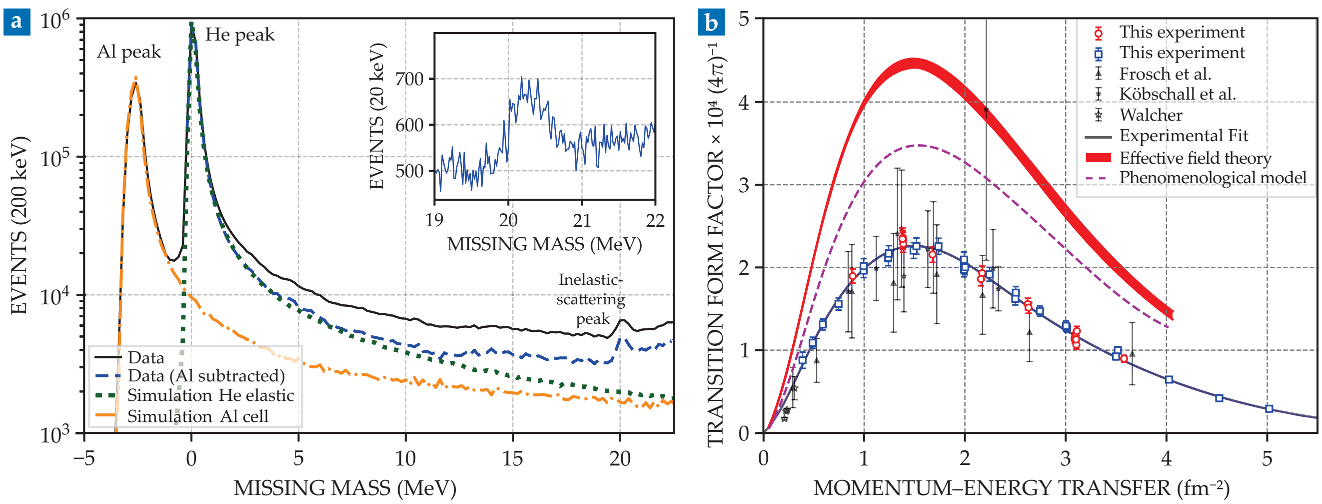

FIGURE 2. ELECTRON-SCATTERING DATA yield information about the helium nucleus's first excited state that conflicts with theory. **(a)** Given in terms of the missing mass, which captures the electron's change in energy and momentum, the two strong peaks at left arise from electrons that bounce off an aluminum container and that elastically scatter off helium nuclei. The inelastic scattering peak from electrons exciting helium nuclei is shown in the inset. **(b)** The associated experimental transition form factor (red and blue data points), which is related to the nucleus's shape, agrees with older experimental data (gray) but with improved error bars. State-of-the-art theoretical models (red and purple curves), on the other hand, predict values as much as twofold greater than those observed. (Adapted from ref. 3.)

colleagues meticulously processed the data to track the fate of the scattered electrons and painstakingly subtract out the unwanted signal.

The measured scattering cross section of the excited state was then converted to the transition form factor. The results, the blue and red data points in figure 2b, agree with older experiments (gray data and error bars) but with dramatically reduced uncertainty. But theoretical calculations (red curve) predict a form factor as much as twofold larger than is observed. "Such a strong disagreement was unexpected," says Sfienti, "and it remains unexplained at this point."

Uncertain future

"It's possible that we missed some piece of the nuclear force," says Bacca, "or that this observable is so sensitive to some detail of the nuclear force, that it's almost impossible to get it right." The wide range of predicted form factors supports the idea that the helium transition is sensitive. Compare, for example, the values predicted by ChEFT (red curve in figure 2b) with those predicted by the older, phenomenological Hamiltonian (dashed purple curve).

"If the form factor is super sensitive to a tiny part of the nuclear force, we would like to know which part," says Bacca, "and we would like to calibrate it to see if we screw up any other observables of the many other nuclei that we can accurately calculate these days." Those nuclei include elements as heavy as lead, although fewer studies have looked at excited states.

The ChEFT calculation has around 25 parameters, none of which were varied in the current study. "We just have to find the knob that allows you to agree with the experiment," says Bacca. The first ones Bacca will tweak are two parameters associated with the three-body contributions. Two-body interactions are well constrained by experiments on two-nucleon systems, but with four nucleons, alpha particles have plenty of three-body interactions at play.

On the experimental side, the Mainz team is constructing a new facility that can perform electron-scattering measurements on gases without the aluminum cell—and its pesky background—by instead using a continuous flow of gas. Reducing the background will reveal more of the lower-energy side of the form factor, which is more sensitive to the state's spatial structure and is thus a better test for the disagreement between the models and experiment. Called the Mainz Energy-Recovering Superconducting Accelerator, the new facility should be built by the end of the year, with the first experiments scheduled for 2025.

Understanding the disagreement between ChEFT and electron-scattering experiments could have implications beyond the field of nuclear physics. Neutron stars, for example, have hot, dense nuclear matter at their cores that prevents their collapse into a black hole (see the article by Jorge Piekarewicz and Farrukh Fattoyev, Physics Today, July 2019, page 30). ChEFT is extensively used to predict and understand the nature of that exotic stellar matter.

Heather M. Hill

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