

were all made in the same way: by shooting a beam of calcium-48 into an actinide target. With so-called magic numbers of both protons (20) and neutrons (28),  $^{48}\text{Ca}$  is unusually stable, and it combines readily enough with actinide nuclei of atomic number  $Z$  to yield a few super-heavy atoms of atomic number  $Z + 20$ .

No new elements have been made in

that way, or any other, since the 2010 discovery of element 117, now called tennessine after ORNL's home state. (See PHYSICS TODAY, June 2010, page 11.) It took longer to discover Ts than Og because the Bk target was harder to work with than the Cf one. Until a big enough Es target can be assembled to make element 119, the  $^{48}\text{Ca}$ -fusion technique has

seemingly reached the end of its road. Better Es purification through chemistry may help breathe new life into super-heavy element research.

Johanna Miller

## Reference

1. K. P. Carter et al., *Nature* **590**, 85 (2021).

# Pauli crystals make their experimental debut

When a few ultracold atoms are repeatedly trapped and imaged tens of thousands of times, self-organized patterns emerge out of the quantum blue.

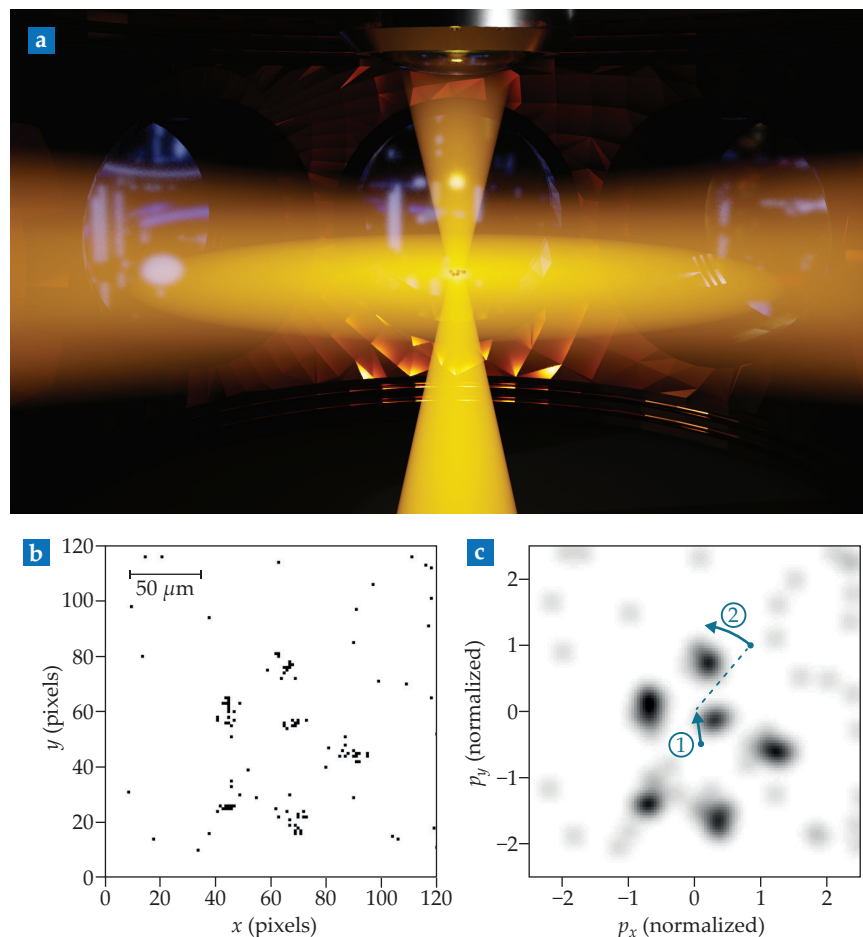
**W**hereas bosons can condense into a single quantum state, fermions, such as electrons in ordinary solids, are forbidden from doing so. Pauli exclusion is the best-known manifestation of Fermi–Dirac statistics, and it accounts for, among other things, the structure of the periodic table and electrical conductivity in metals.

Identical fermions do not even need to interact to behave as if they repel each other. Indeed, the mere presence of fermionic atoms near one another but unable to occupy the same locations produces an emergent Fermi pressure that prompts the atoms to rearrange themselves. The resulting correlations between atoms can be visualized in geometric structures known as Pauli crystals. Mariusz Gajda coined the name five years ago when he and his colleagues at the Polish Academy of Sciences in Warsaw predicted the phenomenon.<sup>1</sup>

Now doctoral student Marvin Holten, postdoc Luca Bayha, and their colleagues, under the direction of Selim Jochim at Heidelberg University, have directly observed Pauli crystals in the momentum correlations of a few lithium-6 atoms trapped in a two-dimensional plane.<sup>2</sup>

## Simulating a solid

Theorists have long tried to account for the electronic behavior of strongly interacting many-body systems by using model Hamiltonians. But when researchers attempt to fabricate materials that embody such Hamiltonians, they often struggle to cope with imperfections, defects, and

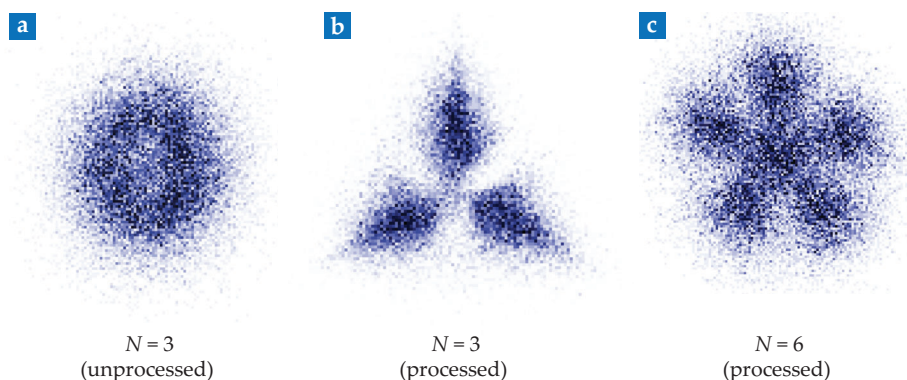


**FIGURE 1. SIX ULTRACOLD** lithium-6 atoms are trapped in the superposition **(a)** of a focused optical tweezer and a single layer of a one-dimensional optical lattice (yellow disk). The atoms can move in the two-dimensional plane but are frozen vertically. **(b)** When the tweezer is switched off, the atoms expand in the 2D plane until a laser pulse prompts them to fluoresce; photons from each atom are registered as momenta (dots) in a CCD detector. **(c)** To reveal correlations between the atoms, researchers subtract their center-of-mass motion (arrow 1) from each atom's momentum  $\mathbf{p}$  (normalized to harmonic oscillator states) and then rotate each image to a common symmetry axis (arrow 2). (Adapted from ref. 2.)

other features of the real material world. A tantalizing alternative, developed about a decade ago, is to study the systems' com-

plicated behavior by using small clouds of ultracold atoms.

To simulate the behavior of itinerant



**FIGURE 2. PAULI CRYSTALS** unveiled. **(a)** This nearly featureless blob of fluorescence measurements is the momentum distribution—or, more precisely, the measured momenta of each lithium-6 atom minus the center-of-mass momentum—for  $N = 3$  atoms. The reduced density in the center is due to the harmonic-oscillator eigenfunctions. **(b, c)** The strong correlations between atoms reveal themselves in the configuration probability densities for  $N = 3$  and  $N = 6$  only when each experimental run has been rotated separately to a common symmetry axis. (Adapted from ref. 2.)

electrons in a solid, researchers typically trap the gases in a 2D periodic array of optical potentials and then tune the atoms' interactions. (Because atoms are electrically neutral, those interactions can be turned on or off on demand using an applied magnetic field.) A separate laser then irradiates the atoms and snaps their photograph, which records the fluorescence they emit. (See *PHYSICS TODAY*, October 2010, page 18, and August 2017, page 17.)

The new Heidelberg experiment uses a similar kind of fluorescence microscope. Its ability to image the positions of single atoms makes the instrument ideal for capturing the shapes of different Pauli crystals. Those shapes, however, are hidden in the correlations in the atoms' relative positions or momenta. Observing them requires preparing noninteracting fermions in a well-defined quantum state at nearly zero temperature and then detecting the correlations. Holten and colleagues' choice of  $^6\text{Li}$  is especially suitable for the job: The atoms can be precisely controlled from a regime in which they rethermalize and cool quickly in an optical trap to one in which they are noninteracting.

Rather than confine the  $^6\text{Li}$  atoms in a periodic lattice—where they would be localized like eggs in a carton—the researchers hold them in the intersection of an optical tweezer and a single layer of a 1D optical lattice. They are thus frozen in the vertical direction but free to move in the 2D plane. Figure 1a outlines the experiment. The researchers loaded the

tweezer's potential well with a few hundred Li atoms and then "spilled" the excess by bending one side of the well with a magnetic field gradient.<sup>3</sup>

The potential well filtered out all but the coldest atoms. In the 2D plane the atoms' energy states are arranged in shells, akin to electron orbitals around a nucleus. The shells are closed—as in noble gases—for one, three, and six atoms. In separate experiments the researchers chose to trap three and six of the  $^6\text{Li}$  atoms to discern the different patterns that emerge. In both cases, the most desirable configuration for the atoms would be to sit exactly at the center of the potential well. Pauli exclusion forces them to adjust their positions to avoid stepping on one another.

## Taking pictures

The group's optical tweezer confines the atoms within about a micron of one another. That's too close to be directly imaged. Instead, the team mapped the atoms' initial momenta onto position by turning off the tweezer—thereby loosening the harmonic trap—and allowing the atoms to expand two dimensionally. After a few milliseconds of free evolution, the distance an atom travels determines its velocity and hence its momentum. The expansion corresponds to an effective magnification of the wavefunction by a factor of 50.

To capture images of those momentum distributions, the researchers take snapshots. Beforehand, the atoms are in

a quantum mechanical superposition, existing as delocalized wavepackets. A flash of laser light forces them to fluoresce, which enables their positions to be recorded by a CCD camera (see figure 1b), but collapses the many-body wavefunction's momentum probability distribution. With the fluorescence measurement, the structure of the wavefunction is lost. So to restore the complete, rotationally symmetric density distribution, the researchers perform some 20,000 experiments—starting each one with a bunch of freshly prepared identical fermions.

That collection of measurements alone cannot reveal the correlations between atoms. The nearly featureless blob of dots in figure 2a bears that out. Because of the random nature of the wavefunction's collapse, each snapshot differs from the last in angular orientation. So before averaging the images, the researchers performed two steps—they subtracted the center-of-mass momentum from each set of atom momenta and then they rotated each snapshot until the clusters of dots in each one match a theoretically predicted pattern. Only then are the Pauli crystals revealed, as shown in figures 2b and 2c.

The Heidelberg team studied the effect of temperature to assure themselves that the crystalline arrangements were not artifacts but a genuine quantum effect. They "melted" the six-atom crystal by shaking its atoms—modulating the confining potential at twice the harmonic trapping frequency. Reassuringly, the melting drastically reduced the contrast of the correlations even when small amounts of energy were added. Only very close to absolute zero temperature did Pauli exclusion remain visible.

The measurements set the stage for the researchers' next round of experiments: incorporating strong physical interactions between atoms. What will happen, for instance, to the self-organization in Pauli crystals that emerge in few-atom systems designed to mimic superconductors, whose electrons can pair up and condense?

R. Mark Wilson

## References

1. M. Gajda et al., *Europhys. Lett.* **115**, 20012 (2016).
2. M. Holten et al., *Phys. Rev. Lett.* **126**, 020401 (2021).
3. A. Bergschneider et al., *Phys. Rev. A* **97**, 063613 (2018).