Nonidentical fermions interact identically

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Citation: Physics Today **73**, 11, 14 (2020); doi: 10.1063/PT.3.4609
View online: https://doi.org/10.1063/PT.3.4609
View Table of Contents: https://physicstoday.scitation.org/toc/pto/73/11
Published by the American Institute of Physics

Nonidentical fermions interact identically

The decoupling of electronic and nuclear spin states allows scattering fermionic atoms to rapidly cool.

Indistinguishable fermions don't typically interact much. Because their wavefunctions are antisymmetric, they tend to stay away from one another. That behavior manifests with particular strength in quantum gases cooled to ultralow temperatures, and it's a problem. Fermions' mutual avoidance limits the efficiency of evaporative cooling at low temperatures, as Deborah Jin observed 21 years ago when cooling potassium atoms (see PHYSICS TODAY, October 1999, page 17). Evaporative cooling relies on elastic collisions to nudge particles to lower energies, and it's an important technique for reaching the necessary temperatures to form Bose–Einstein condensates.

Bosons at ultralow temperatures can occupy the same energy state (see figure 1), which leads to physical proximity and much more scattering. What if fermions could act more like bosons? Not only would it be easier to evaporatively cool a Fermi gas down to the temperature needed for, say, quantum simulations, but there would also be new physics to explore. The challenge is finding fermions that don't mind sharing the same space.

Alkaline-earth fermionic atoms fit the bill. Because their nuclear spin states are decoupled from their electronic states, the energy levels and wavefunctions in an optical trap are identical for an atom in the +9⁄2 nuclear spin state, one in the +7⁄2 nuclear spin state, and so on. But the atoms aren't identical. As a result, fermionic atoms, each with a different nuclear spin value, can cluster together in the same energy state, as shown on the right in figure 1.

The interatom interactions are independent of the nuclear spin state, so for N atoms with different spins, the two-body interactions will have N-fold symmetry: The interaction is identical between any atom and each of the other $N-1$ atoms sharing its energy level. That so-called SU(N) symmetry enhances those interactions and boosts otherwise weak effects into pronounced ones, with N as a tuning knob. Researchers are interested in SU(N)-symmetric systems as a model to explore the physics behind a range of condensed-matter systems—for example, cuprates and other transition-metal oxides that display high-temperature superconductivity.

Research on SU(N) Fermi gases started only in the past decade, and previous studies kept the gases in temperature regimes for which the interactions didn't significantly alter the system's thermodynamic behavior compared with noninteracting Fermi gases that lack SU(N)-symmetric interactions. Now the University of Colorado Boulder's Jun Ye, his graduate student Lindsay Sonderhouse, and their colleagues have cooled an SU(N) Fermi gas down to a deeply degenerate regime, with all the states occupied below the Fermi level. Their ultracold strontium-87 gas with 10 distinct nuclear spin states shows clear signs of SU(N) interactions and demonstrates a new way to rapidly cool fermions.[1]

Clocking in

Ye and his colleagues have worked with ^{87}Sr gases for more than 16 years. Starting in 2014, they characterized the gas's scattering parameters and few-body elastic and inelastic interactions for clusters of up to five atoms.[2]

The Ye group's new study was motivated by three-dimensional optical lattice clocks, which were first demonstrated with a Fermi gas[3] in 2017. (For more on optical-lattice clocks, see PHYSICS TODAY, March 2014, page 12.) 3D lattice clocks have the best intrinsic stability of any clock today. But getting a Fermi gas to the required low temperatures is a slow process. Speeding it up would improve clock performance because the detrimental influence of laser frequency noise depends on the time spent preparing the atoms.

The researchers predicted that the en-

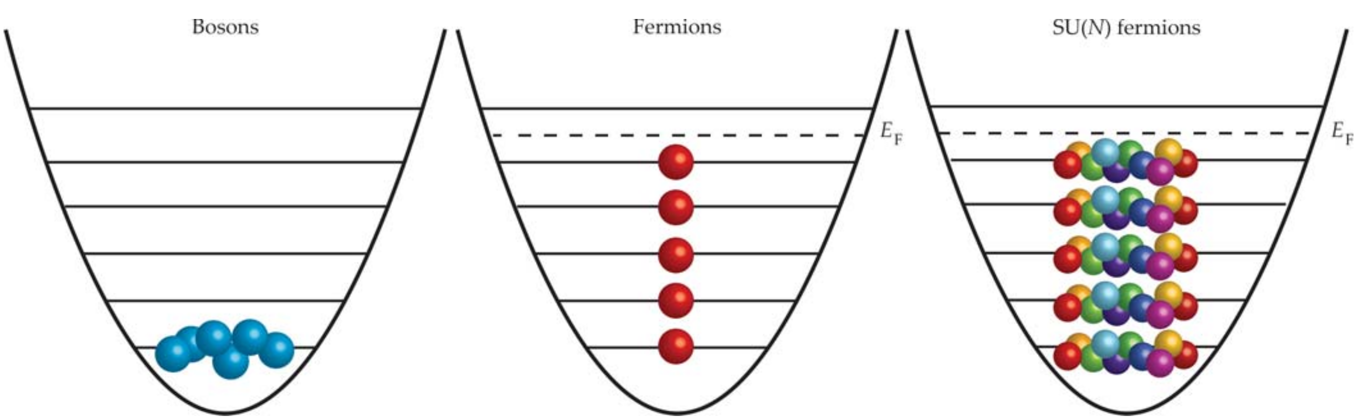

FIGURE 1. BOSONS, FERMIONS, AND SU(N) FERMIONS distribute themselves differently in energy levels at low temperatures. Whereas bosons can settle into the same state, fermions stick to separate levels below the Fermi energy E_F—unless they have interactions with SU(N) symmetry. Those SU(N) fermions can have N interacting particles in each level. (Adapted from ref. 1.)

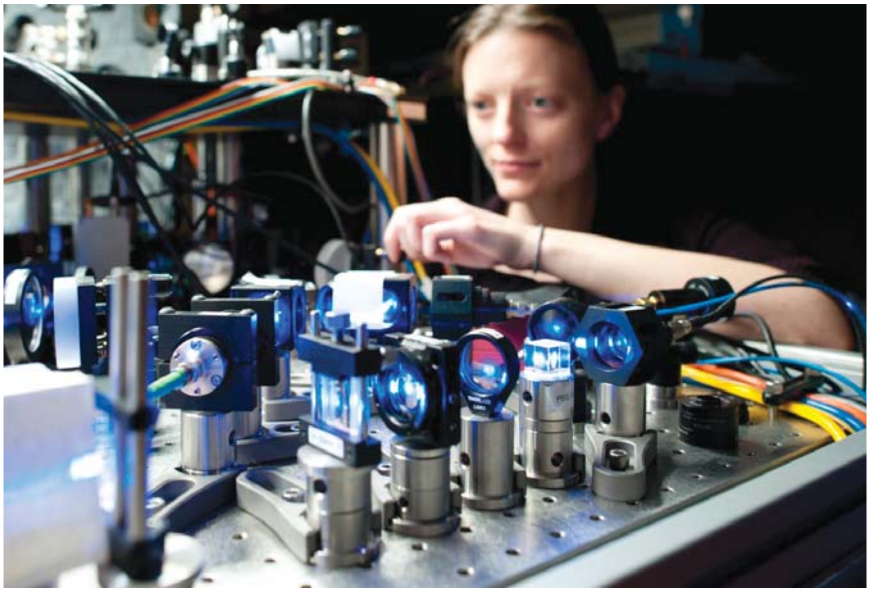

FIGURE 2. LINDSAY SONDERHOUSE adjusts optical components for the laser-cooling experiment in Jun Ye's lab at the University of Colorado Boulder. (Photo by Christian Sanner.)

hanced scattering in an SU(N)-symmetric Fermi gas would hasten cooling. So they timed it. To prepare their gas, the researchers used two stages of laser cooling to bring Sr atoms in a 2D potential down to 2 μK. (A photo of the experimental setup is shown in figure 2.) They then introduced a single dimple trap for the atoms to pool into.

Their goal was to reach the highest density possible inside the dimple. Unfortunately, once atoms were in the dimple, the cooling light created collisions and effective repulsion between them. To overcome that problem, Ye and his colleagues borrowed a technique used for bosons:[4] They added another laser that rendered the atoms inside the dimple transparent to the cooling laser. The transparency laser shifted the excited state of the atoms such that the cooling light was no longer resonant with the transition to the ground state. Atoms outside the dimple continued to be optically cooled, and the ones inside thermalized with them.

The researchers then left the SU(N)-symmetric Fermi gas to evaporate for either 600 ms or 2.4 s, depending on the desired temperature. That evaporation time is down from about 10 s for two-spin gases. They discovered that the more fermions that are colliding in each energy level in the dimple trap, the faster they cool; the total evaporation time scales approximately as $1/(N-1)$. The researchers prepared atoms with all 10 possible nuclear spin states—that is, 10 atoms per energy level—and 5×10^4 atoms per spin state by the end of a 2.4 s evaporation.

Dynamic changes

Although the fermion interactions are weak, they measurably change the system's thermodynamics. One example is the gas's compressibility. The SU(N) interactions are repulsive in ^{87}Sr. And although the compressibility depends only weakly on the number of atoms per spin state, it scales as $N-1$ with the number of spin states.

Ye and his group measured the gas's compressibility from its density fluctuations. To do so, they released the gas from the trap and performed absorption imaging, which gives a snapshot of the density profile. They found that the compressibility was reduced by 18% for $N=10$ compared with the model for a noninteracting Fermi gas at the same density and temperature.

But the density profile alone can't confirm that the system's constituents interact. The fluctuations for an interacting system look the same as a colder noninteracting system, although the mechanisms that limit compression are different: interaction-induced repulsion in the one case and filled energy levels in the other.

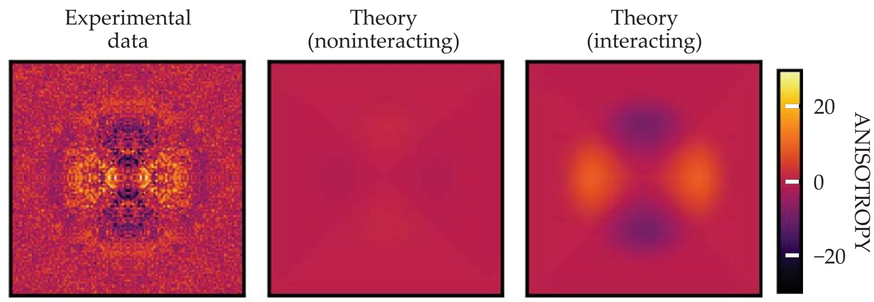

FIGURE 3. SIGNATURES OF FERMI INTERACTIONS in a strontium gas cloud show up as anisotropies in experimental data and theory. After the interacting Fermi gas is released from an optical trap, absorption images record a snapshot of the density profile that may appear anisotropic. But plotting the density profiles' anisotropy reveals a lobed structure in the experimental data and the interacting theory. (Adapted from ref. 1.)

Verifying the presence of interactions requires additional information, such as the expansion dynamics. When an ideal, noninteracting Fermi gas is released from a trap, even an asymmetric one, the gas's profile ends up isotropic because the isotropic momentum distribution produces uniform ballistic expansion. Interactions change the gas's kinetic energy and preferentially propel the atoms along the direction with the largest density gradient, arising from the asymmetry in the trap. As a result, an interacting Fermi gas has a nonuniform distribution. The researchers' gas of ^{87}Sr atoms with 10 different nuclear spin states yielded a noticeably elliptical cloud despite the weakness of the interactions.

Gases with an isotropic density distribution appear circular long after they're released from the trap. But the expansion dynamics of noninteracting and interacting gases still subtly differ. The team's kinetic theory calculations, performed by Ana Maria Rey, show that the density profile n of each gas appears to be circularly symmetric and therefore not indicative of interactions, or the lack thereof. But the differences become clear from the distributions' transpose anisotropy, defined as $n(x, z) - n(z, x)$, shown in figure 3.

In the interacting model and the experimental data, clear lobes emerge in the anisotropy that are not present in the noninteracting model. And because the lobes decrease with increasing temperature, integrals over the transpose anisotropy can be used as a temperature probe with an accuracy of $1/100$ of the Fermi temperature—the temperature at which thermal effects are comparable to quantum effects, defined as $T_F = E_F/k_B$ in terms of the Boltzmann constant and the Fermi energy, or the energy difference between the highest and lowest states occupied by noninteracting fermions at absolute zero temperature.

A new spin

With an efficient preparation method and a basic understanding of their properties, researchers are ready to tackle problems in condensed-matter and high-energy physical systems with SU(N)-symmetric gases. "One can almost think of a deeply degenerate Fermi gas as premium fuel for a quantum simulator," says Ye. Different combinations of kinetic energy, interaction energy, and nuclear spins can be used to systematically explore the phase diagram of, for example, the Fermi–Hubbard model (see the article by Gabriel Kotliar and Dieter Vollhardt, PHYSICS TODAY, March 2004, page 53), whose phase diagram is still unknown despite its common use to describe strongly correlated materials.

The system in the current study follows the Fermi-liquid model for interacting fermions, which describes the normal state of most metals at low temperatures. But in the future, SU(N)-symmetric gases may move to regimes where the theory isn't valid. Exploring the physics in that regime may help researchers understand the origins of the quantum phase transition in heavy-fermion materials.

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References

1. L. Sonderhouse et al., *Nat. Phys.* (2020), doi:10.1038/s41567-020-0986-6.
2. X. Zhang et al., *Science* **345**, 1467 (2014); A. Goban et al., *Nature* **563**, 369 (2018).
3. S. L. Campbell et al., *Science* **358**, 90 (2017).
4. S. Stellmer et al., *Phys. Rev. Lett.* **110**, 263003 (2013).