

QUANTUM GASES

The cold reality of exclusion

Real-space visualizations of the Pauli exclusion principle in clouds of cold fermions show quantum mechanics at work, and suggest a new tool for measuring nanokelvin temperatures.

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The consequences of the Pauli exclusion principle are seen ubiquitously in nature. Pauli exclusion affects how quarks combine into protons and neutrons, and how those in turn stack up to form atomic nuclei. It forces the electrons orbiting the nucleus to occupy different orbits and is thus at the heart of all chemistry. It can decide whether some solid-state material is an insulator or a conductor. On astronomical scales, it keeps white-dwarf and neutron stars from collapsing. Writing in *Physical Review Letters*, Torben Müller and colleagues¹, and Christian Sanner and colleagues² now report independent experiments in which striking effects of Pauli exclusion are observed in dilute gases of atoms cooled down to less than a millionth of a degree above absolute zero. These atomic clouds, 10^{11} times larger than atomic nuclei and 10^{11} times smaller than white dwarfs, can serve as a platform for studying under well-controlled conditions the same fundamental physics that occurs in those seemingly very disparate systems.

The two groups^{1,2} show that at low enough temperature the density fluctuations in their atomic gases are reduced below the level predicted by classical physics, and in agreement with the purely quantum mechanical prediction of ‘anti-bunching’ of identical fermions (in these cases lithium atoms). Related effects were previously studied with electrons and neutrons, and in atomic Fermi gases they have been seen in the suppression of atomic collisions³ and clock shifts⁴, the non-classical size of harmonically trapped clouds⁵, or two-particle correlations in Hanbury Brown–Twiss experiments^{6,7}. But the particular appeal of these new measurements^{1,2} is that Pauli exclusion is directly visualized in real space.

According to the Pauli exclusion principle, two identical fermions cannot occupy the same quantum mechanical state. A more intuitive real-space analogue of this statement is that, simply put, identical fermions avoid each other. But how do we observe this? It is hard to catch fermions in the act of avoiding each other if they almost never meet. The likelihood

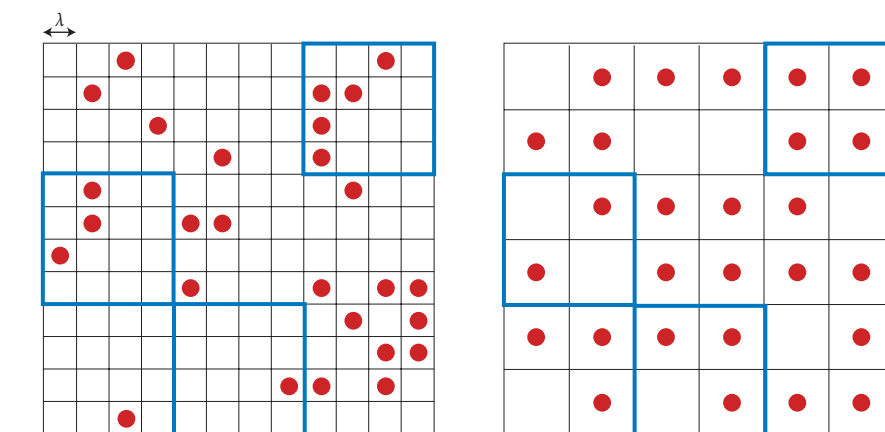


Figure 1 | Fermion anti-bunching. In a hot cloud (left panel) the cell size λ is small and the gas behaves classically. In a sufficiently cold gas (right panel) the effect of the Pauli exclusion principle becomes pronounced. The reduced density fluctuations can be quantified by counting atoms in different regions of the cloud (indicated in blue).

of the dreaded meeting naturally grows with the density of the gas. To understand why it also grows with decreasing temperature, we need to define more precisely the notion of particles bumping into each other in a quantum mechanical sense. In a cold gas, the atomic velocity distribution shrinks and the quantum uncertainty in knowing the positions of the particles grows. This uncertainty defines the size λ of regions of space associated with each particle. What fermions cannot tolerate is another identical particle invading their personal space.

The antisocial nature of fermions becomes pronounced only if the average distance between the particles is comparable to λ (see Fig. 1). To reach this ‘quantum degenerate’ regime one can increase the density or reduce the temperature, or both. The basic idea can be illustrated by considering two samples with equal densities but different temperatures. In the left panel (Fig. 1), the spatial distribution of the particles (shown as red balls) is essentially random, characteristic of a classical gas. Each fermion is in a different unit cell of size λ , but looking from afar we wouldn’t know. In this case λ is so small that it does not

prevent particles from freely mingling and (randomly) bunching into groups. The right panel illustrates the situation where the temperature is lowered so that λ doubles. The average density is still the same, but the atoms are now almost perfectly uniformly distributed owing to Pauli exclusion.

We can quantify the fermion anti-bunching through local fluctuations of the gas density, that is, the variation of particle number between different regions of equal size, such as those indicated by blue squares in Fig. 1. In the left panel, the average number of atoms in such an area is three, and the variance of the atom number is approximately the same. This is what is expected classically, so we cannot tell that we are looking at identical fermions. In the right panel, the average number is the same, but the variance is significantly reduced. This sort of accounting is in essence what Müller *et al.*¹ and Sanner *et al.*² did, using a laser beam and a CCD camera to image and then count the atoms. Repeating the experiments many times and collecting data at different (average) densities and temperatures, they show how the density fluctuations are gradually reduced below

the classical value. There are formidable experimental challenges in attaining the required sub-microkelvin temperatures and extracting clear signals from the tiny atomic clouds, but the basic idea is stunningly simple.

Trusting quantum mechanics, one can then also convert the observed level of fluctuations into a temperature measurement. The results indeed agree with an independent, more classical thermometer based on measuring the momentum distribution in the gas. Now one big hope for the future is that, with the two methods calibrated against each other, the fluctuation-based thermometry can

be extended to even lower temperatures where the momentum method is not sufficiently sensitive.

The present experiments^{1,2} dealt with almost ideal, weakly interacting Fermi gases. This is a perfect setting for showcasing the fundamental principles of quantum mechanics in a beautifully clean fashion. However, even more exciting is the prospect of applying similar techniques to more complex, strongly interacting Fermi gases. In those systems, many issues involving thermometry and particle correlations are yet to be settled, and density fluctuations could very well provide an invaluable

tool for discovering and understanding new physics. □

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HIGH-ENERGY PHYSICS

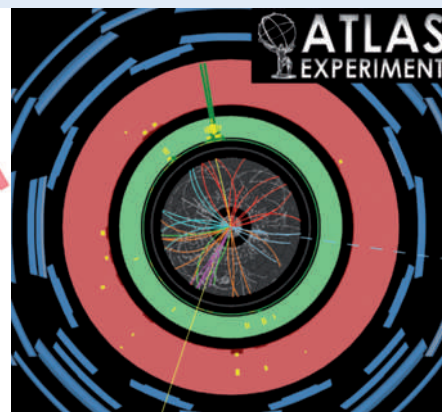
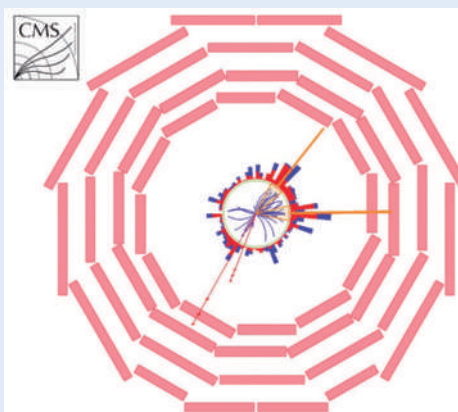
Top of the class

The Large Hadron Collider has been in operation at CERN since the end of March this year, and all is going well. The machine's record-breaking performance, as it collides 3.5-TeV beams of protons, is being matched by the excellent response of the four detectors placed around the collider's 27-km ring. In particular, at the International Conference on High Energy Physics held in Paris, France, at the end of July (www.ichp2010.fr), the collaborations of physicists exploiting the two general-purpose detectors, ATLAS and CMS, were able to report their first probable sightings of top quarks.

Although long thought to complete the line-up of standard-model particles, the existence of the top quark was confirmed by experiment only in 1995, at Fermilab's Tevatron in the USA. The handful of candidate events from ATLAS and CMS are the first direct evidence of top quarks to be gathered in Europe.

Top quarks can be produced in pairs — a top quark and an anti-top quark — in proton collisions of sufficient energy. Each is short-lived and can decay into a *W* boson and another quark, the partner of the top, called 'bottom'. These are also short-lived, the bottom quark creating a spray of other particles known as a jet and the *W* boson producing either two jets, or a lepton (electron, muon or tau) and a neutrino. This 'debris' leaves distinctive signatures in the ATLAS and CMS detectors.

In the events displayed here, CMS has captured two bottom-quark jets, two muons (red tracks) and registered



an energy imbalance in the interaction — missing energy is likely to have been carried off by two undetectable neutrinos; ATLAS has picked up four jets, a single electron (yellow track pointing to a green cluster) and also recorded missing transverse energy (blue dashed line) owing to the escape of a neutrino. Both events match the expected signature of top-quark production.

It's still early days for the LHC experiments (including the two more specialized detectors, LHCb and ALICE), as they 'rediscover' the standard model — checking, calibrating and proving the performance of their systems using the well-understood physics of the known quarks and leptons and of the *W* and *Z* bosons. As data accumulate, the hunt will be on for the unusual: supersymmetric particles are the favourites for an early discovery, possibly in the next year.

But the hunt isn't over yet at Fermilab's Tevatron. In Paris, the Tevatron collaborations, CDF and DØ, presented the outcome of their latest search for the standard-model Higgs boson: its existence is now excluded, at 95% confidence level, in the mass range 158–175 GeV. However, a hint of new physics has emerged in a specific analysis by DØ of particles containing bottom quarks (<http://arxiv.org/abs/1007.0395>). It seems these '*B* mesons' may be subject to a greater level of so-called CP violation than is expected, according to the standard model of particle physics. At present, the significance of the result stands at 3.2σ — tantalizing, but not yet conclusive. Although the Tevatron has been scheduled to shut down for good in 2011, some physicists are now pushing for it to continue running for two or three years more.

ALISON WRIGHT