QUANTUM SCIENCE

Ultracold and unreactive fermionic molecules

Suppressed density fluctuations of $^{40}K^{87}Rb$ gases inhibit molecular collisions and reactions

By **Tanya Zelevinsky**

Many atomic elements have revealed their wavelike quantum nature at temperatures near absolute zero, and matter waves of molecules, which have richer symmetries and dynamics than atoms, could find diverse applications such as fundamental physics measurements, quantum information, and quantum simulations (*1*, *2*). In the past 10 years, techniques of creating and controlling diatomic molecules in the ultracold regime have blossomed (*3*). The challenges of producing large numbers of long-lived ultracold molecules, however, had prevented the formation of a truly quantum molecular gas. On page 853 of this issue, De Marco *et al.* (*4*) now report the creation of a highly nonclassical gas of potassium-rubidium ($^{40}K^{87}Rb$) molecules. Observations of the gas demonstrated that destructive chemical reactions are strongly suppressed in this regime through antibunching effects that arise from Fermi-Dirac quantum statistics.

Classical particles are distinguishable, and interchanging any pair leads to a different configuration. However, quantum particles are identical and can be freely interchanged up to an overall sign change of the wave function. Fermions such as $^{40}K^{87}Rb$ molecules obey the Pauli exclusion principle that forbids more than one fermion per quantum state. For atoms and molecules, fermionic behavior becomes apparent only at very cold sample temperatures T, where de Broglie wavelengths exceed typical separations between the particles. Fermionic quantum degeneracy, characterized by T below the critical Fermi temperature T_F, was first observed in a noninteracting gas with K atoms (*5*).

De Marco *et al.* now demonstrate quantum degeneracy of molecular fermions at 50 nK, or $T < 0.3\ T_F$, by assembling the molecules from exceptionally well-overlapped degenerate atomic gases of K and Rb that have been made extra cold through several steps of laser cooling (*6*). The assembly procedure involves turning K and Rb atom pairs into giant, barely bound dimers with a magnetic field and then shining a light pulse to increase the binding energy without releasing any excess kinetic energy (*7*). The energy diagram for the molecules trapped in a focused laser beam (see the figure) shows their occupation of individual quantum states. At $T < T_F$, the lowest trap energy levels are uniformly filled up to the Fermi energy.

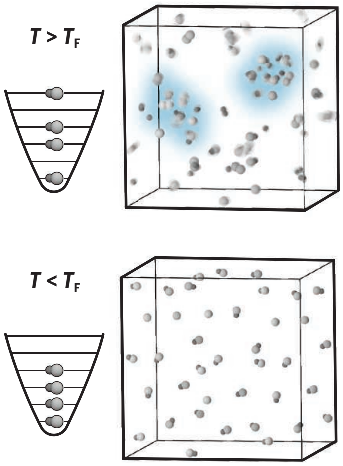
Quantum degeneracy affects not only the energy distribution of the particles but also their spatial distribution. In particular, spatial fluctuations in degenerate gases bear a strong signature of the underlying particle statistics: They are enhanced for bosons and suppressed for fermions. This spatial antibunching expected for KRb is shown in the figure, bottom. At $T > T_F$, the gas behaves classically and exhibits regions of spatial lumping or clustering (highlighted in blue). In the degenerate regime where $T < T_F$, the density is highly uniform. Suppressed density fluctuations in degenerate Fermi gases were first observed with ultracold atoms (*8*, *9*), and the present study breaks into this regime with molecules.

De Marco *et al.* hypothesized that antibunching would have an outsize effect on the reactivity of the molecules. Tens of thousands of molecules are optically trapped as a bulk gas and are normally free to collide. Their residual thermal energy in these collisions can drive the reconfiguration of molecular bonds through chemical reactions, which leads to loss of molecules in the original state. The Pauli exclusion principle partly protects fermionic molecules from reacting at ultracold temperatures (*10*). However, the reaction rate constant that De Marco *et al.* measured for KRb in the degenerate regime was much more strongly suppressed at the coldest temperatures than would be expected. As illustrated in the figure, molecules can react if they find each other and collide, which can only happen in the presence of spatial clumps. Modeling the fermionic antibunching based on the parameters of their optical trap, the authors show that this effect is fully sufficient to explain the anomalously low molecule losses at temperatures $<0.6\ T_F$.

Chemical processes near absolute zero is a fascinating field in itself (*3*). However, the ability to avoid reactions between KRb molecules opens the door to many exciting investigations that require a long-lived, quantum degenerate molecular gas, such as studying many-body correlations facilitated by dipole-dipole interactions between the polar molecules. The interaction-dominated regime can be accessed by aligning the molecules with electric fields, where long loss-free observation times are desirable to maximize the effects of the interactions. The strong suppression of reactions in Fermi-degenerate molecular gases could also help realize protocols for quantum-information processing with polar molecules. ■

Antibunching suppresses reactivity

Quantum gas of fermionic potassium-rubidium molecules ($^{40}K^{87}Rb$) is less reactive at temperatures below the Fermi temperature T_F.



Hotter molecules react and leave
At temperatures T above T_F, many lower energy states in the trap are unfilled (left). Warmer molecules in the trap (shown spatially on the right) occupy random positions, leading to density fluctuations and clustering. In the higher-density region (highlighted in blue), molecules are more likely to collide, react, and leave the trap.

Colder molecules stay chill
For T well below T_F, the lower-energy states have a very high probability of being filled (left). Colder Fermi-degenerate molecules (right) exhibit antibunching behavior. The molecules have a highly uniform density and are largely immune to destructive collisions.

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Department of Physics, Columbia University, New York, NY USA. Email: tanya.zelevinsky@columbia.edu

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