Studying spin physics with moving molecules

The rotation and movement of polar molecules in an ultracold gas are intertwined with each other through dipolar interactions between the molecules, giving rise to rich, tunable dynamics. This molecular platform could advance the understanding of electron-transport phenomena in condensed-matter systems and be used for quantum sensing.

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The mission

Strongly interacting electrons are central to many unusual electric and magnetic properties of materials. However, investigating these systems has been challenging, given their complexity. Using well-controlled quantum systems, such as atoms and molecules, to simulate electron behaviour could help to tackle these challenges. For example, polar molecules have a negatively charged part and a positively charged part, and the dipolar interactions between these molecules (whereby the parts of molecules with the same or opposite charges repel or attract each other, respectively) can be tuned by external fields. The rotations of these molecules can simulate the spin (the intrinsic angular momentum) of electrons. Such features result in various interesting dynamics[1]. When polar molecules are pinned in a lattice made by interfering laser beams (an optical lattice), their dipolar interactions could simulate the electron dynamics that generate magnetism in certain materials.

Introducing molecular motion further enriches the system dynamics, when the quantum states of the molecules and the interactions between them are precisely controlled. In this scenario, molecular collisions and rotations are coupled by the tunable dipolar interactions. Thus, this 'itinerant' (travelling) system should give access to some of the most intriguing phenomena in condensed-matter physics, such as superfluidity (frictionless fluidity) and spintronics (electronics that depend on electron spin).

The observation

We studied the spin-motion dynamics of interacting molecules controlled by electric fields. We produced a quantum gas of potassium–rubidium molecules by associating ultracold atoms using lasers and magnetic fields[2]. Then, we used microwave radiation to induce rotation of the molecules. After a holding time, we analysed the evolution of the rotational states under the influence of the molecular interactions, which can change the rotation frequency and lead to a phase shift in the rotation. By measuring the rotational phase, we assessed the molecules' state evolution and the dynamics of the system.

After short holding times, dipolar interactions influenced the energy, and thus the frequency, of the rotation (Fig. 1a), resulting in an extra rotational phase accumulating after the holding time. We controlled shifts in rotational energy by changing the molecular dipole moment using external electric fields and by inducing different rotational states. We found that the way the molecules rotate determines the strength and sign of the dipolar interaction. After long holding times, the molecules moved and collided with each other. Each collision caused random phase shifts, and so the molecules' rotations lost their phase synchronization. Stronger dipolar interactions sped up the collisions and thus caused a faster loss of phase synchronization (Fig. 1b). Overall, we discovered complex quantum dynamics when the molecules' rotation and motion were coupled with each other by the dipolar interactions, which themselves evolved with molecular rotation.

Future directions

Our platform enables the precise tuning of interparticle interactions and experimental parameters, in turn enabling the investigation of electron-transport dynamics that arise from the competition between interaction and motion, and allows us to realize previously unobserved many-body quantum phenomena with high control. Some examples of these phenomena include spin squeezing[3] (which could be meteorologically useful) and spin–orbit coupling[4] (the interaction between an electron's spin and its motion in certain materials).

The system's usefulness for certain applications is limited by temperature. The exploration of exotic many-body dynamics requires a sufficiently low temperature such that random thermal motion is suppressed compared with the interaction dynamics. We prepared molecular gases in relatively high temperatures (about 450 nanokelvin), which were not low enough to reach a 'quantum degenerate' regime in which the matter waves of the particles strongly overlap and collective quantum behaviours dominate. Quantum degenerate gases of molecules[5] can display surprising, qualitatively different dynamics that remain to be explored in this system.

Reaching quantum degeneracy could be achieved through a process called evaporative cooling, which has previously been demonstrated in molecular systems[5]. This technique could prepare the system for various exciting applications, including exploring phenomena such as spin squeezing and spin transport in one or two dimensions.

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EXPERT OPINION

"This is impressive work characterizing the combined effects of spin–spin interactions and particle motion in a gas of potassium–rubidium molecules confined to 2D planes. The results represent a milestone in the control of molecular quantum gases and open the door to the experimental exploration of fundamental physical phenomena that have been proposed in recent years but that were out of experimental reach, such as spin liquids and many-body localization with dipoles." (CC BY 4.0)

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FIGURE

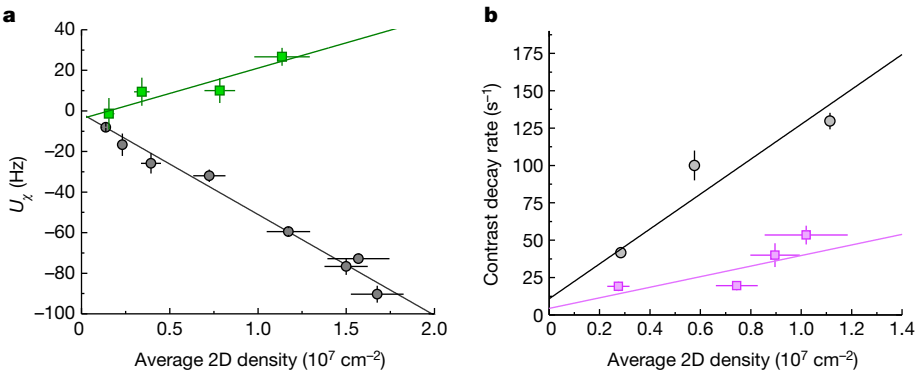

Figure 1 | Coupled spin and motion dynamics in polar molecules. An ultracold gas of polar molecules was trapped in a 2D plane using light. The molecules were induced to rotate, and the dipolar interactions between them were tuned using electric fields. **a**, Dipolar interactions led to density-dependent shifts (U_χ) in the rotational energy. The sign and magnitude of these shifts were controlled by external electrical fields and by inducing different rotational states. Green and black data points represent measurements for two different states of molecular rotation (error bars are one standard error from linear fits). **b**, Moving molecules collide, resulting in random shifts in the phase of the molecules' rotations, leading to decay of their phase synchronization. When the dipolar interactions are stronger (grey, as opposed to purple), collisions are stronger and the rate of this decay (contrast decay rate) is higher at the same molecular density (error bars are one standard error from exponential fits).

BEHIND THE PAPER

Energy shifts caused by dipolar interactions between molecules have been studied in theory, but thus far had not been experimentally demonstrated. This is because of the high sensitivity of molecular transitions to environmental noise from external electric fields and the laser light used for trapping. These factors randomly shift the rotational frequencies and overwhelm the effect given by the dipolar interactions. A key technique that helped us to overcome this challenge is dynamical decoupling. By periodically driving the system with microwave pulses, noisy shifts caused by the environment were suppressed. The effect of dipolar interactions was preserved, enabling us to measure the small shift in rotational energy attributable to the dipolar interactions even against a large noise background. By carefully adjusting the parameters for the dynamical decoupling, we found that environmental noise could be suppressed enough to see even the effect of molecular collisions.

J.-R.L.

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FROM THE EDITOR

This work stands out as a demonstration that research on many-body physics with controllable quantum systems is entering a new phase. Pioneering developments such as this work allow researchers to reliably trap and control ultracold molecules, offering the opportunity to explore an increasing range of physical models that would be difficult to simulate in atomic systems.

Federico Levi, Senior Editor and Team Manager, *Nature*