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Quantum physics

Polar molecules form elusive quantum state

Lauriane Chomaz

A gas of molecules that interact over long distances has been cooled to mere nanokelvins, resulting in the emergence of a state known as a Bose–Einstein condensate — the first of its kind in this type of molecular system. **See p.289**

Three decades ago, physicists created a curious quantum state by controlling a collection of individual atoms using light and magnetic fields[1]. By cooling this gas-like group of atoms to ultracold temperatures, the researchers produced a Bose–Einstein condensate — a state in which the particles of matter (here, the atoms) collectively form a macroscopic quantum wave. The achievement transformed research in quantum physics by giving scientists access to quantum behaviours in well-controlled and tunable settings[2]. But generalizing the approach to objects that interact strongly and in complex ways is challenging, such that many behaviours have remained beyond the scope of the platform. On page 289, Bigagli *et al.*[3] report the realization of another Bose–Einstein condensate — this time, in an ultracold gas of polar molecules.

Polar molecules are particularly interesting for quantum physicists because the molecules can interact strongly with each other even when they are far apart. Long-range interactions are ubiquitous in natural systems — ranging from electrons in solids to cosmological objects — but such interactions are typically absent from ultracold gases, so scientists have long tried to introduce them into these systems. For electrically neutral particles, these interactions are usually dipole–dipole interactions, in which the particles behave like tiny magnets, repelling each other when side by side and attracting each other when head to tail. Remarkable advances have been made in engineering these interactions in atomic systems. But such interactions are either weak, when they occur between atoms in their lowest-energy state, or short-lived, when they are induced by exciting the atoms, and this limits the range of behaviours that they can emulate[4,5].

Another approach is to use ultracold gases made from molecules comprising two chemical elements. These molecules have an uneven distribution of electric charge across their molecular bond — making them polar — and this gives rise to an electric dipole that interacts with the dipoles of other molecules[5]. Ultracold samples of such molecules have been created in laboratories around the world, either by pairing up atoms in ultracold gases containing two atomic species or by directly cooling the molecules. These systems have much stronger dipolar interactions than do those containing atoms in their lowest-energy state. They also show a richer variety of behaviours arising, for example, from the internal rotations and vibrations of the molecules. Yet this richness also makes them more difficult to control, so that the quest for a Bose–Einstein condensate made from polar molecules has been unsuccessful for more than 20 years.

A major obstacle to forming and cooling stable molecular assemblies is the fact that collisions between molecules often cause them to leave the trap (usually made from light) that holds them. This is because the molecules tend to 'stick' together when they collide, forming two-molecule complexes that are more vulnerable than individual molecules (Fig. 1a). They can, for example, easily be forced out of the trap when they collide with a third molecule[6].

Over the past few years, scientists have had some success in taming these molecular losses through a technique called collisional

From the archive

Artificial daylight lacks commercial interest, and a fundamental science kickstarts the bid for the Channel Tunnel.

100 years ago

[O]ne might comment perhaps on the lack of interest shown by commercial firms in the subject of artificial daylight, and the improvement of lighting generally. In 1920 there were 15,000 fully corrected artificial daylight lamps in use in America, and the demand was then rapidly growing. In Great Britain it is doubtful whether a tenth of the American demand has been reached. The saving of time effected by the employment of such lamps in bad weather is so great that this indifference seems extraordinary, and the sooner this state of affairs is remedied the better for those industries to which this subject is of importance.
From *Nature* 12 July 1924

150 years ago

We fear there are still many who fail to see that any good can come of scientific research unless it has some well-defined "utilitarian" object in view ... [T]o the sceptic we could not recommend a better example of how indispensable is thorough scientific research as a basis for the useful arts than the results of the investigation into the geology of the Channel which Mr. Prestwich ... presented to the Institution of Civil Engineers last December ... This study of the strata which underlie the Channel, and which seems to us an almost perfect example of close and careful reasoning on physical facts, is now brought forward to enlighten the projectors of a tunnel between England and France as to the nature of the material with which they will have to work ... Mr. Prestwich's plan is to discuss carefully all the strata which underlie the Channel, from the London clay down to the Palaeozoic series ... [S]ince so cautious a reasoner as Mr. Prestwich thinks it possible to carry out the scheme from a geological point of view, we should think that if it could be proved that the undertaking would pay, our engineers would be eager to show that the resources of their art are quite equal to its successful accomplishment.
From *Nature* 9 July 1874

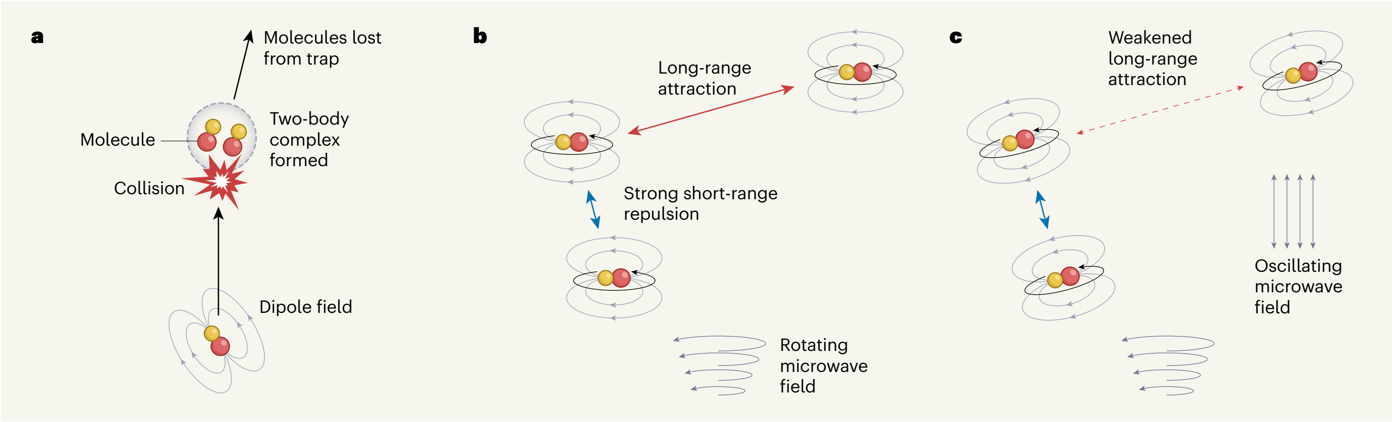

Figure 1 | Taming losses in ultracold gases of polar molecules. Physicists have long tried to form a quantum state called a Bose–Einstein condensate in a gas of polar molecules, which have electric charge distributions that make them interact through their 'dipole' fields. **a**, The molecules are trapped, usually with laser light, but they can form two-body complexes that can be lost from the trap – by colliding with a third molecule, for example. **b**, A rotating microwave field prevents these complexes from forming by making the dipoles rotate and by modifying their interactions so that they are strongly repulsive at short range. However, an attraction at long range remains, and this induces losses through a process known as three-body recombination (not shown). **c**, Bigagli *et al.*[3] introduced a second (oscillating) microwave field, which prevents the three-body losses by weakening the long-range attraction and simultaneously reduces the overall interaction strength (not shown), allowing the authors to form the first Bose–Einstein condensate in a gas of polar molecules.

shielding, which prevents the molecules from getting close enough together to form complexes[7]. Shielding involves engineering the dipolar interactions between molecules so that the energy required for them to get too close to each other is prohibitively high. This approach was first undertaken using a static electric field to orient the molecules' dipoles, and a trap that prevents the molecules from interacting along their dipole axis, thus suppressing the dipolar attraction[8]. Since 2018, another scheme involving a rotating microwave field has been proposed[9] and implemented[10,11]. The microwave field acts on the molecular internal states in such a way that the molecules repel each other when they are close together (Fig. 1b).

These shielding strategies have allowed physicists to realize collective quantum states in systems made up of particles known as fermions, which are prevented by a principle of quantum mechanics (the Pauli exclusion principle) from simultaneously occupying the same quantum state[8,11]. However, Bose–Einstein condensation occurs when many particles occupy a single quantum state, and this can happen only in systems made up of particles known as bosons. Unfortunately, it is precisely this property of multiple occupancy of a quantum state that makes bosons more susceptible to losses than are fermions. This has made Bose–Einstein condensation difficult to realize in systems of polar molecules – a difficulty worsened by the fact that microwave shielding induces losses through a process called three-body recombination, which arises as a result of long-range attractive forces.

Bigagli *et al.* overcame this problem to achieve a polar molecular Bose–Einstein condensate by adapting and refining the microwave-shielding strategy to use not one but two microwave fields: a rotating one and an oscillating one (Fig. 1c). The two-field scheme allowed the authors to suppress the losses arising from the formation of two-molecule complexes, as well as those from three-body recombination, by weakening the long-range attraction. Under the two-field shielding conditions, the ultracold molecules still interact with each other, but they do so less strongly. This results in a weakly interacting gas in which isotropic (direction-independent) repulsive interactions, known as contact interactions, have a similar strength to the anisotropic (direction-dependent) dipolar interactions, creating favourable conditions for forming a conventional Bose–Einstein condensate.

The authors started by bringing ultracold sodium (Na) and caesium (Cs) atoms together to form a gas of 30,000 NaCs molecules, in which the molecules had no internal excitations, such as vibrations or rotations. They then applied their microwave fields and used a technique called evaporative cooling to form a Bose–Einstein condensate containing 200 molecules at a temperature of 6 nanokelvin, and with a typical density of 10^{12} molecules per cubic centimetre and a lifetime of a few seconds. The size and density of the condensate was moderate compared with its atomic counterparts[1,2,4], which typically contain several hundred thousand particles at densities of 10^{14} atoms per cubic centimetre. However, a quantity known as the gas parameter indicates that the molecular and atomic systems are similar in terms of the strength of their interaction, despite the fact that the molecular gas has a lower density.

> **"The quest for a Bose–Einstein condensate made from polar molecules has been unsuccessful for more than 20 years."**

Bigagli and colleagues' achievement is impressive, concluding an effort of several decades, and yet it is only the beginning of further endeavours. A key challenge now is to make the molecules in the system interact strongly with one another. This would, for instance, open up the possibility of creating new states of matter[7], or of simulating quantum behaviours that have so far remained inaccessible. Although the strength of the interaction itself can be readily tuned by modifying the shielding, the stability of such strongly interacting systems is still unknown. It will be exciting to see how the authors' approach can be adapted and improved to meet such challenges.

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