ULTRACOLD ATOMS

Cool ion chemistry

Hybrid traps for laser-cooled ions and neutral atoms make excellent cold-chemistry laboratories. Experiments now show that engineering quantum states can provide additional control for accessing and manipulating chemical reaction rates.

Paul S. Julienne

A promising avenue for precise measurement and control of chemical reaction rates involves trapping reactants and cooling them to extremely low temperatures — a technique that has benefited from considerable advances in recent years. But preparing reactants in specific quantum states can enable even greater control. Now, writing in *Nature Physics*, Lothar Ratschbacher and colleagues report this extra degree of control in cold chemical reactions by engineering the quantum states of single trapped ions and ultracold atoms[1].

Trapped ions are ideal for precision measurements and quantum logic, whereas ultracold gases of trapped neutral atoms are perfectly suited for studying a wide range of exotic quantum phenomena associated with Bose–Einstein condensation or the pairing of fermions. But it is not easy to trap ion and neutral species simultaneously: this requires the combination of different trapping technologies. The confining forces are very strong for charged particles, but orders of magnitude weaker for neutral species. Attempts to overcome these challenges have already started, with the first measurements of cold ion–atom collision rates in clouds or crystals of ions[2–5] — or even a single ion in a Bose–Einstein condensate[6,7].

By combining a single trapped ion with a cloud of extremely cold trapped atoms and introducing simultaneous control over the specific internal states of each species, Ratschbacher *et al.*[1] have taken an important step towards combining all the elements needed for achieving the desired control over the collisions and reactions of cold ions with neutral species. The 'chemistry' is especially simple, because the experiment just uses the atomic species $^{174}Yb^+$ and ^{87}Rb, which can have a charge-transfer chemical reaction to make a neutral ^{174}Yb atom and a $^{87}Rb^+$ ion. The reactant $^{174}Yb^+$ ion was prepared in its electronic ground state or by optical pumping in either of two different long-lived excited states. The ~200 nK ^{87}Rb atoms were prepared

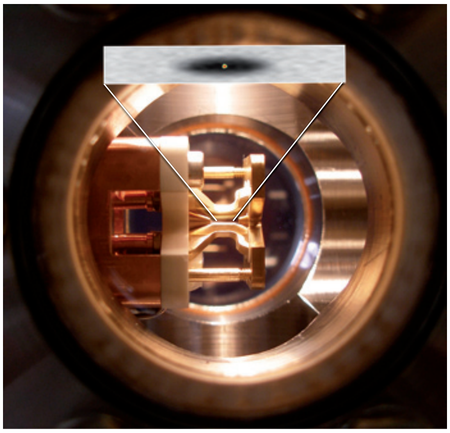

Figure 1 | Ion trap apparatus. A single ion is trapped inside a cloud of ultracold neutral atoms where quantum-state-controlled chemical reactions between the two species take place.

in either of the two different hyperfine spin components of the electronic ground state. By monitoring the subsequent rate of single-ion disappearance for different neutral-atom densities, the inelastic collision rate coefficients were measured for any specific combination of ionic or atomic states. Unlike in previous experiments, after the preparation of the initial state excited-state collisions occur 'in the dark' (without optical mixing of ground and excited states). Excited species can be lost either by an inelastic de-excitation collision or by a charge-transfer reaction. If the two reactant species are in their ground states, however, loss is only possible through the charge-transfer reaction. Although it should also be possible to trap and probe ionic reaction products, Ratschbacher *et al.*[1] were only able to take some very preliminary — albeit important — steps in this direction.

The simplest theory for ion–neutral collisions, dating back to 1905, is the Langevin model[8], which calculates the ability of the long-range polarization potential between the ion and atoms to capture the two particles as they move towards one another along classical trajectories. If the two species have unit probability of reacting once captured, then the reaction rate is just the Langevin capture rate. Ratschbacher *et al.*[1] compared their measured collision rates to the Langevin rate, and found a wide variation. Only the rate involving one of the excited $^{174}Yb^+$ levels had a rate near the Langevin value, whereas all other rates were much smaller.

The cold non-resonant charge-transfer reaction of these two unlike species in their electronic ground states is expected to be relatively small, as it occurs through a radiative mechanism requiring the emission of light. But the experiment revealed that the measured collision rates differ by a factor of 35 when the ^{87}Rb atoms are prepared in two different hyperfine levels. This is striking and represents rather unusual 'chemistry', as the two hyperfine levels are separated in energy by only 30 μeV — a negligible amount compared with the chemical bond energy or the trap depth. Nuclear spin and hyperfine structure do not normally affect chemical reaction rates. This cold ion–atom system is still far too 'hot' to experience the kind of nuclear spin-dependent quantum-statistical modification of the threshold collision rates demonstrated for the reaction of two ultracold molecules[9]. It seems that theorists will have their work cut out to understand these new data on ion–neutral collisions.

The active control of the collisions of cold neutral atoms using magnetic fields has been extraordinarily successful in the context of quantum gases with temperatures of the order of microkelvins or less[10]. Research into control of the chemical reactions of cold polar molecules with electric or electromagnetic fields is only just beginning. Will tunable field control be possible for ion–atom or ion–molecule collisions? In current experiments, the ion temperature is only around 50 mK, limited by inherent micromotion in the ion trap, and therefore the collisions are still far from the quantum threshold regime that has been explored with nanokelvin molecules[9]. Better control of micromotion will be necessary to explore lower temperatures where control prospects are better.

Ion–atom collisions are expected to have a much higher density of tunable scattering resonance states than do neutral-atom collisions — and ion–molecule collisions should have an even larger density of states. How the scattering resonances of cold ionic and neutral species are affected by external fields has yet to be explored. These resonances could potentially be fine-tuned to match the tiny thermal energy spread of extremely cold reactants, thus selecting different resonant-modified reaction paths. The very long-range nature of ion–neutral interactions may also open up the investigation of exotic few-body or many-body effects, just as cold atoms have provided new directions in these topics. Hybrid ion–neutral systems are definitely worth keeping an eye on, particularly as experimental techniques continue to mature. ❐

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QUANTUM GASES

Superfluidity goes 2D

In two-dimensional systems, superfluidity occurs in the absence of the long-range order associated with Bose–Einstein condensates. This phenomenon is illustrated in the direct observation of superfluidity in a 2D atomic Bose gas.

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Superfluidity has a rich history. Writing in *Nature Physics*, Rémi Desbuquois and colleagues[1] add another experiment to the chapter of superfluidity in atomic gases. That story began almost 75 years ago, in 1938, when two independent groups — Pyotr Kapitza[2] in Moscow, and Jack Allen and Don Misener[3] in Cambridge — showed that at low temperatures, below the so-called lambda temperature, helium flows without resistance. Given the similarity to the behaviour of superconductors, in which current flows without resistance, Kapitza named this phenomenon superfluidity.

Within months of the first experimental demonstrations, Fritz London[4] suggested that superfluidity could be related to Bose–Einstein condensation — the macroscopic occupation of the same state, characterized by long-range phase correlations. However, this suggestion proved controversial. Just a few years later, Lev Landau[5] published an alternative description, arguing that the observed behaviour could be explained using a two-fluid model, with a 'normal' component that has viscous flow and a 'superfluid' component that flows without friction. Landau also predicted the existence of a critical velocity for the superfluid flow, above which it would dissipate into excitations.

It took almost 50 years for the condensate fraction to be measured in superfluid helium, proving that Bose–Einstein condensation (macroscopic occupation of a single state) and superfluidity (lack of viscosity) are in fact related. However, in superfluid helium, even at the lowest temperature, where the superfluid fraction should be nearly 100%, the strong interactions between the helium atoms limit the condensate fraction to only 10%. Although it is now widely accepted that superfluidity and Bose–Einstein condensation are related, important questions remain about the fundamental relationship between these two phenomena.

Ultra-cold atomic gases are ideal systems for studying these questions. Unlike liquid helium, atomic Bose gases are weakly interacting, making the theory much more tractable. In 1995, Bose–Einstein condensation was first realized with a dilute atomic gas[6], and within a few years it was shown that atomic Bose–Einstein condensates (BECs) are also superfluids[7]. The first atomic BEC was created with a 3D gas. In a 3D atomic Bose gas, the condensate is also a superfluid, with the condensate fraction and superfluid fraction essentially equal. In lower-dimensional systems, however, things get very interesting.

A 2D Bose gas is expected to behave in a very different way. At low temperature, a phase transition does occur, but it is not a transition to a BEC with long-range order. Given the link between superfluidity and Bose–Einstein condensation, one might expect that superfluidity would not occur either, but surprisingly this is not the case. A striking feature of the transition, called the Berezinskii–Kosterliz–Thouless (BKT) transition, is a sudden jump in the superfluid fraction without the long-range order that typically characterizes a BEC. Although recent experiments have shown evidence of this transition[8–10], until now superfluidity has not been directly observed in a 2D atomic Bose gas.

Desbuquois *et al.*[1] present the first direct observation of superfluidity in a 2D Bose gas. To demonstrate the superfluid behaviour Desbuquois and colleagues measured the critical velocity of the superfluid flow. To stir the atomic gas an object was dragged through a portion of it. When the gas is in the normal regime the object experiences a viscous drag force, which leads to the heating of the gas, regardless of the object's velocity. However, if the gas is in the superfluid regime, the object flows without resistance as long as the object's velocity is below a critical value. Above that value, as originally predicted by Landau, excitations occur, which in turn increase the temperature of the gas.

To create a 2D gas, Desbuquois and colleagues used an atom trap with tight confinement in the vertical direction, and