Quantum LEGO—building ultracold molecules

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Cooling matter is not easy. Atoms and molecules have the tendency to jump around, to rotate and to vibrate. Freezing these particles by slowing them down is a complicated process. For individual atoms, physicists have figured out over the years how to carry out this cooling process, using techniques like laser cooling, where finely tuned lasers remove energy from the particles. Molecules, on the other hand, are much harder to cool down so that they stand still. These particles consist of two or more atoms that are bound together, and as compound particles they are able to jiggle around in many more ways.

First cool, then build

Still, physicists would like to have a dense gas of ultracold molecules at their disposal. Since it is not yet possible to directly cool the molecules themselves into this regime, physicists first cool down atoms – a process which is much easier – and then attempt to build molecules. The question is: how does one get these super cold, motionless atoms to 'click together' to form the desired molecules?

The answer to this question is a process that exploits a phenomenon known as Feshbach resonance. Molecules of a given type can exist for different configurations of the atoms' internal states, and all of these states have slightly different energies. By applying a magnetic field, the energy of an unbound atom pair can be tuned to exactly the energy of a specific molecular level. Florian Schreck, the research group leader, explains: "If a coupling mechanism between the atom pair and the molecule exists, one can create a situation in which atom pairs 'resonate' with molecules, thereby clicking together and forming the desired end product."

New type of ultracold molecules

So far, only gases of molecules that consist of two alkali atoms, atoms with a single electron that can form chemical bonds, have been created with the desired high density and ultracold temperature. The group of experimental physicists at the University of Amsterdam, together with theoretical physicists from Nicolaus Copernicus University in Torun, Poland and from Durham University in the UK, have now made an important step towards the creation of a second type of ultracold molecule. More precisely: they have discovered Feshbach resonances between the alkali element rubidium and the alkaline-earth element strontium, which has two electrons to form bonds with. These resonances are suitable to construct ultracold rubidium-strontium molecules, particles with very different properties from the ultracold molecules that have been constructed so far.

The main challenge in this work was that the usual strong coupling mechanisms that exist between alkali atoms do not exist for alkaline-earth atoms. Eight years ago, theorists Piotr Zuchowski and Jeremy Hutson predicted very weak and unusual coupling mechanisms that would still lead to Feshbach resonances. However, the theory was unable to predict the value of the magnetic fields at which these resonances would occur. Employing precise molecular spectroscopy, the experimental team was now able to find the magnetic field values and to experimentally confirm the existence of the sought-for Feshbach resonances.

Interesting applications

There are several reasons why physicists are interested in creating different types of ultracold molecules. First of all, a very low temperature allows researchers to study the properties of the molecules themselves better: anyone who has ever tried to study a fly knows that this is much easier if the fly is motionless on the wall than if it is buzzing around, and the same thing is true for molecules. Precision studies of molecules could uncover fundamental physics going beyond the current standard model of fundamental particle interactions.

Secondly, cold molecules can be prepared in very precise states that can then be used for quantum-controlled chemistry: performing delicate chemical reactions with full control over all aspects of the initial components and the reaction conditions.

Finally, there are applications to the many-body physics of quantum particles. When molecules are very cold, their quantum fuzziness becomes apparent. Molecules can be at several locations or in several internal states at the same time and the locations or states of several molecules may depend on each other in intricate ways. New quantum phenomena can emerge, which are hard or impossible to describe using even the best supercomputers. By controlling the interactions between the molecules or the potential landscape through which they are moving, physicists hope to learn about these emergent phenomena. Schreck says: "Gaining insights into the collective behavior of many quantum particles, be it molecules in a gas or electrons in a metal, may open the door to materials with unheard of properties."

The results expand the set of available tools for the 'quantum LEGO' of building ultracold molecules from atoms. Schreck: "With this knowledge, it should soon be possible for the first time to make an ultracold, high density gas of rubidium-strontium molecules. Given the number of potential applications that such a gas has, we are very excited about these new possibilities."

More information: Observation of Feshbach resonances between alkali and closed-shell atoms, *Nature Physics* (2017), DOI: 10.1038/s41567-018-0169-x

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