COLD MOLECULES

Making perfectly controlled arrays of molecules at rest

Molecular collisions are probed with ultracold optical traps

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Since their invention in the early 1970s, optical tweezers have evolved from enabling simple manipulation to applying calibrated forces on—and measuring nanometer-level displacements of—optically trapped objects. Optical tweezers use laser light to create a force trap that can hold nanometer- to micrometer-sized dielectric objects (*1*). They can noninvasively manipulate objects such as biological cells in water, as well as apply piconewton forces to single molecules in solution or in free space. Combining these optical traps with laser cooling, which stops atoms and small molecules from moving in free space at ultracold temperatures, allows for precision measurements. On page 1156 of this issue, Anderegg *et al.* (*2*) created an array of optical tweezers filled with ultracold calcium monofluoride (CaF) molecules. Individual molecules were brought together by tweezer traps, enabling their interaction. Such unprecedented control should allow high-precision observations of molecular collisions and could provide insight into specific chemical reactions.

Laser cooling and optical tweezers are an important outgrowth of the development of laser technology. Nearly stopping atoms and small molecules has revolutionized atomic and molecular physics. The strategy allowed the creation of quantum phases of matter such as Bose-Einstein condensates, where a group of atoms clump together and behave as a single atom. Cold atom traps are important for metrology, as they improve atomic clocks and atom interferometer precision. Cold traps also allow manipulation of coherences among spin states of chains of currently up to 50 ions or neutral atoms, which is of importance for quantum information science. Creating ultracold CaF molecules in a single ro-vibrational quantum state at tens of microkelvin holds promise for controlling molecular collisions and chemical reactions.

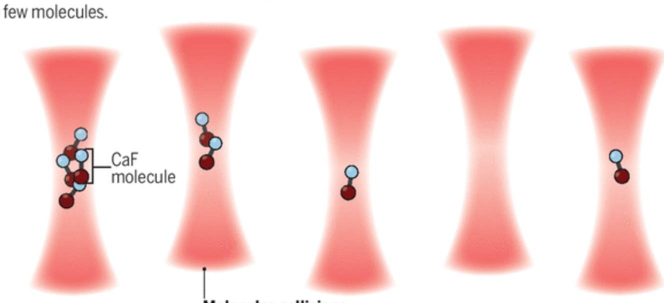
Ultracold molecules can have a de Broglie wavelength larger than the range of their intermolecular forces. This difference requires treating the rearrangement of chemical bonds quantum-mechanically. Most research with ultracold neutral molecules has been performed in optical lattices, in which the molecules are held at the intensity minima of a laser beam reflected from a mirror. This means that molecules are separated from their neighbors by exactly one-half of the wavelength of the laser (approximately 500 nm). Anderegg *et al.* created an array of five tweezers by diffracting a single laser beam into many spots, whose locations can be rearranged in real time. This strategy most recently led to arrays of rubidium atoms that were used for simulating collective phenomena, specifically an Ising-type spin model, and with an eye toward performing quantum information processing (*3*). The authors focused on the CaF molecule because it has so-called nearly diagonal Franck-Condon factors. These factors enable electronic excitation by absorption of a laser photon, which is then followed by spontaneous emission to the initial state (*4*). The emissions provide a way to detect the molecules.

The density of CaF molecules reported by Anderegg *et al.* was such that a small but unknown number of molecules were initially held in each tweezer (see the figure). Light-assisted collisions (*5*) were then used to systematically remove molecules, resulting in tweezers that were either empty, contained a single molecule, or, crucially, contained two molecules (with significant probability, as inferred by a high-fidelity imaging system). The case where two molecules were present allowed Anderegg *et al.* to observe ultracold molecular collisions. The authors observed a large molecule loss rate from the array, which they attributed to momentum-changing elastic collisions or rotational relaxation. The light-mediated collision rates were one order of magnitude faster than those in the absence of light. In the 1990s, similarly large loss rate coefficients were observed for ultracold atoms in the presence of light (*6*) tuned to wavelengths that specifically stimulated the collisions.

Tweezer array technology for atoms and molecules is still in its infancy. In particular, the promise of a well-controlled quantum system of molecules is exciting, especially when, simply by moving the diffraction pattern in real time, tweezer sites can be brought together to induce "on-demand" collisions. Alternatively, other coolable molecules can replace CaF. Reactive dimers, for instance, might create research avenues in chemistry by allowing the study of the interference between reaction pathways if conical intersections are present (*7*). Trapping of polyatomic molecules offers another exciting direction, as some of these molecules can already be cooled to temperatures well below 1 mK (*8*). ■

Calcium monofluoride molecules in a microtweezer array

Laser light is split into an array where calcium monofluoride (CaF) molecules are cooled and trapped. The traps initially contain several CaF molecules. Light-induced collisions leave the traps with anywhere from zero to a few molecules.



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