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PERSPECTIVE

Sweeping molecules with light

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Abstract

Many areas of physics—precision measurements, quantum information, and physical chemistry, to name a few—are starting to benefit from the enormous advantages offered by cold and ultracold polar molecules. Molecules have more states, more interactions, and more chemical properties compared to atoms, which make them exciting to study but difficult to tame. In particular, the powerful techniques of atomic laser cooling cannot be naïvely applied to molecules due to their complicated structure. Developments over the past few years have made directly laser cooled and trapped molecules a reality, and now much effort is focused on making these samples larger, denser, and colder—an important step to realizing many of their exciting applications. A careful experimental and numerical study by Truppe *et al* (2017 *New J. Phys.* **19** 022001) demonstrates a significant improvement and advance in understanding of one of the most limiting steps in laser cooling and trapping of molecules—slowing them from a molecular beam to a near-standstill, with small enough kinetic energy that they can be loaded into a trap.

Laser cooling and trapping of atoms has been an incredibly fruitful enterprise for decades [2], and is a key first step into the ultracold regime. There has been growing interest in extending these techniques to molecules [3, 4] due to their broad applicability in areas from ultracold chemistry, quantum information, quantum simulation, fundamental physics, and more. Several species of ultracold molecules have been created in the lab by assembling ultracold atoms [5], but there is interest in a wide variety of molecules with distinct chemical and physical properties, including those made from atoms that cannot be laser cooled.

Laser cooling relies on scattering a large number of photons (typically $\gtrsim 10^4$) from the species of interest, and can be stifled by losses to states not addressed by the lasers. Molecules have many internal degrees of freedom, in particular rotation and vibration, that can be easily excited as the molecule decays from an excited electronic state. These loss channels can be plugged ('repumped') with more and more lasers, but a typical diatomic molecule would require more lasers than is practical, and would yield a sample with population spread out over many internal levels. This makes extending laser cooling and trapping molecules quite difficult, in particular magneto-optical trapping (MOT) [6]. However, there are some tricks we can play to deal with these issues.

While there are no selection rules that govern vibrational excitation during electronic decay for polar molecules, there are quite a few molecules that have only ~1% probability of exciting a vibrational mode when they decay [7]. On the other hand, rotational transitions respect strict selection rules due to conservation of momentum, which limit the number of possible decay channels. Stuhl and co-workers [8] proposed a method with no rotational loss channels, but in exchange for the creation of 'dark' molecular sub-levels that do not scatter photons and need to be rapidly re-mixed into the bright levels. The last key ingredient is to use a source of molecules that is already cold and slow—the cryogenic buffer gas beam [9, 10]. By pre-cooling the molecules with an inert, cryogenic gas, they can be emitted from a beam source at only a few Kelvin and with speeds below 200 m s^{-1}, well below those from an oven-type source. This not only significantly reduces the number of photons needed to cool and slow, but also concentrates the population into a small number of internal states. By combining all of these techniques, the first laser cooling [11] and eventually 3D MOT [12] of a diatomic molecule were realized within the past few years.

These schemes do not completely close the loss channels, and the dark–bright remixing is tricky, so laser cooling of molecules continues to be extremely difficult. One of the crucial (and limiting) steps is to slow the beam to the $\lesssim$10 m s^{-1} capture velocity of a molecular MOT [8]. Improving the slowing of molecular beams is key to increasing MOT number and density, which makes the recent result of Truppe *et al* [1] from the Imperial College London group worthy of attention.

As the beam slows, the molecules become Doppler-shifted over a range of ~100 MHz, much larger than the laser line-width or width of the transitions. One method to overcome this problem is to linearly ramp ('chirp') the frequency of the slowing laser, so that the light is always on resonance with some part of the beam as it slows [13]. Molecules are therefore swept from high to low velocities, where they accumulate in a controlled fashion. Truppe *et al* use this method, and perform a very thorough experimental and theoretical study of its performance.

There are many parameters to optimize, and finding a good set is a balancing act; slow to much and the molecules will turn back around, slow too soon and the molecules will diffuse away before hitting the MOT capture region, and so on. Truppe *et al* find a balance, and are able to achieve a record of $\sim 10^6$ molecules in the MOT capture space. Their numerical simulations also shed light on questions that would be difficult to answer experimentally, such as finding where molecules are being lost so that they can plug leaks and keep efficiency high. Like the Imperial group's previous work understanding the trapping forces of molecules in a MOT [14, 15], this insight is sure to be very helpful and applicable to other systems.

As a comparison to another common technique, Truppe *et al* numerically and experimentally test frequency-broadened slowing, where the slowing laser is simply broadened to address all molecules, fast and slow, at all times. This method has been used to successfully slow molecules by other groups [16, 17], but Truppe *et al* find that the frequency chirping method is more efficient in many cases since they can target their resonant laser power where it will have the strongest effect.

An interesting additional property of a beam slowed by chirping instead of broadening is that its velocity can be controlled precisely. Beams are useful for experiments that require a high degree of control over the local environment, such as precision measurements of fundamental constants. Many of these experiments are limited by interaction time, which subsequently limits precision. Combining this method with transverse laser cooling to collimate the molecular beam will yield higher count rates and longer, controlled interaction times for experiments that will benefit greatly from both.

This technique is a powerful addition to the growing toolbox to cool, trap, and control polar molecules, and is sure to be implemented in many of the exciting experiments to come.

Acknowledgments

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