ULTRACOLD PHYSICS
# Molecules riding waves

The pursuit of ultracold atomic gases has revolutionized atomic physics. Will translationally cold molecules — which are now becoming available — similarly transform molecular and chemical physics?

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Recent triumphs of cold-atom physics include the induction of a superfluid-to-Mott insulator transition in a Bose–Einstein condensate[1], controlling the crossover between Bose–Einstein condensation and Bardeen–Cooper–Schrieffer pairing of ensembles of ultracold fermionic atoms[2], and the observation of the long-searched-for Efimov states[3]. To condensed-matter physicists, these feats are a dream come true. However, it was beyond the wildest dreams of most that such central problems of many-body physics would be elucidated by the means of atomic physics, as the latter had been considered a closed chapter of the 20th century science from which few expected to learn anything new.

The prospects of pursuing ultracold matter with molecules are bright, as molecules possess properties that are absent in atoms, such as electric dipole moments. But first of all, sufficiently translationally cold molecules — in the range of a millikelvin or less — have to become available. How to accomplish this, however, has been far from obvious. A simple extension of laser cooling, the workhorse of cold-atom physics, could not be applied to molecules because of their complex energy-level structure. Necessity proved to be the mother of invention, and a variety of alternative techniques to cool pre-existing molecules have been devised and implemented over the past few years[4]. Reporting on page 465 of this issue, Ray Fulton and colleagues[5] add to the toolbox a promising new technique for efficiently slowing down molecules, an important step towards creating ensembles of ultracold molecules.

Ultracold molecules preoccupy an ever increasing number of physicists and chemists, and their effort is already producing, or is about to produce, a tally of significant benefits for a wide variety of research areas. These benefits arise from the unprecedented control over the molecules' internal and translational motion and from the long interaction times available. The sensitivity of key precision measurements can thus be significantly enhanced, including those used in tests of fundamental symmetries in nature. In particular, testing the time-reversal symmetry — whose breaking would be revealed by the existence of an electric dipole moment of the electron — is expected to make great strides with the help of slow YbF molecules. Indeed, this may turn out to be the most important fundamental-physics experiment since the high-energy physics work that had led to the formulation of the Standard Model[6]. In the regime where the de Broglie wavelength exceeds molecular dimensions, molecular collisions exhibit new dynamics governed by quantum mechanical tunnelling. Ongoing collision experiments are taking us to this new realm. Likewise, recent accurate measurements of radiative lifetimes and energy levels of molecules, enabled by molecular slowing and trapping, provide crucial benchmarks for fundamental physics as well as astrophysics[7,8]. Finally, proposals were put forward for harnessing electric dipoles of ultracold molecules as qubits in quantum computers[9,10].

The experimental route to cold molecules starts with fast ones, typically from a molecular beam source, followed by some combination of slowing, cooling and trapping. A versatile method to alter the velocity of polar molecules at will (and to



**Figure 1** Tossed about. There is no escape for the vessels caught in 'The Great Wave off Kanagawa' - masterfully depicted by Katsushika Hokusai (1760-1849). Similarly, in an experiment performed by Ray Fulton and colleagues[5], an optical wave toys with the molecules trapped in its potential. Depending on the adjustable speed at which the wave travels, the molecules are forced to either climb up or ride down the crest, which results in their deceleration or acceleration.

simultaneously select the molecules' internal states) is so-called Stark deceleration[11]. The technique relies on time-dependent inhomogeneous fields, generated by an array of switched electric field stages, to repetitively increase the Stark potential energy of the molecules and thus, by virtue of energy conservation, reduce their kinetic energy. The deceleration process is equivalent to molecules riding 'uphill' waves (Fig. 1). The reverse process, resulting in acceleration, is cherished by surfers who use the 'downhill' slope of the waves to convert potential into kinetic energy. The Stark decelerator underwent many refinements and was combined with other devices, most notably a trap, a buncher and a storage ring. A number of laboratories have by now implemented Stark deceleration. The technique makes it possible to decelerate bunches of about $10^6$ molecules at densities of $10^8$ cm$^{-3}$ and temperatures down to 1 mK (ref. 12).

The deceleration imparted by a Stark decelerator is of the order of $10^5$ m s$^{-2}$, which suffices to bring thermal molecules to a standstill on a path of ~1 m in about 1–10 ms. Fulton *et al.*[5], however, put the brakes on for only about 6 ns (over a path of several micrometres), imparting a deceleration of the order of $10^{10}$ m s$^{-2}$. Their technique uses not electric field stages, but the gradient of an electromagnetic wave. The resulting deceleration is due to a force of the order of a femtonewton. Can the molecules withstand such a force without falling apart in a process that we could call breaking by braking? They easily can, as a femtonewton force would only dissociate a species bound by a sub-kelvin deep well. The large deceleration force is due to the induced-dipole interaction of a non-resonant radiative field (provided by a laser) with the polarizability of the molecules. This interaction scales with laser intensity and exceeds the interaction of a permanent dipole with a state-of-the-art electrostatic field typically at intensities above $10^{10}$ W cm$^{-2}$ (the intensities have to be held below $10^{13}$ W cm$^{-2}$, however, to avoid ionization). Because the non-resonant optical interaction is purely attractive, all eigenstates created by it are high-field seeking, that is, in an inhomogeneous field they are attracted by regions of maximum intensity where their energy is lowest. Focused radiation in free space represents such a field maximum, and so produces a potential well

for high-field seekers. The optical force is versatile, robust, and precludes relaxation losses as it puts all states into a well. In addition, it aligns non-spherical molecules, because it exerts a torque on the molecular axis.

In the experiment of Fulton and co-workers[5], the non-resonant radiative field comes in the form of a one-dimensional optical lattice created by an interference of two nearly counter-propagating laser beams with slightly different frequencies. The frequency difference of the two beams enables tuning the velocity of the lattice. The required intensities of about $10^{12}$ W cm$^{-2}$ are attained by using pulsed lasers. The lattice can be viewed as a wave whose crests and troughs represent, respectively, the wells and hills of the potential energy of the molecules (as they are high-field seeking). In the pioneering experiment of Fulton *et al.*[5], each lattice crest represents a potential well about 22 K deep. By letting the lattice move at a speed lower than the molecule's velocity, the molecule — nitric oxide in this case — is forced to climb a hill. During its ascent, the molecule loses kinetic energy and is therefore decelerated. About 40 such potential wells, spread over merely 20 μm, snatch about $10^5$ molecules per pulse, with an estimated density of $10^{10}$ molecules per cm$^3$. The temperature of the molecules remains close to that of the original molecular beam pulse, around 1 K. The forthcoming stage of this work will involve trapping of the decelerated molecules, and subsequent cooling to the millikelvin range. The new optical deceleration technique has added more than froth and bubble to the tidal wave that molecular physics itself is now riding.

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