Ultracold Turbulence

NIR NAVON and ZORAN HADZIBABIC describe a remarkable new approach to the study of turbulence using an atomic Bose-Einstein condensate.

Turbulence is a ubiquitous phenomenon in nature, and has fascinated scientists for centuries, at least since the time of Leonardo da Vinci. This regime of fluid flow, characterized by spatio-temporal chaos, is encountered in contexts as diverse as biology, physics and engineering. Moreover, it is of fundamental interest to mathematicians, and analogous phenomena have also been observed in finance. Turbulent air flows limit our ability to forecast weather with critical impact on climate-change science, turbulent friction is crucial in the design of re-entry heat shields for space vehicles, and dimples favour turbulence to boost the flight distance of golf balls. In spite of its interdisciplinary importance, many basic aspects of turbulence remain elusive, and Richard Feynman famously dubbed it the 'most important unsolved problem of classical physics.' For instance, it is well established that a key universal feature of turbulence is the transfer of energy across different length scales, the so-called *turbulent cascade*, but the mechanisms responsible for this transfer are still under active investigation.

We study ultracold quantum gases - puffs of atoms a million times thinner than air that are cooled to less than a millionth of a degree above absolute zero temperature; at such temperatures they form a Bose-Einstein condensate (BEC), an exotic state of matter in which the atoms lose their individuality and behave like a single giant matter wave. What do these quantum gases have to do with turbulence? Since they were first produced in 1995, confirming Einstein's prediction of 1925, it has been shown that they display phenomena such as superfluid hydrodynamics and quantum vortices, which are closely related to turbulence. More generally, they are a popular platform for highly controllable studies of complex many-particle phenomena, in essence because the atomic physicists know their atoms well and can relatively easily manipulate them using lasers and magnetic fields. A major hurdle, however, for devising turbulence experiments with clear answers was that the atoms were traditionally trapped in the focus of lasers beams (optical tweezers) or the minima of magnetic fields, and the atomic density in such a trapping potential was inhomogeneous. This, for example, makes it hard to observe the turbulent cascade through different length scales, which is naturally revealed in Fourier, or momentum, space.

In 2013 at the Cavendish Laboratory, using holographic light-sculpting, we produced first atomic BECs in an 'optical-box' trap (see Fig.1a) [1], in which the quantum gas has uniform density; our box provides a 'flat' potential, such as often studied in undergraduate courses on quantum mechanics. This solved many problems in the field of ultracold atoms in general, and in particular it allowed us to observe the emergence of a matter-wave turbulent cascade in 2016 [2]. We devised a simple protocol to excite selectively the lowest-energy excitation (a long wavelength sound wave) in our uniform BEC and saw the energy propagate to smaller-wavelength, meaning higher-energy, excitations. Quantitatively, the smoking gun for a turbulent cascade was the emergence of an isotropic and scale-invariant, power-law atomic momentum distribution.

More recently, we realized that our system naturally provides us with an unusual control 'knob' for novel studies of turbulence. Our optical box has a finite depth, which is readily controlled by the trapping laser power, and the atoms whose energy exceeds this trap depth escape from the box (Fig.1b), which we can easily detect (see Fig.1c) [3]. In the context of turbulence, controlling our trap depth is akin to controlling the microscopic length scale at which the energy dissipation occurs, and counting the escaping atoms gives the particle and energy fluxes through a specific momentum-space shell. In contrast, in conventional fluids, the dissipation length scale, the so-called *Kolmogorov scale,* is set by the viscosity and cannot be easily tuned, and the measurement of the cascade fluxes has been an important outstanding problem. Our experiments allowed a direct demonstration of the counterintuitive "zeroth law of turbulence", which stipulates that as the dissipation length scale is tuned to zero, the particle flux through the cascade vanishes while the energy flux remains nonzero (see Fig.1c). The tuning of the dissipation scale also allowed us to follow in real time how the cascade front moves through momentum space in the early stages of turbulence (see Fig.1c), which was another historically important problem.

Our experiments open several further research directions. These include specific problems such as extending our methods to studies of vortex turbulence which is more closely related to turbulence in classical fluids, but also more generally understanding turbulence in the broad context of far-from-equilibrium behaviour of quantum many-body systems, which is of great relevance for the recently emerging quantum technologies. Even more generally, our work illustrates the importance of the development of new experimental platforms, which can offer a novel angle even on centuries-old problems such as turbulence.

References
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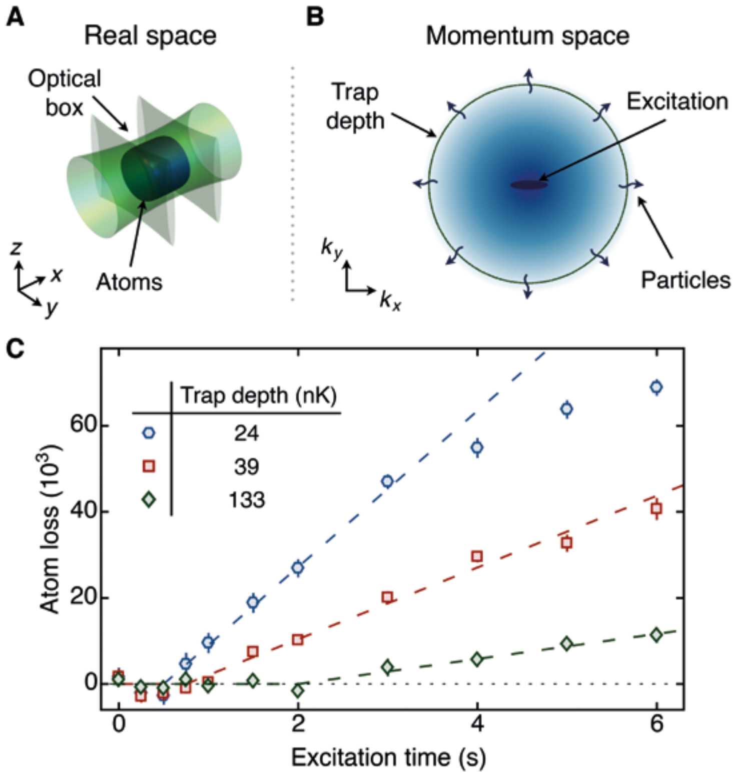

(a) Sketch of our optical box in real space. The atoms (blue) are trapped in a finite-depth potential formed by laser barriers (green) in the shape of a cylindrical box. The excitation scheme is applied along the x axis. (b) Analogous sketch in momentum space. The trap depth sets the dissipation scale; when excitations propagate to that scale, dissipation occurs in the form of particle loss. (c) Atom-loss dynamics due to the turbulent cascade. Atoms lost are shown versus excitation time for different trap depths (in nK). At short times we observe no loss. This is consistent with the expectation that no losses occur before the turbulent cascade front has reached the dissipation scale. After an onset time, the loss rate is essentially constant in time. This rate is the particle cascade flux at the dissipation scale; it vanishes in the limit of infinite trap depth (i.e. vanishing dissipation scale) but in such a way that the energy flux remains constant. The trap-depth-dependent onset time gives access to the cascade front velocity in momentum space.