Unlocking chaos: Ultracold quantum gas reveals insights into wave turbulence

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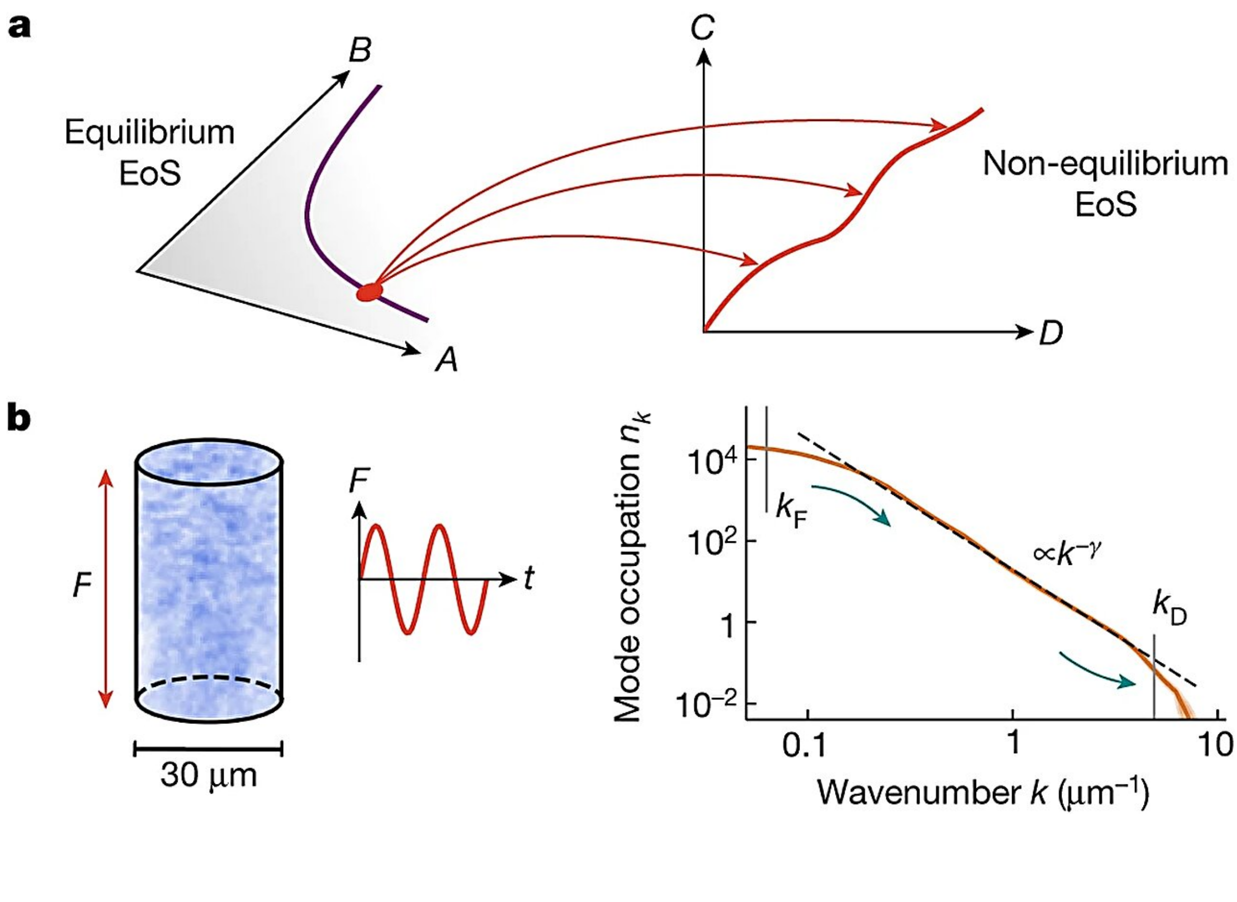

Far-from-equilibrium equation of state and our experiment. **a**, An EoS describes possible states of a macroscopic system by giving the relationship between the state variables, such as pressure or chemical potential. Here, *A* and *B* are some generic equilibrium state variables, all equilibrium states lie in the *A*–*B* plane and out of each of them one can create (arrows) countless far-from-equilibrium ones. If the latter are stationary, they might still obey an EoS with new state variables *C* and *D*. **b**, Using an atomic Bose gas, we study a paradigmatic far-from-equilibrium stationary state, a turbulent cascade with matching energy injection at one length scale (k_F^{-1})and dissipation at another (k_D^{-1}). Left, our gas is held in a cylindrical optical box (cartoon) and continuously driven on a large length scale by a time-periodic force F. Right, in steady state, the gas exhibits a highly non-thermal, but stationary, power-law momentum distribution $n_k \propto k^{-\gamma}$, with $\gamma = 3.2$. Credit: *Nature* (2023). DOI: 10.1038/s41586-023-06240-z

In the intricate realm of wave turbulence, where predictability falters and chaos reigns, new research explores the heart of wave turbulence using an ultracold quantum gas. The study reveals new insights that could advance our understanding of non-equilibrium physics and have significant implications for various fields.

While for physical systems in equilibrium, thermodynamics is an invaluable tool to make predictions about their state and behavior without needing access to many details, finding similarly general and concise descriptions of non-equilibrium systems is an open challenge.

A paradigmatic example of non-equilibrium systems are turbulent systems, which are ubiquitous both in natural and synthetic settings, from blood flow to airplanes. Especially wave turbulence is known to be a very difficult problem, challenging to calculate and not easy to measure, as waves of so many different wavelengths are involved.

Now scientists based at the University of Cambridge, have been able to make some progress by exploring wave turbulence through an ultracold quantum gas. The focal point of this investigation is the Bose-Einstein condensate (BEC), a state of matter achieved when the gas is cooled to near-absolute zero temperatures.

This quantum gas, held within a laser-generated "container" in a vacuum, was subjected to controlled vibrations, generating a cascade of waves akin to fractals called a turbulent cascade. As the BEC is continuously shaken it reaches a steady state that has a cascade form completely different from the equilibrium states.

What sets this research apart is its ability to systematically explore and measure the properties of turbulent cascades and experimentally construct an equation of state (EoS) for it, an endeavor that has remained elusive in other non-equilibrium systems. The findings published in *Nature* elucidate how by varying the energy input through the vibrations, the turbulent state's characteristics is solely hinged on the energy's magnitude, not on external factors like vibration frequency or container shape.

"I always felt there was a general structure in our measured turbulence," shares first author of the paper and Ph.D. student, Cavendish Laboratory, Lena Dogra. "It took us 3 years to find the correct angle from which to look at the data. Finally, everything matched, and we got this beautiful universal relation."

The discovery echoes the universality of the ideal gas law for equilibrium states for far-from-equilibrium turbulent cascades. Thinking of the ideal gas law, that does not depend on how the system reached its current state, the researchers found that the same holds for the far-from-equilibrium turbulent cascade by suddenly changing the shaking strength and switching between different turbulent states.

Finally, varying the internal properties of the BEC, i.e. the density and the strength of the interaction between the atoms, they found that the EoS can be brought into one universal form that captures all of them together.

"Systematic ways of understanding equilibrium systems are well established. This work is a step towards extending such approaches to non-equilibrium systems, which have typically been much harder to understand," said Prof. Zoran Hadzibabic, Cavendish Laboratory. The most interesting aspect of this research is unraveling how a chaotic system can be encapsulated by a simple universal relation.

While a step towards the equation of state (EoS), the study of transitions between turbulent states is captivating on its own. Researchers would like to resolve what happens during the transient time directly after changing the shaking and would like to explore how the measurements connect to predictions for the dynamics a system undergoes on the way from equilibrium to a far-from-equilibrium state and back, which often involves turbulence.

The results have both similarities and discrepancies with turbulence theories that are applied to the so-called Gross-Pitaevskii equation (GPE), which describes the Bose-Einstein condensed gas as one classical object. It also captures many other systems from optical fibers to gravity waves on a water surface.

The discrepancies between the current findings and the theories could both originate from the breakdown of the approximate turbulence theory, or from quantum effects not captured in the GPE. Answering which role both aspects play is an exciting challenge for the future.

More information: Lena H. Dogra et al, Universal equation of state for wave turbulence in a quantum gas, *Nature* (2023). DOI: 10.1038/s41586-023-06240-z

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