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Universal equation of state for wave turbulence in a quantum gas

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Boyle's 1662 observation that the volume of a gas is, at constant temperature, inversely proportional to pressure, offered a prototypical example of how an equation of state (EoS) can succinctly capture key properties of a many-particle system. Such relations are now cornerstones of equilibrium thermodynamics. Extending thermodynamic concepts to far-from-equilibrium systems is of great interest in various contexts including glasses, active matter, and turbulence, but is in general an open problem. Here [1], using a homogeneous ultracold atomic Bose gas, we experimentally construct an EoS for a turbulent cascade of matter waves. Under continuous forcing at a large length scale and dissipation at a small one, the gas exhibits a non-thermal, but stationary state, which is characterised by a power-law momentum distribution sustained by a scale-invariant momentum-space energy flux. We establish the amplitude of the momentum distribution and the underlying energy flux as equilibrium-like state variables, related by an EoS that does not depend on the details of the energy injection or dissipation, or the history of the system. Moreover, we show that the equations of state for a wide range of interaction strengths and gas densities can be empirically scaled onto each other. This results in a universal dimensionless EoS that sets benchmarks for the theory and should also be relevant for other turbulent systems.

[1] L. H. Dogra et al., Nature 2023 (in print), arXiv:2212.08652

Primary authors: DOGRA, Lena (University of Cambridge); MARTIROSYAN, Gevorg (University of Cambridge); HILKER, Timon (University of Cambridge); GLIDDEN, Jake (University of Cambridge); ETRYCH, Jiri (University of Cambridge); CAO, Alec (University of Cambridge); EIGEN, Christoph (University of Cambridge); SMITH, Robert (University of Oxford); HADZIBABIC, Zoran (University of Cambridge)

Presenter: HADZIBABIC, Zoran (University of Cambridge)

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