ULTRACOLD ATOMS

Boltzmann avenged

An experiment with cold atoms confined in an isotropic three-dimensional harmonic potential confirms the long-predicted non-damping oscillations of the breathing mode.

David Guéry-Odelin and Emmanuel Trizac

A gas in an isolated container thermalizes because of collisions that redistribute momentum and energy among the constituents. Writing in *Nature Physics*, Daniel Lobser and colleagues[1] have now shown that an atomic gas, when confined in a harmonic and isotropic trap, may never reach thermal equilibrium and instead evolve towards an undamped breathing mode. This bewildering effect was predicted by Ludwig Boltzmann (pictured) more than a hundred years ago, but has never been observed.

The Boltzmann equation describes the dynamics of rarefied gases. Derived in the 1870s (ref. 2), it is still used to model phenomena in many areas from transport in solids and plasmas to granular gases or population dynamics. From his equation, Boltzmann established the celebrated *H*-theorem, which shows how gases thermalize. This remarkable achievement provided the first explanation for macroscopic irreversibility through a microscopic approach. With this result in mind, most physicists would presume that a confined and self-interacting non-equilibrium gas would eventually thermalize. But it seems that this is not necessarily always the case.

Less known than the *H*-theorem itself is the fact that Boltzmann also identified exotic solutions that could exist under the proviso of harmonic and isotropic confinement. These solutions correspond to breathing modes, in which a perpetual conversion between kinetic and potential energies operates through a swing-like mechanism. Remarkably, these modes are not restricted to small-amplitude oscillations. Furthermore, their existence does not contradict the *H*-theorem, which implies that the velocity distribution of the gas has a Gaussian form at long times — hence the modes are not damped. The breathers indeed exhibit Gaussian statistics. What makes them particularly interesting is their non-trivial position–velocity coupling, which is time-dependent and absent from the thermalized distribution.

Non-damping of the transverse breathing mode of a Bose–Einstein condensate in a highly elongated trap was first observed in 2002 (ref. 3). Studies of strongly correlated quantum systems led to a number of other interesting results, such as the quantum Newton's cradle experiment[4] of bosonic atoms confined in a one-dimensional harmonic trap — a situation where strong interactions lead to integrable dynamics[5]. Yet, until now, no experiment tackled the case of a 3D harmonically trapped gas in the regime where quantum effects are negligible.

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In their experiment, Lobser *et al.* used a very cold gas, but still far from the temperature threshold where quantum effects emerge. They report the first evidence for non-damping oscillations in a classical gas, thus realizing the exotic solution predicted by Boltzmann. This was made possible by the development of an elaborate version of the magnetic time-averaged orbiting potential trap, which produces a good approximation of an isotropic 3D harmonic confinement. This turned out to be a delicate task that required a deft strategy to minimize anharmonicities while circumventing the natural anisotropy of the trap and the role of gravity. Lobser *et al.* used five rotating magnetic fields, whereas the original time-averaged orbiting potential technique involves only one. A small residual damping was observed, which the researchers attribute to remaining anharmonicities.

The perpetual non-equilibrium state hinted by these results is a truly counter-intuitive phenomenon. An open theoretical question concerns the eventual long-time thermalization of the system. For example, small correlations among the constituents — discarded at the level of the Boltzmann equation, but present in any finite system — although innocuous on the medium-term, could still asymptotically drive the gas towards equilibrium. Yet, besides providing a textbook example of the experimental observation of non-equilibrium solutions to the Boltzmann equation, the work by Lobser and colleagues reinforces the idea that cold atoms form an ultraprecise testbed of kinetic theory. ❐

David Guéry-Odelin is at LCAR, IRSAMC, University Paul Sabatier, CNRS, 31062 Toulouse, France. Emmanuel Trizac is at LPTMS, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France.
e-mail: dgo@irsamc.ups-tlse.fr; trizac@lptms.u-psud.fr

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