PERSPECTIVES

QUANTUM GASES

Quantum-limited sound attenuation

Resonantly interacting atoms confined by lasers have implications for neutron stars

By **Thomas Schaefer**

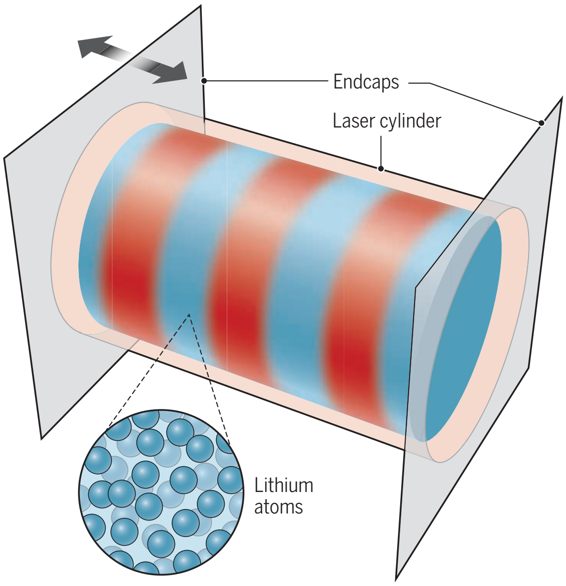
Ordinary sound is a harmonic oscillation in the density, temperature, and velocity of air. Sound intensity decreases because of the spreading of the sound wave, but ultimately, sound attenuation is due to the diffusion of momentum and energy from the crest to the trough of the wave. This effect can be characterized in terms of the diffusivity D of sound. In air, there is a very large separation of scales between the shortest scale, the distance between molecules; an intermediate scale, the mean free path of air molecules, which controls the diffusivity; and the longest scale, the wavelength of the sound mode. On page 1222 of this issue, Patel *et al*. (*1*) study a very different and deeply quantum version of sound attenuation. The authors' result illuminates the transport properties of strongly correlated quantum fluids (*2*), with direct implications for the stability of spinning neutron stars (*3*).

Patel *et al*. confined 2 million lithium atoms in a cylindrical box created using beams of laser light (see the figure). The box is about 100 µm long and 60 µm in radius. A typical standing wave in the experiment has a wavelength that is only about 10 times larger than the mean distance between atoms. To observe sharp collective modes in this regime, the gas must be very strongly correlated. Making the gas very cold and tuning the interaction between atoms to a resonance achieves this correlation. The temperature of the gas is between 50 and 500 nK, which implies that the de Broglie wavelength of the atoms is equal to or larger than the mean atomic distance. The de Broglie wavelength is the wavelength of the quantum mechanical wave function of the atoms. The interaction between the atoms is tuned by means of a so-called Feshbach resonance (*4*). At resonance, we can think of the interaction as having zero range but infinite scattering length. This means that the wave function of two low-energy atoms is modified by interactions even if the atoms are arbitrarily far apart.

The resonant limit is referred to as the unitary Fermi gas, because the isotropic part of the scattering cross section is as large as the conservation of probability (unitarity) in quantum mechanics allows it to be. The unitary Fermi gas is also scale invariant. This means that physical observables are fixed by dimensional analysis and universal functions of dimensionless ratios. We can apply this type of argument to the sound diffusivity. On dimensional grounds, D is proportional to $\hbar/m$, where $\hbar$ is the reduced Planck's constant and m is the mass of the atoms.

Observing quantum sound waves

A cylindrical box made of laser beams, 100 µm long and 60 µm in radius, contains about 2 million ultracold lithium atoms. Changing the light intensity of the cylinder's endcaps excites sound waves. The decay of the sound waves (diffusivity) is measured by tracking the frequency width of the standing waves.



GRAPHIC: KELLIE HOLOSKI/SCIENCE

The constant of proportionality is determined by the detailed mechanism for energy and momentum transfer. If momentum transfer is governed by the diffusion of atoms, then $D \sim \bar{p}l_{\mathrm{mfp}}/m$, where $\bar{p}$ is the mean momentum of an atom and l_{mfp} is the mean free path. In a classical gas, $\bar{p}l_{\mathrm{mfp}} >> \hbar$, but in a strongly correlated gas, we expect the product of $\bar{p}$ and l_{mfp} to be limited by quantum uncertainty, so that D is of order $\hbar/m$.

The results of Patel *et al*. demonstrate this limiting behavior. In the experiment, sound modes are excited by shaking the endcaps of the cylindrical box. The position of resonances determines the speed of sound, and the width of the resonance determines the diffusivity. Patel *et al*. find that the diffusivity drops as the temperature is lowered, settling around $D \sim 1.5\hbar/m$ near the transition to a superfluid. This value is consistent with attempts to measure the shear viscosity and thermal conductivity of the unitary Fermi gas individually (*5*, *6*), as well as with theoretical calculations (*7*). Below the critical temperature, the unitary gas forms a superfluid that is roughly analogous to Bardeen-Cooper-Schrieffer superconductivity, but with a parametrically large pairing gap and critical temperature. Notably, no sharp features are found in the diffusivity at the phase-transition temperature.

The results of Patel *et al*. have direct implications for the structure of spinning neutron stars. The matter in the outer layer, below the crust but outside the core, of a neutron star is a dilute liquid of neutrons. The neutron-neutron scattering length is much larger than the distance between neutrons, making observations of the unitary Fermi gas directly applicable, even though the temperatures and densities are many orders of magnitude larger in the star. The dimensionless ratios, such as the mean particle distance in units of the thermal de Broglie wavelength, being similar is what matters for modeling the stellar interior.

Neutron stars have many possible modes of oscillations. A special class that arises owing to the Coriolis force in rotating stars is

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known as Rossby modes, also called r-modes. These r-modes are unstable, and they would lead to strong gravitational wave emission and a rapid spin-down of the star if not damped by momentum or energy diffusion. Understanding the diffusivity of neutron star matter is crucial to predicting the range of allowed spin frequencies and possible r-mode signals in gravitational wave detectors.

More generally, Patel *et al.* illuminate the mechanism of transport in other strongly correlated quantum gases, such as the quark-gluon plasma investigated in heavy-ion collisions at the Relativistic Heavy Ion Collider and the Large Hadron Collider. The quark-gluon plasma is a state of matter that existed microseconds after the Big Bang, at a temperature $T \sim 2 \times 10^{12}$ K. Measurements indicate that the momentum diffusivity of the quark-gluon plasma is quite low. In a relativistic setting, the mass of the particles is very small, and the natural scale for D is $\hbar c^2/(k_B T)$, where c is the speed of sound and k_B is the Boltzmann constant. Experiments based on the hydrodynamic expansion of the plasma give values as small as $D \sim 0.1\, \hbar c^2/(k_B T)$. This number has been interpreted in terms of holographic models inspired by advances in string theory (*8*). However, in relativistic heavy-ion collisions, the precise mechanism of momentum transport is difficult to determine. This problem can potentially be tackled in future experiments with cold gases, for example, by carefully mapping the frequency dependence of the response of the gas to external perturbations. ■

> **"...observations of the unitary Fermi gas [are] directly applicable [to the physics of neutron stars], even though the temperatures and densities are many orders of magnitude larger in the star."**

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PLANT IMMUNOLOGY

Enzyme formation by immune receptors

Upon pathogen recognition, some plant immune receptors assemble into active enzyme complexes

By **Lei Tian** *and* **Xin Li**

Higher plants have evolved complex immune systems. Intracellular immune receptors known as nucleotide-binding leucine-rich repeat (NLR) proteins are present in both plants and animals; they are essential for immune responses (*1*). Upon infection, NLRs can recognize specific pathogen molecules and activate defense. In contrast to animals, which have a limited NLR repertoire, higher plants usually harbor hundreds of diverse *NLR* genes. However, little is known about their activation and signaling mechanisms. On pages 1184 and 1185 of this issue, Ma *et al.* (*2*) and Martin *et al.* (*3*), respectively, reveal the structure and activation mechanism of two NLRs: *Arabidopsis thaliana* RECOGNITION OF PERONOSPORA PARASITICA 1 (RPP1) and *Nicotiana benthamiana* RECOGNITION OF XOPQ 1 (ROQ1). Both NLRs self-assemble in a similar manner into tetrameric holoenzymes to activate defense responses upon direct effector recognition.

There are two classes of typical plant NLRs for sensing pathogen effectors: Toll–interleukin-1 receptor (TIR)–type NLRs (TNLs) and coiled-coil (CC)–type NLRs (CNLs), which are defined by their different amino-terminal domains. As with mammalian NLRs, plant NLRs also contain a central nucleotide-binding domain (NBD) involved in oligomerization, as well as carboxyl-terminal leucine-rich repeats (LRRs) that often participate in auto-inhibition and ligand recognition (*1*). TNLs and CNLs are activated with dissimilar mechanisms and signal through different downstream components.

Cryo–electron microscopy (cryo-EM) structural analysis of the *A. thaliana* CNL HOPZ-ACTIVATED RESISTANCE 1 (ZAR1) revealed that it assembles into a pentameric "resistosome" upon effector recognition, reminiscent of animal inflammasome rings that mediate innate immune responses (*4*). ZAR1 and an adaptor protein recognize the pathogen effector indirectly through monitoring the status of a host protein (called a decoy) that is directly targeted by the effector. The pentameric ring assembles upon binding of the effector-modified decoy, leading to the formation of a funnel-shaped structure composed of the amino-terminal CC domains of ZAR1. It has been hypothesized that this funnel associates with the cell membrane and triggers immune-related cell death (*5*). Until now, the resistosome structures of full-length TNLs have not been elucidated.

TIR-containing proteins are widely present in bacteria, archaea, mammals, and higher plants (*6*). In mammals, TIR is a signature scaffold domain of immune receptors, including Toll-like receptors (TLRs) and interleukin-1 receptors (IL-1Rs), and of some downstream adaptor proteins. Interactions of TIR domains between receptor and adaptor proteins are required for immune and inflammatory signal transduction. For example, TLR4 recruits the signaling adaptors MYD88 (myeloid differentiation primary response 88) and MAL (MYD88 adaptor-like) through TIR-TIR interactions, thereby activating downstream transcription factors such as nuclear factor κB (NF-κB) to induce inflammation (*7*). By contrast, a large number of TIR domains found in bacteria, archaea, and higher plants seem to serve as oxidized nicotinamide adenine dinucleotide (NAD$^+$) hydrolases (NADases) upon self-association (*6*, *8*, *9*). TIR NADase activity was discovered in mammalian SARM1 (sterile alpha and TIR motif–containing protein 1), a major executor of neuronal axon degeneration (*10*). Like SARM1, TIR domains in a number of plant TNLs also exhibit NADase activity (*8*, *9*).

Cryo-EM analysis of full-length SARM1 revealed that in its resting state, it assembles into an octamer. The carboxyl-terminal Armadillo/HEAT motif (ARM) domains block the contact between adjacent TIRs through binding to NAD$^+$ (*11*). With nicotinamide mononucleotide activator elicitation, the SARM1 octamer undergoes a conformational change, disrupting NAD$^+$ binding sites of the ARM domains to enable TIR-TIR dimerization (*11*, *12*). Interactions be-

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