Sound propagation and quantum limited damping in a two-dimensional Fermi gas

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Strongly interacting two-dimensional Fermi systems are one of the great remaining challenges in many-body physics due to the interplay of strong local correlations and enhanced long-range fluctuations. Here, we probe the thermodynamic and transport properties of a 2D Fermi gas across the BEC-BCS crossover by studying the propagation and damping of sound modes. We excite particle currents by imprinting a phase step onto homogeneous Fermi gases trapped in a box potential and extract the speed of sound from the frequency of the resulting density oscillations. We measure the speed of sound across the BEC-BCS crossover and compare the resulting dynamic measurement of the equation of state both to a static measurement based on recording density profiles and to Quantum Monte Carlo calculations and find reasonable agreement between all three. We also measure the damping of the sound mode, which is determined by the shear and bulk viscosities as well as the thermal conductivity of the gas. We find that the damping is minimal in the strongly interacting regime and the diffusivity approaches the universal quantum bound $\hbar/m$ of a perfect fluid.

One, motivated by holographic duality [17], is that it occurs near scale invariant points in the phase diagram. The unitary 3D Fermi gas is an example that seems to support this hypothesis since it is strongly interacting as well as scale invariant and exhibits quantum limited shear and spin diffusion. In contrast, 2D Fermi gases exhibit a quantum scale anomaly that breaks scale invariance [18–21]. Here, we investigate the propagation and damping of sound in a strongly interacting 2D Fermi gas and thereby probe a crucial test case for this hypothesis. We observe that the damping approaches the quantum limit $D \approx \hbar/m$ in the strongly interacting regime, where scale invariance is most dramatically violated, showing that scale invariance or quantum criticality is in fact not required for quantum limited transport. Similar observations were made for transverse spin diffusion in [9]. Our results confirm a scenario of incoherent transport that has emerged in recent years from the study of anomalous transport in high-temperature superconductors and other ‘bad metals’ [22, 24] and links quantum limited transport to strong correlations.

We perform our studies of sound propagation with an ultracold gas of $^6$Li atoms in a spin-balanced mixture of the lowest two hyperfine states, trapped in a two-dimensional box potential [25, 26]. The gas is vertically confined in a single node of a repulsive optical lattice with trap frequency $\omega_z/2\pi = 8.4(3) \text{ kHz}$. At our densities of about $n_{F1} = n \approx 1 \text{ nm}^{-3}$ per spin state, the chemical potential $\mu$ is smaller than the vertical level spacing $\hbar \omega_z$, which ensures that our gas is in the quasi 2D regime. The confinement in the horizontal plane is created using a digital micromirror device illuminated with blue detuned light ($\lambda = 532 \text{ nm}$), trapping the gas in a two-dimensional box with a typical size of $l_x \times l_y = 30 \times 40 \mu \text{ m}^2$. Ac-
According to the temperature determination performed in [26], our system is in the low-temperature regime with $k_B T/E_F \leq 0.1$, where $E_F = \hbar^2 k_F^2 / 2m$ is the Fermi energy, $k_F = (4\pi n)^{1/2}$ the Fermi momentum and $m$ the atomic mass of $^6$Li.

For our experiments, we build on the experimental procedure developed in [27], where sound propagation was studied in weakly interacting 2D Bose gases. To excite a sound mode in the box we follow the approach of [26] and imprint a relative phase between two halves of the system by illuminating one side with a spatially homogeneous optical potential for a short duration $\tau < h/E_F$. We then observe the resulting density oscillations by imaging the density distribution after different hold times using in-situ absorption imaging. An example of such an oscillation is shown in figure 1(a). A sound wave traveling back and forth between the two sides of the box is clearly visible in the density profile. To extract the oscillation frequency $f = \omega / 2\pi$ and the damping $\Gamma$ of this sound wave, we calculate the relative particle imbalance $\Delta n/n = 2(n_t - n_b) / (n_t + n_b)$ from the densities $n_t$ and $n_b$ in the top and bottom halves of the box and fit it with a damped sinusoidal of the form $A(t) = A_0 \cos(\omega t + \phi) \exp(-\Gamma t / 2) + b$ (see figure 1(b)). We measure the oscillation frequency for different boxes with lengths between $l_x = 15 \, \mu m$ and $l_x = 40 \, \mu m$ and find that it is proportional to the inverse of the box length (see figure 1(c)). This confirms that we observe a sound wave traveling at a constant velocity $c = 2l_x f$ and that edge effects are negligible.

To probe the speed of sound as a function of interaction strength, we perform measurements in a box with $l_x = 30 \, \mu m$ at magnetic fields around the Feshbach resonance. Examples of the resulting oscillations as well as the evolution of the oscillation frequency as a function of magnetic field are shown in figure 2. As the field is varied from the BEC side to the BCS side of the crossover, the oscillation frequency increases, which is expected since the compressibility of a Fermi gas is much lower than that of a weakly repulsive Bose gas. On the Fermi side, the gas is thus stiffer with respect to density fluctuations and sound waves propagate faster than on the Bose side.

We plot the speed of sound extracted from the oscillation frequencies as a function of the 2D interaction pa-
FIG. 3. (a): Speed of sound across the BEC-BCS crossover. Gray lines represent the two theoretical limits: In the BEC regime, Bogoliubov theory predicts $\mu = gn$ and hence $c_B = (gn/2m)^{1/2}$, where $g$ is the interaction parameter between bound dimers defined as in [26, 28]. On the BCS side, $\mu \rightarrow E_F$ yields a constant sound velocity $c_F = v_F/\sqrt{2}$ where $v_F = \hbar k_F/m$ is the Fermi velocity. (b): Static measurement of the compressibility. A repulsive potential $V$ is imprinted onto one half of the box resulting in a density imbalance $\Delta n/n$ (blue points). We extract the compressibility from the initial slope of the data points according to $1/n^2 \kappa = \lim_{\Delta n \rightarrow 0} V/\Delta n$ in a local density approximation. Each data point and the inset are averages of 20 realizations. (c): Comparison between the compressibility scaling functions $f_\kappa$ obtained from the speed of sound (blue circles), the density response to an imprinted static potential (red squares) and QMC calculations [29, 30].

rameter $\ln (k_F a_{2D})$ in figure 3(a). In a superfluid gas, two-fluid hydrodynamics predict the occurrence of two sound modes which propagate at different velocities, as observed in [32]. These modes generally mix density and entropy degrees of freedom. For strongly interacting 2D-superfluids however, density and entropy excitations have been predicted to be well decoupled [33, 34], and hence the sound mode we observe should correspond to an almost pure density wave. In this case, the velocity of a sound wave is given by

$$c = \sqrt{\frac{n}{m} \frac{\partial \mu}{\partial n}_s}$$

and is directly related to the isentropic compressibility $\kappa = \frac{1}{n} \frac{\partial \mu}{\partial n}_s$ [44]. This relation gives us simple zero-temperature expressions for the speed of sound in the BEC and BCS limits of the crossover, which are in good agreement with our data (dashed and dotted lines in figure 3(a)).

For a quantitative analysis we use Eq. (1) to extract the compressibility of our gas from our measurement of the speed of sound. From this, we then determine the dimensionless inverse compressibility scaling function $f_\kappa = 1/nE_F \kappa$ of a two-dimensional Fermi gas.

In addition to this dynamic measurement of the equation of state (EOS), we also perform a static measurement of the compressibility EOS by determining the density response of our system to a static repulsive potential, similar to the work performed in [25, 30, 35] (see figure 3(b)). This results in two independent measurements of $f_\kappa$, which show good agreement with each other (see figure 3(c)).

Finally we compare our data to theory by extracting $f_\kappa$ from Quantum Monte Carlo (QMC) calculations of the ground state energy $E_0$ of a homogeneous 2D Fermi gas [29, 30]. On the BCS side, the experimental results agree well with the theoretical prediction. On the BEC side, both the static and the dynamic measurements lie above the theoretical prediction. One possible explanation for this difference could be finite temperature effects, which have been observed in [37] to decrease the compressibility of the gas, thus increasing $f_\kappa$.

Very recent simulations of the sound velocity in a 2D Bose gas [39] indicate that the density and entropy modes remain coupled even for relatively strongly interacting Bose gases, leading to sound velocities which differ from the Bogoliubov prediction. This should be observable as a difference between the static and dynamic measurements of the compressibility. However, if such a difference exists in our system, it is smaller than the uncertainty of our measurement.

We now turn our attention to the damping of the sound waves. In our strongly correlated system, the mean free path $l_{\text{mfp}}$ of the particles is much smaller than the oscillation wavelength and their collision rate is high with respect to the oscillation frequency. Hence the system is in the hydrodynamic regime. In this regime, the spatial variations in density and temperature that constitute a sound wave lead to diffusive currents of longitudinal mo-
FIG. 4. Sound diffusion coefficient across the BEC-BCS crossover. In the strongly correlated regime, the diffusion coefficient reaches a minimum which agrees well with the universal quantum bound for diffusion at $h/m$ (dashed line).

momentum, transverse momentum and heat, whose magnitudes are proportional to the bulk and shear viscosities $\zeta$ and $\eta$ and to the heat conductivity $\beta$. These diffusive currents smooth out the density and temperature variations and thus damp the sound wave according to the sound diffusion constant

$$D_s = \frac{\eta}{\rho} + \zeta + \frac{\beta}{c_p - c_v} = \frac{\Gamma}{k_0^2}, \quad (2)$$

where $k_0 = \pi/l_x$ is the wave vector of the sound wave and $c_p$ and $c_v$ are the heat capacities at constant pressure and volume. The evolution of $D_s$ across the BEC-BCS crossover is shown in figure 4. It exhibits a broad minimum in the crossover regime $-1 < \ln(k_F a_{2D}) < 2$ and increases steeply towards the BEC and BCS limits.

Before comparing our data to theory, we note that making quantitative predictions for transport coefficients of strongly interacting 2D Fermi gases in the low-temperature regime is still a major theoretical challenge. Approaches such as Fermi liquid theory and BCS theory are only accurate at weak coupling. Results obtained for the high-temperature regime ($T > T_F$) indicate that the shear viscosity and heat conductivity have a minimum in the strongly correlated regime whereas the bulk viscosity is maximal near resonance yet contributes much less to the damping. In total, high-temperature theory predicts a minimum of the sound diffusion in the crossover regime. Although our measurements are performed in the low-temperature regime, the observed behavior is in qualitative agreement with an extrapolation of the high-temperature result to the low-temperature regime.

A prediction for a lower bound of $D_s$ in the strongly interacting regime can be obtained via a simple scaling argument: In kinetic theory, the diffusion coefficient is given by the mean free path and the velocity via $D_s \sim v l_{mfp}$. For a strongly interacting degenerate gas the mean free path $l_{mfp}$ is on the order of the inter-particle separation $n^{-1/2}$ and the velocity on the order of the Fermi velocity $v \sim v_F \sim \hbar n^{1/2}/m$, resulting in a diffusion coefficient $D_s \sim h/m$. Since the inter-particle separation is a lower limit for the mean free path, this yields a generic lower bound for the damping. This lower limit is in agreement with our measured diffusion coefficient of $D_s \approx 1.8(2)/h/m$ in the strongly correlated regime. Thus our strongly interacting 2D Fermi gas is a nearly perfect fluid despite the fact that scale invariance is broken and that the system is not at a quantum critical point.

In this work, we have studied the propagation and damping of sound waves in a homogeneous 2D Fermi gas across the BEC-BCS crossover. We have extracted the compressibility EOS from a measurement of the speed of sound and find good agreement with $T = 0$ QMC calculations. We have measured the sound diffusion constant as a function of the interaction strength and find universal sound diffusion $D_s \sim h/m$ and quantum limited transport in the strongly interacting regime. This lower limit is reached at interactions where scale invariance is violated most severely, but were the mean free path is comparable to the particle spacing. Since sound diffusion is the sum of momentum and heat diffusion, we thus find upper bounds of order $h/m$ on each diffusion channel individually in the crossover regime. This demonstrates that the 2D Fermi gas realizes a nearly perfect fluid and provides a benchmark against which future theoretical predictions can be validated.

An interesting extension of our measurements would be to study the temperature dependence of $D_s$ as done in unitary 3D Fermi gases. In the fermionic regime, this would allow us to observe whether there is a maximum of $D_s$ at the critical temperature of superfluidity, similar to measurements in $^3$He. In the deep BEC regime, control over the temperature of the gas would enable studies of second sound in a strongly interacting Bose gas.

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