

## Two-dimensional hydrodynamic viscous electron flow in annular Corbino rings

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The concept of fluidic viscosity is ubiquitous in condensed-matter systems hosting a continuum where macroscopic properties can emerge. While an important property of liquids and some solids, only recently was the viscosity of an electron shown to play a role in electronic transport experiments. In this Letter, we present nonlocal electronic transport measurements in concentric annular rings formed in high-mobility two-dimensional electron gases, and the resulting data show that viscous hydrodynamic flow can occur far away from the source-drain current region. Our conclusion of viscous electronic transport is further corroborated by simulations of the Navier-Stokes equations that are found to be in agreement with our measurements below  $T = 1$  K. Finally, this work emphasizes the key role played by viscosity via electron-electron ( $e$ - $e$ ) interaction even when the electronic transport is restricted radially, and for which *a priori* it should have played no major role.

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**Introduction.** Consider a gas moving through a small constriction: depending on the density of the gas, flow out of the chamber can vary significantly due to the varying mean-free path of its constituent particles. If the mean-free path greatly exceeds the hole size, individual gas particles will diffuse independently with their own trajectories, akin to single-particle effusive transport. Conversely, if the mean-free path is much smaller than the hole size, the particles will interact more frequently, ultimately leading to a collective flow guided by the broader dynamics of the ensemble and forming a continuum. When this is the case, the flow properties of neutral fluids are typically governed by the Navier-Stokes equations of hydrodynamics, which holds true for the flow of water and other fluids that are ubiquitous in our everyday life.

In the case of electrons in metals governed by Fermi liquid theory, somewhat oppositely single-particle theoretical descriptions are most often used, neglecting electron viscosity arising from a possible continuum. In narrow graphene constrictions, however, collective effects were shown experimentally to be important under the form of current backflow, forming whirlpools of electrons [1]. Recently, Ahn and Das Sarma [2] further proposed that hydrodynamic effects should be observable in the bulk of moderately high electron mobility GaAs/AlGaAs two-dimensional electron gases (2DEGs), provided their scattering parameters place them into a collective regime. In this Letter, we present local and nonlocal

electronic transport measurements in annular regions formed in GaAs/AlGaAs 2DEGs that have no edges and are therefore entirely bulk. Numerical simulation based on the Navier-Stokes equations for a charged fluid that includes the electron viscosity proposed by Polini and co-workers [3] is found to be in good agreement with experimental results, hence confirming the significance of electron viscosity and viscous drag far away from the source drain current region.

**Lengthscales and hydrodynamic electron transport.** In the regime of clean conductors, such as high-mobility 2DEGs, momentum scattering is dominated by electron-electron ( $e$ - $e$ ) interactions, where the mean-free path due to these interactions ( $\ell_{MC}$ ) is much smaller than both the conducting channel width ( $W$ ) as in a Hall bar geometry, and the momentum relaxing mean-free path ( $\ell_{MR}$ ) from either impurity or phonon scattering. In the case in which  $\ell_{MC} \ll W \ll \ell_{MR}$ , a collective behavior of electrons can emerge that resembles a fluidlike continuum rather than discrete single-particle effusive motion. This type of electronic transport is commonly referred to as hydrodynamic transport. This transport regime in metals was first theorized by Gurzhi [4,5] in 1963, and it offers a more complete perspective on electronic transport wherein the resistance to flow is governed by the fluidic viscosity of the electron stream and the geometric characteristics of the conducting channel. This has recently led to a renewed interest in the study of hydrodynamics in electronic systems, and it blossomed into a series of theoretical [1–3,6–16] and experimental [17–28] advances.

**Corbino samples parameters and experimental protocol.** Typical measurements performed in large 2DEG samples utilize the four-terminal setup either in van der Pauw (VdP) or Hall bar geometries, and the latter is shown in Fig. 1(a) for both local and nonlocal measurement configurations. The Corbino geometry shown in Fig. 1(b) was chosen to

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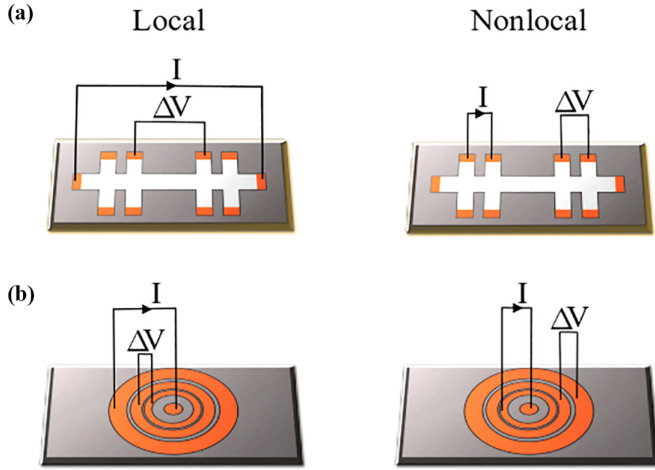


FIG. 1. Schematics of Hall bar and multiterminal Corbino geometry. Measurement lead configurations for local and nonlocal measurements are shown in (a) for the Hall bar and (b) the Corbino geometry.

ensure that only the bulk of the 2DEG was probed. To avoid any contributions from the Ohmic contacts, four-terminal Corbino devices were patterned on two symmetrically doped GaAs/AlGaAs heterostructures, one with a 40 nm (CBM302) and the other with a 30 nm (CBM301) quantum-well width; see the Supplemental Material (SM) for more information [29]. The devices have electron densities of  $n_e = 1.7 \times 10^{11}$  and  $3.6 \times 10^{11} \text{ cm}^{-2}$ , and electron mobilities of  $20.3 \times 10^6$  and  $27.8 \times 10^6 \text{ cm}^2 (\text{Vs})^{-1}$  below 20 mK, respectively. Both Corbino devices consist of three 2DEG active rings with inner/outer radii of (150/750), (960/1000), and (1300/1400)  $\mu\text{m}$ , respectively. These annular regions are defined by Ge/Au/Ni/Au layers of 26/54/14/100 nm thickness that diffuses into the wafer during an annealing process. As a result, Ohmic contacts with resistances on the order of  $\sim 3 \Omega$  are formed. The multiring Corbino geometry was specifically chosen to probe truly bulk nonlocal behavior without edge effects. This approach contrasts with observations made in graphene using a Hall bar geometry, where backflow effects are responsible for the observed nonlocal signal [3,8,13]. By constraining the flow to be purely radial, the Corbino geometry eliminates backflow entirely, while the multiring configuration facilitates nonlocal probing.

From their electron densities, the  $e$ - $e$  interaction parameter  $r_s = (\pi n_e a_B^2)^{-\frac{1}{2}}$ , where  $a_B$  is the effective Bohr radius, was calculated to be 1.33 for CBM302 and 0.91 for CBM301, and from their electron mobilities  $\ell_{\text{MR}}$  values were calculated to be 138  $\mu\text{m}$  for CBM302 and 275  $\mu\text{m}$  for CBM301. The device with a lower electron density, CBM302, has a higher  $r_s$  parameter, indicating an enhanced  $e$ - $e$  interaction compared to CBM301. The multiterminal Corbino devices were cooled down to the base temperature  $T \simeq 6 \text{ mK}$  of a dilution refrigerator, illuminated by a red LED from room temperature to approximately  $T \simeq 7 \text{ K}$  to optimize the electron mobility. All nonlocal measurements presented in this work were performed with a fixed current of 100 nA applied to the two innermost rings, and the voltage difference was measured across the outermost rings.

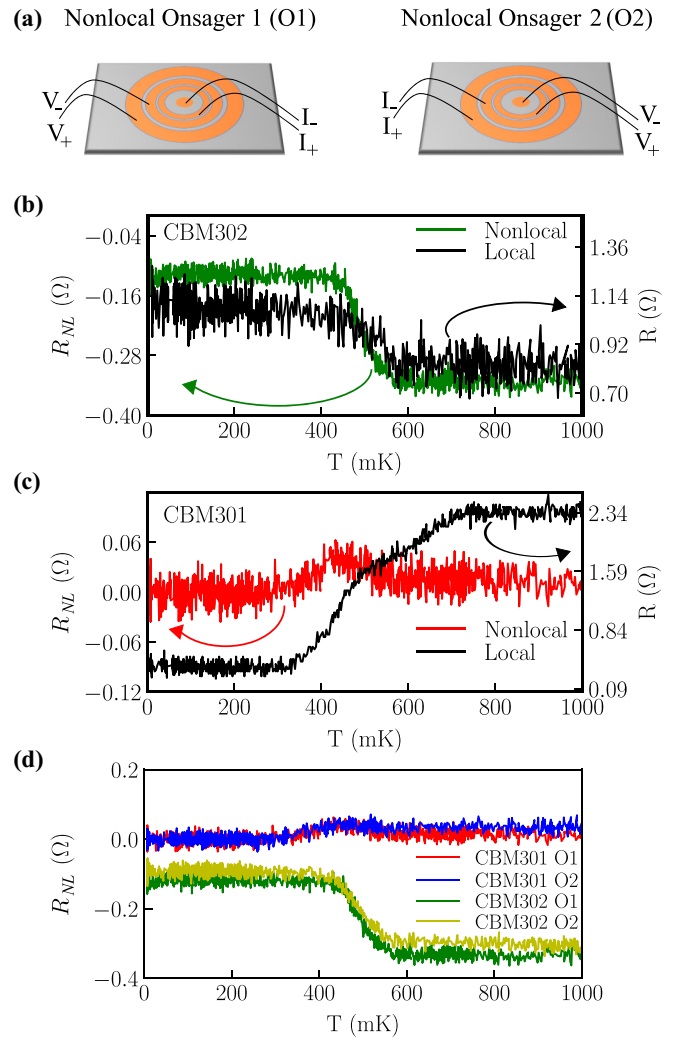


FIG. 2. Local and nonlocal transport measurements in multiterminal Corbino 2DEGs. (a) Schematic representation of two distinct four-point nonlocal measurement configurations. (b) Non-local resistance measured in O1 configuration is compared with local measurements for CBM302 and (c) for CBM301. (d) Non-local measurements in CBM301 and CBM302 for both O1 and O2 configurations. Onsager reciprocity is validated within experimental resolution.

**Local and nonlocal measurements.** To ensure consistency, we performed both local and nonlocal measurements in both multiterminal Corbino devices during the same cooldown, and the results are shown in Figs. 2(b) and 2(c). For the nonlocal measurements, a current  $I$  was applied to the two inner rings, and the voltage difference  $\Delta V_{\text{NL}}$  was measured across the two outer rings [the Onsager 1 (O1) configuration], and vice versa for the Onsager 2 (O2) configuration, shown in Fig. 2(a). The temperature dependence of nonlocal resistance  $R_{\text{NL}} \equiv \Delta V_{\text{NL}}/I$  is shown in Fig. 2(b) by a green line for CBM302 and by a red line for CBM301 in Fig. 2(c), from base temperature (6 mK) to 1 K. In CBM302, a nearly constant negative nonlocal signal was measured up to  $T \simeq 450 \text{ mK}$ , at which point a sharp increase of the negative signal occurs concomitantly with the sharp decrease in local resistance. Between temperatures  $T = 450 \text{ mK}$  and  $T = 1 \text{ K}$ , our

measurements in CBM302 demonstrate a  $\sim 160\%$  increase in negative nonlocal signal, and a  $\sim 33\%$  decrease in local signal. As discussed below, these two observations are inconsistent with ballistic effusive electronic transport [30,31]. Instead, they suggest the formation of a continuum and an electronic flow governed by hydrodynamics. The transition between ballistic effusive and hydrodynamic transport occurs when the dimensionless Knudsen parameter  $\zeta \equiv l_{MC}/l_{MR} \simeq 1$  [2], around  $T = 250$  mK for CBM302. Hydrodynamic-dominant flow begins when  $\zeta \ll 1$  [2]. Around  $T = 450$  mK, where the sharp increase begins,  $\zeta \lesssim 0.3$ , and at  $T = 600$  mK, where the increase plateaus,  $\zeta \simeq 0.1$ , thus satisfying this criterion. Consistent with our previous report [32], CBM301 shows an opposite behavior to CBM302, and within experimental resolution the nonlocal resistance is absent except for a small positive hump occurring at  $T \simeq 400$  mK, where  $\zeta \simeq 0.5$ . For CBM301, the Knudsen parameter only falls below 0.1 near  $T = 1$  K, where phonon interactions become non-negligible. As a result, the higher density device does not exhibit hydrodynamic flow.

*Nonlocal reciprocity measurements.* To test the reciprocity relations, we measured the nonlocal response for both O1 and O2 configuration; see Fig. 2(a). Despite the smaller current-driving area and larger measurement area in the O2 configuration compared to O1, we observe no notable differences in nonlocal resistance, and their temperature dependence is shown in Fig. 2(d). Clearly, the Onsager reciprocity relations are satisfied over the temperature range probed in our experiment, i.e., from  $T = 6$  mK to  $T = 1$  K, as expected in hydrodynamic transport [33]. This also shows that the nonlocal signal is not caused by an accumulation of charges, as reciprocity measurements should have differed with constant electron density between the inner and outer annular rings with significantly different areas. In the SM [29], we show that the reciprocity relations are analytically satisfied for our system based on the hydrodynamic model presented in the following section. Finally, we performed probe symmetry measurements between adjacent contacts, also shown in the SM [29], which are all proved to be satisfied.

*Electron collision and kinetic theory.* In a continuum, the role played by individual particle states diminishes and the flow becomes governed by the transport of a macroscopic fluid ensemble of particles. When this is the case, the details of their macroscopic behavior arise from the description of individual particle states through solving Boltzmann's transport equation (BTE) of kinetic theory and determining macroscopic quantities. For electron flow, however, interparticle interactions become important, requiring higher-order terms for an accurate description. Macroscopically, these interactions are described as body forces acting on the collective behavior of the system. In our case, the interaction mechanisms arise by scattering, and we consider two main forms: momentum-conserving  $e$ - $e$  scattering and momentum-relaxing electron-impurity scattering, with relaxation times  $\tau_{MC}$  and  $\tau_{MR}$ , respectively. We also omit the contribution to momentum-relaxing due to electron-phonon scattering in our modeling since it has been shown to play a negligible role below a temperature of 1 K [34]. Moreover, it is known that well below 1 K, electron-impurity scattering does not depend on temperature, whereas electron-electron scattering has an

inverse square power relationship [2,35]. Despite the common misconception that momentum-conserving interactions do not affect bulk resistivity, in a Corbino device without edges our observations of a nonmonotonic temperature-dependent transport and the realization of the Gurzhi effect must relate to momentum-conserving scattering. As such, when deriving the collective behavior from BTE, we must consider the effects of a collision integral that is nonzero under velocity space integration.

In the presence of an electric field  $\vec{E}$ , the linearized transport equation is [36]

$$\frac{\partial f_{\vec{v}}}{\partial t} + \vec{v} \cdot \frac{\partial f_{\vec{v}}}{\partial \vec{r}} + \frac{q_e}{m^*} \vec{E} \cdot \frac{\partial f_{\vec{v}}^0}{\partial \vec{v}} = \left( \frac{\partial f_{\vec{v}}}{\partial t} \right)_{\text{coll}}, \quad (1)$$

where  $(\vec{v}, \vec{r}, t)$  is the particle velocity and position at time  $t$ ,  $f_{\vec{v}}(\vec{v}, \vec{r}, t)$  is the electron distribution function,  $f_{\vec{v}}^0(\vec{v}, \vec{r}, t)$  is the equilibrium distribution in the absence of an electric field,  $q_e$  is electron charge  $-e$ , and  $m^*$  is effective mass ( $0.067m_e$  for GaAs/AlGaAs). Using the relaxation-time approximation, momentum-relaxing scattering relaxes the system to a field-less equilibrium, whereas momentum-conserving scattering relaxes the system to an equilibrium where electrons drift at velocity  $\vec{v}_{\text{drift}}$  with a shifted distribution function  $f_{\vec{u}}^0$ . The collision integral then becomes

$$\left( \frac{\partial f_{\vec{v}}}{\partial t} \right)_{\text{coll}} = -\frac{f_{\vec{v}} - f_{\vec{v}}^0}{\tau_{MR}} - \frac{f_{\vec{v}} - f_{\vec{u}}^0}{\tau_{MC}}. \quad (2)$$

Then we relate net drift velocity  $\vec{v}_{\text{drift}}$  with average velocity  $\vec{u} \equiv \langle \vec{v} \rangle = \frac{1}{n} \int d\vec{v} \vec{v} f$  by  $\vec{j} = 2e \int d\vec{v} \vec{v} f = ne\vec{v}_{\text{drift}}$  [18]. For small drift velocity, expanding  $f_{\vec{u}}^0 = f_{\vec{v}}^0(\epsilon - m^* \vec{v} \cdot \vec{v}_{\text{drift}})$  around static equilibrium yields

$$f_{\vec{u}}^0 \approx f_{\vec{v}}^0 - 2\vec{u} \cdot \frac{\partial f_{\vec{v}}^0}{\partial \vec{v}}, \quad (3)$$

and substituting this result into Eq. (2) gives

$$\left( \frac{\partial f_{\vec{v}}}{\partial t} \right)_{\text{coll}} = -\frac{f_{\vec{v}} - f_{\vec{v}}^0}{\tau_T} - \frac{2}{\tau_{MC}} \vec{u} \cdot \frac{\partial f_{\vec{v}}^0}{\partial \vec{v}}, \quad (4)$$

where  $\tau_T^{-1} = \tau_{MC}^{-1} + \tau_{MR}^{-1}$  is the total mean-free time of all scattering events by Matthiessen's rule. This result is consistent with previous work in lower dimensions [9,18,27,37,38] and approximates the nonlocal 2DEG region. The Boltzmann's equation now reads

$$\frac{\partial f_{\vec{v}}}{\partial t} + \vec{v} \cdot \frac{\partial f_{\vec{v}}}{\partial \vec{r}} + \left( \frac{q_e}{m^*} \vec{E} + \frac{2\vec{u}}{\tau_{MC}} \right) \cdot \frac{\partial f_{\vec{v}}^0}{\partial \vec{v}} = -\frac{f_{\vec{v}} - f_{\vec{v}}^0}{\tau_T}, \quad (5)$$

and taking the first velocity moment of Eq. (5), we arrive at the Navier-Stokes equation where the third and fourth term give body force with the following scattering corrections:

$$\begin{aligned} \vec{f} &= \frac{q_e}{m^*} \vec{E} + \vec{u} \left( \frac{2}{\tau_{MC}} - \frac{1}{\tau_T} \right) \\ &= -\frac{q_e}{m^*} \vec{\nabla} \phi + \frac{\vec{u}}{\tau}, \end{aligned} \quad (6)$$

where  $\tau^{-1} = \tau_{MC}^{-1} - \tau_{MR}^{-1}$  and  $\vec{E} = -\vec{\nabla} \phi$ . This macroscopic description of the body force originating from the single-particle picture will be shown below to be of paramount importance for the nonlocal electronic transport observed in the hydrodynamic regime. We stress that our treatment of BTE

follows the established procedure from previous studies of hydrodynamic electrons [9,18,27,37,38].

*Hydrodynamics and electron viscosity.* The Navier-Stokes equation of hydrodynamics for incompressible flow can be written as [39]

$$\vec{\nabla} \cdot \vec{u} = 0, \quad (7)$$

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \vec{\nabla}) \vec{u} = \nu \vec{\nabla}^2 \vec{u} + \vec{f}. \quad (8)$$

In our case,  $\vec{u}$  describes the carrier velocity,  $\nu = \frac{v_f \ell_{MC}}{4}$  is the electron viscosity [3] with  $v_f$  the Fermi velocity, and  $\vec{f}$  is the body force per unit mass given by Eq. (6). As the carrier velocity  $\vec{u}$  is fixed by the applied current, we consider a steady-state flow (i.e.,  $\frac{\partial \vec{u}}{\partial t} = \vec{0}$ ) and rewrite Eq. (8) as

$$(\vec{u} \cdot \vec{\nabla}) \vec{u} = \nu \vec{\nabla}^2 \vec{u} - \frac{q_e}{m^*} \vec{\nabla} \phi + \frac{\vec{u}}{\tau}. \quad (9)$$

At zero magnetic field,  $\vec{u} = (u_r, 0, 0)$  in polar coordinates for the Corbino geometry [40], and as shown in the SM [29], analytic solutions to Eqs. (7) and (9) provide the general forms of  $u_r$  and  $\phi$  as

$$u_r \propto \frac{1}{r}, \quad \phi \propto \tau^{-1} \log(r), \quad (10)$$

and as a result when the steady-state solution of  $u_r$  is substituted into Eq. (9), the viscosity term  $\nu \vec{\nabla}^2 \vec{u}$  disappears. Although this may seem unusual as it would suggest that viscosity plays no role at first glance, viscosity is responsible for resisting radial shear deformations, where fluid layers move at different speeds along the direction of motion. This shear deformation occurs due to radial velocity gradients, such as those seen in the discontinuous motion at contact boundaries in Ohmic transport, and it causes flow to extend beyond the discontinuity [41]. It is only at this point that the viscosity term truly does drop out. As flow beyond the boundary is a direct result of this viscosity term, one would expect an explicit dependence of  $\nu$  in the electric potential profile  $\phi$ . In our model, this manifests as the dependence of  $\ell_{MC}$  in  $\tau$ , which is directly related to  $\nu$  and depends greatly on temperature below 1 K. A distinct feature of radial hydrodynamic transport, viscous electron flow can now extend beyond the source-drain region and be experimentally probed.

*Navier-Stokes simulation and comparison with experiment.* To confirm our findings, we modeled the electronic system using the Navier-Stokes equations (7) and (8). We performed simulations of these equations for nonlocal configurations in CBM301 and CBM302 from base temperature to  $T = 1$  K. In this configuration, simulations are extended from the active simulation region (the current path) to the outer rings through extrapolation, by fitting carrier velocity  $\vec{u}$  and electric potential  $\phi$  to general functions resembling Eq. (10). This extrapolation technique is verified by simulating the entire region, and it is shown in sec. 5.3 of the SM [29]. To obtain the voltage difference, we subtracted the electric potential from edge-to-edge of each contact, using the configuration shown in Fig. 2(a), O1. As the Ohmic contacts are made by diffusion, the metal-rich phases penetrate the heterostructure, and one may wonder if it obstructs the 2DEG. In an extensive study of diffusion by way of transmission electron

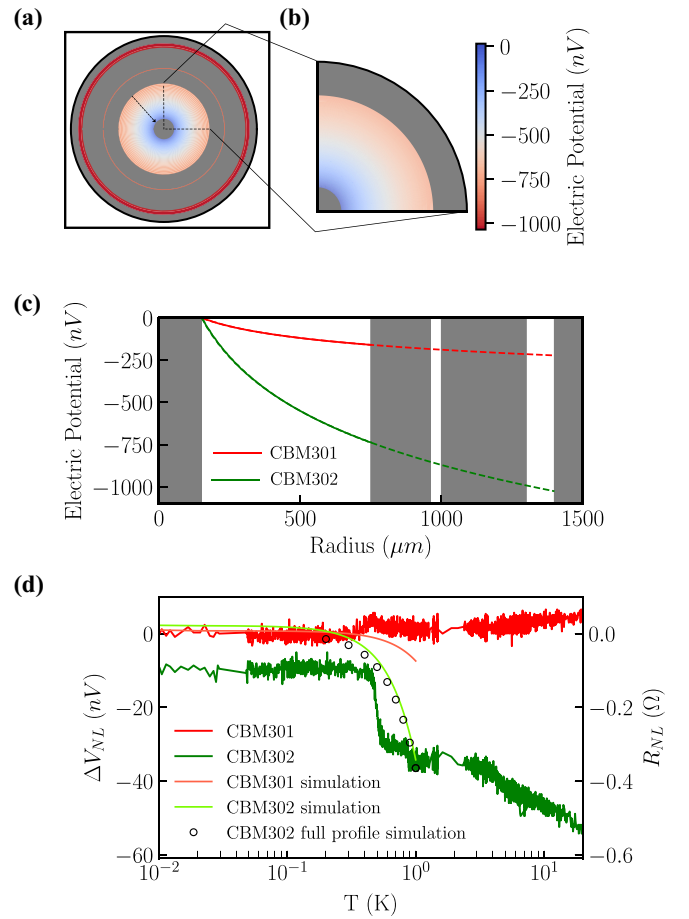


FIG. 3. Nonlocal simulation results. Simulation results are shown with the center contact as the grounding reference point. (a) The results of nonlocal simulation for CBM302 with shaded regions representing Ohmic contacts. (b) A zoom-in of the active simulation region. (c) Results for both CBM301 and CBM302 along the central axis, with the dotted lines indicating the region of extrapolation. Ohmic contacts are shaded gray. (d) Comparison with simulated and experimental results for both devices is shown. The results of the full profile simulations without approximation are shown as open circles (see the main text and the SM [29]).

microscopy and energy-dispersive x-ray spectroscopy, it was concluded [42] that the annealing produces a highly doped region within the 2DEG, making the Schottky barrier very thin. As a result, 2DEGs with heterostructures similar to those presented in our work can retain their electronic transport characteristics. While this obstruction likely induces disorder to some unknown degree, and could modify the profile of  $\phi$  within the contact region, by taking the edge-to-edge potential difference, the overall effect of the obstruction drops out.

The temperature dependence of simulated values of the nonlocal potential is shown in Fig. 3(d) together with the experimental values of potential difference measured. While the simulation does not capture the negative nonlocal potential observed below  $\sim 300$  mK temperature in the superballistic transport regime, it nevertheless semiquantitatively explains the strong (weak) nonlocal voltages observed in CBM302 (CBM301) between 450 mK and 1 K. Furthermore, the obtained simulation value of  $-7.4 \pm 0.1$  nV for CBM301 at

$T = 1$  K confirms that the near-zero nonlocal resistance in our experimental data is not a result of dominant hydrodynamic transport. Finally, for temperatures well above 1 K, we verified that including phonon contributions to resistances by adding experimentally determined electron-phonon scattering rates to our model [43] restored the expected behavior, i.e., a monotonic increase in resistance towards a positive value.

To validate our extrapolation technique, we also performed several transient simulations without the assumptions leading to Eq. (9). These simulations, described in detail in the SM [29], simulated all regions shown in Fig. 3(a) with the sole constraint that the velocity  $\vec{u}$  within the source/drain region is fixed by the applied current. The equation of motion was derived from the first velocity moment of Eqs. (1) and (2), with the first velocity moments of  $f_v^0$  and  $f_u^0$  set to the static and fixed velocities, respectively. In the central and outer 2DEG regions, velocity  $\vec{u}$  was initially set to zero and allowed to evolve naturally. The simulations yielded a positive electric potential profile within the source/drain region, consistent with local measurements and with an abrupt directional change occurring at the discontinuity. The edge-to-edge potential differences obtained from these simulations are shown as open circles in Fig. 3(d), and the resulting velocity profile closely matched the analytic solution of Eq. (7), with the expected  $u_r \propto \frac{1}{r}$  dependence.

**Conclusion.** We have observed nonzero local and nonlocal voltages found to be akin to a Gurzhi effect, albeit in the bulk in a 2DEG Corbino device with high  $e$ - $e$  interaction that meets the lengthscale criteria for hydrodynamic transport, i.e., at Knudsen number  $\zeta \ll 1$ . Importantly, both local and nonlocal transitions in this device occur at the same temperature. The nonlocal signal was found to be nearly absent in a lower  $e$ - $e$  interaction device that failed to meet the same lengthscale criteria in a similar temperature range of investigations. Due to the bulk nature of electronic transport in the Corbino geometry, and considering the Navier-Stokes equations, we conclude that the body force of carriers plays an integral role in dictating the flow of electrons, and necessarily contains the electron viscosity. This in turn allows viscous drag flow to extend beyond the contact boundary, as is observed in the

experiment. Looking forward, our confirmation of hydrodynamic transport in GaAs/AlGaAs Corbino rings may allow the probing of Hall viscosity, an intriguing dissipationless bulk property arising from the odd symmetry of the viscosity tensor in two dimensions [14].

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S.V. and G.G. conceived the experiment. K.W.W. and L.N.P. performed the semiconductor growth by molecular beam epitaxy and provided the material. S.V. fabricated the Corbino samples, conducted the electronic transport measurements at low temperatures, and performed the data analysis. Z.B.K. performed the theoretical modeling and the numerical simulations, assisted by J.M. and S.V. Important expertise and insights on semiconductor physics and data interpretation were provided by L.W.E. and M.P.L. The manuscript was written by S.V., Z.B.K., and G.G., and all authors commented on it. Finally, both S.V. and Z.K.B. contributed equally to this work.

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