Composite Fermions (CF), new quasiparticles initially described as the combination of an electron with an even number of magnetic flux quanta, provide a simplifying physical picture of the fractional quantum Hall effect (FQHE) [1]. The particles have also been argued [2] to possess many of the properties of electrons at zero magnetic field, experiencing an effective field which is zero for a half-filled Landau level even though they exist in the presence of extreme magnetic fields. Numerous experimental investigations, including studies of surface acoustic waves (SAW) [3], cyclotron resonance in antidot lattices [4], activation energies [5] and magnetic focusing [6], have confirmed the existence of these particles and reveal behavior similar to zero-field electrons. The experiments, in addition, clearly support the existence of a Fermi surface for the particles. A common element of these investigations, however, is that they have generally been limited to small wavevector scattering. A key question for the particles, how they respond to large wavevector scattering, especially across the re-emergent Fermi surface, has not been systematically investigated in experiment. It is this response that the experiments presented here were designed to address.

Access to the large wavevectors required for scattering a CF across the Fermi surface is provided here through phonons. The use of phonons permits the scattering wavevector \( q \) to be effectively tunable by changing the temperature, \( T \). At low temperatures, only small wavevector acoustic phonons are thermally excited, limiting scattering of CF to small \( q \) processes. As the temperature is increased, access to larger wavevector phonons permits larger wavevector scattering. For electrons, the transition to large angle scattering is readily evident due to a sharp cutoff [7] for scattering with \( q \) greater than twice the Fermi wavevector \( 2k_F \). The cutoff results directly from the existence of a Fermi surface and the combined restrictions of momentum and energy conservation. A clear change in temperature dependence, the Bloch-Grüneisen transition, has been directly observed in resistivity measurements [8] and in phonon drag [9].

A similar cutoff should exist for composite Fermions. Two key elements are required. The first is the presence of a Fermi surface for the particles. The second is that CF must be able to withstand large wavevector scattering, sending a CF across its Fermi surface. While the first condition is well established [3,4,6], the second has not been theoretically investigated in detail, with studies generally limited to small wavevectors and low temperatures. Details of the phonon interaction with CF should not affect the existence of this cutoff, as they do not for electrons, which depends only on the magnitude of the phonon wavevector as compared to \( 2k_F \).

The isolation of phonon scattering in this work is attained through electron drag measurements between remotely spaced parallel two-dimensional electron gas (2DEG) layers. In electron drag [10] when a current is driven through one of two electrically isolated 2DEG’s, interlayer electron-electron (e-e) interactions transfer momentum to the second layer, inducing a voltage in that layer. The drag transresistivity \( \rho_D \), the ratio of this voltage to the applied current per square, is a direct measure of the interlayer scattering rate [10]. While Coulomb scattering dominates \( \rho_D \) for closely spaced layers, its strong layer spacing dependence [10,11] permits interlayer phonon exchange to completely dominate [10,12] interactions of remote layers.

The samples used in this work, GaAs/AlGaAs double quantum well structures, consist of two 200 Å wide quantum wells which are remotely spaced. The bulk of the CF measurements were performed on a sample with a 5000 Å barrier thickness. Each layer has an electron density, \( n \), near \( 1.5 \times 10^{11}/cm^2 \) as grown, with mobilities approaching \( 2 \times 10^6/cm^2/V/s \). Individual layer densities were varied through the application of a voltage to an overall top gate or by applying an interlayer bias, with the densities in each layer made equal for all measurements. The large two-terminal resistances present in the samples at high fields demanded particular care, requiring measurement frequencies as low as 0.5 Hz and currents as low as 20 nA. Established tests [11] such as interchanging current and voltage leads, testing current linearity, and ensuring the absence of interlayer leakage and other spurious signals.
through ground configuration changes all confirm the validity of the measurements. The lack of change in the drag signal upon reversal of the magnetic field indicates that Hall voltages play no role in these measurements. Comparable results were obtained for a second 5000 Å barrier sample and a 2400 Å barrier sample.

The effect of the 2\(k_F\) cutoff for phonon scattering is shown in Fig. 1a for a zero-field phonon drag measurement on a 2400 Å barrier sample in which Coulomb scattering is negligible. Data are plotted as \(\rho_D/T^2\), revealing a distinct change in temperature dependence and a peak near 2 K. The peak position is known not to change with layer spacing, \([9,12]\); \(\rho_D\) for this sample is shown due to significantly reduced signals for the 5000 Å barrier sample at zero field. The peak position, which varies with the size of the Fermi surface (i.e., \(\propto \sqrt{n}\)) [13], quantifies the transition from a strong temperature dependence with \(q \leq 2k_F\), to the weaker dependence when \(q\) is limited to \(2k_F\) scattering. The inset plots the relative net momentum carried by phonons of a given in-plane wavevector for both deformation potential and piezo-electric coupling at 3 K. This single-layer calculation, based closely on earlier work [3], clearly shows the cutoff at \(2k_F\) is independent of details of the electron-phonon interaction. The temperature of the peak in \(\rho_D/T^2\) is thus directly related to the phonon wavevector which matches \(2k_F\).

Before examining the temperature dependence of phonon drag for composite Fermions, it is necessary to re-establish, at high fields, that phonon scattering dominates \(\rho_D\). This is explored through measurements made below 1K (Fig. 1b, inset) on a 5000 Å barrier sample at 13T corresponding to a half-filled lowest Landau level (\(\nu = 1/2\)). This data is well characterized by a power law dependence with a best fit of \(\rho_D \propto T^{3.7}\) (solid line). This exponent is substantially higher than the sub-quadratic dependence established for Coulomb drag of CF [14, 17] and is more consistent with expectations of phonon scattering from thermopower measurements [18] and theoretical calculations [19]. The behavior of \(\rho_D\) at low temperatures firmly establishes a negligible role for Coulomb scattering in this sample.

Measurements of \(\rho_D/T^2\) for CF at higher temperatures, shown in Fig. 1b, reveal a behavior remarkably similar to that for zero field electrons at the same density. The transition from a strong to a weak temperature dependence mimics the low field data, with a peak position near but slightly lower than that in Fig. 1a. The behavior indicates a distinct wavevector cutoff in the phonon scattering process. A notable difference is the magnitude of \(\rho_p\), being significantly larger for CF. This increase is similar to the enhanced scattering of CF generally observed.

While the data confirm the existence of a wavevector cutoff, the temperature of the peak in \(\rho_D/T^2\), \(T_p\), is substantially lower than expected. Spin polarization of the CFs results in a larger Fermi surface than at zero field, yielding a peak in \(\rho_D/T^2\) at a higher temperature for the same phonon system. The expected \(\sqrt{2}\) increase in the size of the Fermi surface has been established in other measurements [14, 18] and would result in a peak position closer to 3 K as indicated by the arrow in the figure.

The substantial difference between the measured and anticipated peak position for CF raises the possibility that the q cutoff may not result from the CF Fermi surface. Questions of CF stability, for example, must be considered. Theoretical predictions [21] of the CF binding energy are \(\sim 4K\) for these densities. The observed peak position, 1.9 K, however, is below this binding energy and well within the range for which CF effects are observable in SAW measurements [21]. The lack of strong FQHE states at these temperatures does not indicate an invalid regime for CFs, but merely the absence of an energy gap. This distinction is evident in recent magnetization measurements [22].

Another possibility is that the maximum in \(\rho_D/T^2\) is due to single-particle effects of the electron system in a high magnetic field. For example, the scattering wavevector may have a cutoff determined by the width of the Landau level [23] or the magnetic length [24]. These origins of a cutoff have been argued to be responsible for features observed in earlier thermopower measurements at \(\nu = 1/2\) [23] and ballistic phonon absorption at high magnetic fields [24], respectively. Both of these mechanisms would result in an increase of the peak position as
the field is increased. However, examination of \( \nu = 1/4 \) (not shown), another CF state, shows a temperature dependence similar to \( \nu = 1/2 \) for a given density, but with a \( \sim 10\% \) lower peak position. This small decrease in \( T_P \), for a factor of 2 increase in field, clearly contradicts scattering limitations due to the Landau level width or the magnetic length. In addition, the similarity between the peak position for \( \nu = 1/2 \) and \( \nu = 1/4 \) supports the assertion that composite Fermions are observed.

To explore the origin of the discrepancy in the peak position, \( \rho_D \) was measured in the presence of an effective magnetic field. Figure 2a shows the effect of varying the system away from \( \nu = 1/2 \) by changing the magnetic field with a constant density. A striking element of these measurements is the change in the magnitude of \( \rho_D / T^2 \), which increases by roughly threefold. Another is the variation of the peak position with field. The value of \( T_P \) has been quantified through a fit in the vicinity of the maximum, with the resultant peak values, shown in the inset, generally insensitive to the functional form of the fit. At fields near and above half filling, \( T_P \) is proportional to \( \sqrt{B} \) (solid line), while \( T_P \) falls below this dependence at lower fields.

A complimentary method for the application of an effective magnetic field is explored in Fig. 2b, where the external field is constant and the density is varied. Significant changes in magnitude continue to be present as the density is varied with the magnetic field fixed at 12.8T. Compared to the field dependence of Fig. 2a, however, there is substantially less variation in the position of \( T_P \) (inset), with a weak maximum at half filling. This is suggestive that half filling, and thus CF, are important in determining the cutoff.

The changes in magnitude and peak position with the application of an effective field are inconsistent with general expectations for CF away from half filling. For example, field variations have been observed \[\text{[15]}\] to induce cyclotron motion of the composite particles, which experience an effective field equal to the difference of the applied field from that at half filling. Properties related to the Fermi surface of CF should persist for low effective fields, as they do for bare electrons, until the period of cyclotron motion is less than the scattering time. From this perspective, a peak position determined by the size of the Fermi surface should not change over the range of effective fields explored in Fig. 2 and the magnitude should remain relatively constant. It is thus difficult to reconcile the changes in the measured behavior within a simple CF picture.

The complex behavior observed motivates consideration of spin effects, though expectations of spin-splitting energies are large enough that such effects appear unlikely. Measurements of \( \rho_D \), with the sample tilted 22°, matching the perpendicular fields and electron density of Fig. 2a, were indistinguishable from that data in both magnitude and peak position. This rules out a role for spin in the interlayer phonon scattering process.

A common element of the measurements of Fig. 2 is that significant deviations from \( \nu = 1/2 \) were made. The complexity of those measurements is greatly reduced if half-filling is retained while the density is changed, as shown in Fig. 3, eliminating the effective field. A change in the peak position with density is still evident, however the large variations in magnitude of the measurements of Fig. 2 are now absent, with all densities approaching a common \( \rho_D / T^2 \) at higher temperatures. The peak positions, shown in the inset, are reasonably described by \( T_P \propto \sqrt{n} \) (solid line), consistent with changes of the size of the CF Fermi surface. This behavior does not result from a simple combination of the individual dependences on field and density observed in Fig. 2.

Comparison of the density dependence of the magnitude of \( \rho_D \) in Fig. 3 with that of electrons at zero field provides additional support that this data results from a Fermi surface related cutoff of CF scattering. The electronic response, shown in the inset of Fig. 3 for the 2400 Å barrier sample, reflects the general behavior of the CF system. In addition to \( T_P \) varying with the size of the Fermi surface, both show little density dependence in
Another clearly important question involves the position of $T_P$ observed at half filling; it is one-third lower in temperature than anticipated from extrapolation of the zero field measurements. Various reasons for this discrepancy may be considered. One possible cause lies in the significant difference in sound velocity between longitudinal and transverse phonons in GaAs layers. The shift of $T_P$ observed, however, would require that zero-field electrons interact exclusively with longitudinal phonons, but CF predominantly with transverse phonons. Such behavior is inconsistent with both theoretical investigations of phonon drag and the measured position of $T_P$ in the electron system. A second consideration is that the relative contribution of $2k_F$ scattering, as compared to smaller $q$’s, may be substantially weaker for CF than in the electron system. Reducing this contribution could move $T_P$ to lower temperatures. This would contradict preliminary numerical calculations done for low energies. Another possibility is that the internal structure of the particles themselves are probed in these large wavevector scattering events. Resolution of these and other questions raised in this work will likely require additional investigation.

FIG. 3. Temperature dependence of $\rho_D/T^2$ for various carrier densities showing similar behavior for composite Fermions and zero-field electrons (lower inset). For composite Fermions the field was adjusted to maintain the system at $\nu = 1/2$. Upper Inset: Changes in peak position, $T_P$, with density compared to $\sqrt{\nu}$ (solid line), which reflects the change in size of the CF Fermi surface.

$\rho_D/T^2$ at high temperatures despite the density of the electron measurements spanning a wider range than for CF. The striking similarity of the zero field data with the CF measurements, when restricted to $\nu = 1/2$, suggests a simpler response in which the CF system mimics that of electrons.

These data raise a number of puzzling questions. The first regards behavior as $\nu$ is varied from half-filling. The generally accepted picture of an effective field which has little impact until the CF cyclotron period is less than the scattering time is inconsistent with the considerable changes observed in the density and field dependence of $\rho_D$. The origin of these inconsistencies and whether they are related to the large $q$ scattering probed in this work remains an open question.

Another clearly important question involves the position of $T_P$ observed at half filling; it is one-third lower in temperature than anticipated from extrapolation of the zero field measurements. Various reasons for this discrepancy may be considered. One possible cause lies in the significant difference in sound velocity between longitudinal and transverse phonons in GaAs layers. The shift of $T_P$ observed, however, would require that zero-field electrons interact exclusively with longitudinal phonons, but CF predominantly with transverse phonons. Such behavior is inconsistent with both theoretical investigations of phonon drag and the measured position of $T_P$ in the electron system. A second consideration is that the relative contribution of $2k_F$ scattering, as compared to smaller $q$’s, may be substantially weaker for CF than in the electron system. Reducing this contribution could move $T_P$ to lower temperatures. This would contradict preliminary numerical calculations done for low energies. Another possibility is that the internal structure of the particles themselves are probed in these large wavevector scattering events. Resolution of these and other questions raised in this work will likely require additional investigation.

In summary, large wavevector scattering of composite Fermions has been investigated through measurements of interlayer phonon drag. The temperature dependence of these measurements implies the existence of a wavevector cutoff, in agreement with qualitative properties of the electron system at zero field. As the CF system is varied from $\nu = 1/2$, clear changes in magnitude and temperature dependence develop which are inconsistent with current expectations of CF’s. Varying the density but remaining at half filling shows behavior substantially more consistent with the zero field electron system. A clear deviation remains, however, from the temperature dependence anticipated for a wavevector cutoff corresponding to $2k_F$ scattering.

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