Missing $2k_F$ Response for Composite Fermions in Phonon Drag

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The response of composite fermions to large wave vector scattering has been studied through phonon drag measurements. While the response retains qualitative features of the electron system at zero magnetic field, notable discrepancies develop as the system is varied from a half-filled Landau level by changing density or field. These deviations, which appear to be inconsistent with the current picture of composite fermions, are absent if half filling is maintained while changing density. There remains, however, a clear deviation from the temperature dependence anticipated for $2k_F$ scattering.

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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 extreme magnetic fields. Numerous experimental investigations [3–6] have confirmed the existence of these particles and reveal behavior similar to zero-field electrons including the existence of a Fermi surface. A common element of these investigations, however, is that they have generally been limited to small wave vector scattering. A key question for the particles, how they respond to large wave vector 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 examine.

Access to the large wave vectors involved in scattering a CF across the Fermi surface is provided here through phonons. The use of phonons permits the scattering wave vector q, to be effectively tunable by changing the temperature T. At low temperatures, only small wave vector acoustic phonons are thermally excited, limiting scattering of CF to small q processes. Low temperature phonon scattering has been explored in previous thermopower studies [7]. As the temperature is increased, access to higher energy phonons permits larger wave vector scattering. For electrons, the transition to large angle scattering is readily evident due to a sharp cutoff [8] for scattering with q greater than twice the Fermi wave vector ($2k_F$). 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 [9] and in phonon drag [10].

A similar cutoff should exist for composite fermions. Two key elements are required: the presence of a Fermi surface for the particles and the ability of CF to withstand large wave vector scattering. 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 wave vectors and low temperatures. Details of the phonon interaction with CF should not affect the existence of this cutoff, as they do not for electrons, where it depends only on the magnitude of the phonon wave vector 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 [11] when a current is driven through the first 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 ρ_D, the ratio of this voltage to the applied current per square, is a direct measure of the interlayer scattering rate [11]. While Coulomb scattering dominates ρ_D for closely spaced layers, its strong layer spacing dependence [11,12] permits interlayer phonon exchange to completely dominate [10,13,14] interactions of remote layers.

The samples used are GaAs/AlGaAs double quantum well structures, consisting of two 200 Å wide quantum wells. The bulk of the CF measurements was performed on a sample with a 5000 Å well separation. Each layer has an electron density, n, near 1.5×10^{11} cm^{-2} as grown, with mobilities approaching 2×10^6 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 all confirm the validity of the

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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 $2k_F$ cutoff for phonon scattering is shown in Fig. 1a for a zero-field (i.e., electron) phonon drag measurement on a 2400 Å barrier sample in which Coulomb scattering is negligible. Data are plotted as ρ_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 [10,13]; ρ_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., $\propto \sqrt{n}$) [13,15], 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 wave vector for both deformation potential and piezoelectric coupling at 3 K. This single-layer calculation, based closely on earlier work [9,10], clearly shows the cutoff at $2k_F$ is independent of details of the electron-phonon interaction. The temperature of the peak in ρ_D/T^2 is thus directly related to the phonon wave vector which matches $2k_F$.

Before examining the temperature dependence of phonon drag for composite fermions, it is necessary to reestablish that phonon scattering dominates ρ_D. This is explored through measurements made below 1 K (Fig. 1b inset) on a 5000 Å barrier sample at 13 T, corresponding to a half-filled lowest Landau level ($\nu = 1/2$). These data are well characterized by a best-fit dependence of $\rho_D \propto T^{3.7}$ (solid line). This exponent is substantially higher than the subquadratic dependence established for Coulomb drag of CF [16–19] and is more consistent with expectations of phonon scattering from thermopower measurements and theoretical calculations [7]. The behavior of ρ_D at low temperatures firmly establishes a negligible role for Coulomb scattering in this sample.

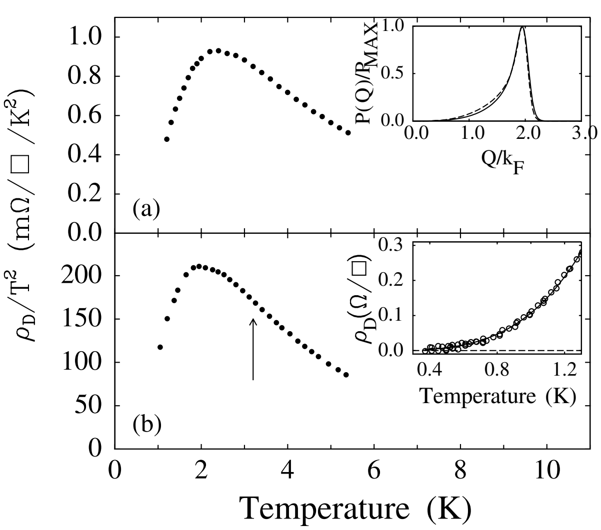

FIG. 1. T dependence of ρ_D/T^2, with density 1.5×10^{11}, shows similar behavior for (a) zero-field electrons and (b) composite fermions. Arrow indicates the anticipated peak position for CF. Upper inset: Relative net momentum transfer rate at 3 K for single-layer phonon scattering vs q, showing $2k_F$ cutoff for deformation potential (solid line) and piezoelectric (dashed line) coupling. Lower inset: Low temperature ρ_D for composite fermions. A fit proportional to $T^{3.7}$ indicates the absence of Coulomb scattering.

Measurements of ρ_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 wave vector cutoff in the phonon scattering process. A notable difference from zero field is the increase in magnitude of ρ_D, which is similar to the enhanced scattering of CF generally observed.

While the data confirm the existence of a wave vector cutoff, the temperature of the peak in ρ_D/T^2, T_P, is substantially lower than expected. Spin polarization of the CF's results in a Fermi surface larger than at zero field, so a $2k_F$ cutoff should emerge 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 [3,4,6] and would result, based on the electron response, 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 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 [20] of the CF binding energy are ~4 K for these densities. The peak position, 1.9 K, however, is below this binding energy and well within the range for which CF effects are observable in surface acoustic wave measurements [21]. The lack of strong FQHE states at these temperatures does not indicate an invalid regime for CF's but merely the absence of an energy gap, a distinction evident in recent magnetization measurements [22].

Another possibility is that the maximum in ρ_D/T^2 is due to single-particle effects of the electron system in a high magnetic field. For example, the scattering wave vector 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 $\nu = 1/2$ [25] 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 ~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, ρ_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 a large change in the magnitude of ρ_D/T^2. 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; 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, is important in determining the cutoff.

The changes in magnitude and peak position upon application of an effective field are inconsistent with general expectations for CF away from half filling. For example, field variations were observed [4,6] 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, while retaining electronlike character. 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 ρ_D, with the sample tilted 22°, matching the perpendicular fields and density of Fig. 2a, were indistinguishable from those data in both magnitude and peak position. This provides evidence against 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 varying density, eliminating the effective field (Fig. 3). Changes in the peak position are still evident; however, the large variations in magnitude of the measurements of Fig. 2 are now absent. The peak positions, shown in the inset, are reasonably described by

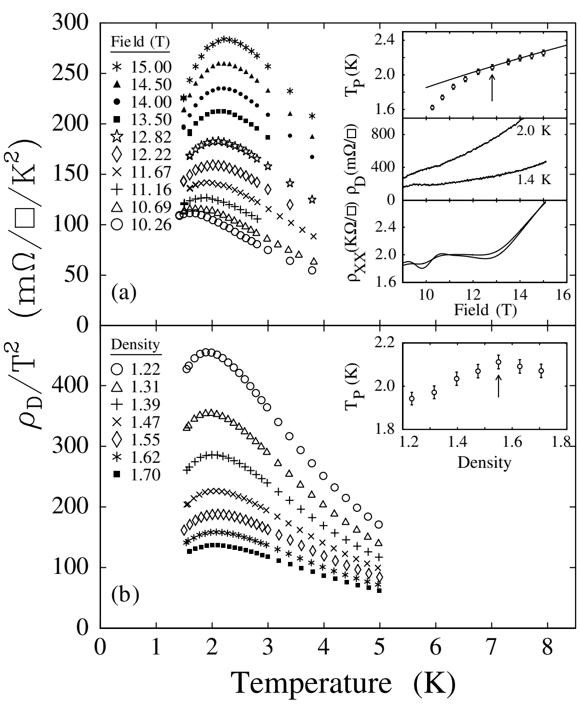

FIG. 2. (a) T dependence of ρ_D/T^2 at various magnetic fields with fixed density, $\nu = 1/2$ occurs at $12.82T$. Upper inset: Peak position vs field. Solid line represents $T_P \propto \sqrt{B}$ at higher fields with the arrow indicating $\nu = 1/2$. Middle and lower insets show ρ_D and the longitudinal resistivity, at 1.4 and 2.0 K, illustrating the vanishing effect of the fractional states at these temperatures. Plot (b) is similar to (a) but with field fixed and density varied in units of (10^{11} cm^{-2}). These behaviors deviate from the anticipated response of CF.

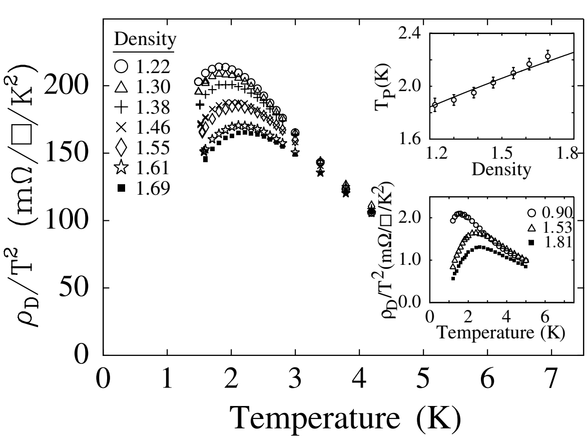

FIG. 3. Temperature dependence of ρ_D/T^2 for various carrier densities showing similar behavior for composite fermions and zero-field electrons (lower inset). For composite fermions the field was adjusted to maintain the system at $\nu = 1/2$. Upper inset: Changes in peak position, T_P, with density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

$T_P \propto \sqrt{n}$ (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 ρ_D in Fig. 3 with that of electrons at zero field provides additional support that these data result from a Fermi surface related cutoff of CF scattering. The electronic response, shown in the inset in Fig. 3 for the 2400 Å barrier sample, clearly 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 ρ_D/T^2 at high temperatures despite the density of the electron measurements spanning a much 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 better mimics that of electrons.

These data raise a number of puzzling questions. The first regards behavior as ν 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 ρ_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. One possible cause for this discrepancy 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 and is inconsistent with both theoretical investigations [15] 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 may be substantially weaker for CF than in the electron system shifting T_P to lower temperatures. This effect, while present, is relatively small in very recent calculations of CF drag [26], which show that a Chern-Simons approach generally cannot reproduce our experimental findings. Alternatively, interaction effects between CF's could conceivably play a role [27]. Another intriguing possibility is that the internal structure of the particles themselves is probed in these large wave vector scattering events. Resolution of these and other questions raised in this work will likely require additional investigation.

In summary, large wave vector scattering of composite fermions has been investigated through measurements of interlayer phonon drag. The temperature dependence of these measurements implies the existence of a wave vector 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 wave vector cutoff corresponding to $2k_F$ scattering.

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