Geometric Resonance of Composite Fermions near Bilayer Quantum Hall States

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Via the application of parallel magnetic field, we induce a single-layer to bilayer transition in two-dimensional electron systems confined to wide GaAs quantum wells, and study the geometric resonance of composite fermions (CFs) with a periodic density modulation in our samples. The measurements reveal that CFs exist close to bilayer quantum Hall states, formed at Landau level filling factors $\nu = 1$ and $1/2$. Near $\nu = 1$, the geometric resonance features are consistent with half the total electron density in the bilayer system, implying that CFs prefer to stay in separate layers and exhibit a two-component behavior. In contrast, close to $\nu = 1/2$, CFs appear single-layer-like (single-component) as their resonance features correspond to the total density.

A clean two-dimensional electron system (2DES), at low temperature and under perpendicular magnetic field ($B_{\perp}$) which quenches the kinetic energy into the discrete Landau levels, displays many exciting phases as a function of Landau level filling factor $\nu$ (number of electrons per flux quantum). Examples include the integer and fractional quantum Hall states (IQHS and FQHS), Fermi sea of composite fermions (CFs), spin texture Skyrmions, stripe and bubble phases, and Wigner crystal [3, 4] as well as QHSs at total filling factor $\nu$ lead to yet more phases such as bilayer Wigner crystal [3] as well as QHSs at total filling factor $\nu = 1$ and $1/2$ which are believed to be the two-component $\Psi_{111}$ and $\Psi_{331}$ states, respectively [5–28]. Here, $\Psi_{mm'n} \sim \prod_{i,j} (z_i - z_j)^m (w_i - w_j)^n \prod_{i,j} (z_i - w_j)^n$ is the two-component Laughlin wave function [29, 30]. In this generalized description, $z$ and $w$ correspond to the complex coordinates of an electron in the different layers while the exponents $(m, m', n)$ characterize the wave function. These bilayer QHSs continue to be widely studied thanks to their many remarkable properties. In particular, the $\nu = 1 \Psi_{111}$ QHS phase is generally understood to be a Bose-Einstein condensate of excitons (interlayer pairing of electrons and holes) which exhibits superfluid transport and interlayer tunneling behavior, similar to the d.c. Josephson effect [15, 17, 24]. As for the $\nu = 1/2$ QHS observed in wide single quantum wells, although generally considered to be the $\Psi_{331}$ state, there is still a debate on whether it might have a single-component (Paffian) origin [6, 9, 10, 18, 23, 26, 28].

Here we probe the bilayer QHSs at $\nu = 1$ and $1/2$ using the Fermi gas properties of CFs at nearby fillings. CFs are exotic electron-flux quasi-particles near $\nu = 1/2$ in single-layer 2DESs that elegantly describe the physics of strongly interacting electrons [11, 2] and exhibit the ferromagnetic properties of CFs at nearby fillings. In the CF picture, each electron combines with two flux-quanta. As a result, CFs feel zero net $B_{\perp}$ at $\nu = 1/2$. Away from $\nu = 1/2$, however, they are subjected to the effective magnetic field $B_{\perp}^* = B_{\perp} - B_{\perp,1/2}$ [12] where $B_{\perp,1/2}$ is the field at $\nu = 1/2$. Thanks to this reduction in flux density, the neighboring FQHSs can be interpreted as the IQHSs of CFs [11, 31]. The flux attachment also explains the compressible state observed at $\nu = 1/2$ in terms of a CF Fermi gas [32]. This Fermi gas state extends to the vicinity of $\nu = 1/2$ much like that of electrons near $B_{\perp} = 0$. Many experimental studies have confirmed the existence of a CF Fermi sea near $\nu = 1/2$ via the geometric resonance (GR) of CFs’ cyclotron orbit with a periodic modulation of the 2DES density [33, 43, 51].

According to a recent study, signatures of CFs are also seen near total filling $\nu = 1/2$ in bilayer samples exhibiting a QHS at $\nu = 1/2$ [20]. Surprisingly, the observed GR features correspond to the total density in the bilayer system, suggesting a single-layer (or single-component) behavior for CFs [26]. This is particularly puzzling, if the nearby $\nu = 1/2$ QHS is indeed the two-component ($\Psi_{331}$) state. Here, we examine the fate of CFs near another bilayer QHS, namely the QHS at $\nu = 1$ which is also believed to be a two-component ($\Psi_{111}$) state. In sharp contrast to the $\nu = 1/2$ case, our GR features are consistent with half of the total density, revealing that CFs split into two layers near the bilayer QHS at $\nu = 1$.

In our measurements we apply a large parallel magnetic field ($B_{||}$) to tune the charge distribution and tunneling in our samples (Fig. 1). Without any $B_{||}$, electrons confined in a wide quantum well (QW) such as ours can be viewed as essentially a single-layer-like 2DES, or as two strongly coupled 2DESs with abundant interlayer tunneling (Fig. 1(a)). By tilting the sample at angle $\theta$ (as shown in (Fig. 1(c)), we apply $B_{||}$ which couples to the electron system through its finite layer thickness and adds an extra out-of-plane confinement, leading to a bilayer charge distribution with significantly suppressed interlayer tunneling (Fig. 1(b)) [14, 25, 52, 53]. Therefore, by changing $\theta$ and adjusting both $B_{||}$ and $B_{\perp}$, one can study the evolution of the 2DES from a single-layer to a bilayer and the stability of its phases at various $\nu$ [54]. In this work, we probe the QHSs and CFs near $\nu = 1$ as well as $\nu = 1/2$ as the system makes its single-layer to a
The resistance minima closely follow their expected positions based on a single-layer 2DES, evincing that at $B_{||} = 0$ our 2DES is indeed single-layer-like. Note that the $i = 1$ and $2$ assignments of the GR features in Fig. 2 and other cases in the manuscript can be verified by the ratio of their respective $B_{||}^*$ positions. For example, such ratio in Fig. 2 inset is $1.9$ which is very close to the expected value of $B_{||,i=1}^*/B_{||,i=2}^*$ ($= 2.25/1.25 = 1.80$) confirming that this assignment is indeed correct.

Figure 3 illustrates the evolution of the ground-state near $\nu = 1$ as a function of $B_{||}$. In Fig. 3(a), the $\theta = 0^\circ$ $R_{xx,pat}$ trace (red) shows a wide minimum at $B_{||} = 1$ that reaches zero and no signatures of GR features. (As seen in Fig. 2, $R_{xx,ref}$ also shows a wide, zero-resistance minimum at $\nu = 1$.) We also observe a wide plateau in the $R_{xy,ref}$ trace (blue); these are characteristics of a strong $\nu = 1$ IQHS, expected for a single-layer 2DES. In contrast, as $B_{||}$ is increased to $\sim 15$ T at $\theta = 66^\circ$ (Fig. 3(d)), the $R_{xx,ref}$ trace (black) shows a broad and shallow minimum, superimposed on an increasing background, across $\nu = 1$ while no plateau is observed in $R_{xy,ref}$, indicating that the ground-state is now compressible, i.e., the QHS is replaced by a CF Fermi sea. The patterned regions’ traces in Fig. 3(d) show additional resistance minima (marked by vertical lines) on both sides of $\nu = 1$. These features, which are absent in the $R_{xx,ref}$ trace, stem from the GR of CFs.
layers each at the GR features near in the Fig. 3(d) inset also corroborates our observation of the distorted Fermi contour of CFs [59], the deduced positions of which are consistent with the B$_\parallel$-induced distortion of the CFs’ Fermi contour which shrinks along B$_\parallel$ and gets elongated in the perpendicular direction [50, 51]. The GR features we report here very clearly show two distinct layers at B$_\parallel$ = 15 T, each possessing half of the total density.

Data taken at slightly smaller values of $\theta$ display more intriguing behavior. As the tunneling is increased by decreasing B$_\parallel$ (see the $\theta = 63^\circ$ traces in Fig. 3(c)), the ground-state at $\nu = 1$ evolves back to a QHS as evidenced by the relatively deep and sharp $R_{xx,ref}$ minimum and the developing $R_{xy,ref}$ plateau. However, we still observe GR features (vertical marks) very near $\nu = 1$ in the $R_{xx,pat}$ and $R_{yy,pat}$ traces similar to the $\theta = 66^\circ$ case. These features too correspond to half density, suggesting that the charge distribution is still bilayer-like. Similar behavior is also confirmed in the $\theta = 61^\circ$ $R_{xx,pat}$ traces of Fig. 3(b) by the presence of GR features surrounding the very strong QHS at $\nu = 1$. These GR features, which are consistent with a bilayer charge distribution in the vicinity of $\nu = 1$, imply that the observed QHS at $\nu = 1$ for $\theta = 63^\circ$ and $61^\circ$ is also of bilayer origin and is therefore the two-component $\Psi_{111}$ state.

The formation of a B$_\parallel$-induced $\Psi_{111}$ state, close to the $\theta$ at which the $\nu = 1$ QHS collapses, is consistent with the density-induced evolution (at $B_\parallel = 0$) in wide QW systems [11]. As the 2DES density is increased to sufficiently high values to render the charge distribution bilayer-like, the ground-state at $\nu = 1$ undergoes a phase transition from QHS to a compressible state. It was argued in Ref. [11] that the $\nu = 1$ QHS observed near this phase boundary is not the single-component IQHS but rather the $\Psi_{111}$ state. The temperature dependence of the $\nu = 1$ QHS near the boundary, quite different from that of the single-component QHS at lower densities, was considered as the main evidence [11]. The GR features we report here very near $\nu = 1$ provide a more direct signature for the $\Psi_{111}$ state by confirming its bilayer characteristics for $\theta = 63^\circ$ and $61^\circ$. The results also indicate that, while the system creates an exciton condensate at $\nu = 1$ in the form of a $\Psi_{111}$ QHS [24], slightly away from $\nu = 1$ it morphs into...
a bilayer (two-component) Fermi gas of CFs [60, 61].

Figure 3 also shows that the QHS at ν = 1 gets stronger as θ is decreased. This is consistent with the increase in interlayer tunneling which is expected to strengthen the ν = 1 QHS. In contrast, as θ is decreased from 66°, the GR features of CFs near ν = 1 become progressively weaker and eventually disappear at θ = 59° (data not shown). The diminishing amplitude of the GR features suggests that, as interlayer tunneling increases with decreasing B∥, the two-component CF phase becomes unstable. This observation is in agreement with Ref. [62].

Data presented so far offer conclusive evidence that CFs near the two-component Ψ111 QHS are also two-component. In contrast, as illustrated in Fig. 4, similar measurements near ν = 1/2 provide a stark difference. From Fig. 2 traces of Rxx,ref and Rxx,pat, we know that the ground-state at and near ν = 1/2 for B∥ = 0 is a CF Fermi sea. Moreover, the GR features, which are consistent with the total density, confirm the single-component nature of CFs near ν = 1/2. At this θ, away from ν = 1/2, the Rxx,pat (red) and Ryy,pat (green) traces show pronounced GR features (vertical lines marking i = 1 and 2). Similar to the ν = 1 case, the positions of these features reflect the B∥-induced distortion in the CF Fermi contour. However, unlike ν = 1, the deduced CF density of 1.65 × 1011 cm−2 agrees well with the total carrier density (within 4%) suggesting that the CFs near ν = 1/2 stay single-component even up to B∥ ∼ 15 T.

In the reference region’s traces, at θ = 46° we observe a sharp minimum in Rxx,ref and a developing plateau in Rxy,ref at ν = 1/2 (Fig. 1). Considering the θ = 0° Rxx,ref and Ryy,ref traces, which show none of these features, we conclude that B∥ has induced a bilayer FQHS at ν = 1/2, presumably the two-component Ψ331 state [14, 25]. Note that, the ν = 1/2 FQHS is stronger at lower temperatures as reported in Ref. [25]. The data of Fig. 1 establish that, although the ground-state of the electron system at ν = 1/2 at θ = 46° is a bilayer QHS, slightly away from ν = 1/2, CFs still behave as single-layer-like (single-component). Similar observations were made for a 2DES, confined to a 65-nm-wide GaAs QW, with density ∼ 1.8 × 1013 cm−2 [26] at θ = 0°, as mentioned near the beginning of the manuscript. In that case, the wider well width results in a bilayer-like charge distribution and a ν = 1/2 QHS without any B∥. The consistency of CFs’ single-component nature near the bilayer QHS at ν = 1/2 (for both the B∥-induced and the B∥ = 0 cases) strengthens our finding that CFs behave differently near the bilayer QHSs at ν = 1 and ν = 1/2. (The single-component CFs near ν = 1/2 should eventually become two-component under very large B∥. However, we are unable to detect them in our measurements. At such large values of B∥, the system prefers a bilayer Wigner crystal phase [3, 4, 25], manifested by very large resistance values and the disappearance of GR features.)

In conclusion, there is a phase transition into a CF Fermi gas state very near the bilayer QHSs at ν = 1 and 1/2. While CFs favor a two-component state near ν = 1, they stay single-component near ν = 1/2. We note that such two- versus single-component contrast between ν = 1 and 1/2 in a bilayer system also extends to the FQHSs observed further away from the GR features. For example, the ν = 6/5 and 4/5 FQHSs near the Ψ111 state are two-component [53] while the ν = 3/5, 5/9 and 5/11 FQHSs near the ν = 1/2 QHS are single-component [9, 25]. The GR features of CFs, together with these surrounding FQHSs of similar characteristics, thus suggest that while the bilayer QHS at ν = 1 is two-component, the ν = 1/2 QHS might be single-component.

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[82] We add that in GaAs 2D hole systems, there is a crossing of lowest two Landau levels $\nu=1$ and $1/2$. In our measurements near such $\nu=1$ QHS, we observe GR features of CFs which also correspond to half the total density. For the $\nu=1/2$ case, however, the 2D hole system shows insulating behavior.

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