Experimental Demonstration of Fermi Surface Effects at Filling Factor 5/2

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Using small wavelength surface acoustic waves (SAW) on ultrahigh mobility heterostructures, Fermi surface properties are detected at 5/2 filling factor at temperatures higher than those at which the quantum Hall state forms. An enhanced conductivity is observed at 5/2 by employing sub-0.5-μm SAW, indicating a quasiparticle mean-free path substantially smaller than that in the lowest Landau level. These findings are consistent with the presence of a filled Fermi sea of composite fermions, which may pair at lower temperatures to form the 5/2 ground state.

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Since its discovery [1], the quantum Hall state at 5/2 filling factor (second Landau level, $N = 1$) has remained enigmatic. The state violates the fundamental property of all other fractional quantum Hall states in that they occur at odd-denominator filling factors in order to preserve the antisymmetry of the many-particle wave function [2]. Subsequent experiments [3] using tilted B fields to increase the Zeeman energy showed degradation of the quantum Hall effect at 5/2, which was taken as a possible sign of nonspin polarization in the ground state. While more recent experiments [4] have confirmed the quantization of the Hall trace at 5/2, discovery [5,6] of exotic phase separated states in nearby higher Landau levels has shown that electron correlations manifest in numerous ways within the magnetic field range near 5/2. Just as a tilted magnetic field can affect the anisotropic transport of the phase separated systems in high Landau levels ($N \geq 2$), it has been seen that tilted B fields can likewise induce anisotropic transport effects at 5/2 [7,8]. As such the 5/2 state has experimentally demonstrated several peculiar properties consistent with its position in the magnetic field spectrum between the high Landau level stripe phases and the lowest Landau level ($N = 0$) fractional quantum Hall states, which are understood in the picture of composite fermions [9,10]. In this model of lowest Landau level physics the series of fractional quantum Hall states represent Landau levels for the quasiparticles, composite fermions, which near 1/2 are electrons and two associated flux quanta. The applied magnetic field can leave the quasiparticle at zero effective magnetic field (just at 1/2), with 1/2 a compressible Fermi-liquid-like state, or potentially at filled quasiparticle Landau levels (such as 1/3), which are incompressible quantum Hall states of the composite fermions. As higher Landau levels are traversed, the validity of the composite fermion picture is questionable.

The theoretical description of the 5/2 state has been developed around models of paired composite particles. Haldane and Rezayi [11] derived a paired-electron state which is spin unpolarized, and so consistent with the early tilted-field experimental work, but which also fit a pseudopotential profile that reflected the occurrence of the state in the second Landau level. This state can be considered a d-wave pairing of composite fermions, forming a spin singlet [12]. Moore and Read [13] produced a spin-polarized state developed as a Pfaffian that represents a p-wave pairing of composite fermions. The picture of a spin-polarized state at 5/2 at first appeared to be in conflict with the experiments using tilt, but it gained support following numerical studies by Morf [14] in which finite size systems were shown to have a large overlap with the Moore-Read state. Their work also showed that by strengthening the interaction, a transition to a Fermi-sea state could occur: an in-plane magnetic field can affect the interactions due to the finite extent of the electron wave function out of the 2D plane. Rezayi and Haldane [15] used a different numerical approach and elaborated the results of Morf to describe the presence of a striped phase state, Fermi liquid, or paired state dependent upon the interaction strength. In their work they describe a condensation from Fermi liquid to a paired state at 5/2 for lower temperatures, but also a transition to a striped phase for some in-plane field due to interaction changes.

While these theoretical pictures implicitly include the composite fermion Fermi liquid as a precursor to the 5/2 state, no explicit experimental evidence to date has shown the existence of composite fermions at 5/2. In the lowest Landau level at 1/2 numerous measurements have established the existence of a filled composite fermion Fermi sea. Surface acoustic wave (SAW) studies [16] first demonstrated an anomalous enhanced conductivity at 1/2 which was later recognized as ballistic transport of the quasiparticles over the small dimension of the SAW potential [17]. Further SAW measurements showed geometric resonance of the composite particle trajectories with the SAW [18] which allowed precise extraction of the sea's Fermi wave vector. Other measurements supported this finding, again all applying a small length-scale conductivity measurement: antidots [19], magnetic focusing [20], and later resonance with a 1D line array [21]. These measurements concerned the state at 1/2, which demonstrates a robust Fermi sea over a wide range of temperatures, a large range of electron densities, and in relatively low mobility electron systems, mobilities much lower than those necessary to support a strong 5/2 state or the higher

Landau level stripe phases. While Fermi surface properties were likewise readily extracted at $3/2$ filling factor [22] using these experimental methods, no evidence for Fermi-sea formation at $5/2$ was observed.

In this Letter we present surface acoustic wave measurements that distinctly demonstrate features at $5/2$ filling factor which, in similarity to findings at $1/2$, indicate the presence of a composite fermion Fermi surface. These SAW propagation features at $5/2$ are observed at temperatures above those at which the system forms a quantized Hall state and were derived using samples of particularly high mobility. These results required SAW of a much smaller wavelength than those used to observe Fermi surface effects at $1/2$, implying the composite particle mean-free path at $5/2$ is substantially shorter than that at $1/2$. The enhanced conductivity at $5/2$ for small λ SAW has a magnetic field extent that may indicate a fully spin polarized Fermi sea in the second Landau level. These results may be supportive of the model of composite fermion pairing at $5/2$ in which quasiparticles condense into a Moore-Read–like state.

In order to determine the presence of a Fermi surface at $5/2$ we have examined the small length-scale conductivity using surface acoustic waves. In a proposed composite fermion system the enhanced conduction will occur in the zero effective magnetic field at the filling factor value where the Chern-Simons field and applied field are equivalent, in this case potentially at $5/2$. Away from $5/2$ the charge will follow a cyclotron radius according to $R_c = \hbar k_F / e\Delta B$, where k_F is the composite particle's Fermi wave vector and the effective magnetic field is $\Delta B = B_{\text{applied}} - B(\nu = 5/2)$. As the effective magnetic field is increased, the charged particle will ultimately follow a small orbit cyclotron path with the guiding center orthogonal to the driving E field. Conduction paths at zero and low effective magnetic fields will preserve their trajectories for length scales smaller than the scattering length; the charge transport will be ballistic. It is these ballistic transport phenomena [22] near the zero effective magnetic field that have been exploited in SAW, split gate, antidot, and focusing measurements to expose the composite fermion Fermi surface at $\nu = 1/2$.

These probes all apply a conduction measurement over some small length scale which must be smaller than the mean-free path of the composite particle in order to expose the consequences of the zero effective magnetic field. In the case of the surface acoustic waves, a longitudinal surface sound wave is launched across the 2DES and its change in sound velocity is measured. Since GaAs is piezoelectric the wave has an associated E field applied over the wavelength of the SAW and in the propagation direction; the electron system responds to this E field. The sound wave is slowed and attenuated through this interaction, with the sound velocity altered according to $\Delta v / v = \alpha / [1 + (\sigma_{xx}/\sigma_m)^2]$, α is the piezoelectric coupling, σ_m is determined by the sample parameters, and σ_{xx} is the sheet conductivity at that SAW frequency and wave vector [23]. This relaxation response shows heuristically that a minimum in σ_{xx} causes a peak in $\Delta v / v$, so that quantum Hall states display peaks in the sound velocity shift. However, in such a SAW measurement at the zero effective magnetic field for a composite fermion the resulting $\Delta v / v$ can be anomalously small, forming a local minimum, as was shown for the composite fermion system at $1/2$ filling factor. If the SAW wavelength is smaller than the quasiparticle mean-free path, the quasiparticle conducts ballistically across the acoustic wave, displaying a minimum in $\Delta v / v$ (enhanced conductivity) at that filling factor compared to the ultrasound response for the surrounding B-field range or for longer wavelength SAW. It is this effect that is an indication of Fermi surface formation, as documented at $1/2$ filling factor. The larger the quasiparticle mean-free path, the larger the SAW wavelength that may be used in order to show enhanced conductivity. This enhanced conductivity grows as the SAW wavelength is reduced below the quasiparticle mean-free path, with $\sigma(q) \sim q_{\text{SAW}}, q_{\text{SAW}} = 2\pi/\lambda_{\text{SAW}}$ [10].

In this study we examine the two-dimensional electron system (2DES) at $5/2$ filling for just such an enhanced conductivity. In this work we optimize this search by applying a low insertion loss small wavelength SAW to the highest purity heterostructures available. A series of six samples from a single wafer were used in this study. Mobilities for samples from this wafer are in excess of 28×10^6 cm^2/V sec, substantially larger than sample mobilities used in previous measurements addressing $1/2$ composite fermions. Measurements were performed in a ^{3}He refrigerator.

The essential finding of this Letter is demonstrated in Fig. 1, which shows SAW response at 5.8 GHz and dc transport for a high mobility sample at 280 mK. The dc transport demonstrates the shallow minimum at $5/2$ that is characteristic of this state at temperatures higher than those at which the quantum Hall effect is observed. Such a minimum in resistivity (σ_{xx}) should be reflected in the ultrasound response as a maximum at $5/2$. Instead a distinct minimum has formed at $5/2$ in $\Delta v / v$, which is as expected for the enhanced conductivity of a composite fermion system.

To further demonstrate this signature of the presence of composite fermions a range of SAW wavelengths (frequencies) was used. As noted previously the enhanced conductivity (minimum at $5/2$) should increase as smaller wavelengths are used in measurement. From Fig. 2 this trend is readily apparent. No obvious minimum is observed for 2.1 GHz SAW (1.3 μm). At 4 GHz the local maximum in $\Delta v / v$ expected from dc response is distorted. At 5.8 GHz (0.48 μm) a minimum at $5/2$ is clearly formed, and a substantial minimum is present using 7.8 GHz SAW. This progression to a larger effect at $5/2$ with increasing the SAW wave vector is just as observed at filling factor $1/2$, but in that case using significantly longer

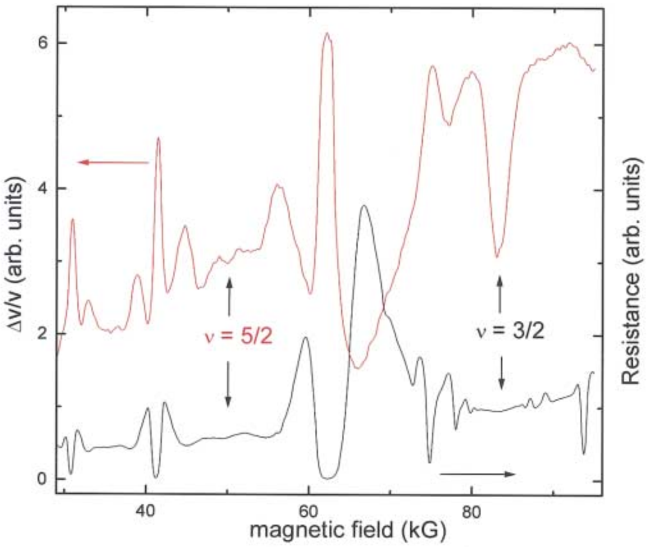

FIG. 1 (color). Surface acoustic wave sound velocity shift versus magnetic field in a high mobility ($> 28 \times 10^6$ cm^2/V sec) 2D heterostructure (sample A) at $T = 280$ mK. The SAW frequency is 5.8 GHz, corresponding to a wavelength of about 0.5 μm. At 5/2 long wavelength SAW and/or low mobility samples show a maximum, rather than the local minimum shown here, which indicates enhanced conductivity at the SAW wavelength and frequency.

wavelengths. From our observations one can state that the enhanced conductivity is first manifest for SAW frequencies between 4 and 6 GHz, or a wavelength of about 0.6 μm. The onset of enhanced conductivity for 1/2 filling factor (in lower mobility samples) was roughly 500 MHz, suggesting that the mean-free path for the 5/2 composite fermion is almost an order of magnitude smaller than that of the 1/2 composite fermion.

The crude temperature properties of this effect at 5/2 are shown in Fig. 3. As the temperature is increased to near 1 K the minimum in $\Delta v/v$ is lost, which is at a much lower temperature than for the composite fermions at 1/2 filling factor (~4 K) [17]. The Fermi wave vector for the 5/2 composite fermion system is expected to be dependent upon a charge density that is 5 times less than the electron system due to the inert filling of the lower Landau level. Consequently thermal broadening is imposed upon a relatively smaller Fermi wave vector. An important measurement is the evolution of the $\Delta v/v$ response at 5/2 as the temperature is lowered, as the transition from filled Fermi sea to quantum Hall fluid should be observed. This measurement was not possible given our available temperature range.

By examining the magnetic field width of the enhanced conductivity effect at 5/2 the spin population can be preliminarily addressed. The width of the $\Delta v/v$ minimum is determined by the composite particle cyclotron radius, which is proportional to the Fermi wave vector, which in turn is determined by the charge density n^* filling the Fermi sea: $[k_F = (4\pi n^*)^{1/2}]$. The width at 5/2 can be compared to that of the 3/2 effect, which by previous studies [22] was shown in geometric resonance effects to be a fully spin polarized Fermi sea [24]. Note that while SAW and antidot resonance measurements [25] may be consistent with a fully spin polarized Fermi system, activation energy measurements [26] indicate that 3/2 is not spin

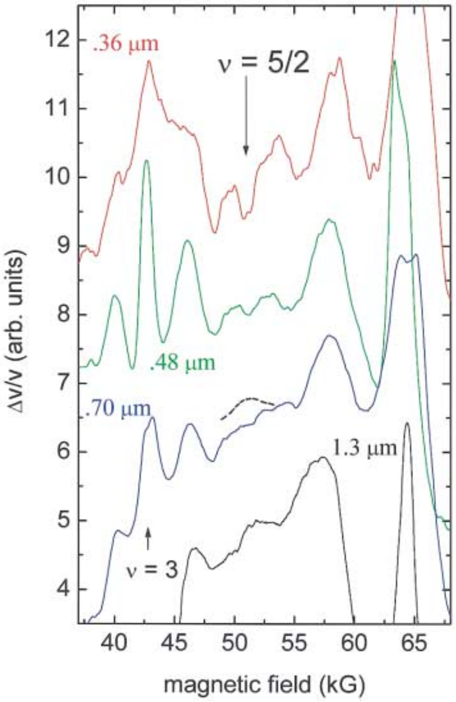

FIG. 2 (color). Sound velocity shift for a series of frequencies (wavelengths) demonstrating the appearance of the enhanced conductivity for decreasing wavelength. The dashed line at 5/2 near the 0.7 μm trace represents the approximate sound velocity shift expected from the dc transport: it is offset for clarity. All measurements were performed at 280 mK on samples A, C, D, and E.

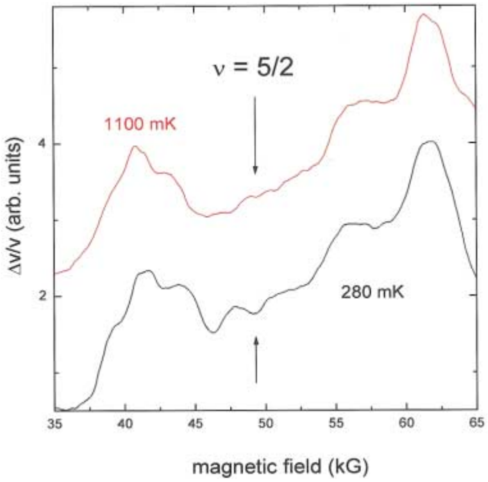

FIG. 3 (color). Coarse temperature dependence of the enhanced conductivity at 5/2 for probing SAW at 5.8 GHz, using sample B, demonstrating that the local minimum at 5/2 is lost at high temperatures.

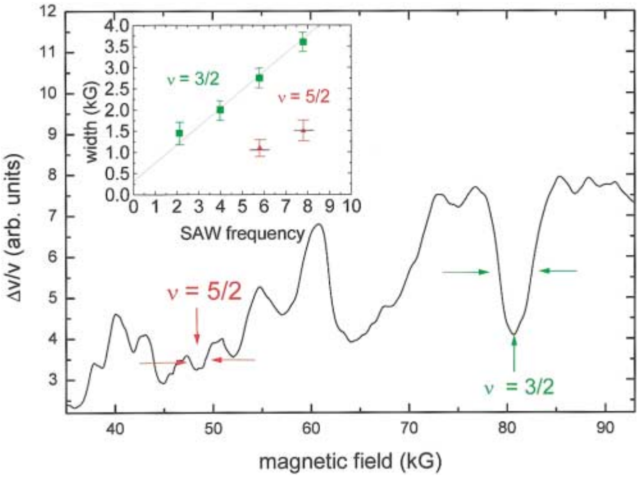

FIG. 4 (color). Comparison of the enhanced conductivity magnetic field width at 5/2 and 3/2. The magnetoacoustic trace is taken using 7.8 GHz SAW at 280 mK on sample *F*. The inset plots the width as derived in the magnetic field trace for different SAW frequencies at both 5/2 and 3/2. The solid horizontal lines through the 5/2 data in the inset plot are the width predicted for 5/2 if the spin population is similar to that of 3/2.

polarized: this discrepancy remains unresolved. With proper consideration of the lower Landau level filling, the width at 5/2 should be about 0.45 that of the 3/2 width. From the raw magnetoacoustic data of Fig. 4 and other measurements summarized in the inset, the preliminary indication is that the width of the effect at 5/2 is consistent with this assessment, both for data at 7.8 and 5.8 GHz. These data suggest that 5/2 and 3/2 are similar in spin polarization as measured by SAW. If it is the case that 3/2 is spin polarized, this implies that the precursor composite fermion Fermi sea at 5/2 is spin polarized. It is reasonable that this spin population could be sustained upon cooling as the system pairs and condenses into a ground state such as described by Moore and Read [13]. This qualified result is subject to further studies of the 5/2 width.

The minimum in $\Delta v/v$ at 5/2 for the 7.8 GHz data in Figs. 2 and 4 appears to have some structure: they are not simple minima as were observed in early studies of 1/2 filling factor [16,17]. A geometric resonance of the cyclotron orbit with the surface acoustic wave could produce such structure; however, this is not supported by the data here since at 3/2 such resonance effects are not present. Instead, the structure at 5/2 may indicate the partial formation of some quantum Hall liquid within the path traversed by the surface wave but not apparent in the dc transport. Further examinations of these possibilities are under way.

In conclusion, our findings demonstrate a minimum in sound velocity shift at 5/2 filling factor at temperatures higher than those at which the quantum Hall effect is observed, and only for small SAW wavelengths. This effect is consistent empirically with the past findings at 1/2 filling factor indicating the presence of a composite fermion Fermi surface. The wavelengths needed to reveal this effect are substantially smaller than those in the 1/2 studies, implying the 5/2 quasiparticles have a significantly smaller mean-free path. Our finding of Fermi surface effects at 5/2 is consistent with theoretical pictures describing the pairing of composite fermions which then condense into a ground state, which in turn demonstrates a quantum Hall effect at 5/2.

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