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

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Abstract

Using small wavelength surface acoustic waves (SAW) on ultra-high 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 $\mu$m 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.

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 wavefunction. [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 non-spin 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 tilted magnetic field can effect 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 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. Moore and Read 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 gained support following numerical studies by Morf in which finite size systems were shown to have large overlap with the Moore-Read state. This work also showed that by strengthening the interaction, a transition to a Fermi-sea state could occur: in-plane magnetic field can effect the interactions due to finite extent of the electron wavefunction out of the 2D plane. Rezayi and Haldane 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 this work they describe a condensation from Fermi-liquid to paired state at 5/2 for lower temperatures, but transition to striped phase for some in-plane field due to interaction changes. This model shows a progression from Fermi-liquid at 1/2 (N=0) to paired state at 5/2 (N=1), to striped phase at 9/2, 11/2, 13/2, ... (N ≥ 2).

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 studies 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. Further SAW measurements showed geometric resonance of the composite particle trajectories with the SAW which allowed precise extraction of the sea’s Fermi wavevector. Other measurements supported this finding, again all applying a small length-scale conductivity measurement: antidots, magnetic focusing and later resonance with a 1d line array. These measurements concerned the state at 1/2, which demonstrates a robust Fermi sea over a wide range of temperatures, 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 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 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 conduction will occur in 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 \( R_c = \frac{\hbar k_F}{e \Delta B} \) where \( k_F \) is the composite particle’s Fermi wavevector and the effective magnetic field is \( \Delta B = B_{\text{applied}} - B(\nu = 5/2) \). As effective magnetic field is increased, the charged particle will ultimately follow a small orbit cyclotron path with guiding center orthogonal to the driving E-field. Conduction paths at zero and low effective magnetic field will preserve their trajectories for length scales smaller than the scattering length; the charge transport will be ballistic. It is these ballistic transport phenomena near 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 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 \( \Delta v/v = \alpha/(1+(\sigma_{xx}/\sigma_m)^2) \), \( \alpha \) the piezo-electric coupling, \( \sigma_m \) determined by the sample parameters, and \( \sigma_{xx} \) the sheet conductivity at that SAW frequency and wavevector. \[23\] This relaxation response shows heuristically that a minimum in \( \sigma_{xx} \) 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 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 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 \( \sigma(q) \sim q_{SAW}, q_{SAW} = 2\pi/\lambda_{SAW} \). \[10\]

In this study we examine the 2DES at 5/2 filling for just such enhanced conductivity. In this work we optimize this search by applying low insertion loss small wavelength SAW to the highest purity heterostructures available, with potentially large quasiparticle mean-free-paths. A series of six samples from a single wafer were used in this study. Mobilities for samples from this wafer are in excess of \( 28 \times 10^6 \text{cm}^2/\text{V-sec} \), substantially larger than sample mobilities used in previous measurements addressing 1/2 composite fermions. Measurements were performed in a He3 refrigerator, with particular accomodation of low-loss high frequency lines.

The essential finding of this paper is demonstrated in Figure 1, which shows SAW response at 5.8GHz and d.c. transport for a high mobility sample at 280mK. The d.c. 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 ($\sigma_{xx}$) 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. This effect at $5/2$ is substantially smaller than that shown at filling factor $3/2$.

To further demonstrate this signature of the presence of composite fermions a range of SAW wavelengths (frequencies) were used. As noted previously the enhanced conductivity (minimum at $5/2$) should increase as smaller wavelengths are used in measurement. From Figure 2 this trend is readily apparent. No obvious minimum is observed for 2.1 GHz SAW (1.3 $\mu$m). At 4 GHz the local maximum in $\Delta v/v$ expected from d.c. response is distorted. At 5.8 GHz (0.48 $\mu$m) a minimum at $5/2$ is clearly formed, and a substantial minimum is present using 7.8 GHz SAW. This progression to larger effect at $5/2$ with increasing SAW wavevector is just as that observed at filling factor $1/2$ but in that case using significantly longer 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 $\mu$m. 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 Figure 3. As the temperature is increased to near 1K 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 ($\sim 4K$) [17]. The Fermi wavevector for the $5/2$ composite fermion system is expected to be dependent upon a charge density that is five times less than the electron system due to the inert filling of the lower Landau level. Subsequently thermal broadening is imposed upon a relatively smaller Fermi wavevector. An important measurement is the evolution of the $\Delta v/v$ response at $5/2$ as the temperature is lowered, as it is here that the transition from filled Fermi sea to quantum Hall fluid should be observed. This measurement was not possible given our available temperature range, since the quantum Hall effect is observed at $5/2$ in these samples at temperatures less than about 80mK.

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 wavevector, which in turn is determined by the charge density $n^*$ filling the Fermi sea: ($k_F = (4\pi n^*)^{1/2}$). For a first look at this question of spin population 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 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 magneto-acoustic data of Figure 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.

Interesting details of the ultrasound response are suggested by the high frequency (7.8 GHz) magnetic field sweep measurements in Figures 2 and 4. The minimum in $\Delta v/v$ at 5/2 in each case appears to have some structure: they are not simple minima as were observed in early studies of 1/2 filling factor [16,17]. Other preliminary measurements not shown here corroborate the finding of structure within the effect at 5/2, but only for data taken at our lowest available temperatures. 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 d.c. transport. Further examinations of these possibilities are underway.

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, which becomes more pronounced at smaller SAW wavelength, 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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FIGURE CAPTIONS

Figure 1. Surface acoustic wave sound velocity shift versus magnetic field in a high mobility ($> 28 \times 10^6 \text{cm}^2/\text{V} - \text{sec}$) 2D heterostructure (sample A) at T=280mK. 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.

Figure 2. Sound velocity shift for a series of frequencies (wavelengths) demonstrating appearance of the enhanced conductivity for decreasing wavelength. All measurements were performed at 280mK, on samples A, C, D, and E.

Figure 3. 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.

Figure 4. Comparison of the enhanced conductivity magnetic field width at 5/2 and 3/2. The magneto-acoustic trace is taken using 7.8 GHz SAW at 280mK 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.
Figure 1
Figure 2
Figure 3
Figure 4