Experimental Demonstration of a Fermi Surface at One-Half Filling of the Lowest Landau Level

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We report the first direct observation of the cyclotron motion of new quasiparticles in a 2D electron system near $\frac{1}{2}$ filling factor. Just as electrons in a metal geometrically resonate with a sound wave when a magnetic field is applied perpendicular to the sound propagation direction, near $\frac{1}{2}$ filling factor we observe resonance of a surface sound wave with cyclotron orbits of charge carriers. The presence of a Fermi surface and geometric resonance of a sound wave with Chern-Simons gauge transformed fermions were explicitly predicted in a recent theory of the half filled Landau level.

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The two dimensional electron system (2DES) in low disorder GaAs/AlGaAs heterostructures has produced a wealth of experimental results that are changing our understanding of lower dimensional physics. When a large magnetic field is applied to a 2DES containing little disorder, the electron-electron interaction will become manifest at low temperatures. Our understanding of these interactions has been limited largely to what has been gleaned by examining the dominant finding in simple dc transport measurements, the fractional quantum Hall effect (FQHE) [1]. Yet because the interactions are present at more than the odd denominator filling factors of the FQHE, our comprehension of the underlying physics in the electron system is lacking. A picture describing the entire filling factor spectrum is a goal of both theory and experiment. Such a theoretical picture has recently been developed [2], as we outline below. Experimentally it is important to examine the electron-electron interactions throughout the spectrum with a technique that does not destructively perturb the interaction. We have accomplished this and have explored the 2DES in a previously unreachable small length scale regime. In doing so we have revealed a remarkable phenomenon new to the 2DES, and have critically tested this new theory.

A useful approach to the problem of the interacting 2D electron system is that of the field theoretic construction. In this method a singular gauge transformation converts the electrons to a system of particles interacting with a "fictitious" or Chern-Simons gauge field. A flux tube containing an integer number n of quanta of Chern-Simons magnetic field is attached to each particle. If n is an odd integer, the transformed particles obey Bose statistics, and if n is even they obey Fermi statistics. In the 2DES the motivation for such a construction is that in a simple Hartree approximation for some choice of n at various rational filling factors the resulting ground state is nondegenerate and as such has a chance of being an approximation to the system's true ground state. While these statistical transmutations have provided a new means of examining the correlated 2DES in an abstract sense, they have not in general presented explicit new properties that are experimentally testable.

Recently, however, Halperin, Lee, and Read [2] (HLR) have used the fermion Chern-Simons method to examine the properties of a single layer 2D electron system at $\nu=\frac{1}{2}$ and at various other even denominator fractions. Choosing $n=2$, at $\nu=\frac{1}{2}$ in their construction the average Chern-Simons field just cancels the external magnetic field. The resultant Hartree ground state is a filled Fermi sea of particles *in zero magnetic field* with a distinct Fermi wave vector $k_F=(4\pi n_e)^{1/2}$, and n_e the areal density of the electrons. Away from $\frac{1}{2}$ filling, the particles are expected to execute cyclotron motion with radius $R_c=\hbar k_F/e\Delta B$ in an effective magnetic field $\Delta B=B-B(\nu=\frac{1}{2})$.

The consequences of this Fermi surface are significant in that they may explain the major observed properties of the 2DES in the extreme quantum limit. For large effective B fields, the Shubnikov-de Haas oscillations of these gauge transformed fermions are precisely the series of observed odd denominator fractional quantum Hall states at $\nu=p/(2p+1)$, p an integer: $\frac{1}{3}$ filling for the electrons is a filling factor $p=1$ for the gauge transformed fermion, $\frac{2}{5}$ is $p=2$, and so on. In the vicinity of $\nu=\frac{1}{2}$, where dc transport exhibits no quantum Hall effect, HLR explain previously reported anomalies in surface acoustic wave (SAW) propagation. At $\nu=\frac{1}{2}$ it was shown [3,4] that conductivity is markedly enhanced for large wave vector (q) sound waves: In this technique the 2DES conductivity is probed on the length scale of the ultrasound wavelength. The conductivity at $\nu=\frac{1}{2}$, $\sigma_{xx}(q)$, was found to be proportional to q, with the magnetic field range of the enhanced conductivity also proportional to q. Both of these findings are consistent with the fermion Chern-Simons picture as developed by HLR. As such, the theory has substantial support in the SAW derived $\sigma_{xx}(q)$.

However, a definitive piece of evidence for the HLR theory has been missing: direct observation of the Chern-Simons quasiparticles and measurement of the quasiparticle Fermi wave vector. In electron systems measurement of the Fermi wave vector has been accomplished through several means. Two studies [5,6] used a periodic density fluctuation imposed on a 2DES to extract the

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electron k_F. A magnetic field is applied to the 2DES containing this periodic density. Magnetoresistance oscillations are observed with the resistance a maximum for the cyclotron orbit nearly a multiple of the imposed density periodicity. From these resistance measurements k_F was extracted. Another technique has been demonstrated for measuring the electron Fermi wave vector in normal metals [7]. When a magnetic field is applied normal to the sound propagation direction, the absorption of ultrasound oscillates as a function of B field due to geometric resonance of the electron cyclotron orbit with the ultrasound wavelength. It is explicitly predicted [2] that the gauge transformed fermion should likewise display resonance of its cyclotron motion with ultrasound waves or with a periodic potential.

We report here the observation of geometric resonance of the charge carriers in a 2DES near $\nu=\frac{1}{2}$ with ultrasound waves moving perpendicular to the applied B field. We use these measurements to determine the k_F of the carriers. Our k_F results are in close agreement with $k_F=(4\pi n_e)^{1/2}$ as expected for the Fermi wave vector of Chern-Simons gauge transformed fermions. These results emphatically demonstrate the presence of a Fermi surface at $\nu=\frac{1}{2}$.

These experiments were performed on a set of GaAs/AlGaAs heterostructures all cut adjacently from the same wafer; electron mobility at zero magnetic field is $\sim 3\times 10^6$ cm^2/V sec and areal density $n_e \sim 6.6\times 10^{10}$ cm^{-2}. Surface acoustic waves were generated and detected using lithographically defined interdigitated transducers evaporated onto the heterostructures. The 2DES was etched away in the vicinity of each transducer and they were placed roughly 1 mm apart with a mesa containing the 2DES between. The fundamental spatial period of the transducer is the sound wavelength. Frequencies ranged from 2.4 to 8.5 GHz, corresponding to wavelengths of approximately 1.2 to 0.3 μm. The high end frequencies are to our knowledge the highest reported SAW on GaAs.

The SAW is launched from one transducer at a frequency $f=v_s/\lambda=v_s q/2\pi$ where v_s is the velocity of sound, λ is the SAW wavelength, and q is the SAW wave vector. The sound wave traverses the 2DES where it is attenuated and slowed by the interaction of its piezoelectric field and the 2D electrons, according to a simple relaxation process. The sound velocity shift monotonically decreases with increasing wave vector dependent sheet conductivity, as shown in the following expression:

$$\frac{\Delta v}{v}=\left(\frac{\alpha^2}{2}\right)\frac{1}{1+[\sigma_{xx}(q)/\sigma_m]^2}, \tag{1}$$

where the piezoelectric coupling constant $(\alpha^2/2)=320\times 10^{-6}$ for GaAs, and $\sigma_m=v_s(\varepsilon+\varepsilon_0)$ [8,9]. By measuring the sound velocity shift the wave vector dependent conductivity of the 2DES is measured.

Figure 1 demonstrates the sound velocity shift versus magnetic field and the standard dc transport over the same range. Using Eq. (1) the measured σ_{xx} (dc) will map directly onto the $\Delta v/v$ trace over the entire B field range shown except at $\nu=\frac{1}{2}$ and $\frac{3}{4}$, demonstrating the presence of enhanced conductivity at these even denominator ν.

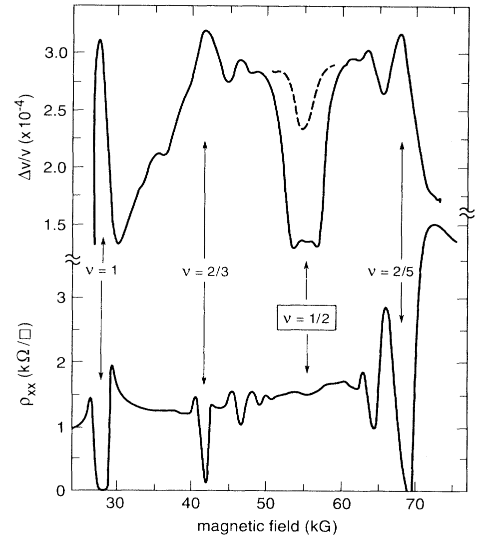

FIG. 1. Top: sound velocity shift versus magnetic field at $T\sim 400$ mK for SAW frequency of 5.4 GHz (solid line). The dashed line is a similar measurement at 2.4 GHz. Note the structure present near $\nu=\frac{1}{2}$ for the higher frequency. Bottom: simultaneous dc transport.

New structure is present in the $\Delta v/v$ minimum at $\nu=\frac{1}{2}$, and this is the focus of this Letter. Past results have shown only a simple minimum in the sound velocity at $\frac{1}{2}$, as demonstrated by the dashed trace in Fig. 1. For the higher frequencies featured here, one clearly sees local minima, or resonances, in the sound velocity on each side of $\frac{1}{2}$. The two minima are symmetrically spaced about $\nu=\frac{1}{2}$ and correspond to resonances of the sound wave and motion of the charge carriers. This effect is similar to geometric resonances found in the propagation of acoustic waves in a direction perpendicular to an applied magnetic field in a 3D metal [7]. In the model of this effect and in our interpretation of our data a cyclotron orbit $(R_c=\hbar k_F/e\Delta B)$ resonates with the sound wave. Therefore, a measurable cyclotron radius reflects a distinct Fermi wave vector for the charge carriers, and this implies a distinct Fermi surface is present. *The data show that the effective zero magnetic field for this cyclotron motion is* $\nu=\frac{1}{2}$.

Figure 2 (and the trace in Fig. 4) shows how these resonances develop as the SAW q increases. In general, structure becomes more prominent as the SAW frequency (wave vector) increases. At low frequency (2.4 GHz) no resonances are apparent in $\Delta v/v$. As SAW q is increased the side minima appear. Using $B=0$ of the cy-

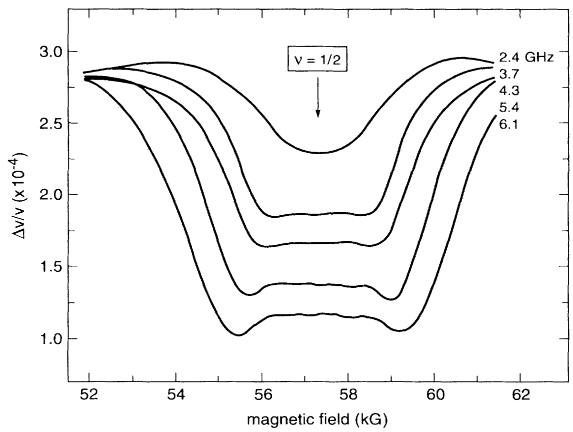

FIG. 2. Development of the gauge transformed fermion geometric resonance with increasing SAW frequency in sound velocity shift versus magnetic field. $T \sim 200$ mK.

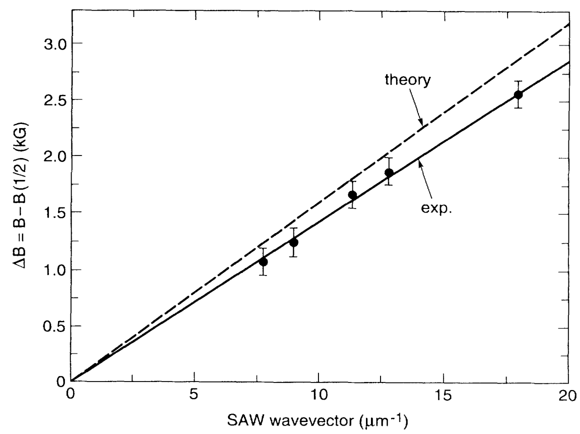

FIG. 3. Position of the principal resonance in ΔB versus SAW wave vector. The dashed theoretical line assumes gauge transformed fermion wave vector $k_F = (4\pi n_e)^{1/2} = 93\ \mu\text{m}^{-1}$.

clotron orbit at $\nu = \frac{1}{2}$ is dramatically supported by plotting the resonance positions in $\Delta B = B - B(\frac{1}{2})$ versus SAW q, as shown in Fig. 3. Note that the data are consistent with a line extrapolating through the origin, as expected for $\Delta B = 0$ at $\nu = \frac{1}{2}$.

The results described above are explicitly predicted for the Chern-Simons gauge transformed fermion at $\nu = \frac{1}{2}$: An outline of this theoretical construction follows. According to the theory of HLR, enhanced conductivity occurs at $\frac{1}{2}$ because the quasiparticle will have a component of linear motion in the direction of the sound propagation. At $\frac{1}{2}$ there is no magnetic field apparent to the gauge transformed fermion, and therefore no Lorentz force. For SAW wavelengths small compared to the quasiparticle mean free path l $(q \gg 2/l)$, the quasiparticle conductivity is proportional to q: $\sigma_{xx}(q) = (q/k_F)(e^2/8\pi\hbar)$. As the magnetic field is tuned away from $\frac{1}{2}$, the quasiparticle will now move in an *effective* B field ΔB. With a distinct Fermi surface, the motion will be along a cyclotron orbit of radius $R_c^* = \hbar k_F/e\Delta B$. As ΔB increases the cyclotron radius becomes smaller and the quasiparticle will move more laterally rather than along the direction of the sound wave. This determines roughly the width in ΔB of the overall enhanced conductivity effect at $\frac{1}{2}$. But the conductivity is actually more complicated. This is due to the commensurability of the cyclotron orbit with a wavelength, or wavelengths, of the surface acoustic wave. It is this commensurability that allows us to measure the gauge transformed fermion k_F and therefore demonstrate the presence of a Fermi surface.

In a semiclassical sense, if the quasiparticle can traverse an entire cyclotron orbit without scattering (e.g., $2\pi R_c^* < l$) and if $\lambda_{\text{SAW}} \sim 2R_c^*$, then a geometric resonance of the quasiparticle motion and the sound wave can occur. This principal resonance manifests itself as a peak in the conductivity (minimum in the sound velocity) versus magnetic field as the orbit is commensurate with the dimension of the wavelength. Note that the quasiparticle Fermi velocity is much larger than the sound velocity; therefore the SAW is like a standing wave. As the λ_{SAW} is made smaller, higher order resonances can occur if the mean free path is sufficiently large. Higher order resonances appear when the orbit diameter passes through higher multiples of the wavelength dimension.

While we have described the general concept of the geometric resonance above, the actual conductivity (see Ref. [2]) may be approximated for appropriate l as

$$\sigma_{xx}(q) = \frac{\rho_{yy}(q)}{\rho_{xy}^2}, \quad \rho_{yy}(q) \approx \frac{1}{\tilde{\sigma}_{yy}} \text{ near } \tfrac{1}{2} \tag{2}$$

and

$$\tilde{\sigma}_{yy}(q) = \frac{2}{\rho_0} \sum_{n=-\infty}^{\infty} \frac{[dJ_n(X)/dX]^2}{1 + n^2(ql/X)^2}\,; \tag{3}$$

$J_n(X)$ is the Bessel function and $X = qR_c^*$. In the limit $ql \gg 1$, the semiclassical approximation predicts oscillations in $\sigma_{xx}(q)$, $(\Delta v/v)$, with maxima occurring close to the zeros of $J_1(qR_c^*)$, or at $\Delta B/B = q/K_{1,n}k_F$ where $K_{1,n}$ is the position of the nth zero of J_1:$K_{1,1} = 3.83$. For larger n, $K_{1,n} \approx \pi(n + \frac{1}{4})$. Therefore, the peak position of the resonances as a function of SAW q gives a measure of the quasiparticle k_F.

The magnitudes of the first order resonances $(n=1)$ are dependent upon l, but the position in ΔB is only very weakly dependent upon l. This means that identification of the resonance minima allows direct determination of the quasiparticle k_F. The small sample to sample variation in disorder may give varying prominence of the resonances, but will not significantly affect the resonance position.

From the resonance positions in ΔB plotted versus SAW q in Fig. 3, the gauge transformed fermion Fermi

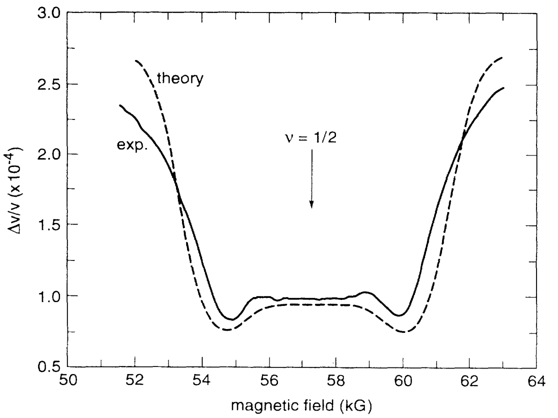

FIG. 4. Sound velocity shift versus magnetic field for SAW frequency of 8.5 GHz at $T \sim 200$ mK. The dashed line is the theoretical curve as described in the text including sample density inhomogeneity.

wave vector is extracted. Using $k_F = q/(3.83 \Delta B/B)$ for the data and $k_F = (4\pi n_e)^{1/2}$ for the theoretical line, the figure shows the data to be just below the theoretical prediction, almost within experimental error.

Figure 4 shows a comparison of the theoretical prediction for the sound velocity shift near $\frac{1}{2}$ and that measured at 8.5 GHz. The parameters for this theory curve are extracted from the data as follows. We use the dc resistivity value at $\nu = \frac{1}{2}$ to give an approximation to the gauge transformed fermion mean free path $l \sim 0.4$ μm. Using this l and the SAW wave vector value of Fig. 4 results in $ql \sim 8$. This ql can be used in Eqs. (1) to (3) to produce theoretical $\Delta v/v$ versus B. Note that we adjust the minimum and background [10] theoretical $\Delta v/v$ to match that of the data: The relative magnitude of the resonances is set by ql. To compare this to the data we must impose the density inhomogeneity which we know to be present in the samples. This inhomogeneity can be measured by plotting the width of the enhanced conductivity at $\nu = \frac{1}{2}$ versus the SAW wave vector. This straight line is offset from the origin by a B-field value that directly reflects the amount of density inhomogeneity in the SAW path. A value of $\sim 1.5\%$ is derived from these data, which is independently typically observed in these heterostructures. We convoluted the original $\Delta v/v$ with a Gaussian distribution of densities whose FWHM is 1.5%. The resultant theoretical curve is shown in the figure to closely mimic the actual measured sound velocity. It is important to note that the convolution of the density inhomogeneity into the theoretical trace moves the resonances to smaller relative ΔB: In the theory trace shown this reduction is about 5% of ΔB. The theoretical line of Fig. 3 does not include this correction. Therefore, the correction moves the theory into better agreement with the data.

In conclusion, our experimental results demonstrate distinct resonances in the measured sound velocity [and therefore $\sigma_{xx}(q)$] for large SAW q near $\nu = \frac{1}{2}$. These results obey all the properties expected of a particle with $k_F = (4\pi n_e)^{1/2}$ moving in a magnetic field ΔB referenced to $\frac{1}{2}$, and driven by a sound wave with wave vector q. These resonances are the *sine qua non* of a distinct Fermi surface at $\nu = \frac{1}{2}$. Demonstration of this Fermi surface provides conclusive support for the gauge transformed fermion construction proposed by Halperin, Lee, and Read.

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