Testing Composite Fermions With Phonon Drag

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Abstract

The composite fermion is a new particle in condensed matter physics. It is the bound state of an electron and an even number of quantum mechanical vortices, often thought of as an electron carrying an even number of magnetic flux quanta. When two dimensional electron gas (2DEG) is exposed to a strong magnetic field, electron capture an even number of quantum mechanical vortices. In order to describe the fractional quentum hall effect, this phenomological theory of composite fermions was originnaly proposed by Jainendra Jain. Numererous experimental investigations have confirmed the existance of of these particles including existance of a Fermi surface. In this article, the response of composite fermions to large wave vector scattering is examined in phonon drag measurements. All the experimental data was taken from reference 1 and 13. Also, an introduction of composite fermions is presented.

1 What is composite fermion ?

We know that all of the particle that go into the Hamiltonian, which are electrons and ions. However, systems are often much simpler if we imagin them as collection of new particles, rather than the ones which they officialy are. Imigining them as the new particles isn't less accurate than imigining them as the old particles. Strongly interacting particles recognize themselves to become more weakly coupled particles of a new kind. Often they are simple bound states of the old particles. Sometimes they are very complicated collective objects, such as solitons, that behave as legitimate particles with well defined charge, spin, statistics, etc. These new particles are, in sense, the true particles of the system because they are nearly independant objects. Once we think of it in terms of these new particles, phenomena that were difficult or impossible to understand in terms of the old particles become very easy to explain as properties of almost free particles. Therefore condensed matter systems are often described in terms of phonon, magnons, Landau quasiparticles or cooper pairs, rather than electrons and ions.

The system of electrons confined to two dimensions in a strong transverse magnetic field at sufficently low temperatures, exhibit very unusual properties that are entirely inexplicable when we think of them simply as a collection of weakly interacting electrons. In this two dimensional system, electrons take over all or a large fracrion of the external magnetic field, thus transforming themselves into particles called composite fermions. Jainendra Jain and his colleagues predicted the existance of this new particle and they have calculated the properties of this particle[2].

2 Why are composite fermions born ?

Over 100 years ago, E.H Hall discoverd that when a magnetic field is applied perpendicular to the direction of a current flowing through a metal, a valtage is developed in the third perpendicular direction. This clasical Hall effect is well understood.

In 1985, Klaus Voklitzing won the nobel prize for discovery of the integer quantum Hall effect. In a two dimensional metal or semiconductor, the Hall effect is also observed, but at low temperature, a series of steps appear in the Hall resistance as a functon of magnetic field instead of the monotomic increase. The resistance is quantized in units of $\frac{h}{e^2}$ divided by an integer. This integer quantum hall effect (IQHE) can be explained using the non interacting picture of the electron system.

In high mobility semiconductor heterojunctions, the IQHE plateaux are much narrower than for lower mobility samples. Between these narrow IQHE more plateaux are seen at fractional filling factors. This is the fractional quantum hall effect (FQHE). In 1998, Dan Tsui and Horst Stomer won the nobel prize for the descovery of FQHE.

Just as in the IQHE, FQHE plateaux are formed when the Fermi energy lies in a gap of the density of states. The difference is the origin of the energy gap. While in the integer effect, gaps are due to magnetic quantization of the single particle motion, in the fractional effect, the gaps arises from collective motion of all the electrons in the system. In order to explain the FQHE, Jainendra Jain proposed the composite fermion which is consist of an electron bound to an even number of magnetic flux quanta(fig 1[2]).

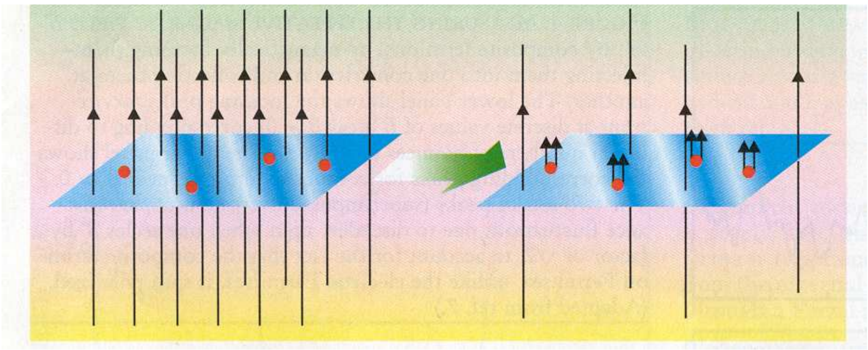

Figure 1: Capturing two flux quanta transform each electron into a composite fermion[2].

3 What are the properties of composite fermion ?

As we discussed above, when a 2DEG is exposed to a strong transverse magnetic field, electrons capture an even number of quentaum mechanical vortices each to transform into composite fermions in order to minimize their interaction energy. Then the compex strongly correlated liquid of interacting electrons become a simple, weakly interacting gas of composite fermions. It is experimentally established that CFs:

- Fill Fermi sea (The composite Fermi sea)
- Execute semiclassical cyclotron orbits
- Form Landau levels (CF-Landau levels)
- Exhibit Shubnikov-de Hass oscillations
- Show IQHE (FQHE of electrons)
- Can be seen in mesoscopic experiments
- Perhaps even from BCS like pair state (?)

Many quantum numbers and parameters of the CF have been determined experimentally. These are :

• Charge • Spin • Statistics • Magnetic moment • Fermi wave vector • Mass

Also its many excitations have been observed.

• Charge excitations • rotons • Two-roton bound state • Skyrmions (?)

4 What is phonon drag ?

The fractional drag experiment is a novel probe of the properties of bilayer systems. This concept is similar to conventional friction.

A current is driven in one layer, and interlayer electron-elctron interaction transfer momentum to a nearby layer (Fig 2). The drag layer is convensionally in a open circuit configaration, where no drag current is allowed to flow. A valtage is therefore build up in the drag layer to counteract the drag force, which gives a direct measure of the interlayer electron-electron scatering rate. The drag relies on inhomogeneities in the two layers, otherwise the each layer experience only a smooth potential from the adjacent layer. These inhomogeneities are density fluctuations within each layer, and the fluctuations in the two layer are coupled either by the coulomb or phonon interactions. The drag measurements

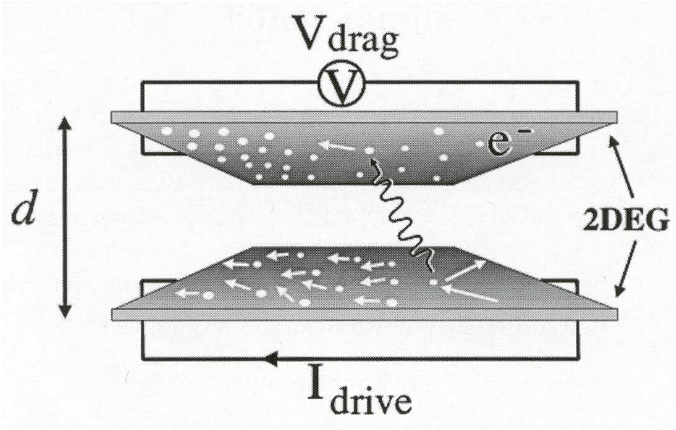

Figure 2: Frictional drag

therefore probes both the excitations within the layer and the interlayer interactions.

5 Why do we use phonon drag measurements ?

During the interaction with a phonon, the component of wave vector (WV) parallel to the 2DEG (Q) is conserved[3]. At low temperature, there is a additional restriction that Q must be less than $2K_F$ because of the fermi statistics of the 2DEG. If a phonon is absorbed by the 2DEG, the Q component of the phonon WV is transformed first to one electron. Within a very short period of time, this momentum is distributed over all the electrons of the 2DEG by electron-electron scattering.

The use of phonon permits the scattering WV Q to be effectively tunable by changing the temperature T. At low T, only samll WV accoustic phonons are thermally excited, limiting sacttering of CF to samll Q processes. As the temperature is increased, access to higher energy phonon permits layer WV scattering. For electrons, the transition to layer angle scattring is readily evident due to a sharp cut off[4] for scattering with Q greater than twice the Fermi WV($2K_F$). The cut off results directly from the exsistance of a Fermi surface and combine restriction of momentum and energy conservation.

A similar cut off should be exist for composite fermions. Two key elements are required: the presence of a Fermi surface for the particles and the ability of CF withstand large WV scattering.

The drag tranresistivity ρ_D, the ratio of the drag voltage to the applied current per squre, is a direct measure of the interlayer scattering rate[5]. While coulomb scattering dominates ρ_D for closely spaced layers, its strong layer spacing dependance[6] permits interlayer phonon exchange to compleatly dominate interactions of remote layers.

6 How is the sample prepared ?

The samples used are GaAs/AlGaAs double quantum well structures consisting of two 200^0A wide quantum wells. The bulk of the CF measurements was performed on a sample with a 5000^0A well seperation. Each has an electron density n, near $1.5 * 10^{11}cm^{-2}$ as grown, with mobilities($\mu = \frac{e\tau}{m^*}$) approaching $2 * 10^6cm^2/Vs$. Individual layer densities

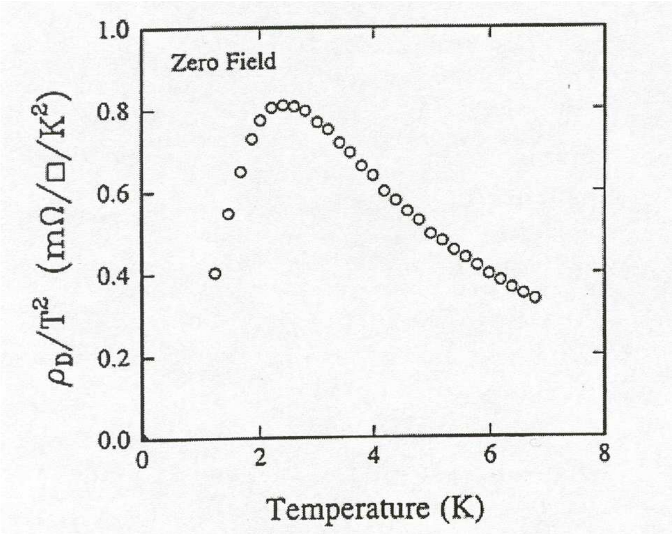

Figure 3: T dependence of ρ_D/T^2 for zero field[13].

were varied through the application of a valtage to an overall top gate or by applying an interlayer bias, with the densities in each layer made equal for all measurements.

7 What are the results ?

The effects of the $2K_F$ cut off for phonon scattering is shown in fig 3[13] for zero-field (i.e. electron) phonon drag measurements on a 2400^0A barrier sample in which coulomb scattering is neglegible. The $\frac{\rho_D}{T^2}$ vs temperature curve at zero-field, peak position appears around 2K. It is found that the peak position is not changing with layer spacing[7]. The peak position varies with the size of the fermi surface (i.e.$\alpha\sqrt{n}$). The temperature of the peak in $\frac{\rho_D}{T^2}$ is directly related to the phonon WV which matches $2K_F$.

Fig 4[13] represents the ρ_D vs temperature on a 5000^0A barrier sample at 12.5T corresponding to a half filling lowest landau level ($\nu = \frac{1}{2}$). These data are well characterized by a best fit of $\rho_D \alpha T^{3.7}$. This exponent is higher than subquadratic dependance ($\alpha T^{1.5}$) for coulomb drag of CF[8] and consistant with T dependance of phonon drag ($\alpha T^{3.5}$)[9]. So the behavior of ρ_D at low T firmly establishes a neglegible role for coulomb scattering in this sample.

Fig 5[13] shows $\frac{\rho_D}{T^2}$ for CF and general behavior just like zero-field electron with same density as expected.

The behavior indicates a WV cut off in the phonon scattering process for CF. Since K_F for CF is $\sqrt{2} * K_F$ of electron (Since spin polarized), we expect peak position at $\sqrt{2}*$ peak position of zero field (Arrow in fig 5.). However, peak position is not in right place, instead moves down.

The difference between the measured and anticipated peak position raises:

• Q cut off may result from CF Fermi surface. Stability of CF must be considered. Theoritical prediction of CF binding energy $\sim 4K$ for these densities[10]. The peak position is 1.9K, however below this binding energy.

• Maximum $\frac{\rho_D}{T^2}$ is due to single particle effect of the electron system in a high magnetic field. For example, the scattering WV may be a cut off determined by the width of the

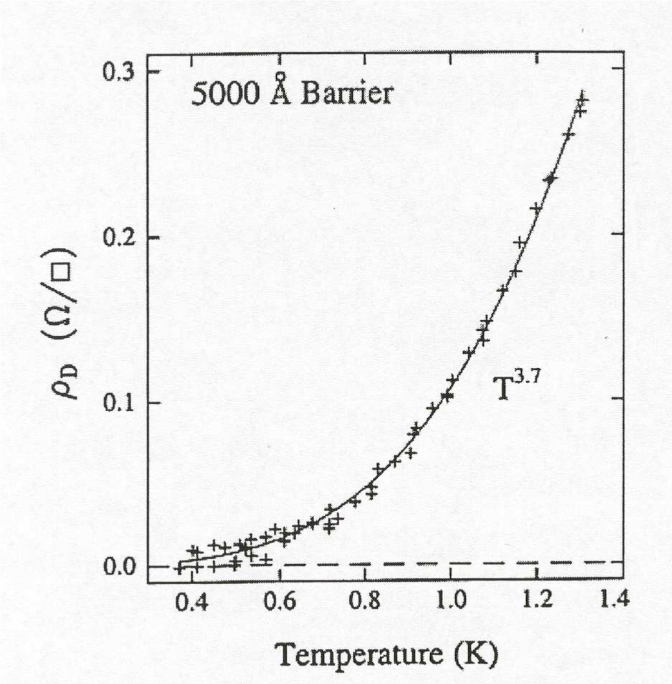

Figure 4: Low temperature ρ_D for composite fermions[13].

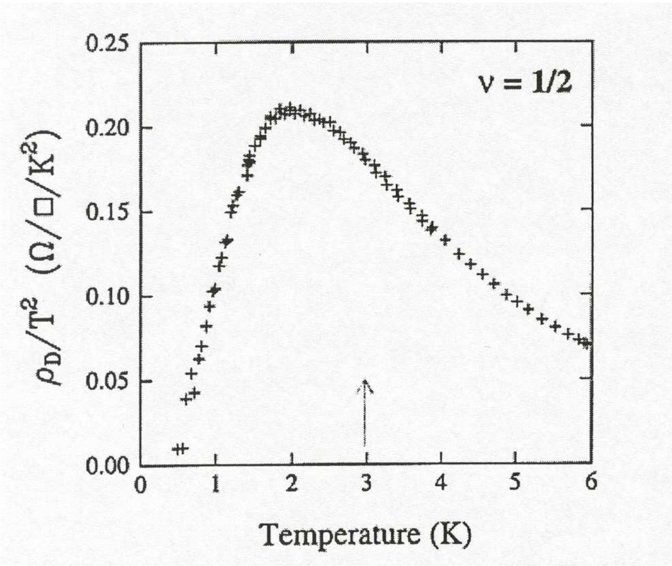

Figure 5: T dependence of ρ_D/T^2 for composite fermions[13].

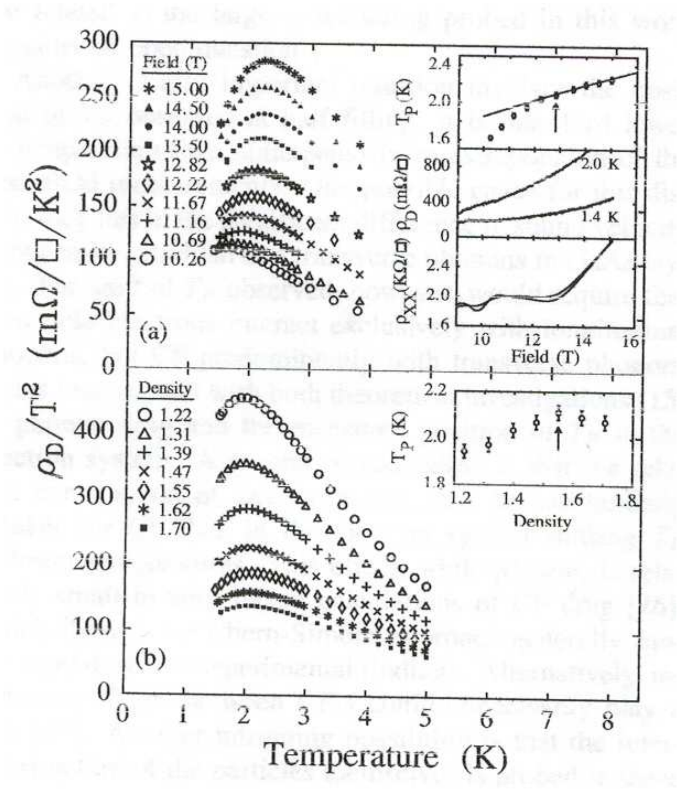

Figure 6: (a). T dependence of ρ_D/T^2 at various magnetic field with fixed density, $\nu = 1/2$ occurs at 12.82T. Upper inset: Peak position vs field. Middle and Lower inset: LR at at 1.4 and 2.0K. (b). T dependence of ρ_D/T^2 at various density with fixed magnetic field[1].

Landau level[11] or magnetic length[12]. However, it is found that both of these effects result in a increase of the peak position. As well as CF state of both $\nu = \frac{1}{2}$ and $\nu = \frac{1}{4}$ give almost the same T_ρ for given density. These certify that we observe CF and Landau level and magnetic length do not responsible for the peak.

In order to explore the discripancy in the peak position, B dependance is examined for fixed n. Data shows the amplitude varies considerably with B, peak position moves as B changes (i.e$\alpha\sqrt{B}$) at fields near and above half filling(Fig 6a[1]). Since n is fixed, K_F should be fixed too.

Then n dependence is examined for fixed B (Fig 6b[1]). Results shows that amplitude is still monotomic with n, but peak position shows maxumum at $\nu = \frac{1}{2}$.

The change in magnitude and peak position upon application of an effective field are inconsistent with general expectation for CF away from half filling. If spin plays a role, this might be a reason of above inconsistency. In order to explore this, sample is tilted by 22^0 and B dependence is remeasurd. Data shows exactly the same behavior for same ν. Which means spin does not play any role here.

To reduce the complexity of above measurements, n is varied, but B is adjusted to remain filling factor at $\frac{1}{2}$. As shown in fig 7[1], amplitude is independant above 3K. Peak position is still moves with n, but $T_\rho\alpha\sqrt{n}$, consistent with change of the size of the CF Fermi surface.

Comparision of the density dependance of the magnitude of ρ_D, with that of electrons at zero-field provides additional support that these data result from a Fermi surface related

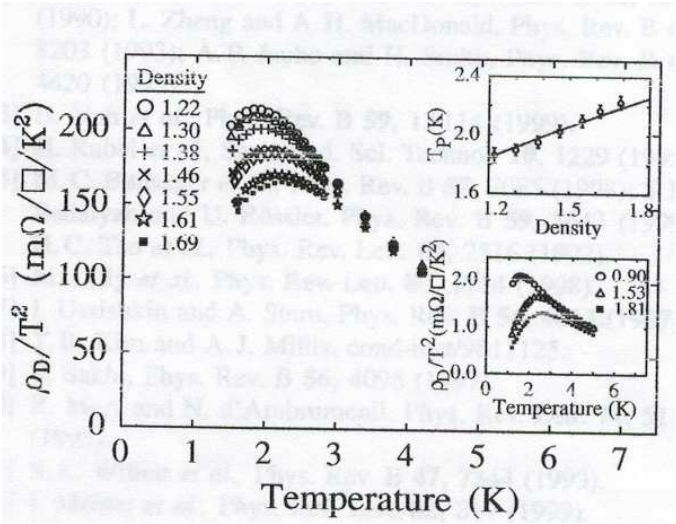

Figure 7: T dependence of ρ_D/T^2 for various carrier density. Magnetic field is adjusted to maintain the system at $\nu = 1/2$, Upper inset: Change in peak position, Lower inset: Zero field electron.[1].

cut off of CF scattering.

8 what can we summarize ?

Large WV scattering of CF has been investigated through measurements of inter layer phonon drag. The temperature dependence of these measurements implies that the existence of a WV cut off with qualitative properties of electron system at zero field. However $2K_F$ response is missing for CF in phonon drag measurements.

These data raise number of puzzling questions. One is the position of T_ρ observed at half filling. It is one-third lower in temperature than anticipated from extrapolation of the zero field. The other one is the behavior as ν is varied from half filling.

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