Probing Composite Fermions with a Wigner Crystal and Vice-Versa

Cyclotron Orbits of Composite Fermions in the Fractional Quantum Hall Regime
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Recommended with a Commentary by S. M. Girvin, Yale University

Two-dimensional electron gases in high magnetic fields have proven to be a remarkably rich playground for the study of strongly-correlated quantum many-body systems. In two dimensions with a strong magnetic field, the cyclotron motion of the electrons completely quenches the particle kinetic energy into Landau levels which are macroscopically degenerate–the number of states in a Landau level is equal to the number of flux quanta from the external field that penetrate the sample. This degeneracy is lifted solely by Coulomb interactions (and by weak disorder) making the system automatically strongly correlated. Remarkably, there is a huge zoo of correlated states that occur at different rational values of the fractional filling of the (highest occupied) Landau level. For simple filling fractions like 1/3 and 2/5, the Laughlin liquid states are most stable. For very small filling fractions the potential energy is minimized by placing the electrons into a spatially ordered Wigner crystal. Near filling factor 1/2, it is useful to view the system as consisting of 'composite fermions' (CFs are electrons or holes with two quantized flux tubes or vortices attached [1, 2, 3]). At the mean-field level, the flux attachment transformation creates a pseudo magnetic field which cancels the physical magnetic field when the filling factor is precisely one-half.

Slightly away from filling factor 1/2, the composite fermions behave as if they are in a weak magnetic field and hence move in cyclotron orbits with relatively large radius (on the micron scale, which is large compared to the mean distance between particles). The dynamics on this new characteristic length scale can be probed with surface acoustic waves [4], but it is challenging to launch phonons with wavelengths on this scale and to continuously vary that wavelength.

In a remarkable experiment, Jo et al. use a double quantum well to form a quantum Hall bilayer system (for holes). By means of an intrinsic doping asymmetry in the sample and application of a tunable voltage gradient normal to the plane of the bilayer, they can bias one layer to have low filling factor and the other to have filling factor near 1/2. The holes in the low filling-factor layer form a triangular Wigner crystal which induces a spatially periodic potential on the composite fermions in the other layer. Because of their larger mass and increased Landau level mixing, the Wigner crystal for holes is more stable than in the corresponding electron case and this stability extends to somewhat higher densities (filling fractions) than would be the case for electrons.

When the weak pseudo magnetic field of the composite fermions is commensurate with the Wigner crystal (that is when the unit cell of the periodic potential contains a rational number of pseudo flux quanta), the transport properties of the composite fermions are predicted to change because of changes (e.g. small gaps opening) in the composite-fermion band structure. The semi-classical picture is that there are geometric resonances between the cyclotron orbits and the periodic potential.

By varying the Wigner crystal density Jo et al. are able to probe the composite fermions on different length scales. Because the Wigner crystal of holes is stable to higher densities, composite-fermion cyclotron motion can be probed at higher pseudo B fields than previously (i.e. filling factors further away from 1/2 can be studied). In the composite fermion picture, fractional quantum Hall states that form further away from filling factor 1/2 are viewed as integer Hall states of the composite particles [1]. Jo et al. find that even in this regime, the composite fermion Fermi wave vector seems to remain well-defined and yields commensuration effects with the periodicity of the Wigner crystal. In particular, in the regions of filling factor between FQHE gapped states, the gapless correlated composite fermion fluid seems to have a peak in its magnetoresistance when the geometric resonance condition is satisfied.

The simplest interpretation of this result is that in between FQHE states, the CFs retain a well-defined Fermi wave vector (cyclotron orbit radius). On the other hand there may be a particular susceptibility to the periodic potential due to competition between adjacent FQHE states at nearby densities. It is also possible that the heavier hole mass and resulting Landau level mixing produces peaks in the susceptibility at relevant wave vectors. These possibilities raise interesting theoretical questions that call for new analytic theories (i.e. trial wave functions) and/or numerical calculations to resolve the underlying mechanism of the modulation of the magnetoresistance by the Wigner crystal. The data show an asymmetry in the strength of the geometric resonance for positive and negative pseudomagnetic fields, similar to previous results in a different electron antidot system. The origin of this asymmetry remains mysterious and is an open theoretical problem (presumably associated with breakdown of the particle-hole symmetry at filling factor 1/2 that is rigorously present only in the absence of Landau-level mixing).

Interestingly, the composite fermions can be used to probe the melting of the Wigner crystal which is seen in the data when the temperature is raised to approximately 200mK and the magnetoresistance peaks associated with the geometric resonances begin to disappear. In contrast to experiments on highly-regular antidot lattices, only the lowest geometric resonance is visible in the data and Jo et al. suggest that this implies that the Wigner crystal has strong local order but weak long-range crystalline order.

In summary, we have two very interesting but very different correlated systems, each probing the other. There is much to be learned from these novel results and it would be interesting to perform analytical and theoretical estimates of the susceptibility of the correlated CF fluid to periodic potentials to see if the heavier hole mass and concomitant Landau level mixing that affects the Wigner crystal layer also changes the response of the CF layer. It would also be interesting to consider the extent to which the presence of the composite fermions could actually help stabilize the Wigner crystal if the disorder potential in the low-density layer were sufficiently small.

References

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