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Evidence of superfluidity in double layer 2D electron systems

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Abstract

When two parallel two-dimensional electron gases are sufficiently close together, interlayer Coulomb interactions are of comparable importance to intralayer ones. If the total number of electrons in the bilayer system equals the number of states in the lowest spin-resolved Landau level produced by a large perpendicular magnetic field, an exotic many-body state develops. This state exhibits a variety of remarkable properties including Josephson-like interlayer tunneling and precise quantization of the frictional drag between the layers. These findings lend strong support to the notion that this quantum coherent state is an example of a new kind of superfluid, one in which the underlying bosons are excitons comprised of electrons in one layer bound to holes in the other.

Keywords: Two-dimensional electron systems; Excitonic superfluidity; Josephson effect; Coulomb drag

1. Introduction

A new form of superfluidity was predicted about 10 years ago in theoretical studies of double layer two-dimensional electron systems (2DES) [1]. Although there are a number of equivalent ways to describe this new effect, it may be viewed as arising from a Bose condensation of excitons consisting electrons in one layer bound to holes in the other [2]. From this perspective, the system is very similar to those excitonic condensates which were predicted much earlier but have yet to be convincingly demonstrated in the experiments (for an early example, see Ref. [3]). In the present case, however, no valence band holes are involved; the excitons are formed entirely within the conduction band of a semiconductor heterostructure.

This new collective phenomenon occurs in the presence of a large magnetic field B perpendicular to the 2D planes. The field quantizes the single-electron kinetic energy spectrum into a ladder of discrete, yet highly degenerate, Landau energy levels. At high enough field only the lowest such level is occupied with electrons and a large energy gap to the next Landau level (LL) exists. Under these circumstances, Coulomb interactions between electrons cannot be treated perturbatively and numerous possibilities for exotic strongly correlated many-body states result. The fractional quantized Hall liquids, which exist in both single and double layer 2D systems, are the best known, but by no means only, examples.

The collective state to be discussed here does indeed exhibit a quantized Hall effect (QHE); its Hall resistance ρ_{xy} is precisely h/e^2. In common with all other QHE states, the longitudinal resistance ρ_{xx} of the present system, which reflects energy dissipation, is exponentially small at low temperatures. We emphasize, however, that this is *not* what is meant by superfluidity in the present context. As we shall discuss, an excitonic quantized Hall state is believed to exhibit a unique superfluid mode which is dissipationless (in linear response) even at finite temperature. More importantly, this collective state possesses a condensate with a macroscopic phase variable ϕ in exact analogy to superfluid ^{4}He and conventional superconductors. Ordinary QHE states do not possess such a condensate or quantum phase. This paper will review, superficially, our recent experiments which strongly suggest that this new form of superfluidity has, in fact, been observed.

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2. The QHE in bilayer electron systems

In its simplest form, the fractional quantized Hall effect (FQHE), occurs when the density of electrons in the system, N, is a rational fraction $\nu = p/q$ of the degeneracy eB/h of the lowest spin-resolved LL (for a review of quantized Hall phenomena in single and double layer systems, see Ref. [4]). In a single layer system the FQHE is only observed at certain filling fractions $\nu = p/q$ and then only with q an odd integer. The exceptions to this rule are the $\frac{5}{2}$ and $\frac{7}{2}$ states which occur in the first excited Landau Level. At these special fillings, interactions between electrons lead to the condensation of a remarkable quantum fluid ground state with an energy gap to charged excitations. The lowest lying such excitations carry a precise fraction of an electron's charge. FQHE states are observed at $\nu = \frac{1}{3}, \frac{2}{5}, \frac{2}{3}$, etc., but none has ever been reported at $\nu = \frac{1}{2}$, i.e. at half-filling of the lowest LL. The half-filled case is interesting in its own right [4], but the system does not possess the key energy gap needed for Hall quantization.

In a double layer 2DES there are new possibilities owing to the presence of both intra- and interlayer Coulomb interactions [4]. The most interesting case studied so far is that in which the individual layers are each at filling factor $\nu = \frac{1}{2}$. If the layers are sufficiently close together the system *does* possess an energy gap and does exhibit a QHE. In this situation it is more appropriate to consider the total filling factor $\nu_{tot} = \frac{1}{2} + \frac{1}{2} = 1$ rather than the individual filling factors. Discovered nearly 10 years ago [5], it is by now well established that this QHE state collapses when the separation d between the layers is increased beyond a critical value. At large layer separation the two layers behave independently and, consistent with the above discussion, no QHE is expected.

The $\nu_{tot} = 1$ bilayer QHE was suspected early on to be quite unusual [1,6–8]. The reason for this is embodied in the concept of spontaneous interlayer phase coherence. In the ground state electrons in the system are no longer in one layer or the other, but are instead in quantum mechanical superpositions of individual layer eigenstates. This seems reasonable since there is always some amount of tunneling through the barrier layer which separates the two 2D layers. In the presence of such tunneling one expects hybridization of the individual layer states into symmetric and antisymmetric linear combinations which are separated in energy by a gap Δ_{SAS}. The key point, however, is that at $\nu_{tot} = 1$ this hybridization occurs *even in the limit of zero tunneling*: Coulomb interactions alone are sufficient, provided that the layers are close enough together. Indeed, recent experimental work has demonstrated the existence of the $\nu_{tot} = 1$ QHE even when the single-particle tunneling gap Δ_{SAS} is more than five orders of magnitude smaller than the mean inter-electron Coulomb energy.

In the simplest situation, the electrons in the ground state at $\nu_{tot} = 1$ have a 50% probability of being found in either layer. Naturally, if an electron were found to be at some location in one layer, an immediate subsequent measurement would find no electron in the opposite layer at the same location in the plane. Thus, the correlations built into the ground state may be viewed as excitonic; electrons in one layer are bound to holes in the other. Of course, one cannot tell in advance which layer the either particle is in. Furthermore, the $\frac{50}{50}$ nature of the electronic states does not fully specify the quantum state. The same probabilities will result from any linear combination of the form $|\uparrow\rangle + e^{i\phi}|\downarrow\rangle$, where the kets $|\uparrow\rangle$ and $|\downarrow\rangle$ denote the two different layer eigenstates and ϕ is a phase. Strong exchange interactions between electrons in the same (and different) layers force the phase to be the *same for all electrons*, at least in an ideally clean system at zero temperature. This constitutes a spontaneously broken symmetry which may be visualized via an attractive analogy with easy-plane ferromagnetism. The phase ϕ is a macroscopic quantum variable, very analogous to that in superfluid ^{4}He or an s-wave superconductor.

There is a complicated family of elementary excitations above the $\nu_{tot} = 1$ ground state (See the chapter in Ref. [9]). Vortices in the ϕ field form one class. These objects, called *merons* and *anti-merons*, carry electrical charge $q = \pm e/2$, but usually exist in pairs of charge zero or e. In addition, a Goldstone collective mode in the system is associated with the spontaneously broken symmetry. This mode, which is crudely analogous to an interlayer plasma mode, is gapless in the long wavelength limit. Finally, there are superfluid flows in the condensate itself. A uniform spatial gradient in ϕ produces this new kind of superflow, one which consists of oppositely directed electrical currents in the two layers. Within the excitonic condensate point of view, this corresponds to a uniform flow of excitons in one direction. The experimental evidence which supports the existence of such superfluid counterflows is the subject of the remainder of this paper.

3. Tunneling at $\nu_{tot} = 1$

Direct measurements of tunneling between parallel 2D ES were first reported by Smoliner et al. [10]. At zero magnetic field fairly sharp resonances are observed in the tunneling conductance dI/dV. These resonances occur when energy levels in the two wells line up. The sharpness of the resonances results from the twin constraints of energy and in-plane momentum conservation which characterize tunneling in high mobility GaAs/AlGaAs heterostructures at low temperatures.

When a large perpendicular magnetic field is applied, the tunneling current–voltage (I–V) characteristics are altered qualitatively. The narrow resonances seen at $B = 0$ are absent and the tunneling is spread out over a relatively wide range in energy. This width reflects the broadening of the LL induced by electron–electron interactions. In addition, there is also a region of strongly suppressed tunneling centered at zero interlayer voltage [11,12]. This *Coulomb pseudo-gap*, which is pinned to the Fermi levels of the two 2D systems,

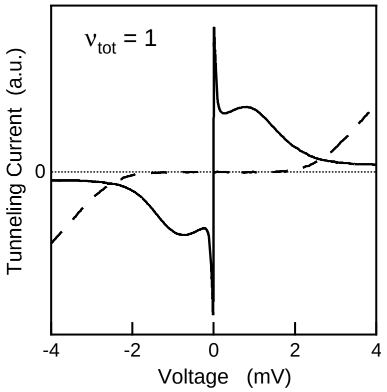

Fig. 1. Two tunneling I–V characteristics at $\nu_{tot}=1$ and $T=25$ mK. (Solid curve) Effective layer separation is small enough to stabilize excitonic QHE phase and Josephson-like tunneling results. (Dashed curve) Strongly suppressed tunnel current near-zero bias that is characteristic of widely separated, and thus weakly coupled, layers.

demonstrates that electrons cannot be injected (or extracted) from a clean 2D ES at high magnetic fields at low energies. This suppression effect is quite generic, it does not depend upon whether either 2D system is in a gapped quantized Hall state or a gapless compressible state like $\nu=\frac{1}{2}$. The important point is that tunneling is essentially instantaneous. An electron attempting to tunnel in must force its way into an "interstitial" location in the strongly correlated N-particle fluid. This costs an energy of order the mean Coulomb energy between electrons. A similar energetic penalty accompanies the rapid extraction of an electron. Even though low-energy $N+1$ particle states may exist (as they do at $\nu=\frac{1}{2}$), tunneling cannot access them on short time scales. As a consequence, electrons with less than the mean Coulomb energy simply cannot tunnel at low temperatures.

Recent experiments have shown that the above argument fails qualitatively when the effective separation between the two layers is reduced below a critical value. Instead of a suppression of the tunneling at low energy, a dramatic enhancement is observed [13]. This enhancement is very sharply resonant in energy, typically only occuring within a few μV of $V=0$. Very crudely speaking, the Coulombic penalties associated with the injection and extraction processes associated with tunneling are cancelled by the excitonic attraction in the final state. Fig. 1 illustrates the stark change in the I–V tunneling characteristics which occurs when the phase boundary separating the large separation, no QHE phase from the small separation, interlayer phase coherent excitonic QHE phase is crossed. The data in the figure were obtained from a single sample: the effective layer separation is adjusted by symmetrically changing the density of the two 2D ESs and adjusting the magnetic field accordingly to maintain $\nu_{tot}=1$.

The solid trace in Fig. 1 is reminiscent of the DC Josephson effect in a superconductor tunnel junction. We stress, however, that so far no clear Josephson effect has been detected in the $\nu_{tot}=1$ case. The jump in the tunnel current near-zero bias occurs over a finite, if small, region of voltage. This voltage width falls with temperature, saturating below about 40 mK, but it is not yet clear whether this saturation is an intrinsic or extrinsic effect.

The resonant enhancement of tunneling at $\nu_{tot}=1$ is a direct indicator of the existence of the predicted linearly dispersing Goldstone mode in the system. Indeed, measurements of the tunneling in the presence of a small in-plane magnetic field (added to the large perpendicular field), have verified the predicted linear dispersion of this mode [14]. More intriguingly, the enhanced zero bias tunneling indirectly suggests that the novel superfluidity of the $\nu=1$ state does indeed exist. When an electron tunnels it creates a transient charge buildup in one layer and a charge deficit in the other layer. To relax these defects, current must flow away from the tunneling site in one layer and toward it in the other layer. This constitutes counterflow, the very transport mode which is superfluid at $\nu=1$. So, unlike the situation with tunneling between uncorrelated 2D layers, it is very easy in the present $\nu=1$ case to relax the charge defects created by tunneling.

4. Coulomb drag

Direct generation and detection of superfluid counterflows at $\nu_{tot}=1$ is possible, but difficult. As an intermediate step we have performed Coulomb drag experiments in which a current is driven through just one of the layers, while voltage drops in the other layer are recorded [15]. This novel technique provides direct access to the interlayer electron–electron scattering rates in the system.

In the presence of a perpendicular magnetic field, there are both longitudinal and transverse, or Hall, drag voltages. Until the present experiments, however, Hall drag had not been observed. An oversimplified, yet instructive, explanation for this is that since no current is allowed to flow in the drag layer there can be no net Lorentz force and therefore no voltage build-up transverse to the current in the other layer. As we now show, this argument fails in the $\nu_{tot}=1$ state with its strong interlayer correlations.

Fig. 2 shows the longitudinal and Hall components of Coulomb drag in a sample supporting the $\nu_{tot}=1$ excitonic QHE state. The drag voltages are converted into resistances by dividing by the current flowing in the drive layer. The dotted curve is the conventional longitudinal resistance of the sample; as expected it becomes very small in the region of the $\nu_{tot}=1$ QHE. The dashed curve is the longitudinal *drag* resistance, and it too becomes very small around the $\nu_{tot}=1$ QHE. This vanishing of the longitudinal drag in a QHE state is not surprising since there is an energy gap to charged excitations. More interesting, however, is the behavior of the Hall drag. Instead of being zero, or at least small, near $\nu_{tot}=1$ it rises up and becomes quite large. Careful

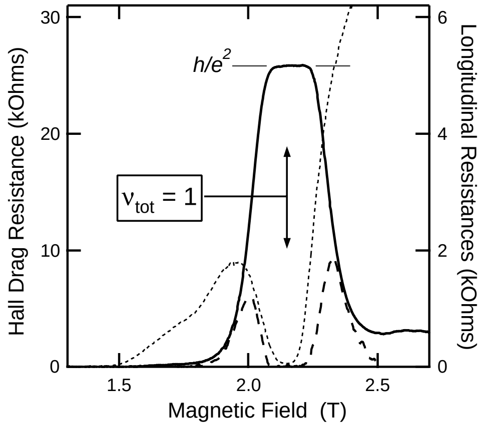

Fig. 2. Quantization of Hall drag at $\nu_{tot} = 1$. (Solid trace) Hall drag resistance at $T = 25$ mK. (Dashed trace) Longitudinal drag resistance. Dotted trace: Conventional longitudinal resistance.

measurements have shown that the Hall drag is accurately *quantized* at $\rho_{xy,D} = h/e^2$. This is remarkable: No current is flowing in the drag layer and yet it exhibits a quantized drag voltage transverse to a current flowing in the opposite layer! This seemingly unphysical result was in fact predicted [8,16]. Its existence is due to the strong interlayer Coulomb correlations in the system.

The quantization of Hall drag might not seem so strange when one remembers that electrons in the system are coherently spread between both layers. This suggests that a electrical currents cannot be restricted to one layer alone, as a drag experiment requires. Careful examination, however, demonstrates that the *net* current flowing in the drag layer is indeed very close to zero. This apparent paradox is resolved by allowing for counterflow superfluidity. In addition to a symmetric transport current flowing equally in the two layers, a excitonic supercurrent develops. In the drive layer these two currents add to give the imposed current; in the drag layer they subtract to give zero. Only the symmetric current produces a Hall resistance, and it is necessarily quantized at h/e^2. Thus, quantized Hall drag offers a second strong indication that the predicted excitonic superfluidity of the $\nu_{tot} = 1$ state does indeed exist.

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