Evidence for a finite temperature phase transition and phase competition in a bilayer 2D electron system

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(Dated: September 5, 2007)

We study the Josephson-like interlayer tunneling signature of the strongly correlated $\nu_T = 1$ quantum Hall phase in bilayer two-dimensional electron systems as a function of the layer separation, temperature and interlayer charge imbalance. Our results offer strong evidence that a finite temperature phase transition separates the interlayer coherent phase from incoherent phases which lack strong interlayer correlations. The transition temperature is dependent on both the layer spacing and charge imbalance between the layers. The phase boundary is found to be re-entrant as a function of charge imbalance thus suggesting an intricate competition between the interlayer coherent phase and various independent layer states.

PACS numbers: 73.43.Jn, 71.10.Pm, 71.35.Lk

Bilayer two-dimensional electron systems (2DES) at high magnetic fields can exhibit drastically different quantum collective phases depending on whether their interlayer spacing is large or small. When the spacing is large the two layers act independently and display the familiar fractional quantum Hall and related effects. Conversely, at small interlayer separation, bilayer collective phases with no single layer analog appear [1]. When the layer spacing is intermediate between these two extremes, the situation is complex and poorly understood.

An interesting example of the richness of bilayer 2DES quantum phenomena occurs when the total density $n_T$ of electrons in the bilayer equals the degeneracy $eB/h$ of a single spin-resolved Landau level created by the magnetic field $B$. In this situation the total Landau level filling factor is $\nu_T = n_T/(eB/h) = 1$. If the spacing between the two layers is small, the 2DES is a gapped quantum Hall (QH) liquid well described by Halperin’s $\Psi_{111}$ wavefunction [2] and may be viewed as a Bose condensate of interlayer excitons [3] or, equivalently, as a pseudospin ferromagnet [4]. This collective state exists even in the absence of interlayer tunneling, and exhibits an unusual broken symmetry, spontaneous interlayer phase coherence, which renders it robust against layer density differences so long as the total density remains fixed. When the layer separation is large, interlayer phase coherence is lost. For the simple case of equal layer densities, the system is then well described as two independent composite fermion metals each at $\nu = 1/2$ [5].

The transition from the coherent excitonic phase at small layer separation to the incoherent compressible phase at large layer separation is believed to be a zero temperature quantum phase transition. There is by now very strong experimental evidence for this transition coming from a variety of experimental probes [3]. In particular, interlayer tunneling studies reveal the emergence of a sharply resonant peak in the tunneling conductance at zero bias when the layer separation is reduced below a critical value [6]. Theory, however, predicts that below the critical layer separation there is also a finite temperature Kosterlitz-Thouless (KT) transition in the $\nu_T = 1$ bilayer 2DES [7]. Vortices in the pseudospin field are expected to pair up as the temperature is reduced below the KT transition and engender a type of superfluidity in which counterflowing electrical currents in the two layers are dissipationless. Strongly suppressed dissipation in the counterflow channel has in fact been observed [8,9,10], but true superfluidity and a KT transition remain undetected. Beyond the question of superfluidity, the prediction of a KT transition was exciting because previously only zero temperature quantum phase transitions [11] were anticipated in QH systems. So far, experiments have only provided suggestive evidence for a finite temperature transition [12,13].

Here we report strong evidence that the $\nu_T = 1$ bilayer 2DES does exhibit a finite temperature phase transition. Specifically, we demonstrate that the critical layer separation at which enhanced zero bias tunneling appears evolves smoothly with temperature. We find that the peak tunneling conductance in balanced (i.e. equal density) $\nu_T = 1$ bilayers exhibits a consistent empirical scaling law near the temperature-dependent critical layer separation. In addition, our observations of a characteristic evolution of the dependence of interlayer tunneling on layer density imbalance reinforce these conclusions and allow us to construct a phase boundary surface in the layer spacing-temperature-density imbalance 3D space. We speculate that the transition we observe may be unrelated to the predicted KT transition but instead reflect energetic competition between the coherent excitonic QH state and independent layer correlated phases.

Figure 1(a) shows a typical low temperature tunneling conductance spectrum for the coherent phase at $\nu_T = 1$. The conductance, $dI/dV$, shows a very strong and narrow (FWHM = 7 $\mu$V) resonance centered at zero interlayer voltage [6]. For these data, taken at $T = 55$ mK...
and \( B = 2.05 \, \text{T} \), the bilayer is density balanced and the effective layer separation, defined as the center-to-center quantum well spacing \( d \) divided by the magnetic length \( \ell = (\hbar/eB)^{1/2} \), is \( d/\ell = 1.56 \). The sample consists of a \( 250 \times 250 \, \mu\text{m} \) mesa with two individually contacted modulation-doped 18 nm GaAs quantum wells separated by a 10 nm \( \text{Al}_{0.9}\text{Ga}_{0.1}\text{As} \) barrier. Tunneling is extremely weak in this sample, with the estimated splitting between the lowest symmetric and anti-symmetric bilayer eigenstates roughly six orders of magnitude smaller than the mean Coulomb repulsion energy between electrons.

Figure 1(b) shows the conductance \( G_0 \) at the peak of the tunneling resonance vs. \( d/\ell \) at various temperatures. The shape of the \( G_0 \) vs. \( d/\ell \) curves is qualitatively the same at all \( T \). The peak conductance rapidly collapses, by up to four orders of magnitude, as \( d/\ell \) increases and extrapolates to zero at a temperature-dependent critical effective layer separation, \( (d/\ell)_c \). The solid lines in Fig. 1(b) are power law fits of the form, \( G_0 = K[(d/\ell)_c - (d/\ell)]^p \). Figure 1(c) shows that the exponent \( p \) is roughly constant at \( p \approx 3 \), while Fig. 1(d) demonstrates that \( (d/\ell)_c \) falls linearly with increasing temperature [14]. The solid line in Fig. 1(d) is a linear best fit to the \( (d/\ell)_c \) data; we believe that this line represents a true phase boundary, in the \( d/\ell \)-temperature plane, separating the coherent excitonic fluid from an incoherent compressible fluid in balanced bilayers at \( \nu_T = 1 \).

Additional evidence for a finite temperature phase transition at \( \nu_T = 1 \) is provided by the dependence of the tunneling conductance upon layer density imbalance. Electrostatic gating allows us to independently tune the densities of the two layers while keeping the total density fixed [15]. Figure 2(a) shows the dependence of the zero bias tunneling conductance \( G_0 \) on the filling factor \( \nu_{\text{top}} = 1 - \nu_{\text{bot}} \) of the “top” 2DES at \( T = 55 \, \text{mK} \) and various \( d/\ell \). For \( d/\ell \lesssim 1.7 \, G_0 \) is largest at balance \( (\nu_{\text{top}} = \nu_{\text{bot}} = 1/2) \) and falls gently as imbalance is imposed. This behavior is in qualitative agreement with theoretical predictions [17] which suggest that the tunneling conductance is controlled by the projection of the pseudospin magnetization in the symmetry plane. Since pseudospin “up” and “down” correspond to states localized in the top and bottom layers, imbalanced bilayers have a non-zero component of pseudospin perpendicular to the plane and hence a smaller projection in the plane.

At larger layer separations, the imbalance dependence of the tunneling conductance changes qualitatively. Instead of a maximum at balance a minimum is formed; small imbalances about the balanced state increase the tunneling conductance. Figure 2(a) shows that this change occurs around \( d/\ell = 1.74 \) at \( T = 55 \, \text{mK} \). Increasing \( d/\ell \) enhances this effect until ultimately the tunneling conductance vanishes in the vicinity of density balance but returns when the system is sufficiently imbalanced. At \( T = 55 \, \text{mK} \), \( G_0 \) first vanishes near \( d/\ell = 1.82 \), which coincides with the critical layer separation for the balanced case shown in Fig. 1(d).

The restoration of the \( \nu_T = 1 \) tunnel resonance by small density imbalances strongly suggests that the excitonic phase itself is restored and that imbalance represents an important dimension of the phase space filled by this exotic quantum fluid. Enlargement of the excitonic phase space by imbalance was first predicted by Hanna [15] and studied by Joglekar and MacDonald [19]. Transport and tunneling experiments [20, 21, 22] have verified the effect qualitatively. The essential point here is that the restoration of the zero bias tunneling peak by imbalance is a property of the phase boundary itself, reflecting the free energy competition between the coherent excitonic phase and incoherent phases of the bilayer 2DES at \( \nu_T = 1 \).

Figure 2(b) shows that the same imbalance phenomenology observed at \( T = 55 \, \text{mK} \) (Fig. 2(a)) is also observed at \( T = 200 \, \text{mK} \); the only significant differences
are the values of $d/\ell$ at which the various features appear. Data at intermediate temperatures (not shown) evolve smoothly between the data in Fig. 2(a) and (b). At $T = 200$ mK the local maximum of the tunneling conductance at balance is replaced by a local minimum by $T = 55$ mK. Similarly, the tunneling conductance first vanishes at balance near $d/\ell = 1.69$ at 200 mK while the same effect occurs near $d/\ell = 1.82$ at 55 mK. Thus, just as the qualitative shape of the $d/\ell$ dependence of the tunneling conductance at balance shown in Fig. 1(b) remains the same at all temperatures, so does the dependence upon layer density imbalance. In both cases the only qualitative effect of temperature is to shift the various curves along the $d/\ell$ axis. Imbalance, therefore, offers independent evidence of a finite temperature phase transition in the $\nu_T = 1$ bilayer 2DES.

If, as seems likely, there are spatial fluctuations in the barrier thickness or density of the 2DES in our bilayer sample, then near the phase boundary there may be isolated puddles of coherent fluid surrounded by incoherent fluid [23]. The critical layer separation shown in Fig. 1(d) therefore corresponds to the complete elimination of these puddles. Alternative definitions of the critical layer separation are of course possible. For example, one could instead define the phase boundary by the $d/\ell$ value at which the imbalance dependence of the tunneling conductance first shifts from a local maximum to a local minimum at the balance point. This definition produces a phase boundary very similar to that shown in Fig. 1(d), only shifted to slightly lower values of $d/\ell$. Our qualitative conclusion that a finite temperature phase transition exists at $\nu_T = 1$ is unaffected.

We now discuss the nature of the $\nu_T = 1$ phase boundary as a function of imbalance. Figure 2 reveals a re-entrant behavior of the coherent tunneling peak close to the phase boundary. In this regime the coherent state is absent at balance, present over a narrow range of non-zero imbalance, and then absent again at large imbalance. This suggests a complex pattern of phase competition in the $\nu_T = 1$ bilayer system. Near balance the competition is between the coherent $\nu_T = 1$ QH state and a compressible $\nu_T = 1/2 + 1/2$ state. The enhancement of the coherent state with small imbalance is reminiscent of the enhancement induced by strong interlayer tunneling [4]. In that case the tunneling explicitly breaks the easy-plane $U(1)$ symmetry, suppresses quantum fluctuations and forces the pseudospins to align. Imbalance has a similar symmetry-breaking effect by adding an easy-axis anisotropy which again suppresses fluctuations and encourages the pseudospins to align. We stress, however, that a full understanding of the effect requires consideration of the free energies of both the coherent and incoherent phases at $\nu_T = 1$. The situation at large imbalance is still less clear. In this case there are numerous possible incoherent phases including compressible non-QH combinations like $(\nu_{\text{top}}, \nu_{\text{bot}}) = (1/4, 3/4)$ or incompressible QH combinations like $(1/3, 2/3)$. At even larger imbalances the possibility of crystalline insulating phases arises [24].

Figure 3 displays two representations of the phase boundary surface separating the coherent and incoherent phases at $\nu_T = 1$. Panel (a) shows the boundary in the $d/\ell$-imbalance plane at various temperatures. The data represent the highest $d/\ell$ values, at given imbalances, for which a tiny zero bias tunneling peak can still be detected. Figure 3(b) presents a 3D surface plot of this phase boundary. Away from the balance point, Fig. 3 illustrates the re-entrant nature of the phase boundary. At high temperature no anomaly at any special filling factor pairs is evident. At low temperature the phase boundaries shown in Fig. 3 display some subtle variations. First, near $(\nu_{\text{top}}, \nu_{\text{bot}}) = (1/3, 2/3)$ and $(2/3, 1/3)$ a shoulder in the phase boundary develops. Secondly, at these same filling factors there is a clear suppression of the temperature dependence of the phase boundary below about $T = 125$ mK. This is in strong contrast to the linear temperature dependence of $(d/\ell)$, visible at $(1/2, 1/2)$ and also shown in Fig. 1(d). These observations suggest that the conjugate pair of fractional QH states at $(1/3, 2/3)$ is especially stable against formation of the $\nu_T = 1$ bilayer coherent phase. Evidence of interplay be-

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**FIG. 2:** $G_0$ at $\nu_T = 1$ vs. the filling fraction in the “top” layer $\nu_{\text{top}} = 1 - \nu_{\text{bot}}$, for various $d/\ell$, at $T = (a) 55$ mK, (b) 200 mK. The solid lines are guides to the eye.
between the imbalanced $\nu_T = 1$ coherent state and single layer states has been reported previously \[22\]. At extremely large imbalances the collapse of the critical layer separation may also reflect the increasing importance of disorder in the low density layer. Disorder can disrupt the correlations essential to the coherent $\nu_T = 1$ phase and thereby suppress interlayer tunneling \[25\].

In summary, interlayer tunneling spectroscopy has been used to map out the phase boundary between the interlayer coherent $\nu_T = 1$ bilayer quantum Hall phase and the incoherent states at larger layer separation as functions of temperature and interlayer charge imbalance. Our data offers strong evidence that a finite temperature phase transition is present in this system. The complex interplay of the coherent and incoherent phases in imbalanced $\nu_T = 1$ bilayers supports this conclusion and offers new insight into the competition between bilayer quantum phase coherence and independent layer physics.

We are grateful to S. Das Sarma, A.H. MacDonald, G. Refael, and X.G. Wen for discussions, and to I.B. Spielman, G. Granger and L.A. Tracy for technical help. This work was supported by the DOE under grant DE-FG03-99ER45766 and the NSF under grant DMR-0552270.

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[14] Alternatively, one can analyze the area under the tunneling resonance rather than its height. We find that the dependence of the area as a function of $d/\ell$ reproduces the qualitative picture of Fig. 1. Using the same fitting procedure for the area as for $G_0$ we find almost identical values for the $(d/\ell)$, as a function of $T$, and exponents $p \approx 2.5$ that are temperature independent.

[15] Calibration of the effect of the gates on layer densities is complicated by their mutual interaction and the non-negligible effects of compressibility of the two 2DES layers at high magnetic field \[10\]. We have carefully combined extrapolations of low field Shubnikov-de Haas density determinations with high field (and high temperature) Hall effect measurements to arrive at calibrations which we believe are accurate to $\Delta \nu = \pm 0.01$ in the balanced case ($\nu_{top} = \nu_{bot} = 1/2$) and $\Delta \nu = \pm 0.02$ at imbalances as large as $\nu_{top} = 1/3$, $\nu_{bot} = 2/3$.


[25] At very high imbalance, disorder can also reduce the conductivity of the low density layer to values comparable or smaller than the tunneling conductance. If this occurs, it is not possible to accurately measure the tunneling conductance. A careful study of the temperature dependence of the net device conductance allows us to identify and avoid this problem. None of the data presented here are compromised by this effect. The minimum layer densities at which we report tunneling conductance data range from 1.2 to $1.8 \times 10^{10}$ cm$^{-2}$ depending on temperature.