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Evidence of interlayer correlation in spin excitations of quantum Hall bilayers with negligible tunneling

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Manifestations of interlayer excitonic coherence in a quantum Hall bilayer with negligible tunneling occur in low-lying spin excitations measured by inelastic light scattering. The observation of quasiparticle spin-flip excitations with energies below the Zeeman gap identifies a composite-fermion metal as the high-temperature phase of the quantum Hall coherent state. Spin-flip intensities enable the determination of a critical temperature for this transformation that is in general agreement with those obtained from charge transport experiments.

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Two-dimensional electron systems in double quantum wells in the limit of vanishingly small tunneling gap ($\Delta_{SAS} \to 0$) support quantum fluids that manifest interlayer coherence in the quantum Hall (QH) states at total filling factor $\nu_T=1$ (just one Landau level fully occupied).[1,2] The interlayer correlated quantum state underlying the QH effect is now understood as an easy-plane pseudospin ferromagnet (up and down pseudospins label the electron occupation in the two layers). Equivalently, the state can be viewed as a Bose-Einstein condensate of interlayer excitons by making a particle-hole transformation [see Fig. 1(A)].[3,4]

Transport experiments in a configuration of separate Ohmic contacts to the two layers have probed the onset of interlayer coherence when the parameter d/l_B (d is the interlayer distance and l_B is the magnetic length) is made sufficiently small.[2,5–9] Such measurements have indicated a superfluidlike behavior of the excitonic pairs.[3,6,7] More recent transport experiments have stressed the role of spin demonstrating that the transition from the strongly correlated to the compressible phases depends on $\eta = E_Z/E_C$ (E_Z is the Zeeman energy and $E_C = e^2/\epsilon l_B$ is the Coulomb energy).[10]

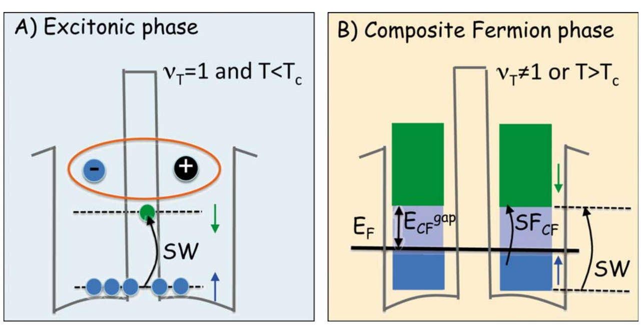

FIG. 1. (Color online) (A) Particle-hole transformation in bilayers at total filling factor $\nu_T=1$ allows us to describe the population of one of the two layers in terms of holes. The resulting ground state consists of a condensate of interlayer excitons and a conventional quantum Hall fluid formed by the excess charge that fully occupy the spin-up Landau level and supports a well-defined SW mode across the Zeeman gap. (B) Schematic of CF levels and spin excitations of the bilayer CF metal. E_F is the CF Fermi energy. In the CF phase, a spin-flip (SF_{CF}) continuum of excitations across the Fermi level extends from the Zeeman gap down to an energy value E_{gap}^{CF} determined by the relative position of the Fermi level within the spin-up and -down CF states. The drawing shown in the figure refers to the case of a spin-polarized CF metallic state.

Theoretical formulations have raised the possibility that the compressible phase competing with the excitonic fluids corresponds to (metallic) states of composite fermions (CFs).[11,12] In these interpretations a CF phase, metallic or BCS-like, occurs in the limit of large d/l_B when the system is regarded as two single layers each of them at $\nu=1/2$. The competing character of the CF state in the quantum phase diagram has been invoked in the interpretation of magnetotransport experiments both in the broken-symmetry regime at zero tunneling[10,13] and at finite tunneling.[14]

The emergence of a Fermi sea of CFs has key manifestations in excitations above the quantum ground state: in the low-lying sector of spin modes that are below the Zeeman energy E_Z there is a continuum of spin-flip excitations from transitions between spin-up and -down states across the CF Fermi energy.[15] The quasiparticle transitions in this scenario are shown in Fig. 1(B) for a bilayer structure with zero tunneling. Studies of this class of low-lying spin modes should offer direct insights on the interplay between excitonic and CF phases in bilayers with a strong interlayer correlation.

Here, we provide evidence of the occurrence of a CF metallic phase through a phase transition at finite temperature in QH bilayers with $\Delta_{SAS} \to 0$. The evidence is based on measurements of low-lying spin excitations by resonant inelastic light scattering. The modes occur at the long-wavelength spin-wave (SW) energy E_Z and at the energies of spin-flip CF excitations that are below E_Z.

At the lowest temperatures and $\nu_T=1$, in the regime where interlayer coherence and excitonic superfluidity have been reported, we found a SW mode peaked at E_Z and a minimum in the intensity of low-lying spin-flip CF excitations. CF spin-flip modes appear in light scattering spectra when ν_T deviates slightly from $\nu_T=1$, indicating that away from $\nu_T=1$ the two electron layers become largely decoupled and that electrons in each layer coalesce into a CF metallic state similar to that in single layers at $\nu \to 1/2$.[15]

The evolution of spin excitations at $\nu_T=1$ was carefully monitored as a function of changes in temperature. While at the lower temperatures of the excitonic superfluid phases only the Zeeman mode is present, CF spin-flip excitations below E_Z appear at higher temperatures. These results indicate that the high-temperature phase of the coherent QH excitonic state is a CF bilayer metal. These results reveal an intriguing finite-temperature behavior dictated by the competition between quantum and thermal effects. The analysis of the light scattering spectra enables a determination of a transition temperature that offers evidence of a finite-temperature transition between the two highly correlated states. The determinations of critical temperatures from light scattering spectra for the transformation from excitonic to CF phases are in general agreement with transition temperatures reported in charge transport experiments.[13] The similar temperature dependence suggests that CF phases also occur in the transport studies.

Measurements were performed with the sample mounted on a mechanical rotator in a dilution refrigerator with a base temperature of 50 mK under light illumination. The sample is a nominally symmetric modulation-doped $Al_{0.1}Ga_{0.9}As/GaAs$ double quantum well with AlAs barrier in between the wells to suppress the tunneling, having a well width of 18 nm and a barrier width of 7 nm. The total electron density is $n_T \sim 6.9\times 10^{10}$ cm^{-2} and the electron mobility is above 10^6 cm^2/V s. A perpendicular magnetic field of 2.85T was applied to bring the electron bilayer in the QH state corresponding to $\nu_T=1$. The sample has $d/l_B=1.65$, a value that guarantees that at sufficiently low temperatures the electrons are in the correlated phase where exciton condensation and counterflow superfluidity take place.[3]

Spin excitations were measured by resonant inelastic light scattering in a backscattering configuration with perpendicular incident and scattered photon polarizations.[16] A tilt angle $\theta=67.5°$ between the magnetic field direction and the plane of the sample was used in order to have a large value of the Zeeman energy of $E_Z=0.15$ meV at $\nu_T=1$ and to facilitate the experimental observation of the SW mode. A single-mode tunable Ti:sapphire laser at around 810 nm and a triple-grating spectrometer equipped with a charge-coupled device detector were used. Laser power densities were kept at $\sim 10^{-4}$ W/cm^2 to avoid electron heating effects.

Figure 1 describes the energy-level structure and electronic spin-flip excitations of the excitonic QH phase [Fig. 1(A)] and of the Fermi seas of CFs [Fig. 1(B)] that occur when interlayer coherence is lost. We recall that a CF quasiparticle can be viewed as an electron with an even-integer number of magnetic flux quanta attached to it.[17] As a consequence, the CFs sense an effective magnetic field that is zero when the electron filling factor is $\nu=1/2$. In this limit the spacing between the CF Landau levels vanishes and the CFs coalesce into a Fermi sea[18] as shown in Fig. 1, right panel in the case of double layers with $\nu_T=(\nu=1/2)+(\nu=1/2)=1$.

In the excitation spectra, the formation of a Fermi sea of CFs manifests into a continuum of spin-flip modes SF_{CF} between spin-up and -down states across the CF Fermi energy [see the diagram in Fig. 1(B)].[15] Such excitations that are accessible by inelastic light scattering methods represent the hallmark of the CF phase in bilayers. The collective spin excitation in the excitonic phase, instead, can be understood by considering the excess spin-up electrons that remain after the particle-hole transformation. These electrons fill exactly one Landau level and support a well-defined long-wavelength SW mode at the Zeeman energy as shown in Fig. 1(A).

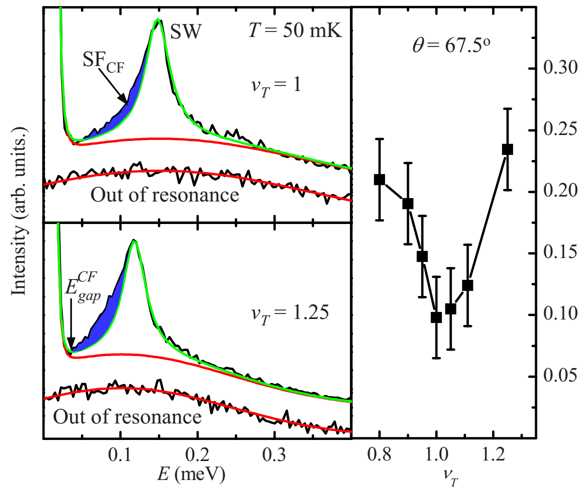

FIG. 2. (Color online) Left panels: representative spin excitation spectra (upper black lines) at $T=50$ mK and two values of filling factors $\nu_T=1$ and $\nu_T=1.25$ after on-resonant excitation with incoming laser energies $E_L=1526.7$ and 1526.2 meV, respectively. The luminescence backgrounds obtained with an off-resonant excitation at $E_L=1527.7$ meV are also shown and fitted with a Gaussian function (red/gray lines). A Lorentzian fit to the SW superimposed to the luminescence background (green/light gray lines) highlights the impact of the continuum of spin-flip excitations SF_{CF} (shaded in blue/dark gray). Right panel: evolution of the integrated intensity of SF_{CF} as a function of filling factor at $T=50$ mK normalized to the intensity of the SW peak.

Figure 2 reports representative low-lying spin excitations measured at two different filling factors at the lowest temperature of 50 mK and explains the procedure adopted to analyze the data. First a spectrum is collected under an outgoing resonance condition in which the scattered photons are in resonance with the luminescence (see upper spectra in the two panels of Fig. 2). In this case the SW mode at E_Z is clearly resolved on top of the magnetoluminescence background. Then a second spectrum is taken in the identical experimental conditions but with off-resonance excitation with a laser energy larger than the luminescence energy (see lower spectra in Fig. 2). This enables us to carefully fit the luminescence background (red/gray lines in Fig. 2). The fitting curve is then used to determine the SW line shape and the presence of the low-lying CF spin-flip modes below E_Z. To this end the SW peak is fitted with a Lorentzian function.[19] The results shown as green/light gray lines in Fig. 2 allow us to identify the additional spin-flip signal below E_Z (blue region) in accordance to what has been reported for single layers at the filling factor of 1/2 (Ref. 15) and in $\nu_T=1$ bilayers at finite tunneling.[20,21] We finally note that the CF spin-flip continuum in the bottom panel of Fig. 2 stops at a finite value E_{gap}^{CF} suggesting that at these values of E_Z the CF metal is spin polarized [see also Fig. 1(B)]. This is in agreement with previous results in single layers[15] and recent magnetotransport studies in bilayers.[10]

The right panel of Fig. 2 shows that the continuum of

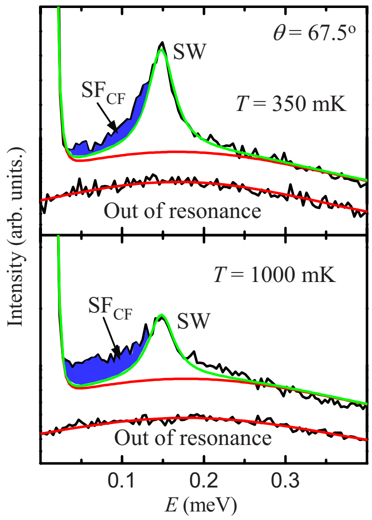

FIG. 3. (Color online) Representative spin excitation spectra at $\nu_T=1$ and two different temperatures. Red/gray and green/light gray lines are as in Fig. 2. The blue/dark gray shaded region represents the contribution of the continuum of composite-fermion spin-flip excitations SF_{CF}.

SF_{CF} displays a pronounced minimum when the bilayer is in the QH state at $\nu_T=1$. This significant result indicates a trend for the compressible CF metal to transform into a new phase with interlayer coherence when the total filling factor approaches $\nu_T=1$. We remark that the observation of residual (SF_{CF}) modes seen at $\nu_T=1$ at the lowest temperatures (see Fig. 4 also) suggests that, even in the QH state, CF compressible puddles are diluted in the majority excitonic phase in agreement with previous experimental and theoretical analysis[22–25] based on the role of disorder. No spin-flip mode is seen above the SW. This mode is indeed observed in samples with finite values of Δ_{SAS}.[16,21] Its absence supports the conclusion of negligible interlayer tunneling in the sample studied here.

The observation of SF_{CF} excitations demonstrates the emergence of a CF metallic state by varying the filling factor. As interlayer coherence disappears the physics becomes dominated by the intralayer correlations that build up the CF quasiparticles. These results highlight that spin excitations represent probes of the competition between interlayer and intralayer correlations in QH bilayers with negligible tunneling.

Particularly revealing is the behavior of spin excitations as a function of temperature. Figure 3 reports representative spectra at two different temperatures. At $T=350$ mK the spectrum looks similar to that at $T=50$ mK and shown in Fig. 2 except for a slight increase in the intensity of the SF_{CF} continuum. At $T=1$ K, on the contrary, the SF_{CF} intensity is remarkably larger while the SW intensity has decreased significantly. In addition, the lowest-energy value of the spin-flip continuum is lowered to values below the experimental resolution (30 μeV) suggesting that at this temperature there is loss of spin polarization of the CF.

The remarkable presence of a large signature of CF spin-flip modes demonstrates unambiguously that at this high temperature the bilayer at $\nu_T=1$ has transformed into a CF metallic state. Further insights into the transformation from the interlayer coherent QH state to the CF metallic phase can be gained by plotting the evolution of the SF_{CF} integrated intensity normalized to the SW intensity as a function of temperature. The data shown in Fig. 4 reveal that the intensity of the spin-flip continuum remains small and constant up to a critical temperature T_c. The marked increase seen above T_c suggests that the bilayer enters into a CF metallic state. The observed T_c is consistent with that found in tunneling experiments on a bilayer sample with similar parameters[13] reinforcing the interpretation that T_c signals the crossover from the interlayer coherent QH phase to the compressible CF metal. Nevertheless the role of disorder and its impact on the nature of this crossover should be further explored. In addition, whether the venue for the transition is a Kosterlitz-Thouless mechanism as expected for the broken-symmetry bilayer state remains an open issue that deserves additional experimental investigation.

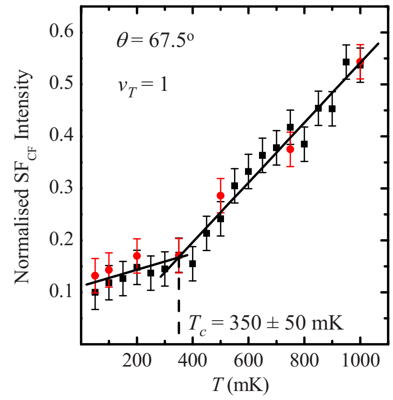

FIG. 4. (Color online) Evolution of the composite-fermion spin-flip intensity normalized to the spin-wave intensity at $\nu_T=1$ as a function of temperature. Red/gray and black points refer to two sets of measurements on different positions on the sample.

The increase in the intensity of the spin-flip continuum of CF excitations at $T>T_c$ is not abrupt, possibly due to roles of the disorder potential. We argue that CF regions nucleate at T_c around specific points in space determined by the disorder potential and then expand as temperature increases yielding the observed increase in the SF_{CF} signal, which follows an activated behavior with an activation energy of $E_a=0.10\pm0.02$ meV. A similar activation energy was found in the analysis of the Rayleigh scattering data in samples with finite tunneling[23] and linked to the energy required to inject free electrons into the incompressible domains. It is thus conceivable that a similar mechanism for the temperature-driven evolution of the CF regions is at work here. We also remark that the Lorentzian peak used to fit the SW does not show any significant variation as a function of temperature except for the decrease in the intensity due to thermal population of the collective excitations. This result demonstrates that the coexistence of CF compressible and excitonic incompressible puddles due to disorder, which is strongly temperature dependent, does not affect the SW line shape and therefore the determination of the SF_{CF} continuum. We also stress that a Gaussian fitting to the SW does not yield appreciable modifications of the data shown in Fig. 4.

In conclusion, we have shown that low-lying spin-flip excitations offer venues for the study of interlayer coherence and intralayer correlation in QH bilayers with negligible tunneling. The experiments reveal that the low-temperature QH coherent state undergoes a finite-temperature transition to a composite-fermion metal. Determinations of the critical temperature will characterize the finite-temperature phase diagram. Of particular interest is the case of lower values of the Zeeman energy where the CF phase becomes partially polarized.

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[1] A. H. MacDonald and S. Girvin, *Perspectives in Quantum Hall Effect* (Wiley, New York, 1997).

[2] I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **84**, 5808 (2000).

[3] J. P. Eisenstein and A. H. MacDonald, Nature (London) **432**, 691 (2004).

[4] K. Moon, H. Mori, K. Yang, S. M. Girvin, A. H. MacDonald, L. Zheng, D. Yoshioka, and S. C. Zhang, Phys. Rev. B **51**, 5138 (1995).

[5] M. Kellogg, I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **88**, 126804 (2002).

[6] M. Kellogg, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **93**, 036801 (2004).

[7] E. Tutuc, M. Shayegan, and D. A. Huse, Phys. Rev. Lett. **93**, 036802 (2004).

[8] R. D. Wiersma, J. G. S. Lok, S. Kraus, W. Dietsche, K. von Klitzing, D. Schuh, M. Bichler, H. P. Tranitz, and W. Wegscheider, Phys. Rev. Lett. **93**, 266805 (2004).

[9] I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **87**, 036803 (2001).

[10] P. Giudici, K. Muraki, N. Kumada, Y. Hirayama, and T. Fujisawa, Phys. Rev. Lett. **100**, 106803 (2008).

[11] S. H. Simon, E. H. Rezayi, and M. V. Milovanovic, Phys. Rev. Lett. **91**, 046803 (2003).

[12] G. Möller, S. H. Simon, and E. H. Rezayi, Phys. Rev. Lett. **101**, 176803 (2008).

[13] A. R. Champagne, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **100**, 096801 (2008).

[14] T. S. Lay, Y. W. Suen, H. C. Manoharan, X. Ying, M. B. Santos, and M. Shayegan, Phys. Rev. B **50**, 17725 (1994).

[15] I. Dujovne, A. Pinczuk, M. Kang, B. S. Dennis, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **95**, 056808 (2005).

[16] S. Luin, V. Pellegrini, A. Pinczuk, B. S. Dennis, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **94**, 146804 (2005).

[17] J. K. Jain, Phys. Rev. Lett. **63**, 199 (1989).

[18] B. I. Halperin, P. A. Lee, and N. Read, Phys. Rev. B **47**, 7312 (1993).

[19] A Gaussian fit to the spin wave does not change the observed behavior.

[20] B. Karmakar, S. Luin, V. Pellegrini, A. Pinczuk, B. S. Dennis, L. N. Pfeiffer, and K. W. West, Solid State Commun. **143**, 499 (2007).

[21] B. Karmakar, V. Pellegrini, A. Pinczuk, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **102**, 036802 (2009).

[22] M. Kellogg, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **90**, 246801 (2003).

[23] S. Luin, V. Pellegrini, A. Pinczuk, B. S. Dennis, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **97**, 216802 (2006).

[24] A. Stern and B. I. Halperin, Phys. Rev. Lett. **88**, 106801 (2002).

[25] H. A. Fertig and G. Murthy, Phys. Rev. Lett. **95**, 156802 (2005).