Evidence for a first-order quantum phase transition of excitons in semiconductor bilayers

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When dominated by quantum-mechanical fluctuations, ground state transformations display a tendency towards quantum criticality associated with collapse of the characteristic energy scale expressed by softening of low-lying excitation modes. In the presence of competing interactions and weak residual disorder the nature of the quantum phase transition is predicted to become discontinuous as the critical point is approached. The observation of these elusive effects require a fine tuning of the impact of the interaction terms that is difficult to achieve in experiments. We demonstrated that coupled electron bilayers realized in double quantum wells display excitonic and metallic ground states stabilized by different terms of electron interactions that can be tuned with high precision. This competition drives this soft-mode system to undergo a first-order quantum phase transition

In coupled electron bilayers confined in modulation-doped GaAs double quantum wells, the energy levels split into symmetric and anti-symmetric combinations separated by the tunnelling gap Δ_{SAS}. In the presence of a quantizing perpendicular magnetic field and at total Landau level filling factor $\nu_T = n_T 2\pi l_B^2 = 1$ (n_T is the total electron density in the bilayer and l_B is the magnetic length), the electron bilayer displays two distinct phases separated by a quantum phase transition (QPT). The two phases result from the competing impacts of inter- and intra-layer electron interaction [1,2] parameterized by d/l_B, where d is the distance between the two layers and by Δ_{SAS}/E_c, where $E_c = e^2/\varepsilon l_B$ (ε is the dielectric constant) is the intra-layer Coulomb energy [1,3].

At sufficiently low d/l_B or large Δ_{SAS}/E_c , the ground states at $\nu_T = 1$ are incompressible QH fluids [1,2]. A different phase occurs for low Δ_{SAS}/E_c (at sufficiently large d/l_B), when intra-layer correlations prevail on the inter-layer correlations. The compressible (non-QH) ground state of this phase is currently described as a Fermi metal of composite fermions (CFs) [4] (see Fig.1). The incompressible phase is also highly correlated and it is populated by coherent

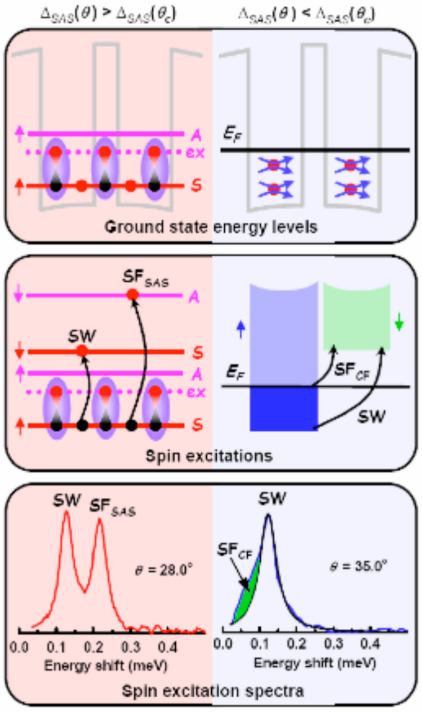
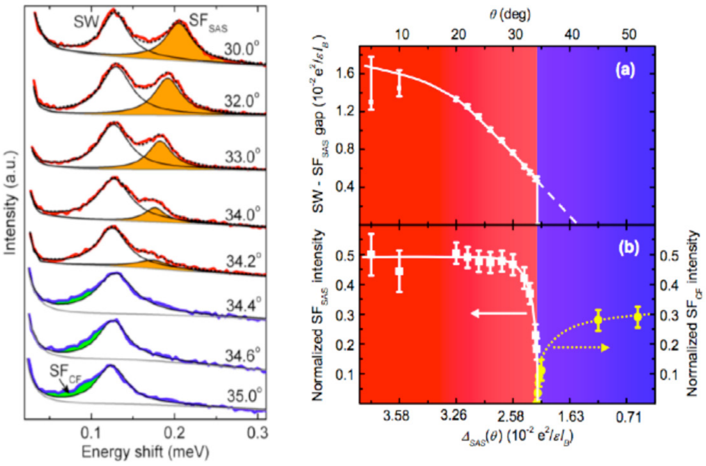


Fig. 1
Upper panel: Schematic representation of the correlated phases at $\nu_T = 1$. The excitonic quantum Hall phase is shown on the left. Electron-hole pairs occur between symmetric (S) and anti-symmetric (A) spin-up Landau levels. The composite fermion (CF) phase is shown on the right. In the limit of $\nu_T = \nu = 1/2 + \nu = 1/2$ and layers decoupled, the CF Landau level spacing vanishes and the CFs coalesce in a Fermi sea. The Fermi energy indicates the occupied CF levels. Middle panel: Schematic energy level diagrams and spin excitations in the two phases. SW and SF_{SAS} refer to spin-wave across the Zeeman gap and spin-flip mode across the tunneling gap, respectively. In the CF phase, a spin flip SF_{CF} continuum of collective excitations extends from the Zeeman gap down to an energy value determined by the relative position of the Fermi level within the spin-up and spin-down CF states. Lower panel: Representative spin excitation spectra after background subtraction in the two phases at T = 50 mK. A lorentzian fit to the SW in the CF phase (black line) highlights the impact of the SF_{CF} continuum (shaded in green).

Fig. 2
Left panel: Angular dependence of SF_{SAS} excitation intensity in the excitonic phase (in orange) and the spin-flip continuum SF_{CF} in the composite-fermion metallic phase (in green). Best fit results to the spectra (dotted lines) with two lorentzians (one in the CF phase) and the magneto-luminescence continuum and laser stray light (solid grey lines) are shown. Right panel: (a) Evolution of the correlated gap of the excitonic phase, i.e. the energy splitting between SW and SF_{SAS} excitations, as a function of tunnelling gap or tilt angle. The splitting remains finite at the phase boundary between the excitonic phase (red shaded) and the composite fermion metal (blue shaded). (b) Plot of integrated spin-flip excitation intensity. Data corresponds to the SF_{SAS} (white) and SF_{CF} (yellow) intensity (solid and dotted lines are guide for the eyes). The values are obtained after normalization with respect to the spin-wave SW intensity to take into account the angular dependence of oscillator strength of spin excitations.



electron-hole excitonic pairs across Δ_{SAS} with a density that is a fraction of $n_T/2$ (see Fig.1) [5,6]. These two phases display remarkable manifestations in light scattering spectra as shown in Fig.1 lower panels.

We have employed the technique of resonant inelastic light scattering to study the spin excitations in the excitonic and CF phases, as shown in the middle panels of Fig.1 and determine the character of the QPT in bilayers. Measurements were performed on the sample mounted on a mechanical rotator in a dilution refrigerator with base temperatures below 100 mK under light illumination. The in-plane magnetic field reduces the tunnelling gap [7]. We reached a precision on angle of 0.1° (precision on Δ_{SAS}/E_c of 1×10^{-4}) enabling the investigation of the evolution of the correlated phases with unprecedented accuracy. Long wavelength spin excitations were measured following the procedure described in Refs. [4,5]. The sample studied in this work is a nominally symmetric modulation-doped $Al_{0.1}Ga_{0.9}As/GaAs$ double quantum wells grown by molecular beam epitaxy with $n_T = 1.1 \times 10^{11}$ cm^{-2}, mobility above 10^6 cm^2/Vs, $d/l_B = 2.18$ (d= 25.5 nm is the interlayer distance and the well width is 18 nm) and $\Delta_{SAS} = 0.36$ meV.

The data in Fig. 2 demonstrate a QPT linked to the disappearance of the SF_{SAS} excitation at a finite value of $\Delta_{SAS}(\theta)$, which is the correlated gap and order parameter of the excitonic phase [5]. These striking results offer evidence of a first-order character of the transformation [8]. Figure 2 right panel is revealing. The evolution of $\Delta_{SAS}(\theta)$ in the excitonic phase suggests a continuous QPT at an angle slightly above 40°. There is, however, a marked discontinuity in the value of $\Delta_{SAS}(\theta)$ (at the critical angle $\theta_c = 34.2°$) that points to a first-order QPT and to a subtle competition of the collective excitonic state with the CF metal phase. First-order transitions in the absence of disorder are predicted in QH insulators [9] in other condensed matter systems [10] and in particle physics [11]. One key property of the electron bilayer system studied here is that the roles of different electron correlation terms at the QPT can be tested by finely tuning their relative strength.

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