**Unusual Landau Level Pinning and Correlated Quantum Hall States in 2D Hole Systems**

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**Introduction**

A strong perpendicular magnetic field *B* applied to a 2D electron/hole system (2DES/2DHS) quantizes the particles’ kinetic energies into discrete Landau levels (LLs), and give rise to novel correlated quantum phases such as quantum Hall states (QHSs). In our work, we study 2DESs/2DHSs confined in wide GaAs quantum wells (QWs), where multiple electric subbands are occupied. Via changing the angle  between the sample normal and magnetic field (see Fig. 1(a)), we study multi-component QHSs with spin and subband degrees of freedom at 1 <  < 3 through their pseudo-spin polarization transitions [1], and the two-component QHSs at  = 1/2 and 1 when the two lowest-energy LLs become nearly degenerate [2, 3].

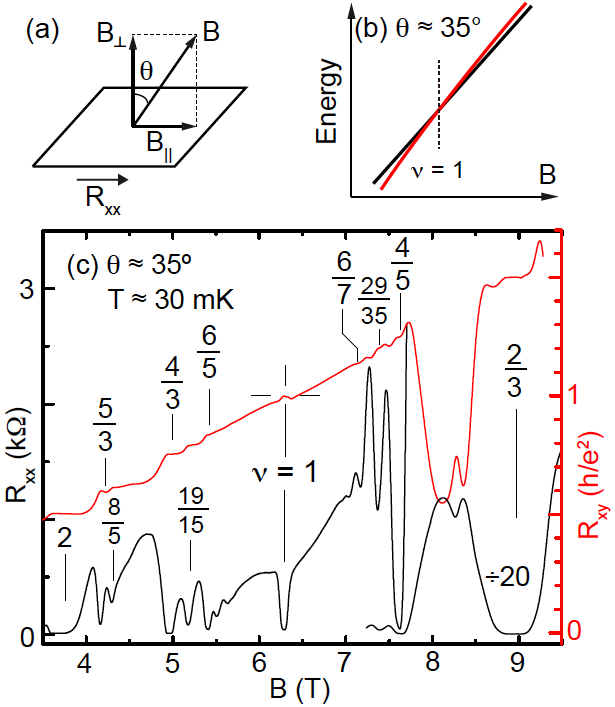
**Experimental**

Each of our samples consists of a high-quality GaAs QW bounded on its sides by undoped AlGaAs spacer and symmetric Si/C -doping layers. We carefully control the density and charge distribution by applying front- and back-gate voltages. The measurements were carried out in SCM1.

**Results and Discussion**

Figure 1(c) highlights our discovery of the unusual LL pinning (or near-pinning, see Fig. 1(b)) and the correlated  = 1 QHS in 2DHSs [3]. It shows the longitudinal (Rxx) and Hall (Rxy) magneto-resistance traces measured from a 2DHS confined to a 40-nm-wide GaAs QW at p ≈ 1.28 × 1011 cm-2 and  ≈ 35°.

At lower and higher  (data not shown here), the  = 1 QHS is strong (excitation gap  ≥ 10 K) and fractional QHSs appear at  = i/(2i ± 1) fillings (i > 0 is an integer). The Fig. 1(c) data, however, are similar to what is seen in bilayer 2DESs with extremely small energy separation between the lowest two LLs, and thus are consistent with a LL crossing occurring near  ≈ 35°. The  = 1 QHS becomes unusually weak ( ≈ 0.2 K), and strong QHSs develop at the even numerator fillings  =4/3, 6/5, 6/7, and 4/5. This implies that these are two-component QHSs, each component having half of the total filling. In Fig. 1(c) we also observe QHSs at very unusual fillings such as  = 19/15 and 29/35. Such states were only seen when the two lowest-energy LLs are nearly degenerate, and were interpreted as “imbalanced” two-component QHSs: for example, the  = 19/15 QHS has fillings 2/3 and 3/5 for its two components.



**Fig. 1:** (a) Experimental setup. (b) Schematic diagram, showing the crossing of the two lowest-energy Landau levels at  ≈ 35° near  = 1. (c) Longitudinal (Rxx) and Hall (Rxy) resistances measured in a 40-nm-wide QW at 2D hole density *p* ≈ 1.28 × 1011 cm-2.

We perform extensive studies on this unusual LL crossing and the stability of the  = 1 QHS at the crossing, and find that:

1) The two lowest-energy LLs can only cross when the 2DHS is confined in wide, symmetric QWs and its density is large.

2) The crossing, if it happens, is always seen near a magic angle  ≈ 35°, which is independent of the 2DHS density, the QW well-width and the filling factors.

2) At the crossing, the  = 1 QHS turns into a compressible Fermi sea if the density and well-width are very large.

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**References**

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