# Unusual Landau level pinning and correlated $\nu=1$ quantum Hall effect in hole systems confined to wide GaAs quantum wells

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# Unusual Landau Level Pinning and Correlated $\nu = 1$ Quantum Hall Effect in Hole Systems Confined to Wide GaAs Quantum Wells

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In two-dimensional hole systems confined to wide GaAs quantum wells, where the heavy- and light- hole states are close in energy, we observe a very unusual crossing of the lowest two Landau levels as the sample is tilted in magnetic field. At a magic tilt angle $\theta \simeq 34^\circ$, which surprisingly is independent of the well-width or hole density, in a large filling factor range near $\nu = 1$ the lowest two levels are nearly degenerate as evinced by the presence of two-component quantum Hall states. Remarkably, a quantum Hall state is seen at $\nu = 1$, consistent with a *correlated* $\Psi_{111}$ state.

Among the most fascinating phases of two-dimensional electron systems (2DESs) in a strong perpendicular magnetic field ($B_\perp$) are the quantum Hall states (QHSs). These are incompressible phases signaled by vanishing longitudinal resistance ($R_{xx}$) and quantized Hall resistance ($R_{xy}$), and are observed at integral or certain fractional Landau level (LL) filling factors ($\nu$) [1–3]. Adding a layer (or subband) degree of freedom leads to exciting twists. A bilayer electron system with nearly degenerate LLs from different subbands and comparable inter- and intra-layer interaction can support new, two-component (2C) QHSs that have no counterpart in standard single-layer (or one-component, 1C) 2DESs. An example is the $\Psi_{331}$ state, a QHS formed at the *even-denominator* filling $\nu = 1/2$ [4–7]. The correlated $\Psi_{111}$ QHS, stabilized at $\nu = 1$, is another example [5, 8–12]. This state is generally considered to be an excitonic superfluid which can support Josephson-like interlayer tunneling and superfluid transport.

Recent experimental studies of 2D *hole* systems (2DHSs) confined to wide GaAs quantum wells (QWs) have unraveled unique phenomena, arising from the non-trivial spin-orbit coupling of the heavy- and light-holes. Graninger *et al.* reported a reentrant behavior of the $\nu = 1$ QHS as a function of parallel magnetic field $B_{||}$ in symmetric, wide QWs [13]. Later, Liu *et al.* observed an unusual crossing of the two lowest-energy LLs at $B_{||} = 0$ as a function of $B_\perp$ [14]. For a given density ($p$) and well-width ($W$), the crossing occurs at a particular filling (Fig. 1(a)); it destroys or weakens the odd-denominator QHSs near this filling, and stabilizes a unique even-denominator QHS when it happens at $\nu = 1/2$ [14].

Here we present low-temperature transport data for 2DHSs confined to symmetric, wide GaAs QWs, as we change the tilt angle ($\theta$) between the sample normal and the magnetic field direction. We find that at low and high $\theta$, if $W$ and $p$ are sufficiently large, LLs from different subbands are well separated from each other and the 2DHSs exhibit normal QHSs at the *standard* fillings $\nu$ = 2/3, 1, 4/3, 7/5, 8/5 and 5/3. But near an intermediate $\theta$, the 2DHSs exhibit 2C QHSs similar to those reported in bilayer 2DESs with vanishing subband separation [15]. This observation indicates that the two lowest-energy LLs are nearly degenerate and is consistent with a $B_{||}$-induced LL crossing [16]. Remarkably, as schematically shown in Fig. 1(b), this near degeneracy persists in a *large magnetic field range* near $\nu = 1$ when $\theta \simeq 34^\circ$, a magic angle which does not depend on $W$ or $p$. Moreover, when the two LLs are degenerate, the 2DHS is compressible at $\nu = 1$ if $p$ and $W$ are large so that $d/l_B \gtrsim 1.3$, but exhibits a QHS when $d/l_B \lesssim 1.3$, consistent with the development of a correlated 2C ($\Psi_{111}$) state ($d$ is the interlayer separation and $l_B$ is the magnetic length) [8, 12, 17].

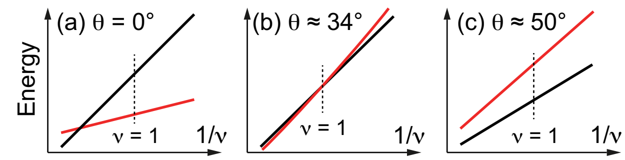


FIG. 1. Schematic diagram of the lowest two LLs at different tilt angles ($\theta$).

Our samples, grown by molecular beam epitaxy on GaAs (001) wafers, consist of GaAs QWs flanked by undoped $Al_{0.3}Ga_{0.7}As$ spacer and carbon $\delta$-doped layers. The 2DHSs have as-grown densities ranging from 0.98 to 2.12, in units of $10^{11}$ cm$^{-2}$ which we use throughout this report, and very high low-temperature mobilities $\mu \geq 100$ m$^2$/Vs. We made samples in a van der Pauw geometry, $4 \times 4$ mm$^2$, and alloyed In:Zn contacts at their four corners. Each sample is fitted with an evaporated Ti/Au front-gate and an In back-gate to control the 2DHS density and QW symmetry. The data presented here were taken in symmetric QWs. The transport measurements were carried out in a dilution refrigerator with a base temperature of $T \approx 30$ mK and a superconducting magnet up to 18 T. We changed $\theta$ with an in-situ rotator, and used low-frequency ($\sim 30$ Hz) lock-in technique. Here we focus primarily on $R_{xx}$ traces; the $R_{xy}$ data corroborate $R_{xx}$ and show corresponding plateaus.

We first describe data taken in a 2DHS confined to a 40-nm-wide QW as a function of density at $\theta = 0^\circ$. In Fig. 2, the QHS transitions (marked by solid circles)

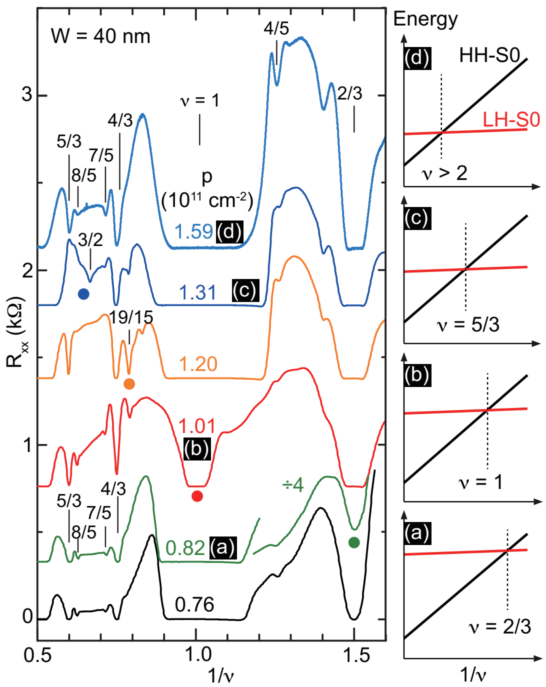


FIG. 2. $R_{xx}$ traces measured in a 2DHS confined to a 40-nm-QW at $\theta = 0$ and different densities. Right panels show schematically the two lowest-energy LLs' energy vs $1/\nu$ at different densities, corresponding to the traces as marked.

which appear when two LLs are nearly degenerate, can be seen moving from low to high $\nu$ as we increase $p$. At $p = 0.76$, we observe QHSs at the standard fillings, similar to what is seen in systems where LLs from different subbands are well-separated [3]. The $\nu = 2/3$ QHS becomes weak at $p = 0.82$ but is restored at higher $p$. The weakening of the $\nu = 1$ QHS at $p \simeq 1.01$ is evidenced by a profound narrowing of its $R_{xx}$ plateau, and serves as direct evidence that the two lowest-energy LLs are crossing at $\nu = 1$ [18–22]. At $p = 1.20$, a strong $\nu = 1$ QHS is restored, and a 2C QHS develops at an unusual filling $\nu = 19/15$ [15, 23]. The transition continues moving to higher $\nu$ at $p = 1.31$. The $\nu = 5/3$ QHS disappears and another 2C QHS develops at $\nu = 3/2$, which is the particle-hole counterpart of the 2C $\nu = 1/2$ ($\Psi_{331}$) QHS [6]. In the top trace ($p = 1.59$), the 2DHS reverts back to 1C for $\nu < 2$, exhibiting QHSs at standard fillings. The above evolution of the QHSs, which implies a LL crossing that moves from low $\nu$ to high $\nu$ as density is increased, is consistent with previous observations and theoretical calculations [14].

The above LL crossing can be qualitatively understood in a simplified picture (see the right panels in Fig. (2)). When confined to QWs, because of their heavier mass in the $z$-direction, the heavy-hole (HH) subband is lower in energy than the light-hole (LH) subband. But the HHs have a smaller effective mass in the $xy$-plane than the LHs, so the ground-state ($N = 0$) LL of the HH symmetric subband, which we refer to as HH-S0 for simplicity, increases faster in energy than the LH-S0 LL as we sufficiently increase $B_\perp$, leading to a LL crossing. In a more quantitative picture, the spin-orbit coupling mixes the HH and LH subbands and LLs, and results in a more complex, non-linear LL fan diagram. However, the crossing between the two lowest-energy LLs is preserved in symmetric QWs [14]. In our wide QW samples, the HH and LH subbands are close in energy, so the two levels cross at moderate $B_\perp$.

Data presented in Fig. 3 reveal that QHS transitions can also be induced at a fixed density by varying $\theta$, but the behavior is dramatically different. In Fig. 3(c), we show $R_{xx}$ vs $B_\perp$ traces measured at $p = 2.05$ and different $\theta$. The density is high so that the LH-S0 LL is well below the HH-S0 LL at $\theta = 0°$ in the range $\nu < 2$ (see Fig. 2(d)), and the 2DHS exhibits 1C QHSs at standard fillings. At $\theta \simeq 34°$, the 2DHS becomes 2C in a large range of fillings $2/3 < \nu < 2$. This is evinced by the development of insulating phases around $\nu = 2/3$ (i.e., around $\nu = 1/3$ for each component [24]), the complete disappearance of the QHSs at $\nu = 5/3$ and 1, as well as the stabilization of QHSs at twice the standard fillings $\nu = 4/3$, 6/5, 6/7, 2/3, and at unusual fillings such as $\nu = 19/15$ and 29/35 [15, 23]. At larger $\theta$, the $\nu = 1$ and 5/3 QHSs reappear while many 2C QHSs remain, suggesting the two lowest-energy LLs are separated by a small but finite energy [25].

Figure 3(d) data taken at $p = 1.59$ exhibit a more complete and revealing evolution. The system is essentially 1C for $\theta \lesssim 20°$ and $\theta \gtrsim 44°$, showing strong QHSs at standard fillings [25]. It becomes 2C for $\nu < 2$ when $25° \lesssim \theta \lesssim 44°$, exhibiting insulating phases flanking $\nu = 2/3$ and 2C QHSs at $\nu = 19/5$, 6/5, 29/35, etc., while QHSs at $\nu = 1$ and 5/3 become weak and essentially disappear as $\theta$ approaches 34°.

Figure 3(e) shows traces taken at $p = 1.28$ where, at $\theta = 0$, the LL crossing occurs near $\nu = 3/2$, as evidenced by the stabilization of the correlated, 2C QHS at $\nu = 3/2$, and the absence of a QHS at $\nu = 5/3$. Similar to the data of Figs. 3(c) and (d), the system becomes 2C near $\theta \simeq 34°$ and 1C when $\theta \gtrsim 49°$. However, in contrast to Figs. 3(c) and (d) data, the $\nu = 1$ QHS becomes weak at $\theta = 34°$ but never disappears. The fact that the system is 2C near $\nu = 1$ suggests that the $\nu = 1$ QHS seen at $\theta \simeq 34°$ in Fig. 3(d) is also a 2C QHS; we will return to this later.

The transition from 1C to 2C as a function of increasing $B_{||}$ has been reported previously for *electrons* confined to wide GaAs QWs [15, 26]. In such systems, the coupling of $B_{||}$ to the orbital (out-of-plane) motion of electrons renders the system progressively more bilayer-like at higher $B_{||}$ and quenches the energy separation between the $N = 0$ LLs of the symmetric and anti-symmetric subbands, making them essentially degenerate [15, 26]. Further increasing $B_{||}$ does not lift this degener-

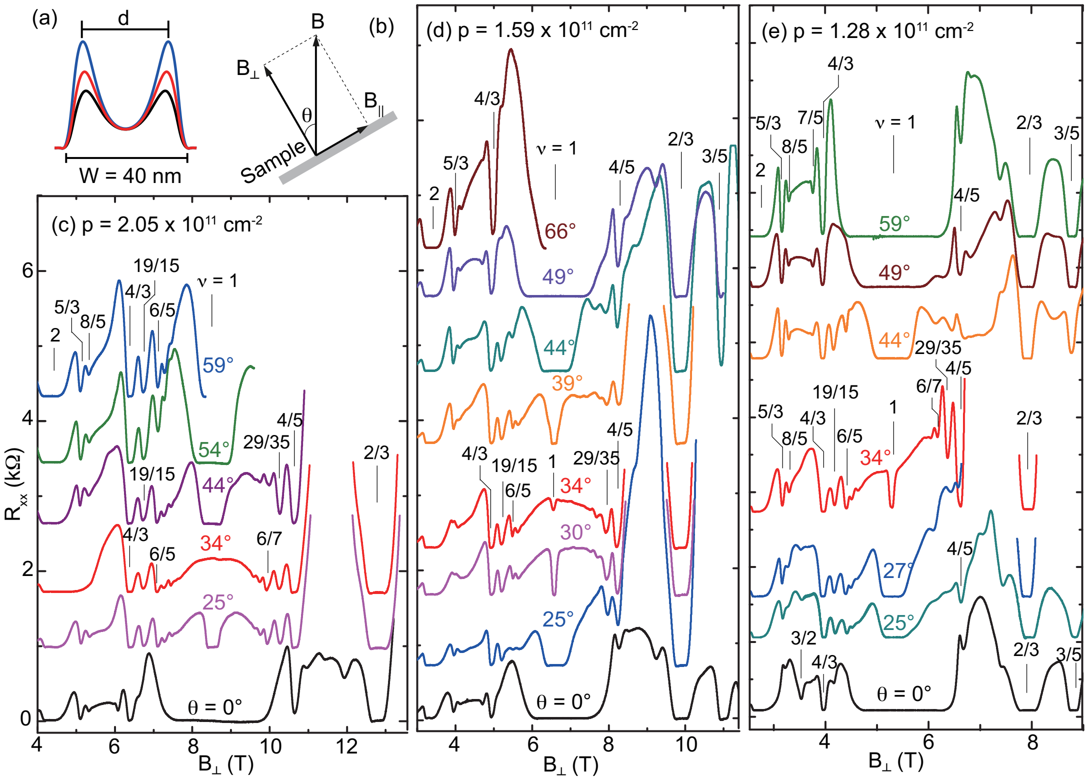


FIG. 3. (a) Self-consistently calculated charge distribution of the 2DHS confined to the 40-nm-wide QW at densities $p = 2.05$, 1.59 and 1.28. (b) Experimental geometry. (c)-(e) $R_{xx}$ vs $B_\perp$ traces measured at different $\theta$. In all panels, the QHS at $\nu = 1$ is strong at $\theta = 0$, disappears or weakens at $\theta \simeq 34°$, and becomes strong again at larger $\theta$.

acy and the system remains 2C at the highest $B_{||}$. This is very different from our data shown in Figs. 3(d) and (e), where the 2DHS near $\nu = 1$ becomes 2C only near $\theta \simeq 34°$, but is 1C at smaller and *higher* $B_{||}$.

We attribute the evolution in Fig. 3 data to a $B_{||}$-induced LL crossing [13, 27, 28]. Unfortunately, no accurate calculations of LLs in the presence of both $B_\perp$ and $B_{||}$ are available, particularly for 2DHSs with multiband structure. The tilted-field geometry implies complicated couplings between Landau harmonic oscillators from different subbands, and makes numerical calculations extremely demanding. Qualitatively, we can explain the crossing as follows. The densities of Fig. 3 data are sufficiently large so that the LH-S0 level is lower than the HH-S0 level near $\nu = 1$ at $B_{||} = 0$ (Figs. 2(c) and (d)). Finite $B_{||}$ introduces additional confinement of the 2DHS in the $z$-direction, raises the LH-S0 LL relative to the HH-S0 LL, and causes a crossing of these levels at intermediate $\theta$ (see Fig. 4(d)).

The most remarkable feature of Fig. 3 data, however, is not the LL crossing at an intermediate $\theta$. Rather, it is the behavior of the 2DHS near the crossing angle, suggesting a very unusual "pinning" of the LLs in a very large range of $\nu$ (Fig. 1(b)). Note in Fig. 3 that at a given density the system exhibits 2C behavior in the entire range of $\nu < 4/3$ at $\theta \simeq 34°$. This is very different from the $\theta = 0$ data of Fig. 2 where the LL crossing features for any given density appear near a specific $\nu$ which moves from low to high values as the density is increased. Moreover, in Fig. 3 the angle $\theta \simeq 34°$ at which the 2DHS becomes 2C appears to be independent of the 2DHS density. In other 2DHS samples, confined to QWs with $W$ ranging from 35 to 50 nm, we have observed similar phenomena as in Fig. 3 at the same $\theta \simeq 34°$. This independence of the 2C behavior on $\nu$, $p$, and $W$ at this critical angle is astonishing, and demands a theoretical explanation.

The evolution of the QHS at $\nu = 1$ is also very intriguing. As seen in Fig. 3, it disappears completely at $\theta \simeq 34°$ when $p = 2.05$ but only becomes weak at $p = 1.28$. In Fig. 4(a) we summarize our results for many 2DHSs, illustrating the conditions for the stability of the $\nu = 1$ QHS. Data are shown as a function of $\theta$ and $d/l_B$, which compares the interlayer ($e^2/4\pi\epsilon d$) and intra-layer ($e^2/4\pi\epsilon l_B$) correlations and is widely used to characterize bilayer QHSs [8–12, 17, 29, 30]. Figure 4(a) shows that no LL crossing at $\nu = 1$ can be induced via tilting if $d/l_B \lesssim 1.0$, and the $\nu = 1$ QHS is always strong. When $d/l_B \gtrsim 1.0$, at $\nu = 1$, the LH-S0 level is lower than the HH-S0 level at $\theta = 0$, and the two levels cross at $\theta \simeq 34°$; see Fig. 4(d). At the crossing, we observe a QHS at $\nu = 1$ if $d/l_B \lesssim 1.3$, and the ground state becomes compressible if $d/l_B \gtrsim 1.3$. The $d/l_B \lesssim 1.3$ condition for the

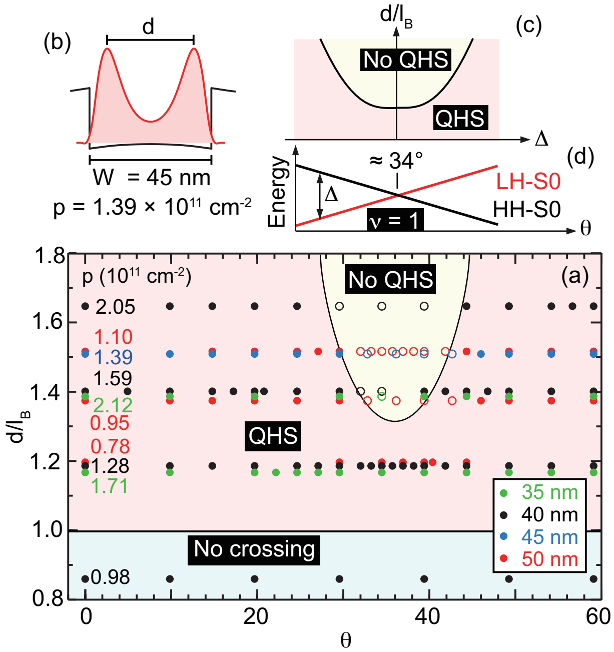


FIG. 4. (a) Phase diagram for the stability of QHS at $\nu = 1$ as a function of the tilting angle $\theta$ and $d/l_B$. The solid (open) symbols mark the presence (absence) of a QHS at $\nu = 1$. In narrow QWs and at low density, no crossing is seen as a function of $\theta$, shown as the blue region. Once $d/l_B \gtrsim 1.0$, a crossing occurs near $\theta \simeq 34°$. At the crossing, a QHS appears at $\nu = 1$ if $d/l_B \lesssim 1.3$, consistent with the $\Psi_{111}$ state. (b) Calculated charge distribution for a 45-nm-wide QW with $p = 1.39$ showing the interlayer distance $d$. (c)-(d) Schematic phase and LL diagrams at $\nu = 1$ showing how the LL separation $\Delta$ increases as $\theta$ deviates from $\simeq 34°$.

stability of the $\nu = 1$ QHS at the crossing, and the fact that the 2DHS is 2C at nearby fillings, suggest that it is a 2C QHS with strong interlayer correlations, likely the $\Psi_{111}$ state reported in GaAs bilayer electron [8–10, 12] or hole [11, 17] systems confined to double QWs. In those systems, when the lowest LLs from different subbands are degenerate, the $\nu = 1$ QHS is stable at $d/l_B \lesssim 2$, and turns into a compressible state if $d/l_B$ becomes large [8, 12]. Also note that in our experiments the energy separation between the two crossing LLs increases as $\theta$ deviates from $\simeq 34°$ (see Fig. 4(d)). We show in Fig. 4(c) a schematic "phase diagram" for the stability of the $\nu = 1$ QHS as functions of $\Delta$ and $d/l_B$. The resemblance of Fig. 4(c) and the phase diagram of $\nu = 1$ QHS in double QWs [8, 12] is striking. We emphasize that in our experiments, we are essentially tuning $\Delta$ through zero as we tilt the sample near $\theta \simeq 34°$; see Figs. 4(d).

In conclusion, 2DHSs confined to wide GaAs QWs and with sufficiently high density, reveal an unusual crossing of the two lowest-energy LLs near $\nu = 1$ as we tilt the sample in magnetic field. It appears at a magic angle $\theta \simeq 34°$, essentially independent of the QW width, density, or $B_\perp$ (filling), suggesting a pinning of the LLs near the crossing. The crossing and the pinning likely stem from the complex interplay of the heavy- and light-hole LLs in $B_{||}$, and should stimulate further theoretical investigation. Near this angle, the 2DHS becomes 2C at $\nu < 2$ and, if $d/l_B$ is small, exhibits a $\nu = 1$ QHS, consistent with a correlated, 2C, $\Psi_{111}$ state.

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