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Even-Denominator Fractional Quantum Hall State at Filling Factor $\nu = 3/4$

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Fractional quantum Hall states (FQHSs) exemplify exotic phases of low-disorder two-dimensional (2D) electron systems when electron-electron interaction dominates over the thermal and kinetic energies. Particularly intriguing among the FQHSs are those observed at even-denominator Landau level filling factors, as their quasiparticles are generally believed to obey non-Abelian statistics and be of potential use in topological quantum computing. Such states, however, are very rare and fragile, and are typically observed in the excited Landau level of 2D electron systems with the lowest amount of disorder. Here we report the observation of a new and unexpected even-denominator FQHS at filling factor $\nu = 3/4$ in a GaAs 2D *hole* system with an exceptionally high quality (mobility). Our magnetotransport measurements reveal a strong minimum in the longitudinal resistance at $\nu = 3/4$, accompanied by a developing Hall plateau centered at $(h/e^2)/(3/4)$. This even-denominator FQHS is very unusual as it is observed in the *lowest* Landau level and in a 2D *hole* system. While its origin is unclear, it is likely a non-Abelian state, emerging from the residual interaction between composite fermions.

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Since its discovery in 1982 [1], the fractional quantum Hall effect has been one of the most active topics in condensed matter physics [2]. It is observed in low-disorder two-dimensional electron systems (2DESs) at low temperatures and large, quantizing, perpendicular magnetic fields, when electrons' thermal and kinetic energies are quenched and the Coulomb interaction between the electrons dominates. The vast majority of fractional quantum Hall states (FQHSs) are observed in the lowest Landau level (LL) at *odd-denominator* LL filling factors, and can be mostly understood in a standard composite fermion (CF) model [2–5]. By attaching $2m$ flux quanta to each electron, the FQHSs at $\nu = p/(2mp \pm 1)$, the so-called Jain-sequence states, can be mapped to the integer quantum Hall states at the Lambda level (ΛL) filling factor p of the weakly interacting $2m$-flux CFs (^{2m}CFs).

Thanks to intense experimental efforts over the last few decades and improvements in sample quality (mobility), new FQHSs which cannot be explained in the standard Jain sequence have been reported [2,6–25]. Among these are FQHSs observed at certain *even-denominator* fillings, e.g., at $\nu = 5/2$ [6]. Although its origin is not yet entirely clear, theory [26–28] strongly suggests that the $\nu = 5/2$ FQHS is a spin-polarized, p-wave paired (Pfaffian) state with non-Abelian statistics, rendering it a prime candidate for fault-tolerant, topological quantum computing [29]. Even-denominator FQHSs have also been reported at other filling factors, e.g., at $\nu = 1/2$ and $1/4$ in wide GaAs quantum wells [8,10,14,16,17,19–21,24,25]. The origin of these states is also unclear: some experimental and theoretical results are consistent with these being two-component, Halperin-Laughlin, Abelian states [10,16,19,30], although the latest data and calculations suggest a one-component, Pfaffian, non-Abelian origin [17,25,31–33].

Here we present the experimental observation of an even-denominator FQHS in the lowest LL, at filling factor $\nu = 3/4$, in an ultrahigh-quality GaAs 2D *hole* system (2DHS). As highlighted in Fig. 1(a), our magnetotransport measurements show a strong minimum in the longitudinal resistance (R_{xx}), concomitant with a developing Hall resistance (R_{xy}) plateau centered at $(h/e^2)/(3/4)$ to within 0.2%. Our finding is unexpected as there is no analogue of such a FQHS in GaAs 2DESs [Fig. 1(b)] [34] where the ground state at $\nu = 3/4$ is a ^{4}CF Fermi sea, flanked by odd-denominator FQHSs at nearby fillings ($4/5, \ldots, 5/7$) which fit into the Jain sequence: $\nu = 1 - p/(4p \pm 1)$. In our experiments, we find that the $\nu = 3/4$ FQHS is fairly robust when a strong in-plane magnetic field is applied, but it eventually gets weaker, with FQHSs at $\nu = 4/5$ and $5/7$ emerging on its flanks. We discuss the possible origins of this novel FQHS based on our experimental data and available theories, and suggest that it is likely a non-Abelian state. We also observe a qualitatively similar, but somewhat weaker, FQHS at the even-denominator filling $\nu = 3/8$, with likely same origin as $3/4$.

The high-quality 2DHS studied here is confined to a 20-nm-wide GaAs quantum well grown on a GaAs (001) substrate [35–40]. The 2DHS has a hole density of

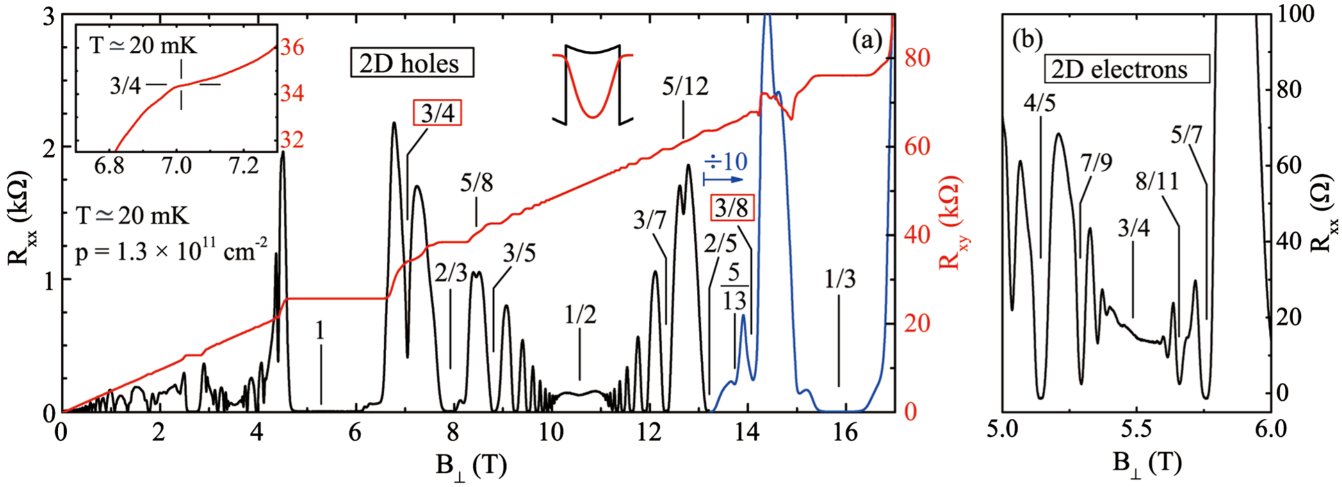

FIG. 1. (a) Longitudinal resistance (R_{xx}, in black and blue) and Hall resistance (R_{xy}, in red) vs perpendicular magnetic field $B_\perp$ traces for our ultrahigh-mobility 2D hole sample. The height of the blue trace is divided by a factor of 10. The $B_\perp$ positions of several LL fillings are marked. A strong minimum in R_{xx} accompanied by a developing Hall plateau is observed at $\nu = 3/4$. An enlarged version of the R_{xy} vs $B_\perp$ near $\nu = 3/4$ at 20 mK is shown in the top-left inset. The self-consistently calculated hole charge distribution (red) and potential (black) of the 2DHS are also shown in a top inset. (b) R_{xx} vs $B_\perp$ at $T \simeq 30$ mK near $\nu = 3/4$ for an ultrahigh-mobility 2D *electron* sample with density 1.0×10^{11} cm^{-2} from Ref. [34].

1.3×10^{11} cm^{-2} and a low-temperature (0.3 K) record-high mobility of 5.8×10^6 cm^2/Vs [36]. We performed our experiments on a 4 mm × 4 mm van der Pauw geometry sample. Ohmic contacts were made by placing In/Zn at the sample's four corners and side midpoints, and annealing at 450 °C for 4 min. The sample was then cooled down in two different dilution refrigerators with base temperatures of ≃ 20 mK. We measured R_{xx} and R_{xy} using the conventional lock-in amplifier technique, with a low-frequency (≃ 13 Hz) excitation current of ≃ 10 nA.

Figure 1(a) shows the full-field traces of R_{xx} and R_{xy} vs perpendicular magnetic field $B_\perp$ [41]. The $B_\perp$ positions of several LL fillings are marked. A deep minimum in R_{xx} accompanied by a developing R_{xy} plateau is observed at $\nu = 3/4$. Weaker R_{xx} minima are also observed at other even-denominator fillings $\nu = 3/8$, as well as 5/8 and 5/12. Numerous high-order odd-denominator FQHSs are also seen near $\nu = 1/2$, up to $\nu = 12/25$ and 13/25, and near $\nu = 3/2$, up to $\nu = 16/11$ and 17/11 (not marked in the figure; see Fig. 4 of [36]). These attest to the exceptionally high quality of the 2DHS. Note that the $\nu = 3/4$ FQHS is the only FQHS observed between $\nu = 1$ and 2/3. This is in sharp contrast to what is observed in high-quality 2DESs, namely, a smooth and shallow R_{xx} minimum with no quantized R_{xy}, and flanked by the standard (Jain-sequence) odd-denominator FQHSs such as $\nu = 4/5$, 7/9, … and 5/7, 8/11, … [see Fig. 1(b)] [34]. It is also in contrast to previous GaAs 2DHSs where, between $\nu = 1$ and 2/3, only weakly developed FQHSs were observed at $\nu = 4/5$ and 5/7 [42,43]. We also studied another 2D hole sample with higher density, showing weak R_{xx} minima at both $\nu = 3/4$ and 5/7; See Supplemental Material (SM) [35] for details.

In Fig. 2 we show the temperature (T) dependence of R_{xx} and R_{xy} between $\nu = 1$ and $\nu = 2/3$, measured with a different contact configuration and in a different cool down. When T is reduced, the R_{xx} minimum becomes smaller but its flanks rise steeply, as seen in Fig. 2(a). In Fig. 2(b), we show an Arrhenius plot of R_{xx} at $\nu = 3/4$. The activated behavior of R_{xx} strongly suggests a FQHS at $\nu = 3/4$. An energy gap of ≃ 22 mK is deduced from the linear fit to the data points at intermediate temperatures. We note that the temperature range where R_{xx} at $\nu = 3/4$ vs $1/T$ follows a linear fit is very narrow. On the low-temperature (large $1/T$) side, the data points start to deviate from the linear fit below ≃ 30 mK. Several factors could be causing this deviation: (i) At very low T, the 2DHS temperature might be slightly higher than T read by the thermometer; (ii) R_{xx} at $\nu = 3/4$ could be influenced by the rising background on its flanks at very low T [Fig. 2(a)]; (iii) it is also possible that the deviation is caused by the emergence of a different scattering mechanism (e.g., hopping) at very low temperatures [44]. On the high-temperature (small $1/T$) side, the temperature dependence of R_{xx} reverses its trend, and R_{xx} decreases with increasing temperature above 130 mK. A similar phenomenon was observed for other FQHSs [23], and can be attributed to a decreasing background R_{xx} at high temperatures. While the very narrow T range in which we observe an activated behavior in Fig. 2(b) limits the accuracy of the ≃ 22 mK energy gap that we determine for the $\nu = 3/4$ FQHS, it is likely that this value is an underestimate and is influenced by the strong temperature dependence of R_{xx} on the flanks of $\nu = 3/4$. The fact that the $\nu = 3/4$ R_{xx} minimum survives at high temperatures (up to 188 mK) supports this conjecture.

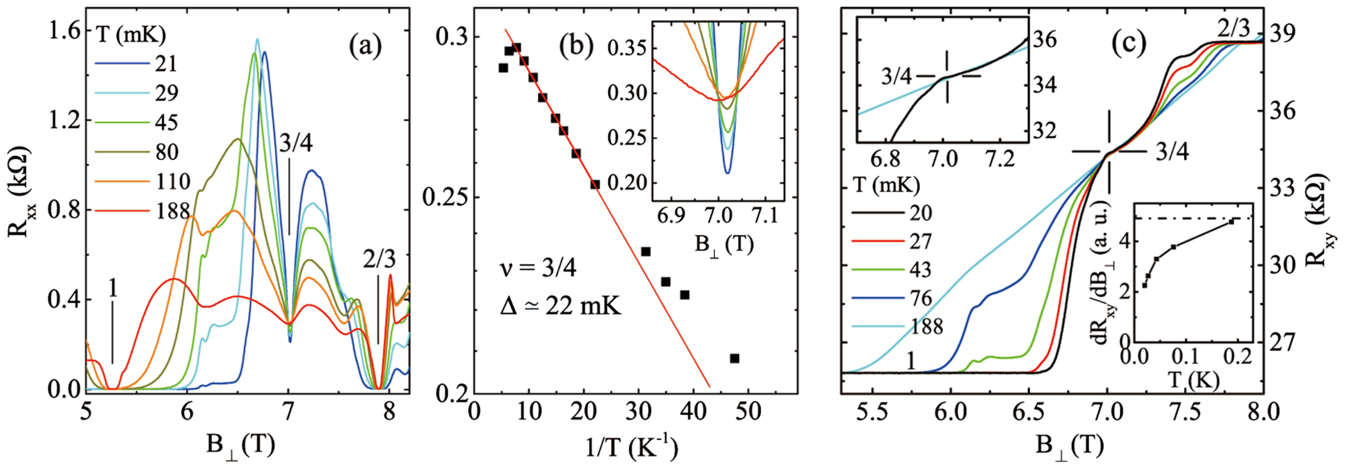

FIG. 2. Temperature dependence of R_{xx} and R_{xy}. (a) R_{xx} vs $B_\perp$ traces near $\nu = 3/4$, taken at different temperatures, showing fully developed (nearly zero) R_{xx} minima at $\nu = 1$ and $2/3$, as well as a strong minimum at $\nu = 3/4$. (b) Arrhenius plot of R_{xx} at $\nu = 3/4$. An energy gap of $\simeq 22$ mK is obtained from the linear fit to the data points at intermediate temperatures. Inset: enlarged version of Fig. 2(a) near $\nu = 3/4$. (c) Hall (R_{xy}) traces taken at different temperatures. R_{xy} is well quantized at its expected value at $\nu = 1$ and $2/3$ in the whole temperature range, and shows a developing plateau at $\nu = 3/4$ at the lowest temperatures. Top-left inset: enlarged R_{xy} vs $B_\perp$ traces near $\nu = 3/4$ at $T \simeq 20$ and 188 mK. Bottom-right inset: Hall resistance slope $dR_{xy}/dB_\perp$ vs T at $\nu = 3/4$, showing its approach to the expected (classical) value at high T (the dash-dotted line), and to zero as T approaches zero, confirming the R_{xy} quantization.

To further support the presence of a FQHS at $\nu = 3/4$, in Fig. 2(c) we show Hall traces taken at different T. R_{xy} is well quantized at the expected values at $\nu = 1$ and $2/3$ over the whole temperature range, and shows a nearly quantized plateau at $\nu = 3/4$ at the lowest temperature ($\simeq 20$ mK). The top-left inset of Fig. 2(c) shows an enlarged view of R_{xy} vs $B_\perp$ near $\nu = 3/4$ at $T \simeq 20$ and 188 mK. At $\simeq 20$ mK, a plateau occurs at exactly the expected field position of $\nu = 3/4$ and is centered at $R_{xy} = (h/e^2)/(3/4)$ to within 0.2%. The bottom-right inset of Fig. 2(c) shows the Hall resistance slope $dR_{xy}/dB_\perp$ vs T at $\nu = 3/4$. The dash-dotted line represents the expected, classical, high-temperature Hall slope based on the 2DHS density. At low temperatures, $dR_{xy}/dB_\perp$ exhibits a trend towards zero, consistent with a developing R_{xy} plateau.

Next we study the role of an in-plane magnetic field ($B_\parallel$) on the $\nu = 3/4$ FQHS. Figure 3 shows the tilt angle (θ) dependence of R_{xx} vs $B_\perp$ between $\nu = 1$ and $\nu = 2/3$ at $\simeq 20$ mK where θ denotes the angle between total field (B) and its perpendicular component ($B_\perp$); see the top-left inset in Fig. 3. The R_{xx} minimum at $\nu = 3/4$ remains fairly strong up to $\theta \simeq 60°$. With further increase in θ, the 3/4 FQHS becomes significantly weaker, while a FQHS at $\nu = 4/5$ starts to appear and get stronger; see also Fig. 3 top-right inset. A hint of a FQHS at $\nu = 5/7$ is also observed at large θ, but does not change much with increasing θ. The simultaneous weakening of the FQHS at 3/4 and appearance of the 4/5 and 5/7 FQHSs imply a competition between these states. The origin of this competition is unclear.

Our observation of a $\nu = 3/4$ FQHS is unexpected as no such state has been previously seen in experiments or predicted by theory. While a plethora of odd-denominator FQHSs are observed when the Fermi level lies in the lowest ($N = 0$) LL, even-denominator FQHSs in single-layer

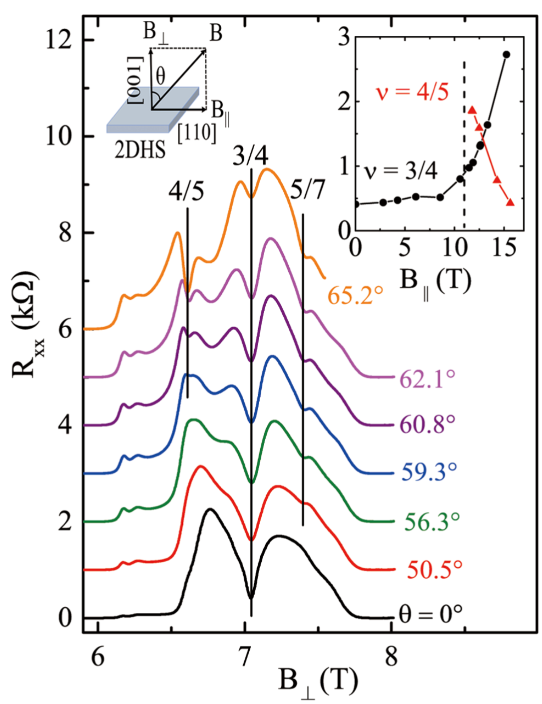

FIG. 3. Tilt angle dependence of R_{xx} is shown vs $B_\perp$ at 20 mK. The left inset shows a schematic of the experimental setup for applying tilted fields; the sample is mounted on a rotating stage to support *in situ* tilt. The traces are vertically shifted for clarity. The vertical lines indicate the $B_\perp$ positions for $\nu = 3/4$, 4/5, and 5/7. The right inset shows R_{xx} vs $B_\parallel$ at $\nu = 3/4$ (black circles) and 4/5 (red triangles).

2DESs confined to different materials such as GaAs [6], ZnO [45], and AlAs [46] have been predominantly reported only in the excited ($N = 1$) LL. In the $N = 0$ LL, in the CF picture and assuming that particle-hole symmetry holds, the ground states at $\nu = 3/4$ and $1/4$ are both expected to be Fermi seas of ^{4}CFs. In experiments on GaAs 2DESs, a ^{4}CF Fermi sea has indeed been directly observed by geometric resonance near $\nu = 1/4$ [47], and a series of standard (Jain-sequence), odd-denominator FQHSs is seen on the flanks of $\nu = 1/4$. A similar sequence of FQHSs is also observed near $\nu = 3/4$ in GaAs 2DESs [see Fig. 1(b)] [12,34], supporting a ^{4}CF Fermi sea ground state. However, in our 2DHS, a CF Fermi sea is not favored at $\nu = 3/4$ as evinced by the presence of a FQHS at this filling. The obvious question is: Why is the 3/4 FQHS observed in our GaAs 2DHS and in the lowest ($N = 0$) LL? While we do not have a definitive answer, we discuss below possible explanations.

An unlikely possibility is that the $\nu = 3/4$ FQHS in our experiments has an origin similar to the FQHSs reported in the $N = 0$ LL of 2DESs in wide GaAs quantum wells at $\nu = 1/2$ [8,10,19,25] and $\nu = 1/4$ [14,16,17]. The origin of these states is in fact still unclear and the possibilities of both a two-component, Ψ_{331}, Halperin-Laughlin, Abelian state [10,16,19,30], and a single-component, Pfaffian, non-Abelian state [17,25,31–33] have been discussed. Regardless of their origin, these states have only been observed in 2DESs with *bilayerlike* charge distributions. They are also very sensitive to different parameters such as carrier density, quantum well width and symmetry [10,19], and magnetic field components [48]. In GaAs 2DHSs, $\nu = 1/2$ FQHSs are also seen but, again, only when the charge distribution is bilayerlike [20]. Our 20-nm-wide GaAs quantum well clearly has a single-layer charge distribution [see Fig. 1(a) inset], and a density well below where a $\nu = 1/2$ FQHS is expected based on the phase diagram of Ref. [20]. In GaAs 2DHSs, a $\nu = 1/2$ FQHS has also been reported when the two lowest-energy LLs cross [21]. As seen in the calculated LL diagram for our sample (see SM [35]), the crossings between the two lowest-energy LLs are far away from the position of $\nu = 3/4$, rendering the crossing origin unlikely. Furthermore, the 3/4 FQHS we observe is quite robust when a strong $B_{\|}$ is applied (Fig. 3). In contrast, the FQHS at $\nu = 1/2$ in Ref. [21] only appears in a limited range of tilt angles when the crossing occurs close to $\nu = 1/2$, and disappears very quickly away from the crossing.

A more likely origin for the emergence of a $\nu = 3/4$ FQHS in our 2DHS is the interaction between CFs, caused by the much larger effective mass of holes (compared to electrons) and the ensuing LL mixing. It is well known that CFs interact more strongly when the LL mixing is significant, and that the interaction can lead to unusual odd-denominator FQHSs that do not follow the standard Jain sequence [7,12,22,23,49–53], as well as a Bloch-like spontaneous spin polarization of CFs at low densities [54]. Theory in fact predicts that the CF interaction can lead to an even-denominator FQHS at $\nu = 3/8$ [55,56] by mapping this electron filling to the $p = 3/2$ effective CF Lambda level (ΛL) filling of parallel-spin ^{2}CFs. The CFs in the half-filled, excited ΛL capture two additional vortices to turn into ^{4}CFs and condense into a paired FQHS where a non-Abelian, anti-Pfaffian state is favored [56]. Note that this $p = 3/2$ FQHS would be formed in the excited ($N = 1$) ΛL of CFs, and be equivalent to the celebrated FQHS at $\nu = 5/2$ which occurs in the $N = 1$ LL of electrons. Experiments have also shown hints of a FQHS at $\nu = 3/8$ in GaAs 2DESs, although no conclusive evidence, e.g., a quantized R_{xy}, has been reported [12,18,34,57–59].

A qualitatively similar scenario can be applied to electrons at $\nu = 3/4$ as their filling can be mapped to $p = 3/2$ of *antiparallel* ^{2}CFs. [Antiparallel (parallel) here means that the magnetic flux quanta attached to electrons to form ^{2}CFs are opposite to (same as) the residual magnetic field felt by the ^{2}CFs]. We note that the $\nu = 3/4$ FQHS is spin-polarized, consistent with our observation that the $\nu = 3/4$ FQHS is quite robust against $B_{\|}$. Similar physics might also explain R_{xx} minima in our data at other even-denominator fillings ($\nu = 5/8$ and $5/12$) as they can also be interpreted by mapping onto $p = 5/2$ (antiparallel and parallel) ^{2}CFs, respectively. It is worth noting that in Ref. [56], the effect of LL mixing was not included, and calculations estimated the gap of the 3/8 FQHS to be 5 times smaller than the theoretical gap of the 5/2 FQHS for a given density. In our 2DHS, however, we see only a hint (weak minimum in R_{xx}) of a FQHS at $\nu = 5/2$, but much stronger R_{xx} minima at $\nu = 3/4$ and 3/8. LL mixing may play an important role in stabilizing the FQHSs at $\nu = 3/4$ and 3/8.

The unexpected $\nu = 3/4$ FQHS we observe in a GaAs 2DHS with ultrahigh mobility confirms yet again that the fabrication and availability of samples with unprecedentedly high quality go hand in hand with the discovery of new interaction phenomena. From this perspective, the GaAs 2D holes, with their large effective mass and unusual LL fan diagram, provide a particularly fruitful platform for exploring novel physics.

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