New Fractional Quantum Hall State in Double-Layer Two-Dimensional Electron Systems

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Transport studies on bilayer two-dimensional electron systems in GaAs double quantum wells have revealed a new fractional quantum Hall state that has no known counterpart in a single-layer 2D system. At total filling fraction $\nu=\frac{1}{2}$ we observe a deep minimum in the diagonal resistivity and a flat Hall plateau within 1.5% of $2h/e^2$. Studies of this new state in several samples with varying densities and layer separations strongly suggest this new state arises from interlayer Coulomb correlations. The data also suggest that the $\nu=1$ quantum Hall effect seen in these samples has a similar origin.

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In the standard model of the fractional quantum Hall effect (FQHE) the two-dimensional electron system (2DES) is treated as infinitely thin, fully spin polarized, and in an infinite magnetic field [1]. Intense experimental effort over the last several years has shown the FQHE to be of broader scope than these assumptions allow within the standard model. For example, recent work has revealed novel unpolarized spin configurations for certain FQHE states [2]. If the spin-flip energy is not too large, the 2DES can exploit the spin degree of freedom and form FQHE states not contained within the standard model. In particular, the only known [3] even-denominator FQHE in a conventional single-layer 2DES (at Landau-level filling fraction $\nu=\frac{5}{2}$) is thought to be an example of such an unpolarized state. By analogy, a *double-layer* 2DES possesses an extra degree of freedom, the layer index, that is expected [4–6] to give rise to new FQHE states not present in single-layer systems. For such new states to exist, interlayer electron-electron interactions must be comparable to the ordinary intralayer interactions. Since the length scale for the latter is the magnetic length $l_B=(\hbar/eB)^{1/2}$, the interlayer separation will need to be of this order as well. As typical FQHE studies have $l_B\sim100$ Å, significant fabrication problems attend the growth of such 2DES systems. In this paper we report the observation of a new FQHE state, at total filling factor $\nu=\frac{1}{2}$, in a double-layer 2DES and present evidence that it arises from an interplay of interlayer and intralayer Coulomb interactions.

Both the integer and fractional quantum Hall effects have been observed previously in double and multiple quantum well 2D systems [7]. For those structures where both interlayer tunneling and Coulomb interactions are negligible, and in which each layer contains the same electron density, the observed QHE states are identical to those observed with a single-layer 2DES. Defining the Landau-level filling fraction as $\nu=hN_{\rm tot}/eB$, with $N_{\rm tot}$ the *total* carrier density in the structure and B the magnetic field, a widely spaced double-layer system will exhibit only even-integer QHE states and fractional QHE states with even numerators. If, however, the layers are close enough to be coupled by tunneling or Coulomb effects, these restrictions are lifted. In particular, if the tunneling gap between the lowest-lying symmetric and antisymmetric states is resolved, then odd-integer QHE states are observed. We emphasize, however, that the single-particle tunneling gap itself cannot create *new* fractional states. In fact, for very strong tunneling the system becomes effectively a single layer (since only the lowest symmetric state is occupied) and both the integral and fractional QHE's assume their familiar spectra. Interlayer Coulomb interactions, however, can alter *both* the integral and fractional quantum Hall effects in a double-layer system. For example, Boebinger *et al.* [8] have observed a novel phase transition in which interlayer Coulomb interactions are observed to destroy the odd-integer QHE states arising from tunneling.

For these experiments a set of four modulation-doped GaAs/AlGaAs double quantum well (DQW) structures (see Table I) was grown by molecular-beam epitaxy (MBE). These samples were designed to have minimal tunneling (symmetric-antisymmetric gap $\Delta_{\rm SAS}\lesssim0.9$ K)

TABLE I. Sample parameters. $\Delta_{2/3}$ is the activation energy at filling factor $\nu=\frac{2}{3}$, d is the well center-to-center distance, and l_B is the magnetic length. Quantum well widths are 180 Å in all cases.

Sample	Barrier width (Å)	Density (10^{11} cm^{-2})	Mobility (10^6 cm^2/V s)	$\Delta_{2/3}$ (K)	d/l_B at $\nu=\frac{1}{2}$	Strength of $\nu=\frac{1}{2}$
A	31	1.04	0.5	1.7	2.4	Strongest
B	31	1.29	1.5	2.3	2.7	Strong
C	31	1.52	1.0	1.7	2.9	Weak
D	99	1.31	0.5	2.8	3.6	Absent

and yet still be coupled via Coulomb interactions. All samples contain two 180-Å-wide GaAs quantum wells separated by an undoped pure AlAs barrier layer. For samples *A*, *B*, and *C* this barrier is 31 Å wide, while for sample *D* it is 99 Å. For each sample Si δ-doping layers, placed on both sides of the DQW (in the alloy $Al_{0.15}Ga_{0.85}As$), were positioned so as to produce nearly equal 2D densities in each quantum well. While residual imbalances in the densities (as determined by low-field magnetotransport studies) were small, they could be removed almost entirely by illumination of the samples at low temperature with a red-light-emitting diode. Samples *A*, *B*, and *D* represent distinct MBE wafers while sample *C* was taken from the same wafer as sample *B*. Each sample was a 4×4 m square with diffused In contacts on each side and corner. Magnetotransport measurements were performed with a combination of pumped ^{3}He and dilution refrigerator cryostats with magnetic fields up to 15 T. Low-frequency (3-17 Hz) excitation currents between 5 and 100 nA were employed.

Figure 1 shows the diagonal resistivity ρ_{xx} and Hall resistivity ρ_{xy} for sample *A* at $T=150$ and 430 mK, respectively. Four quantum Hall states, both integral and fractional, are noted by their total filling fraction ν as defined above. As the figure shows, a new FQHE state, with the requisite deep minimum in ρ_{xx} and flat Hall plateau, is observed at filling fraction $\nu=\frac{1}{2}$. No such state has been observed in a single-layer 2DES.

The $\nu=\frac{1}{2}$ Hall plateau shown in Fig. 1 is about 1.4% below $\rho_{xy}=2h/e^2$. Different contact configurations for the ρ_{xy} measurement yield plateaus in slightly different positions, sometimes above and sometimes below $2h/e^2$. We attribute this lack of exact quantization to the large value of ρ_{xx} (comparable to ρ_{xy}) in the vicinity of $\nu=\frac{1}{2}$.

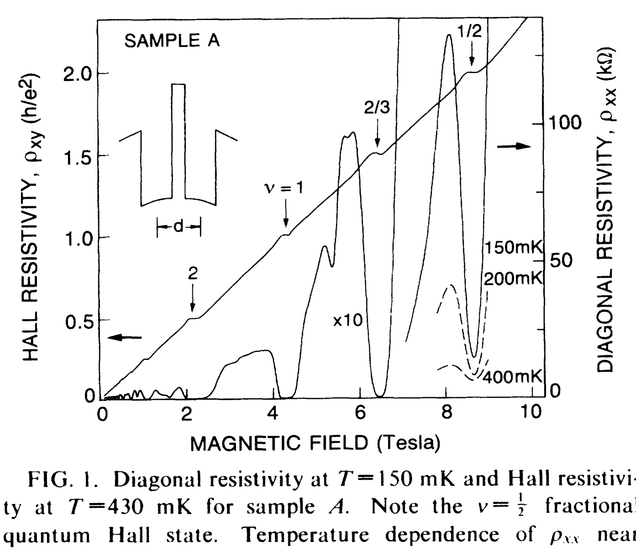

FIG. 1. Diagonal resistivity at $T=150$ mK and Hall resistivity at $T=430$ mK for sample *A*. Note the $\nu=\frac{1}{2}$ fractional quantum Hall state. Temperature dependence of ρ_{xx} near $\nu=\frac{1}{2}$ is also shown. The ρ_{xx} trace for $B<7$ T has been amplified tenfold. Inset: Schematic conduction-band diagram of the double quantum well.

If ρ_{xx} were to fall to zero at $\nu=\frac{1}{2}$, we would expect to find precise Hall quantization. Mixing of the two resistivity components is a common feature of high-field magnetotransport measurements on 2D systems. Indeed, the high temperature (430 mK) used to obtain the Hall trace in Fig. 1 was selected so as to reduce ρ_{xx} and thereby minimize this effect.

The origin of the large increase in ρ_{xx}, beginning around 7 T, is not understood but may simply reflect freeze-out due to the disorder in the sample. Similar behavior is observed [9] with single-layer samples of comparable mobility and density. Despite this rapid rise in ρ_{xx}, which strengthens as the temperature is lowered, the minimum at $\nu=\frac{1}{2}$ is quite deep. In fact, while ρ_{xx} at the minimum itself rises slowly as the temperature falls, the fractional depth of the minimum (measured relative to the peak in ρ_{xx} just below the $\frac{1}{2}$ state) increases rapidly, as the dashed traces in Fig. 1 demonstrate. By 25 mK the "peak-to-valley" ratio exceeds 30:1. While the rising background resistivity prevents measuring an activation energy for the $\nu=\frac{1}{2}$ state, it is clear that the state is not substantially weaker than the nearby $\nu=\frac{2}{3}$ state.

Figure 1 contains several QHE features in addition to the new state at $\nu=\frac{1}{2}$. The states observed at $\nu=2$ and $\frac{2}{3}$ both have well-known counterparts in single-layer systems. For $\nu=2$ this is the ordinary integral QHE obtained when the Fermi level lies in the spin gap of the lowest Landau level. Similarly, the FQHE seen at $\nu=\frac{2}{3}$ in the present double quantum well samples corresponds to the canonical Laughlin $\frac{1}{3}$ state in a single layer. We cannot, of course, rule out modification of these familiar single-layer states by interlayer correlations in the present double quantum well samples. The data in Fig. 1 also reveal a strong QHE at $\nu=1$, for which there is no single-layer analog. We defer discussion of this state for the moment and return to the $\nu=\frac{1}{2}$ FQHE.

The possibility of new correlated states arising in Coulomb-coupled double-layer 2D systems was first suggested by Rezayi and Haldane [4]. Numerical studies for the $\nu=1$ case were subsequently reported by Chakraborty and Pietilainen [5]. Yoshioka, MacDonald, and Girvin [6] (YMG) employed the generalized Jastrow wave functions, first considered by Halperin [10], to systematically outline the possibilities for new FQHE states in double-layer systems (with no tunneling). As YMG made clear, although the double-layer and spin problems are quite similar, they differ in a fundamental way: While the electron-electron interaction is spin independent, it is clearly not independent of the layer in which the electrons reside. This difference makes certain candidate wave functions acceptable for the double-layer problem that are excluded in the single-layer case. In particular, YMG proposed the so-called $\Psi_{3,3,1}$ state as a candidate ground state for a double-layer FQHE at $\nu=\frac{1}{2}$.

The $\Psi_{3,3,1}$ wave function is quite similar to the original Laughlin $\frac{1}{3}$ state insofar as intralayer correlations are concerned, but it contains additional *interlayer* correlations as well. In effect, these latter contributions keep electrons in adjacent layers from occupying the same position in the 2D plane. YMG showed that the $\Psi_{3,3,1}$ was a good candidate state only if the ratio of interlayer separation to magnetic length, d/l_B, was of order unity. This is not surprising since for very small d the system acts as a single 2DES at $\nu=\frac{1}{2}$ while for very large d it can be regarded as two independent layers with $\frac{1}{4}$ filling of the lowest Landau level. In neither limit has an FQHE been observed. The existence of a range of d/l_B values supporting a double-layer $\nu=\frac{1}{2}$ FQHE has been further examined by He *et al.* [11] in finite-size numerical studies of realistic sample geometries. Both interlayer tunneling and finite-layer thicknesses were found to suppress the $\nu=\frac{1}{2}$ effect. Tunneling, in particular, inhibits the anticorrelation of electrons in adjacent layers that is built into the $\Psi_{3,3,1}$ state.

Three additional samples, listed in Table I, were studied in order to clarify the role of interlayer correlations in the observed $\nu=\frac{1}{2}$ FQHE. Figure 2 displays resistivity data, taken at 300 mK, for each sample in the region near $\nu=\frac{1}{2}$. Samples A, B, and C, while structurally equivalent, differ in their 2D densities (A lowest, C highest). Note that while the $\nu=\frac{2}{3}$ ρ_{xx} minima are all similar, the $\nu=\frac{1}{2}$ feature monotonically weakens as the density increases. This is an unusual observation since the single-layer FQHE generally becomes stronger at higher magnetic fields owing to the increasing Coulomb energy (proportional to $B^{1/2}$). For a double-layer system, however, the relative magnitude of intralayer and interlayer Coulomb energies plays a critical role. The ratio of these energies is just d/l_B. Setting d equal to the quantum well center-to-center distance (210 Å for all except sample D), the ratio d/l_B increases from 2.4 for sample A to 2.9 for sample C (see Table I). For sample D, with its increased barrier thickness (99 Å), the ratio $d/l_B=3.6$ at $\nu=\frac{1}{2}$. While this sample has a density nearly equal to sample B and exhibits a comparable $\nu=\frac{2}{3}$ FQHE to each of the other samples, the $\nu=\frac{1}{2}$ FQHE is completely absent. Taken together, these data, showing the $\nu=\frac{1}{2}$ FQHE to weaken, and eventually collapse, as d/l_B increases, provide compelling evidence that this new FQHE derives from interlayer electron-electron interactions.

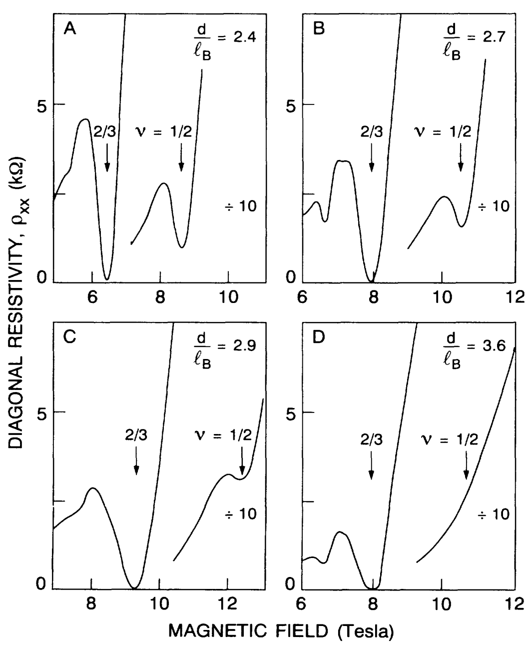

FIG. 2. Comparison of the $\nu=\frac{1}{2}$ state of the four samples of Table I. All data are taken at $T=300$ mK.

Comparisons such as these between different samples are always complicated by unavoidable fluctuations in mobility, homogeneity, etc. As Table I shows, there are substantial differences in the zero-field mobility of the samples. The mobility, however, is a poor predictor of the strength of high-field FQHE states. A more relevant parameter, the measured activation energy $\Delta_{2/3}$ for the $\nu=\frac{2}{3}$ FQHE, is also given in Table I. This parameter varies considerably less among the four samples than does the mobility. In fact, while sample C shows a much weaker $\nu=\frac{1}{2}$ state than does sample A, the two exhibit the same $\Delta_{2/3}$. Similarly, while sample D shows the *largest* $\Delta_{2/3}$, it exhibits no $\frac{1}{2}$ state. We, therefore, do not believe variations in the quality of the present samples weaken the evidence linking interlayer interactions to the $\nu=\frac{1}{2}$ FQHE.

We now turn to the quantized Hall effect appearing at $\nu=1$. As already discussed, single-particle tunneling can create odd-integral QHE states in a double-layer 2DES. Alternatively, interlayer Coulomb interactions could create a QHE at $\nu=1$, even in the absence of tunneling [4–6]. Thus, our observation of a QHE at $\nu=1$ has two

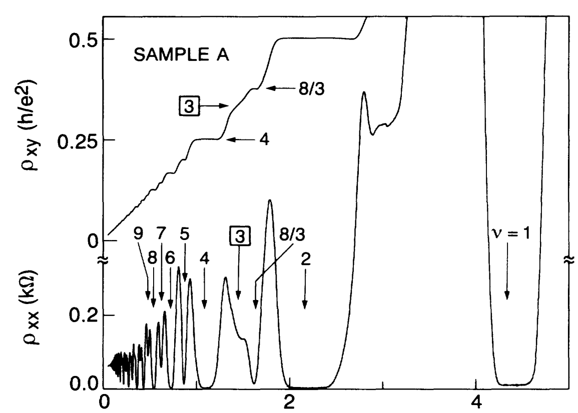

FIG. 3. Low-field ρ_{xx} and ρ_{xy} data for sample A at $T=70$ mK. Note the missing $\nu=3$ state: This suggests that the $\nu=1$ state arises from interlayer Coulomb interactions rather than tunneling.

possible origins: single-particle tunneling or interlayer many-body effects. While the present data cannot unambiguously decide the issue, we believe the evidence favors the many-body alternative. Supporting this are the low-temperature resistivity data, from sample *A*, shown in Fig. 3. Quantized Hall states are observed at $\nu=11$, 9, 7, and 5. Observing these states represents the resolution of the finite tunneling gap in this sample. By contrast, the $\nu=3$ QHE is absent. As a strong fractional Hall state is observed at the nearby $\nu=\frac{8}{3}$, the lack of a $\nu=3$ QHE is not likely due to some anomalous disorder or inhomogeneity effect. In fact, the disappearance of low-order integral QHE states in double-layer systems has been observed [8,12] previously and is attributed to a phase transition in which the interlayer Coulomb interactions destroy the single-particle tunneling gap. A well-defined boundary [13] exists between the larger odd-integral filling factors for which the tunneling gap, and hence the QHE, survives, and the smaller odd integers for which it is collapsed and the QHE is quenched. For sample *A*, this boundary is calculated [13] to be near $\nu=3$. Within this picture then, interlayer interactions have destroyed the tunneling gap in sample *A* for all $\nu\leq 3$. Thus, the *reappearance* of a QHE at $\nu=1$ suggests these same interlayer interactions are now strong enough to create a new, many-body gap to replace the tunneling gap. As already discussed, $\nu=1$ was the first predicted [4] collective QHE state specific to nontunneling double-layer 2D systems. In their generalized Jastrow approach, YMG suggested [6] the $\Psi_{1,1,1}$ wave function for this double-layer QHE state. Like the $\Psi_{3,3,1}$ proposed for $\nu=\frac{1}{2}$, the $\Psi_{1,1,1}$ state combines strong intralayer and interlayer correlations. We note in passing a final observation supporting this interpretation: A preliminary study of both the $\nu=1$ and $\frac{1}{2}$ states in tilted magnetic fields shows little influence of the added in-plane magnetic field. By contrast, tilted fields have been observed [8] to rapidly quench the odd-ν QHE states that arise from tunneling in double-layer systems.

To summarize, a new FQHE state has been observed in a double-layer 2D electron system at filling fraction $\nu=\frac{1}{2}$. A sequence of samples with different densities and layer separations establishes a strong case for this new state arising from an interplay between intralayer and interlayer Coulomb interactions. A second QHE, at $\nu=1$, has both a single-particle and a collective explanation but additional evidence suggests that it, too, represents a new double-layer correlated state.

We note that after the initial observations reported here we learned of similar results of Suen *et al.* [14]. We thank M. Shayegan for kindly giving us a preprint prior to publication.

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