Tunneling gap collapse and $\upsilon = 2$ quantum Hall state in a bilayer electron system

S. J. Geer, A. G. Davies, C. H. W. Barnes, K. R. Zolleis, M. Y. Simmons, and D. A. Ritchie
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 OHE, United Kingdom
(Received 22 February 2002; published 24 July 2002)

We have investigated the evolution of quantum Hall states in a GaAs-$Al_xGa_{1-x}As$ bilayer electron system by low-temperature magnetoresistivity measurements as the system was driven from a balanced to an off-balanced configuration. At low magnetic fields, odd integer filling factor quantum Hall states were observed on balance owing to the symmetric-antisymmetric tunneling gap. However, at high magnetic fields, in the regime of tunneling gap collapse, we observed anomalous quantum Hall states at $\upsilon = 2$ off balance and $\upsilon = 3$ on balance. At $\upsilon = 2$, an energy gap was present all the way from the balanced configuration to far off balance, when only one quantum well was occupied. This is attributed to a transition from a spin-polarized state on balance to a spin-singlet state off balance, either by an abrupt exchange-driven phase transition or a continuous phase transition via a series of interlayer phase coherent states.

DOI: 10.1103/PhysRevB.66.045318 PACS number(s): 73.43.−f, 73.21.Fg

I. INTRODUCTION

The physics of bilayer electron systems is still not fully understood even after over a decade of intense research. In a bilayer electron system, electrons are confined to two quantum wells separated by a tunnel barrier. These versatile structures allow control over the relative strengths of interlayer and intralayer electron-electron interactions and tunneling through the barrier. They are of great interest because many new states of matter emerge in a magnetic field. Both integer[1] and fractional[2] quantum Hall (QH) effects have been observed in bilayer electron systems and a variety of new QH states revealed.[3]

Considerable work has been performed on bilayer electron systems on balance, where the quantum-well potential is symmetric about the barrier, as shown schematically in the inset to Fig. 1(a). At zero magnetic field, the lowest energy electron subband has a symmetric wave function, and the second-lowest energy subband has an antisymmetric wave function. Their energies are separated by a tunneling gap (Δ_{SAS}) the magnitude of which depends on the size of the barrier. When the two subbands are occupied, this tunneling gap leads to the observation of odd integer filling factor QH states on balance.[4] However, in some bilayer systems the expected odd QH states are absent at high magnetic fields, and this has been attributed to a magnetic-field-driven collapse of the tunneling gap.[5–8] A phase diagram for the presence and absence of odd QH states has been proposed and investigated experimentally at filling factor $\upsilon = 1$, using a set of samples with different tunneling gaps and well separations,[9] and at $\upsilon = 3$ by varying the carrier density in a single sample.[10]

Further studies revealed a reappearance of the $\upsilon = 1$ QH state at high magnetic fields and the observation of a fractional QH state at $\upsilon = 1/2$ which is not seen in single-layer systems.[11,12] Both the $\upsilon = 1/2$ state and reappearance of the $\upsilon = 1$ state have been attributed to interlayer Coulomb correlations forming QH ground states with Jastrow-type wave functions.[8,13] Similar physics has been observed in bilayer electron systems formed in wide single quantum-well structures[14] and bilayer hole systems.[15]

In this paper, we investigate the evolution of QH states as the bilayer system is taken off balance in the regime of magnetic-field-driven tunnel gap collapse.[5–8] We observe anomalous QH gaps along $\upsilon = 2$ as the system is driven off balance and at $\upsilon = 3$ on balance. We compare our measurements to recent theory[16,17] for $\upsilon = 2$ and propose Jastrow-type wave functions at $\upsilon = 2$ off balance and $\upsilon = 3$ on balance, comprising a $\Psi_{1,1,1}$ state[13] in the upper two partially filled Landau levels. To the best of our knowledge, we have made the first identification of a possible off-balance Jastrow-type QH state at $\upsilon = 2$ in a bilayer system.

II. EXPERIMENT

The measurements were made on a molecular-beam-epitaxy (MBE) grown modulation-doped double-quantum-well structure[18] with 15-nm GaAs wells and a 4.5-nm $Al_{0.33}Ga_{0.67}As$ barrier. This structure had a symmetric-antisymmetric tunneling gap of 0.4 meV on balance at zero magnetic field. Hall bar samples with Schottky top gates and indium bottom gates were fabricated from the MBE wafer. The gates allowed control over the electron density in the two quantum wells. Four terminal, low frequency ac diagonal (ρ_{xx}) and Hall (ρ_{xy}) magnetoresistivity measurements were made on two samples: one at 300 mK in a helium-3 cryostat (sample I), and one at 100 mK in a dilution refrigerator (sample II).

III. RESULTS

Figure 1 shows magnetoresistivity measurements taken on sample I at 300 mK on balance. On balance, this sample had two subbands occupied, a mobility of 260 $m^2\,V^{-1}\,s^{-1}$, and a total carrier density of 2.43×10^{15} m^{-2}. At low magnetic fields, both odd and even filling factor QH states are observed, as expected when the tunneling gap is greater than both kT and the width of the disorder-broadened Landau levels. However, at higher magnetic fields, the $\upsilon = 3$ QH state is missing. This absence has been attributed to a magnetic-field-driven collapse of the tunneling gap[5–8] owing to Coulomb interactions. This can be understood as the formation of an interlayer correlated state where nearest-

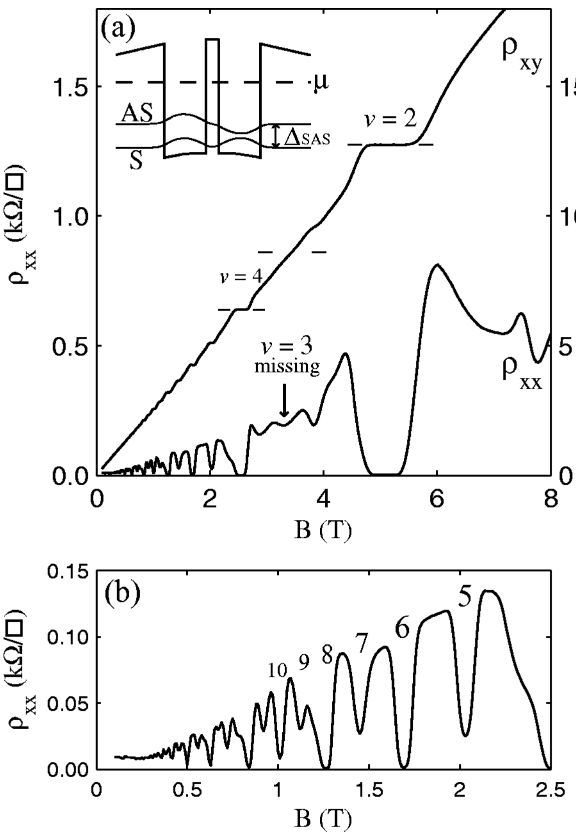

FIG. 1. Measurements on balance at 300 mK on Sample I (0 V back gate). (a) Resistivity as a function of magnetic field. Note the missing $v=3$ ρ_{xx} minimum and ρ_{xy} plateau. Inset: schematic diagram of the band edge, symmetric (S) and antisymmetric (AS) wave functions, tunneling gap Δ_{SAS}, and chemical potential μ. (b) Low-field Shubnikov–de Haas oscillations. Some of the minima are labeled by the total filling factor. Both even and odd integer filling factors are present.

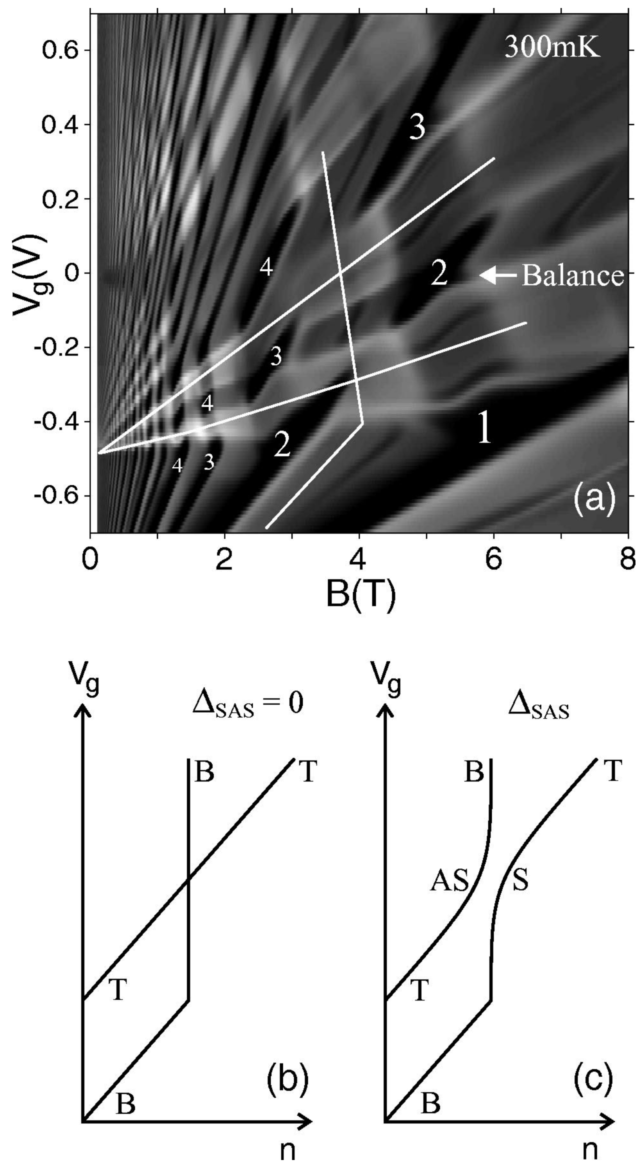

FIG. 2. Measurements off balance at 300 mK on sample I (0 V back gate). (a) Normalized ρ_{xx} plotted as a gray scale against magnetic field (B) and front gate voltage (V_g). Overlay lines are a guide to the eye to show approximate pattern of ρ_{xx} maxima. (b) Schematic plot of top and bottom well subband densities (n_T and n_B) against V_g, when there is no tunneling gap. (c) Schematic plot of subband densities against V_g when there is a energy gap between the symmetric (S) and antisymmetric (AS) wave functions on balance.

neighbor electrons occupy different quantum wells to minimize the Coulomb energy at the expense of the tunneling energy.[3] The presence or absence of odd filling factor states depends on the interplay between the well separation, magnetic length, and size of the zero magnetic field tunneling gap.[9]

Figure 2(a) shows ρ_{xx} for sample I as a function of top gate bias (V_g) and magnetic field (B), measured at 300 mK and plotted as a gray scale. Black regions are ρ_{xx} minima, and some of these are labeled by a total filling factor. The trace marked "balance" corresponds to the $\rho_{xx}(B)$ trace shown in Fig. 1.

The overall pattern of ρ_{xx} maxima in Fig. 2(a) can be understood from the dependence of the subband electron densities on V_g. The electron densities of the top (n_T) and bottom (n_B) quantum wells are shown schematically in Fig. 2(b) for the case of zero interwell tunneling. When the top well is occupied by electrons, the bottom layer is predominantly screened from the top gate and has an approximately constant density. Negatively biasing the top gate reduces the top well electron density approximately linearly. This behavior is similar to that in a parallel plate capacitor.[19] Once the top well is depleted, the density in the bottom well can be reduced by further negatively biasing the gate.

Figure 2(c) schematically shows the subband electron densities in the presence of tunneling. Away from balance, the wave functions are predominantly localized in separate wells as for the zero tunneling case. However, close to balance the wave functions become delocalized across both wells, and there is a difference in the subband electron densities owing to the tunneling gap.[4]

Returning to Fig. 2(a), for $B<2$ T the ρ_{xx} maxima pattern observed arises from the beating of Shubnikov–de Haas oscillations of the two subbands. The magnetic-field positions of the ρ_{xx} maxima originating from the two subbands approximately follow the subband densities shown in Fig. 2(c). On balance the ρ_{xx} maxima anticross and odd filling factor QH minima arise owing to the tunneling gap.[4] However, at high magnetic fields ($B>2$ T) the pattern is different: on balance the ρ_{xx} maxima cross at $v=3$ and the pattern looks like that which would be expected for the zero tunneling case [Fig. 2(b)]. Hence this is consistent with a collapse of the tunneling gap.

Further structure was revealed in measurements made on sample II at 100 mK. These measurements are shown in Fig. 3(b), while measurements made on sample I at 300 mK are given in Fig. 3(a) for comparison. Sample II had a lower electron density of 1.8×10^{15} m^{-2} on balance[20] than sample I, and so for Fig. 3(a) a negative back gate bias of -250 V was applied to reduce the electron density to a similar value. Finally in Fig. 3(c), we show Hartree calculations[4] of the diagonal-resistivity.

In Fig. 3(b) the pattern of ρ_{xx} maxima at low magnetic fields ($B<2$ T) is consistent with the presence of a tunneling gap, and is successfully modeled by the Hartree calculations. At higher magnetic fields, the pattern is more consistent with tunneling gap collapse but with two important exceptions: an anomalous QH gap has appeared around $v=3$ on balance and another has appeared at $v=2$ off balance ($V_g\approx-0.3$ V). By comparison of the measurements at 100 mK [Fig. 3(b)] with those at 300 mK [Fig. 3(a)], it can be seen that the QH states have activation energies $\Delta\leqslant0.025$ meV. These activation energies are considerably less than the zero field Δ_{SAS}. In addition at 300 mK, we observe a QH gap at $v=1$ on balance in measurements made up to 8 T (not shown).

At $v=3$ on balance, the small size of the QH gap could either be due to incomplete tunneling gap collapse or the emergence of a new gap after the tunneling gap has collapsed. However, the gap at $v=2$ off balance is new. This is because the gap is observed at a crossing of ρ_{xx} maxima which should occur either in the presence or absence of a tunneling gap. The single-particle Hartree calculations [Fig. 3(c)] show the presence of a crossing of ρ_{xx} maxima at $v=2$ ($V_g\approx-0.3$ V) when a tunneling gap is present. Around $v=2$, on balance [Fig. 3(b)] there is strong evidence that the Δ_{SAS} gap has collapsed from the pattern of $v=2/3$ and 4/3 fractional ρ_{xx} minima arising from the two subbands. These minima cross on balance, giving ρ_{xx} minima at total filling factors $v=4/3$ and 8/3. This is consistent with an absence of a tunneling gap.

Another interesting aspect of the QH gap at $v=2$ off balance is that it has a clear density dependence: In Fig. 3(b) a ρ_{xx} maxima crossing is observed along $v=2$ on the high-density side of balance ($V_g\approx0.2$ V), but the anomalous gap is observed on the low density side of balance ($V_g\approx-0.3$ V). A similar behavior can also be observed in measurements made on a bilayer hole system[15] and in other measurements on a bilayer electron system.[21,22]

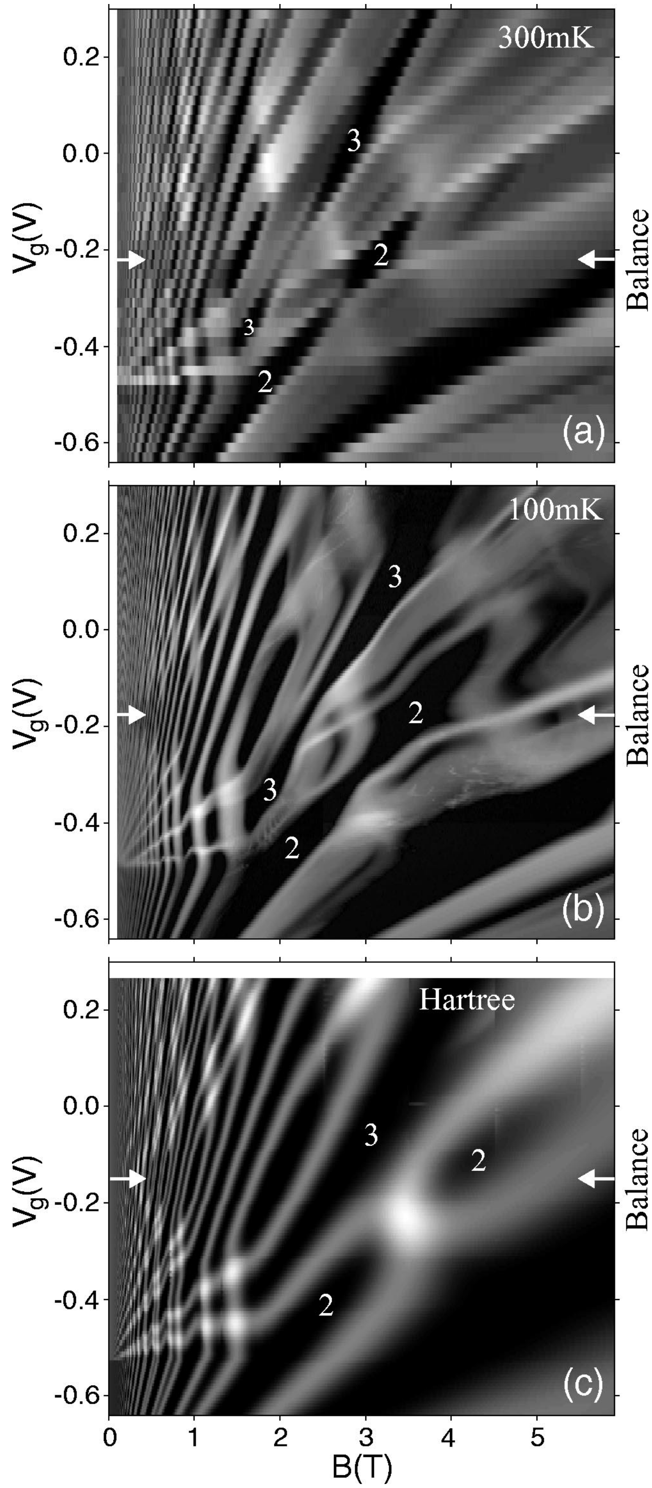

FIG. 3. Measurements of $\rho_{xx}(B,V_g)$. (a) Sample I at 300 mK (-250 V back gate). (b) Sample II at 100 mK (0 V back gate). (c) Hartree calculations.

IV. DISCUSSION

Recently the nature of the $v=2$ QH state on balance has been of experimental and theoretical interest. A filling factor $v=2$ corresponds to the occupation of the two lowest spin-split Landau levels. If the tunneling gap Δ_{SAS} is larger than the Zeeman splitting Δ_Z, the spin-up (↑) and spin-down (↓) states of the lowest symmetric subband Landau level are filled. This can be viewed as a spin singlet (SS) or antiferromagnetic state.[23] If $\Delta_{SAS}<\Delta_Z$, the spin down states of

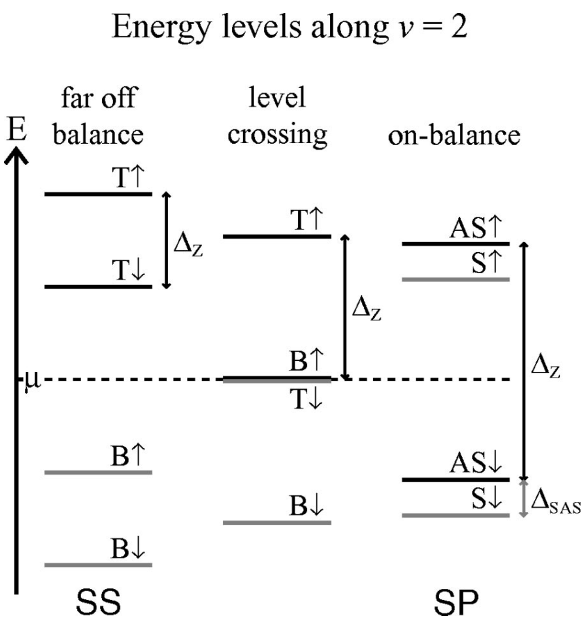

FIG. 4. Schematic diagram of energy levels along $\nu=2$.

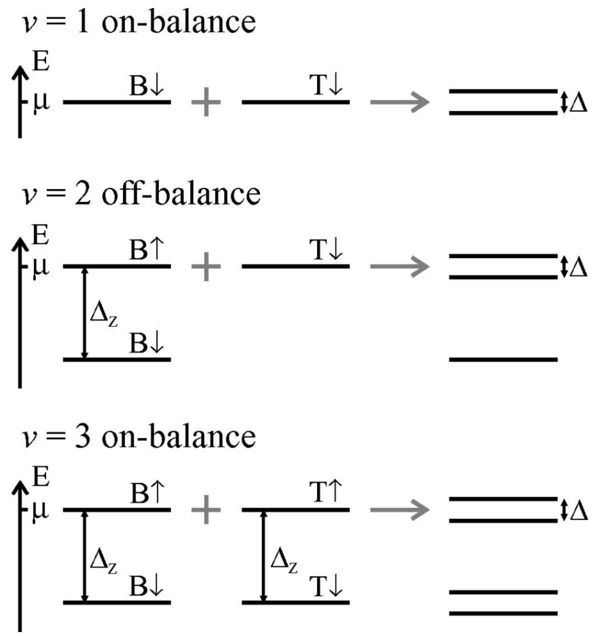

FIG. 5. Schematic diagram of energy levels at $\nu=1$ on balance, $\nu=2$ off balance, and $\nu=3$ on balance.

the lowest symmetric and antisymmetric subband Landau levels are filled. This is a spin-polarized (SP) or ferromagnetic state. Exact diagonalization and Hartree-Fock studies[23–25] predicted a continuous phase transition between the two states via a canted antiferromagnetic phase. This has been studied by inelastic light scattering[26] using a tilted magnetic field to vary the Zeeman splitting.

In our sample, the on-balance $\nu=2$ state corresponds to the spin-polarized configuration with $\Delta_{SAS}<\Delta_Z$. Instead of varying the Zeeman splitting on balance, we use a gate bias to tune from a spin polarized state on balance to a spin singlet state far off balance. This spin-singlet state corresponds to the occupation of the spin-up and -down states of the lowest Landau level in a single quantum well. The energy levels along $\nu=2$ are shown schematically in Fig. 4, neglecting many-particle effects and higher Landau levels. A crossing of dissipative resistivity maxima is expected where the spin up Landau level of the bottom layer (B↑) and the spin down Landau level of the top layer (T↓) cross. This is where we observe the anomalous $\nu=2$ gap.

There are two possible explanations for the continuity of the $\nu=2$ QH gap from far off balance to on balance in the measurements made on sample II at 100 mK. One is an abrupt exchange-driven antiferromagnetic to ferromagnetic phase transition, as observed in a single layer two dimensional hole system in a tilted magnetic field.[27,28] Another is a continuous evolution of the QH state along $\nu=2$ through a series of intermediate many-body states. This explanation is supported by recent theoretical work by both Brey *et al.*[16] and MacDonald *et al.*[17] They calculated the phase diagram of the $\nu=2$ bilayer QH system in the presence of an interlayer bias and found a continuous phase transition from the spin-polarized state on balance to the spin-singlet state far off balance via interlayer phase-coherent states. MacDonald *et al.*[17] found that an energy gap existed throughout the transition. Our anomalous gap at $\nu=2$ can be attributed either to these interlayer phase coherent states or to an abrupt exchange driven phase transition. The two mechanisms can only be distinguished in transport measurements by a detailed comparison along $\nu=2$ of the activation energy with theoretical predictions.

An interesting aspect of the results presented in Fig. 3 is that we simultaneously see anomalous states at $\nu=1$ on balance and $\nu=2$ off balance, and an anomalously small gap at $\nu=3$ on balance. The reappearance of the $\nu=1$ QH state on balance was observed by Eisenstein and co-workers[11,12] and attributed to a many-body QH state with a gap at the chemical potential formed by interlayer Coulomb interactions. The $\nu=1$ many-body QH state is thought to be a two-component $\Psi_{1,1,1}$ Jastrow-type wave function when the tunneling is small.[8,13] Assuming the Δ_{SAS} gap has collapsed, the anomalous states that we observe at $\nu=1$, 2 and 3 occur where Landau levels cross at the chemical potential and correspond to a half-filling of the upper two Landau levels. This is shown schematically in Fig. 5. A possible explanation of the $\nu=2$ and 3 states is that they correspond to a $\Psi_{1,1,1}$ like state formed from the upper two half-filled Landau levels. This hypothesis could be investigated by exact diagonalization studies[8] such as those performed at $\nu=1$.

V. CONCLUSIONS

Anomalous QH gaps were observed at $\nu=2$ off balance and $\nu=3$ on balance in the regime of tunneling gap collapse. At $\nu=2$, as the bilayer electron system was driven from a spin-polarized QH state on balance to a spin singlet QH state far off balance, a QH gap was present throughout the transition. This could be attributed to either an abrupt exchange driven phase transition or a continuous phase transition via a series of interlayer phase-coherent states. Possible Jastrow-type wave functions were proposed at $\upsilon=2$ off balance and $\upsilon=3$ on balance, comprising a $\Psi_{1,1,1}$ like state in the upper two half-filled Landau levels. There is potential that more of these Jastrow-type states will be observed at higher filling factors both on and off balance.

ACKNOWLEDGMENTS

We would like to thank Luis Brey for helpful discussions. A.G.D. acknowledges the support of the Royal Society. This work was funded by the UK Engineering and Physical Sciences Research Council.

[1] K. von Klitzing, Phys. Rev. Lett. **45**, 494 (1980).

[2] D. C. Tsui, H. L. Stormer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).

[3] *Perspectives in Quantum Hall Effects*, edited by S. D. Sarma and A. Pinczuk (Wiley, New York, 1997), Chap. 2.

[4] A. G. Davies, C. H. W. Barnes, K. R. Zolleis, J. T. Nicholls, M. Y. Simmons, and D. A. Ritchie, Phys. Rev. B **54**, 17 331 (1996).

[5] G. S. Boebinger, H. W. Jiang, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **64**, 1793 (1990).

[6] A. H. MacDonald, P. M. Platzman, and G. S. Boebinger, Phys. Rev. Lett. **65**, 775 (1990).

[7] L. Brey, Phys. Rev. Lett. **65**, 903 (1990).

[8] S. He, S. D. Sarma, and X. C. Xie, Phys. Rev. B **47**, 4394 (1993).

[9] S. Q. Murphy, J. P. Eisenstein, G. S. Boebinger, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **72**, 728 (1994).

[10] G. S. Boebinger, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **45**, 11 391 (1992).

[11] J. P. Eisenstein, G. S. Boebinger, L. N. Pfeifer, K. W. West, and S. He, Phys. Rev. Lett. **68**, 1383 (1992).

[12] G. S. Boebinger, S. Q. Murphy, J. P. Eisenstein, L. N. Pfeiffer, K. W. West, and S. He, Surf. Sci. **305**, 8 (1994).

[13] D. Yoshioka, A. H. MacDonald, and S. M. Girvin, Phys. Rev. B **39**, 1932 (1989).

[14] Y. W. Suen, L. W. Engel, M. B. Santos, M. Shayegan, and D. C. Tsui, Phys. Rev. Lett. **68**, 1379 (1992).

[15] A. R. Hamilton, M. Y. Simmons, F. M. Bolton, N. K. Patel, I. S. Millard, J. T. Nicholls, D. A. Ritchie, and M. Pepper, Phys. Rev. B **54**, 5259 (1996).

[16] L. Brey, E. Demler, and S. D. Sarma, Phys. Rev. Lett. **83**, 168 (1999).

[17] A. H. MacDonald, R. Rajaraman, and T. Jungwirth, Phys. Rev. B **60**, 8817 (1999).

[18] MBE wafer number T246.

[19] C. H. W. Barnes, A. G. Davies, K. R. Zolleis, M. Y. Simmons, and D. A. Ritchie, Phys. Rev. B **59**, 7669 (1999).

[20] At 100 mK the lower density may be due to pinning of the conduction band to chemical potential below the quantum wells.

[21] A. Sawada, Z. F. Ezawa, H. Ohno, Y. Horikoshi, Y. Ohno, S. Kishimoto, F. Matsukura, M. Yasumoto, and A. Urayama, Phys. Rev. Lett. **80**, 4534 (1998).

[22] A. Sawada, Z. F. Ezawa, H. Ohno, Y. Horikoshi, A. Urayama, Y. Ohno, S. Kishimoto, F. Matsukura, and N. Kumada, Phys. Rev. B **59**, 14 888 (1999).

[23] J. Schliemann and A. H. MacDonald, Phys. Rev. Lett. **84**, 4437 (2000).

[24] L. Zheng, R. J. Radtke, and S. D. Sarma, Phys. Rev. Lett. **78**, 2453 (1997).

[25] S. D. Sarma, S. Sachdev, and L. Zheng, Phys. Rev. Lett. **79**, 917 (1997).

[26] V. Pellegrini, A. Pinczuk, B. S. Dennis, A. S. Plaut, L. N. Pfeiffer, and K. W. West, Science **281**, 799 (1998).

[27] A. J. Daneshvar, C. J. B. Ford, M. Y. Simmons, A. V. Khaetskii, A. R. Hamilton, M. Pepper, and D. A. Ritchie, Phys. Rev. Lett. **79**, 4449 (1997).

[28] C. H. W. Barnes, A. G. Davies, K. R. Zolleis, M. Y. Simmons, and D. A. Ritchie, in *Proceedings of the 24th International Conference on the Physics of Semiconductors, Jerusalem, 1998*, edited by D. Gershoni (World Scientific, Singapore, 1999).