Evolution of the Second Lowest Extended State as a Function of the Effective Magnetic Field in the Fractional Quantum Hall Regime

Tse-Ming Chen,[1] C.-T. Liang,[1,*] M. Y. Simmons,[2,3] D. A. Ritchie,[2] and M. Pepper[2]

[1]*Department of Physics, National Taiwan University, Taipei 106, Taiwan*

[2]*Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK*

[3]*School of Physics, University of New South Wales, Sydney 2052, Australia*

(Received December 15, 2003)

It has been shown that, at a Landau level filling factor ν=1/2, a two-dimensional electron system can be mathematically transformed into a composite fermion system interacting with a Chern-Simons gauge field. At ν=1/2, the average of this Chern-Simons gauge field cancels the external magnetic field B_{ext} so that the effective magnetic field B_{eff} acting on the composite fermions is zero. Away from ν=1/2, the composite fermions experience a net effective magnetic field B_{eff}. We present the first study of the evolution of the second lowest extended state in a vanishing effective magnetic field in the fractional quantum Hall regime. Our result shows that the evolution of the second lowest extended state has a good linear dependence on the effective magnetic field B_{eff} within the composite fermion picture.

PACS numbers: 73.43.-f, 73.40.-c

The fractional quantum Hall effect (FQHE) [1] observed in high-quality two-dimensional (2D) electron systems in the low-temperature, high-magnetic-field regime, arises from strong electron-electron interactions [2]. In the composite fermion (CF) picture the FQHE can be understood as a manifestation of the integer quantum Hall effect (IQHE) of weakly interacting composite fermions [3]. It has been shown that at a Landau level filling factor ν=1/2, a 2D electron system can be mathematically transformed into a CF system interacting with a Chern-Simons gauge field. At ν=1/2 the average of this Chern-Simons gauge field cancels the external magnetic field B_{ext}, so that the effective magnetic field B_{eff} acting on the composite fermions is zero. Away from ν=1/2 the composite fermions experience a net effective magnetic field $B_{\text{eff}} = (1-2\nu)B_{\text{ext}}$. In this CF picture, we can easily regard the FQHE of electrons in the external magnetic field B_{ext} as the IQHE of composite fermions in the effective magnetic field B_{eff}. At ν=1/2 each composite fermion is composed of an electron bound to two magnetic flux quanta, thus the density of the composite fermion system is equal to that of the electron system.

The existence of the extended (delocalized) states is an essential ingredient in the theory of the quantum Hall effect. It is now well established that the energy of an extended state in a quantum Hall system in the high-magnetic-field regime is centered around its Landau levels $E_N = (N + 1/2)\hbar\omega_c$. When the magnetic field is decreased so as to push the 2D electron system toward complete localization, the extended-state bands move down through the Fermi energy. However, it is believed [4, 5] that as $B \to 0$ the extended states cannot disappear discontinuously below the Fermi level, but must "float up" in energy. With a strong promise of experimentally verifiable predictions in both the integer and fractional quantum Hall effect regime, the global phase diagram (GDP) proposed by Kivelson, Lee, and Zhang [6] has attracted lots of interest in this particular issue [7–11]. In the seminal work of Glozman, Johnson, and Jiang [11], there is compelling evidence that the second lowest extended state floats up, piercing the Fermi surface as $B \to 0$.

In the seminal work of Goldman, Jain, and Shayegan [12], the positions of the extended states in the fractional quantum Hall regime have been extensively studied. In their work, transitions between two major fractional filling factors, for example, 2/3 and 3/5, 3/5 and 4/7, and 2/5 and 1/3 have been investigated. To further study the most pronounced extended state at the effective filling factor $\nu_{\rm eff} = 1.5$ between $\nu = 2/5$ and $\nu = 1/3$, in this work we present the first experimental study of the evolution of the second lowest extended state as a function of the effective magnetic field in the fractional quantum Hall regime. Experimentally the evolution of the peaks in the longitudinal conductivity σ_{xx} (or the longitudinal resistivity ρ_{xx}) can be used to map out the extended states in the density (or energy)–magnetic field space. We performed the low-temperature measurements on a high-quality gated GaAs electron system. By changing the applied gate voltage, we were able to study the evolution of the second lowest extended state as a function of the electron density. In mapping out the diagram of the second lowest extended state of the FQHE within the composite fermion picture, we show that the evolution of the second lowest extended state conforms to the theoretical prediction in a finite effective magnetic field.

The sample investigated in this work was a modulation doped GaAs/AlGaAs heterostructure grown by molecular beam epitaxy. The structure consists of a semi-insulating (SI) GaAs (001) substrate, followed by an undoped 20 nm GaAs quantum well, an 80 nm undoped $Al_{0.33}Ga_{0.67}As$ spacer, a 210 nm Si-doped $Al_{0.33}Ga_{0.67}As$, and finally a 10 nm GaAs cap layer. The Hall pattern was made by standard lithography and etching processes. At zero gate voltage, our sample has a carrier density of $9.12 \times 10^{14}\ m^{-2}$ with a mobility of $300\ m^2/Vs$ without illumination. Magneto-transport measurements were performed with a top-loading He^3 system and a superconducting magnet. The low-frequency AC lock-in technique with a current of 10 nA applied to the sample was used in this work.

To identify the region for our study, we show in Fig. 1(a) and (b) the longitudinal magnetoresistivity traces $\rho_{xx}(B)$ in the magnetic-field sweeps at two typical gate voltages. Each peak in ρ_{xx} at a particular magnetic field and gate voltage represents the occupation of an extended state energy band and yields one point for the n_e–B phase diagram. A strong localization at low density was expected, due to a reduction of the screening of a charged impurity potential in the dilute electron limit [12]. Therefore, by changing the applied gate voltage (electron density), we were able to change the localization of the 2DEG and study the evolution of the extended state in the n_e–B phase diagram. What interests us most in this paper is the second lowest extended state (labelled C in Fig. 1) in the fractional quantum Hall regime. From the measurement of the Hall and longitudinal resistance in the magnetic-field sweeps at fixed gate voltage, we can obtain the electron density, which shows a linear dependence on the applied gate voltage. By varying the applied gate voltage from 0 V to -0.34 V, we obtain an electron density from $9.12 \times 10^{14}\ m^{-2}$ to $2.15 \times 10^{14}\ m^{-2}$.

The n_e–$B_{\rm ext}$ phase diagram of the second lowest extended state is presented in Fig. 2.

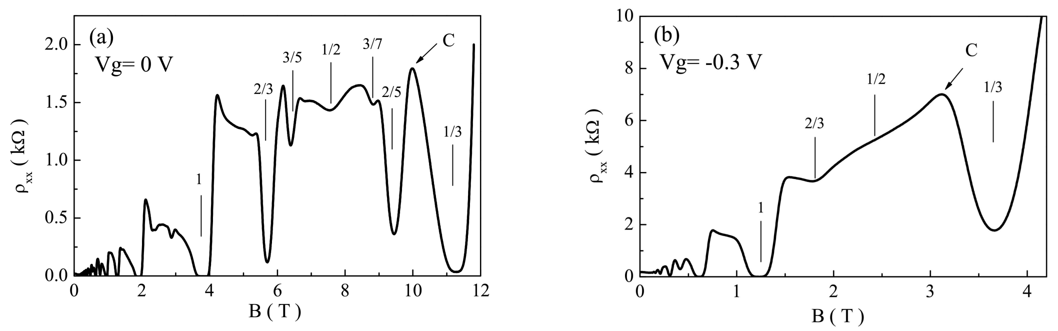

FIG. 1: ρ_{xx} as a function of the magnetic field for different gate voltages at T = 300 mK. The peaks in ρ_{xx} (labelled C) for various gate voltages are used to map out the lowest extended state in the n–B phase diagram.

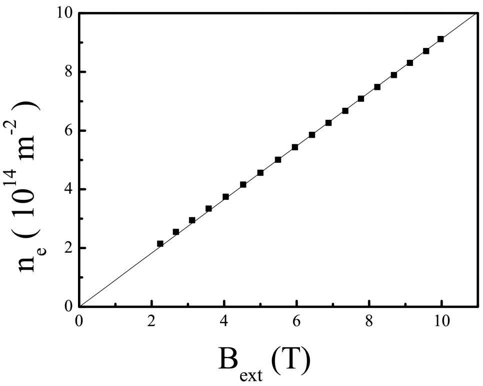

FIG. 2: The n_e–B_{ext} phase diagram for the lowest extended state. The lowest extended state shows a linear dependence on the external magnetic field.

As the applied gate voltage V_g is made more negative, the effective disorder increases (or the magnetic field decreases) and the extended-state band moves down in energy. The energy of these extended states can be considered to be directly proportional to n in the data region. Our results also show that the evolution of the second lowest extended state in the FQHE shows a linear dependence on B_{ext} in the n_e–B_{ext} phase diagram.

We now turn to our main experimental results. Within the composite fermion picture, we studied the evolution of the second lowest extended state in the density-effective magnetic phase diagram, as shown in Fig. 3. We observed that the evolution shows a good linear dependence on the effective magnetic field B_{eff} in the high B_{eff} or low disorder region. It is well established that within the CF picture the Fermi energy of the composite fermions

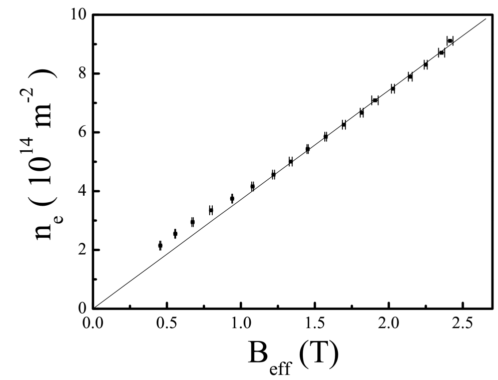

FIG. 3: The n_e–$B_{\rm eff}$ phase diagram for the extended state determined from the peaks in ρ_{xx}. The dotted lines represent the conventional levels in the CF picture.

is given by

$$E_F^{CF} = \frac{\hbar^2 k_F^2}{2m_{CF}^\star} = (N + \frac{1}{2})\hbar \frac{eB_{\rm eff}}{m_{CF}^\star}\,, \tag{1}$$

where $k_F = \sqrt{4\pi n_e}$ for a CF and n_e is the carrier concentration. For the second lowest extended state, with $N = 1$ and the cancellation of $m_{CF}^\star$ in Eq. (1), we can derive the relation

$$\frac{n_e}{B_{\rm eff}} = \frac{3e}{2h}\,, \tag{2}$$

which is consistent with the relation

$$\frac{\nu_{\rm eff} e B_{\rm eff}}{h} = n_e\,, \tag{3}$$

in the conventional Landau fan diagram in the composite fermion picture, while $\nu_{\rm eff} = 1.5$ for the second lowest extended state in the FQHE regime. Our experimental results show that the slope in Fig. 3 is 3.715×10^{14}, close to the theoretical value, which is consistent with Eq. (2). Moreover, we also found that, in the low effective magnetic field or high effective disorder limit, the second lowest extended state starts to show a deviation from the traditional Landau level within the CF picture.

In conclusion, we have performed the first study of the second lowest extended state as a function of the effective magnetic field $B_{\rm eff}$ in the fractional quantum Hall regime. Our experimental results show that the most pronounced resistance peak which corresponds to an effective filling factor $\nu_{\rm eff} = 1.5$ shows a linear dependence on $B_{\rm eff}$. In this device, we can only approach $B_{\rm eff} \sim 0.5T$ so that we are not able to study the fate of this extended state at a vanishing B_{eff}. We hope that with better-quality samples, we will be able to study whether floating-up can occur, which is a fundamentally important issue in the 2D field.

This work was funded by the NSC, Taiwan and the EPSRC, United Kingdom. C. T. L. thanks T. Chin for her support.

References

* Electronic address: `ctliang@phys.ntu.edu.tw`

[1] T. Charkraborty and P. Pietilainen, *The Fractional Quantum Hall Effect*, (Springer-Verlag, New York, 1988).

[2] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).

[3] J. K. Jain, Phys. Rev. Lett. **63**, 199 (1989).

[4] D. E. Khmelnitskii, Phys. Lett. **106**, 182 (1984).

[5] R. B. Laughlin, Phys. Rev. Lett. **52**, 2304 (1984).

[6] S. A. Kivelson, D. H. Lee, and S. C. Zhang, Phys. Rev. B **46**, 2223 (1992).

[7] H. W. Jiang, C. E. Johnson, K. L. Wang, and S. T. Hannahs, Phys. Rev. Lett. **71**. 1439 (1993).

[8] A. A. Shashkin, G. V. Kravchenko, and V. T. Dogopolov, JETP Lett. **58**, 220 (1993).

[9] T. Wang, K. P. Clark, G. F. Spencer, A. M. Mack, and W. P. Kirk, Phys. Rev. Lett. **72**, 709 (1994).

[10] R. J. F. Hughes, J. T. Nicholls, J. E. F. Frost, E. H. Linfield, M. Pepper, C. J. B. Ford, D. A. Ritchie, G. A. C. Jones, E. Kogan, and M. Kaveh, J. Phys. Condens. Matter **6**, 4763 (1994).

[11] I. Glozman, C. E. Johnson, and H. W. Jiang, Phys. Rev. Lett. **74**, 594 (1995).

[12] V. J. Goldman, J. K. Jain, and M. Shayegan, Phys. Rev. Lett. **65**, 907 (1990).

[13] A. L. Efros, Solid State Commun. **70**, 253 (1989).