Cascade of Quantum Phase Transitions in Tunnel-Coupled Edge States

I. Yang,[1] W. Kang,[1] K.W. Baldwin,[2] L. N. Pfeiffer,[2] and K.W. West[2]

[1]*James Franck Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*

[2]*Bell Laboratories, Lucent Technologies, 600 Mountain Avenue, Murray Hill, New Jersey 07974, USA*

(Received 2 November 2003; published 4 February 2004)

We report on the cascade of quantum phase transitions exhibited by tunnel-coupled edge states across a quantum Hall line junction. We identify a series of quantum critical points between successive strong and weak tunneling regimes in the zero-bias conductance. Scaling analysis shows that the conductance near the critical magnetic fields B_c is a function of a single scaling argument $|B - B_c|T^{-\kappa}$, where the exponent $\kappa = 0.42$. This puzzling resemblance to a quantum Hall-insulator transition points to the importance of interedge correlation between the coupled edge states.

DOI: 10.1103/PhysRevLett.92.056802 PACS numbers: 73.43.Jn, 73.43.Nq

Edge states in the quantum Hall effect provide a highly tunable system for the study of quantum transport in one dimension [1]. Following the prediction of chiral Luttinger liquids in the fractional quantum Hall effect [2,3], extensive effort has been devoted to the study of tunneling between quantum Hall edge states [4–11]. Tunneling of an electron into a Luttinger liquid is strongly suppressed and theories predict a power-law tunneling conductance with a universal exponent related to the quantum number of the bulk quantum Hall liquid. Experimental studies of tunneling between edge states across a quantum point contact [8] and tunneling between an edge state and a three-dimensional metal [9,10] have generally tended to support the predicted Luttinger liquid behavior. However, there remain important open questions regarding the experimentally observed exponent and its correlation to the bulk quantum Hall states [11].

A different and perhaps more intriguing geometry for the study of edge state tunneling involves a line junction that juxtaposes two parallel, counterpropagating edge modes against each other. Such a junction has been initially envisioned as a Hall bar with a long narrow gate that couples two right- and left-moving edge channels of fractional quantum Hall liquids [12,13]. In the limit of weak bias, the conductance across the line junction remains quantized as backscattering between the edge states is negligible. For strong bias, interedge backscattering is suppressed and the conductance across the line junction vanishes. In between the two limits, the intermode backscattering is mediated by defects in the line junction and a metal-insulator transition is predicted [12,13]. The transition is characterized by a temperature dependent conductivity that vanishes in the insulating phase and diverges in the metallic state in the limit of zero temperature.

Confirmation of the predicted metal-insulator transition has remained elusive as lithographic limitations and vertical offset of the gates from the plane of two-dimensional electrons complicate the realization of a line junction. An alternate approach to a line junction involves taking advantage of the inherent atomic precision of molecular beam epitaxy (MBE) and inserting a precisely defined semiconductor barrier in the plane of a two-dimensional electron system through the technique of cleaved edge overgrowth [14,15]. Such a junction strongly couples two counterflowing edge modes through inter-edge tunneling and features sharp resonances whenever the single particle energy levels coincide with the chemical potential [15]. These resonances are particularly enhanced in its width and height at zero-bias crossings, indicating the importance of electron-electron interaction. Proposed explanations include enhanced tunneling driven by electron-electron interaction [16–18], mixing of the states with equal transverse momentum from the opposite sides of the barrier [19–21], and a coupled Luttinger liquid interacting through a strongly backscattering center in the barrier [22].

In this Letter, we report on the observation of a cascade of quantum phase transitions exhibited by tunnel-coupled edge states of quantum Hall line junctions. Two counter-propagating edge states are separated by an 8.8-nm-wide, $\sim$100-μm-long semiconductor barrier. We identify a series of quantum critical points between successive strong and weak tunneling regimes that are reminiscent of the metal-insulator transition in two dimensions. Scaling analysis shows that the conductance near the critical magnetic field B_c is a function of a single scaling argument $|B - B_c|T^{-\kappa}$, where the exponent $\kappa \approx 0.42$. This apparent similarity to the quantum Hall-insulator transitions is quite puzzling due to the one-dimensional character of edge states. Whether the resemblance to a quantum Hall-insulator transition is coincidental or occurs from some deeper physics remains to be clarified.

The line junctions are fabricated by cleaved edge overgrowth using MBE [14,15]. The initial growth on a standard (100) GaAs substrate consists of an undoped 13-μm GaAs layer followed by an 8.8-nm-thick digital alloy of undoped $Al_{0.1}Ga_{0.9}As/AlAs$, and completed by a 14-μm layer of undoped GaAs. This multilayer sample is cleaved along the (110) plane in an MBE machine and a modulation-doping sequence is performed over the exposed edge, forming two strips of two-dimensional electron systems separated from each other by the 8.8-nm-thick barrier. A mesa incorporating the barrier and the two-dimensional electron systems into a junction that is ~100 μm long is defined by photolithography. The inset of Fig. 1(a) shows the planar layout of the line-junction device. In the quantum Hall regime, Landau quantization creates two counterpropagating edge states that are separated by a smooth, rectangular barrier. The density of the two-dimensional electron system in the devices studied was $n = 2 \times 10^{11}$ cm^{-2} with a mobility of $\sim 1 \times 10^5$ cm^2/V sec.

Figure 1 illustrates the zero-bias conductance (ZBC), $G = I/V$, across the line junction and the magnetoresistance of the two-dimensional electron system parallel to the tunnel barrier. The ZBC exhibits a series of conductance peaks that oscillates with increasing magnetic field before abruptly dropping to zero above 6.7 T. No oscillatory features can be seen at higher magnetic fields. This is thought to occur from decoupling of the counterpropagating edge modes beyond the last zero-bias conductance peak [16,20–22]. Shubnikov–de Haas oscillations are found in the magnetoresistance for low magnetic fields and integer quantum Hall states beyond 2 T. The period of Shubnikov–de Haas oscillations of the two-dimensional electron systems does not match the conductance oscillations, which are sharper and more distinct than the oscillations in the magnetoresistance. The mismatch in the oscillations arises naturally as a consequence of the electronic states near the junction occurring at higher energies than the corresponding bulk states with the same quantum number [15,19]. The single particle energy levels near the barrier consist of a series of intersecting Landau levels from the left and right sides of the barrier. The uncompensated carriers beneath the barrier further shifts the energy levels in the vicinity of the tunnel barrier from that of an ideal two-dimensional electron with uniform areal density [16].

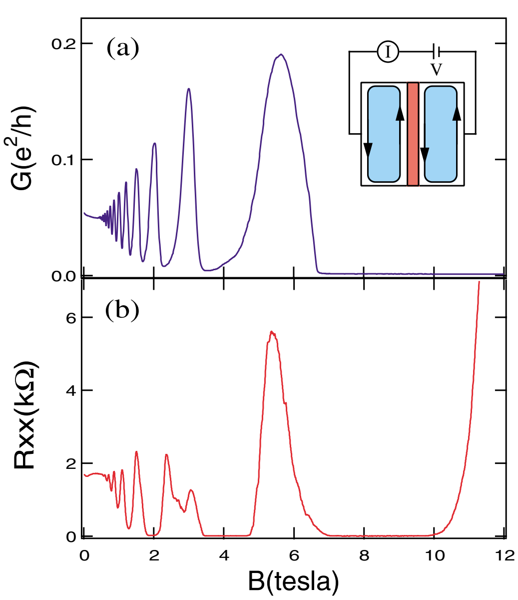

FIG. 1 (color online). (a) Representative zero-bias conductance, $G = I/V$, of the line junction at 300 mK. Inset: layout of the line junction and measurement geometry. Two counterpropagating edge states are juxtaposed against the barrier in the quantum Hall regime. (b) Magnetoresistance from one of the two-dimensional electron systems in the line junction.

In the noninteracting picture of tunneling across the line junction, the ZBC peaks occur whenever the energy levels of the left and right edges coincide with the Fermi level at zero bias. Under Landau quantization the spatial coordinate, x, corresponds to a guiding center state with a well-defined transverse momentum, k_y, through the relation $x = -k_y \ell_\circ^2$, where $\ell_\circ$ is the magnetic length. In the case of a high quality, low disorder barrier, tunneling across the junction must conserve momentum as the transverse momentum, k_y, is a good quantum number. Whenever the levels coincide, states with equal transverse momentum are mixed and electrons from one side of the barrier can tunnel over to the opposite side. The ZBC peaks consequently represent tunneling between edge states with $x = 0$ or conversely $k_y = 0$ momentum states. Since the $x = 0$ guiding center state lies at the center of the barrier, there is a large overlap of the electronic wave functions which facilitates tunneling through the barrier. Introduction of electron-electron interaction creates a tunnel gap in the energy spectrum as the gain in the correlation energy compensates for the cost of Coulomb interaction energy [16,18]. This is thought to be responsible for the enhancement in the width and height of the ZBC peaks.

Figure 2 shows the magnetic field dependence of the ZBC between 1.5 and 8.3 K. The ZBC peaks grow in amplitude with increasing magnetic field and decreasing temperature. Above 7 T, the ZBC becomes vanishingly small as the momentum conserved tunneling across the line junction can no longer be satisfied and the conduction occurs parallel to the junction, along the barrier. A striking feature of the conductance data in Fig. 2 is the series of critical points on the high field side of the conductance peaks. These critical points separate the ZBC peaks from the low conductance regions where the tunneling is largely suppressed. Interestingly, no critical points can be seen on the lower field side of the ZBC peaks. In terms of single particle levels, there are excess states above the energy level crossings on the low field side prior to the entry into the zero-bias peaks. On the other hand, electronic states are depopulated as soon as the system exits the ZBC peaks on the high field side. Consequently, the observed asymmetry may be reflecting the structure of the energy level crossings as the population of the filled states changes as a function of magnetic field. The inset of Fig. 2 illustrates the temperature dependence of ZBC at the three largest zero bias-conductance peaks. ZBC increases slowly as temperature is reduced and saturates below 1 K.

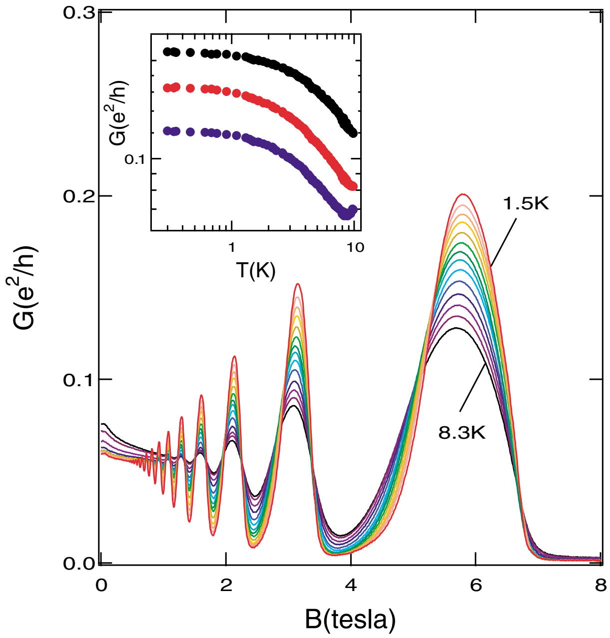

FIG. 2 (color online). Conductance of a line junction for various temperature between 1.3 and 8.5 K. Inset: temperature dependence of conductance for the first three peaks.

Figures 3(a) and 3(b) show an expanded view of the ZBC near the critical points around $B_c = 3.39$ and 6.73 T with corresponding critical conductance values of G_c of approximately $0.05e^2/h$ and $0.03e^2/h$. Immediately above (below) the critical magnetic field, B_c, ZBC decreases (increases) with temperature. Such a behavior about the critical points is reminiscent of the quantum Hall-insulator transitions in two dimensions. Figures 3(c) and 3(d) illustrate the results of the scaling analysis of the ZBC about the critical points. For both cases we find that the tunneling conductance G near B_c can be scaled as an argument of $|B - B_c|T^{-\kappa}$, where $\kappa = 0.42$. While the critical point at $B_c = 3.39$ T features a limited scaling regime and consequently a greater uncertainty in the value of the critical exponent, the extended scaling regime around $B_c = 6.73$ T and its smaller variance of the exponent provide confidence on the scaling form. Remarkably, this is the same universal scaling form and the exponent found in quantum Hall-insulator transitions in bulk two-dimensional electron systems [23].

The scaling result seen above raises a number of important questions regarding the quantum Hall line junctions, namely, (1) what is the physics behind the observed phase transitions? (2) what phases lie on either side of the critical points? and (3) what is the significance of the similarity to the quantum Hall-insulator transitions? Answers to these questions are largely unknown and require further theoretical investigation. Based on the separation of the edge states by a tunnel barrier on the order of magnetic length, it follows that the correlation of electrons on the opposite sides of the barrier should play an important role in the electronic transport across the

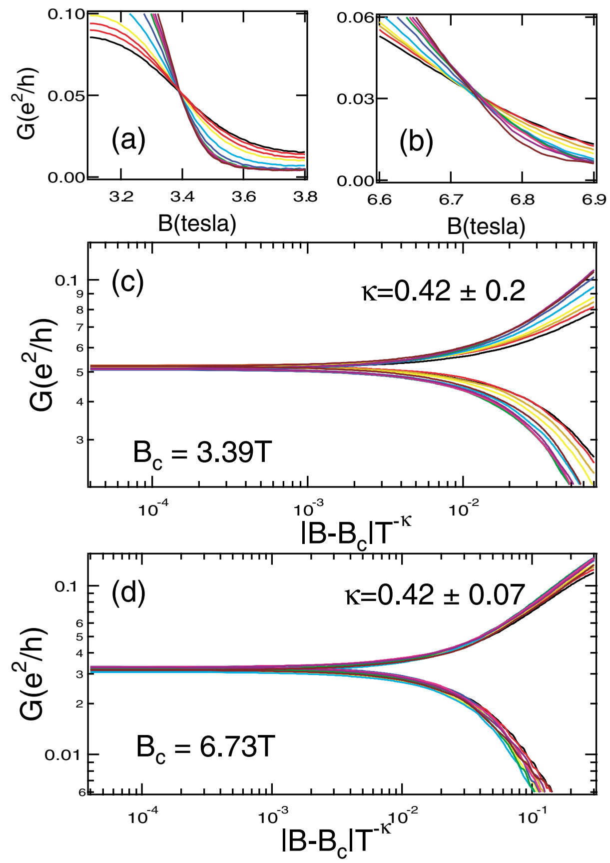

FIG. 3 (color online). Critical points and scaling analysis of the tunneling conductance. (a) Conductance data near $B_c = 3.39$ T. (b) Conductance data near $B_c = 6.73$ T. (c) Scaling analysis of the conductance data near $B_c = 3.39$ T as a function of $|B - B_c|T^{-\kappa}$. (d) Similar analysis performed for data near $B_c = 6.73$ T.

line junction. The effect of electron-electron interaction is then to transform the pair of counterpropagating edge states into ground states characterized by the interedge Luttinger correlation.

The high conductance and the low conductance regimes then represent a pair of highly correlated ground states that are separated by a quantum phase transition and that differ primarily in its ability to tunnel across the line junction. The high conductance, "metallic" phase corresponds to a state with a number of edge electrons partaking in the tunneling across the barrier and backscattering parallel to the junction. Above the critical magnetic fields, tunneling become suppressed and primary conduction now occurs parallel to the barrier in the low conductance, "insulating" phase. While the resemblance to a quantum Hall-insulator transition is suggestive of some type of quantum Hall physics, edge states are generally coupled weakly to the bulk quantum Hall states and are predominantly one dimensional in character. Whether these states possess significant enough quantum Hall correlation to produce the observed exponents remains unclear.

Although a disorder driven metal-insulator transition in a line junction has been predicted earlier [12,13], the high quality of the MBE-grown barrier and the momentum conservation in the single particle tunneling lead us to discount the likelihood of disorder playing a prominent role. The ballistic property of edge states further minimizes the possible decoherence effects associated with disorder. Based on these features of the line junction, we conclude that disorder should not be playing an appreciable role in the observed transitions.

In the theory of tunneling based on the interedge phase coherence across the line junction, the ZBC peak states are explained in terms of a broken symmetry state characterized by a tunnel gap in the energy spectrum [16]. Interaction between the left and the right edge states produces a Luttinger liquid whose symmetry is broken by a phase transition into a one-dimensional pseudospin ferromagnet. The gap in the tunnel spectrum is estimated to be $\sim$1 K in the samples with 8.8-nm-wide barrier [16,18]. As the magnetic field is switched away from the ZBC peaks, the cost in the Coulomb energy increases as the tunnel gap is reduced. The system evolves continuously until it can no longer sustain a tunnel gap. Subsequent motion of electrons occurs parallel to the barrier as tunneling is no longer possible. It remains to be seen whether such a scenario will produce a quantum phase transition with observed critical exponents.

In the model of Kim and Fradkin [22], interedge tunneling in the line junction is equivalent to a coupled one-dimensional system interacting through short range interactions. Instead of considering a continuous distribution of tunneling sites along the junction, it is postulated that the tunneling between the right- and left-moving edge modes occurs primarily through a weak tunneling center. Introduction of electron-electron interaction within the proposed framework allows for a rigorous mapping of two parallel edge channels into a coupled Luttinger liquid characterized by an effective Luttinger parameter K. Depending on the coupling constant between the left and right moving branches, there is a quantum phase transition between a state with no tunneling for $K > 1$ or perfect tunneling $K < 1$. The experimentally observed sequence of critical points represents a series of $K = 1$ quantum critical points between the strongly and weakly tunneling regimes. The sequence of critical point therefore mimics a series of opening and pinching off of the tunneling center as a function of the magnetic field. While our data are qualitatively consistent with the proposed scenario by Kim and Fradkin, further clarification of the predicted transitions and associated critical exponents is necessary.

In conclusion, we have studied the temperature dependent transport across a quantum Hall line junction. The tunnel-coupled, counterpropagating edge states produce a series of quantum critical points between the highly and weakly tunneling regimes. These critical points indicate a series of quantum phase transitions between two correlated one-dimensional ground states arising as a result of strong interedge correlation. Scaling analysis shows that the conductance near the critical behavior scales as $|B - B_c|T^{-\kappa}$, $\kappa \approx 0.42$, similar to that of quantum Hall-insulator transitions. Whether there is a strong quantum Hall correlation across the line junction or some other physics is responsible for the observed transitions remains to be explained.

We thank E. Fradkin, S. Girvin, I. Gruzberg, E. Kim, A. Ludwig, A. Mitra, H. L. Stormer, and P. Wiegmann for useful discussions. The work at the University of Chicago is supported by NSF DMR-0203679 and by NSF MRSEC Program under DMR-0213745.

[1] See the review by C. L. Kane and M. P. A. Fisher, in *Perspectives on Quantum Hall Effects*, edited by S. Das Sarma and A. Pinczuk (Wiley, New York, 1997).
[2] X. G. Wen, Phys. Rev. B, **41**, 12 838 (1990).
[3] X. G. Wen, Phys. Rev. B **43**, 11 025 (1991).
[4] C. L. Kane and M. P. A. Fisher, Phys. Rev. B **46**, 15 233 (1992); Phys. Rev. Lett. **71**, 4381 (1993).
[5] C. L. Kane and M. P. A. Fisher, Phys. Rev. Lett. **72**, 724 (1994).
[6] P. Fendley, A.W.W. Ludwig, and H. Saleur, Phys. Rev. B **52**, 8934 (1995).
[7] C. de C. Chamon and E. Fradkin, Phys. Rev. B **56**, 2012 (1997).
[8] F. P. Milliken, C. P. Umback, and R. A. Webb, Solid State Commun. **97**, 309 (1996).
[9] A. M. Chang, L. N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **77**, 2538 (1996).
[10] M. Grayson, D.C. Tsui, L. N. Pfeiffer, K.W. West, and A. M. Chang, Phys. Rev. Lett. **80**, 1062 (1998).
[11] A.V. Shytov, L. S. Levitov, and B. I. Halperin, Phys. Rev. Lett. **80**, 141 (1998).
[12] S.R. Renn and D.P. Arovas, Phys. Rev. B **51**, 16 832 (1995).
[13] C. L. Kane and M. P. A. Fisher, Phys. Rev. B **56**, 15 231 (1997).
[14] L. N. Pfeiffer, K.W. West, H. L. Stormer, J. P. Eisenstein, K.W. Baldwin, D. Gershoni, and J. Spector, Appl. Phys. Lett. **56**, 1697 (1990).
[15] W. Kang, H. L. Stormer, K. B. Baldwin, L. N. Pfeiffer, and K.W. West, Nature (London) **403**, 59 (2000).
[16] A. Mitra and S. M. Girvin, Phys. Rev. B **64**, 41309 (2001).
[17] H.C. Lee and S. R. E. Yang, Phys. Rev. B **63**, 193308 (2001).
[18] M. Kollar and S. Sachdev, Phys. Rev. B **65**, 121304 (2002).
[19] Tin-Lun Ho, Phys. Rev. B **50**, 4524 (1994).
[20] Y. Takagaki and K. H. Ploog, Phys. Rev. B **62**, 3766 (2000).
[21] S. Nonoyama and G. Kirczenow, Phys. Rev. B **66**, 155334 (2002).
[22] E. Kim and E. Fradkin, Phys. Rev. B **67**, 45317 (2003).
[23] S. L. Sondhi, S. M. Girvin, J. P. Carini, and D. Shahar, Rev. Mod. Phys. **69**, 315 (1997).