Explanation of the tunneling phenomena between the edges of two lateral quantum Hall systems

Shinji Nonoyama [a,b], George Kirczenow [a]

[a] *Department of Physics, Simon Fraser University, Burnaby, B.C., Canada V5A 1S6*

[b] *Faculty of Education, Yamagata University, Yamagata 990-8560, Japan*

Abstract

We identify the physics behind the results of recent measurements [W. Kang *et al.*, Nature **403**, 59 (2000)] of electron transfer between the edges of two two-dimensional electron systems (2DES). We find that a consistent explanation of *all* of the observed phenomena is possible if the barrier between the 2DES is surrounded by a strong potential well that supports quantum railroads of edge channels that, in the presence of disorder, exhibit directed localization.

Key words: tunneling; quantum Hall system; disorder

Measurements of quantum tunneling through a barrier between the edges of two two-dimensional electron systems (2DES) in a transverse magnetic field (see the left inset of Fig. 1(a)) have revealed a richness of puzzling phenomena [1]. The energetics of the simplest model of this system that omits disorder and electron-electron interactions is shown in Fig. 1(a). In this model, for a long, high barrier electrons having energies within the gaps that occur at Landau level crossings (see right inset of Fig. 1 (a)) are transmitted through the barrier while electrons at other energies are not [1]. As was pointed out in Ref. [1] the predictions of this simple model disagree with the data: The differential conductance peaks at zero bias that are the experimental signature of tunneling persist over ranges of magnetic field far larger than expected from the very small widths of the energy gaps. Also these peaks are observed at magnetic fields larger than predicted by factors of 2-4. More elaborate models of this system have been studied [2]. However this work assumed [2] that the 2DES's are *fully* spin polarized when the first zero-bias conductance peak (which occurs at Landau level fillings $\nu > 1$) is observed. This requires an anomalously large enhancement of the spin splitting of the 2DES. The absence of features due to spin in the data [1] is also difficult to reconcile with this assumption. Theories to date [2] have either not treated finite bias voltages at all or yielded qualitative inconsistencies with the data [1] in that regime. Here we propose an explanation of the experiment [1] that is based on the physics of directed localization in disordered 1D waveguides known as "quantum railroads" [3]. In our theory the spin splitting is smaller than the Landau level broadening and thus can be neglected as a first approximation. Unlike the previous theories [2], we explain *all* of the features of the data of Kang *et al.* [1].

We carried out computer simulations of tunneling through the barrier using a recursive Green's function technique [4,5]. We found that in the presence of disorder the tunneling takes the form of a dense array of extremely narrow transmission resonances. But at the experimental temperature [1] the individual resonances are not resolved and we find transmission peaks with widths comparable to $\hbar\omega_c$, broad enough to explain the observed persistence of the tunneling features and the absence of features due to spin in the data [1]. However the transmission maxima are not shifted significantly by disorder from the energies at which the crossings in Fig. 1 (a) occur. Thus disorder cannot by itself explain the observed positions [1] of the tunneling peaks. We therefore carried out Hartree calculations of the Landau level crossing energies assuming a positive charge

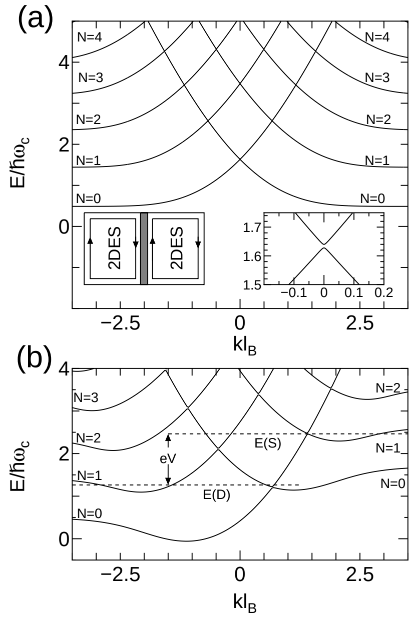

Fig. 1. Landau levels $N = 0,1,2,...$ become edge channels near barrier. a, Edge state energies E at zero bias vs. electron wave vector k along barrier in the simplest model of 2DES's and barrier. Left inset: 2DEG's, barrier and edge channels. Right inset: Energy gap at edge channel crossing. b, Edge channel energies for bias V between the 2DES's. Dashed lines are source and drain Fermi energies.

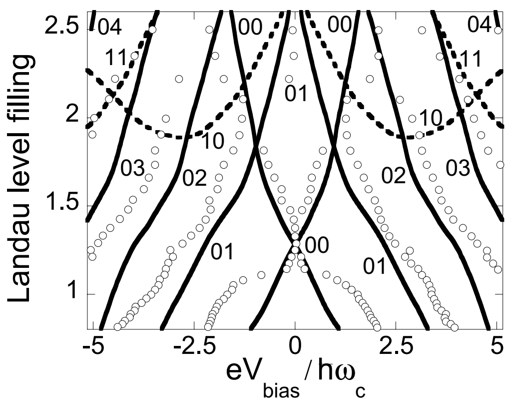

Fig. 2. Comparison of theory (curves) and maxima of measured conductance[1] (circles) for 2DEG's with density $2\times10^{11}\mathrm{cm}^{-2}$. ij indicates tunneling from (to) Landau level i(j).

density ρ to be present in the barrier such as might be introduced by doping the barrier in the plane where it was cleaved during fabrication of the sample. This yielded a downward shift of the crossings sufficient to explain the observed positions [1] of the zero bias conductance peaks for $\rho = 11 \times 10^{11} e\ \mathrm{cm}^{-2}$.

Edge channel energies calculated for this charged barrier under applied bias are shown in Fig. 1b. The energy of each edge channel now has a minimum due to the electrostatic potential well near the barrier. Therefore electrons can travel in opposite directions in edge channels on the *same* side of the barrier and thus quantum railroads exhibiting directed localization [3] are formed. The locations of the conductance maxima predicted by our calculations of the edge channel crossings are compared with the observed positions [1] of the conductance peaks in Fig. 2. Dashed (solid) curves indicate edge channel crossings at which tunneling is (not) expected to be suppressed by competition between tunneling and the interchannel- and back-scattering of electrons associated with directed localization in the quantum railroad [5]. There is an obvious one-to-one correspondence between the solid curves and the loci of experimental conductance maxima and good quantitative agreement at Landau level fillings >1.14 for positive and small negative bias. However the solid curves do not follow the bell-shaped structure at lower Landau level fillings or exhibit the asymmetry seen experimentally between positive and negative bias. We explain these deviations as manifestations of the breakdown of the quantum Hall effect (QHE): This occurs at zero bias in 2DES's with *weak* spin polarization (as in our theory) when ν falls below a value somewhat larger than 1. When the QHE breaks down the 2DES becomes resistive and the measured bias voltage acquires a contribution from the bulk of the 2DES *in addition* to that due to the barrier that is our theoretical bias voltage. Thus when the QHE breaks down the experimental bias voltage of a conductance maximum begins to exceed the theoretical one as happens abruptly below $\nu = 1.14$ in Fig. 2. This explanation of the bell structure can be tested *directly* by measuring the resistance of the 2DES. At high bias the QHE breaks down in a *sample-dependent* way at *all* values of ν. This explains why at high bias the data [1] is asymmetric and why for high bias the experimental maxima occur at somewhat higher bias values than the solid curves in Fig. 2.

We thank W. Kang for helpful correspondence. This work was supported by the Yamada Foundation (S.N.) and by the CIAR and NSERC (G.K.)

References

[1] W. Kang *et al.*, Nature **403**, 59 (2000).

[2] Y. Takagaki, K.H. Ploog, Phys. Rev. B **62**, 3766 (2000); H. C. Lee, S.-R. E. Yang,Phys. Rev. B **63**, 193308 (2001); A. Mitra, S. M. Girvin, Phys. Rev. B **64**, 041309 (2001); M. Kollar, S. Sachdev, Phys. Rev. B **65**, 121304 (2002); E.-A. Kim, E. Fradkin cond-mat/0205629.

[3] C. Barnes, B. L. Johnson and G. Kirczenow, Phys. Rev. Lett. **70**, 1159 (1993); Can. J. Phys. **72**, 559 (1994).

[4] S. Nonoyama, A. Oguri, J. Phys. Soc. Jpn **64**,3871(1995).

[5] Complete details will be presented elsewhere.