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Absorption spectroscopy in electron double layers: evidence for broken symmetry states

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Abstract

Optical absorption spectroscopy has been used to explore the phase diagram of the double layer electron system at $\nu = 1$. Absorption spectroscopy is shown to be sensitive to the evolution of the electron system from a regime in which a gap in the single-particle tunneling spectrum accounts for the quantized Hall state to a regime of weak tunneling in which inter-layer Coulomb interactions determine the nature of the excitation gap. Qualitative differences in magnetic field and temperature dependence of spectra are observed depending on the relative size of the single-particle tunneling gap. Most intriguingly, our measurements of samples in the regime of weak tunneling do not display a quenching of absorption intensity at $\nu = 1$ characteristic of the quantum Hall effect. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

A new degree of freedom, the layer index, is created when two 2D electron layers are formed in close proximity. In direct analogy with the spin-$\frac{1}{2}$ system, the layer index is associated with the eigenvalues of a double-valued pseudospin operator, S_z. In the presence of inter-layer tunneling, symmetric and antisymmetric combinations of the eigenstates of S_z can be constructed which are eigenstates of S_x and are separated by a single-particle tunneling energy gap, Δ_{SAS} $(B = 0)$. In the quantum Hall regime at $\nu = 1$, the non-interacting ground state would be a fully populated symmetric state of the spin-up branch of the lowest Landau level (LLL). In reality, the interplay of collective electron interactions and single-particle tunneling gives rise to a rich phase diagram of incompressible and compressible states for charge transport at $\nu = 1$ [1].

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Murphy et al. [1] determined the phase boundary between gapped and compressible ground states at $\nu = 1$ in double layer electron systems, and surprisingly, found that the gap in the incompressible sector survives in the limit of zero tunneling. While the ground state must evolve as the tunneling strength is reduced relative to the inter-layer Coulomb interactions, transport cannot clearly distinguish between the two regimes nor directly probe the spin or pseudospin configuration of the ground state. Presently little is experimentally known about the evolution of the ground state as the ratio of intra- to inter-layer Coulomb interactions and single-particle tunneling are modified.

In this work we describe the first measurements of optical absorption in the double layer system in the quantum Hall regime. As absorption can only occur into unoccupied levels, magneto-absorption spectroscopy can discriminate between occupied and unoccupied states in the vicinity of the Fermi level. This technique has been used previously to probe the spin configuration in the single layer system at $\nu = 1$ [2]. Our preliminary experiments in the double layer system have yielded unexpected results. In the limit of strong tunneling we observe a strong quenching of the absorption intensity of left circularly polarized light. This observation is consistent with previous studies of the single layer system and is interpreted as an optical signature of the quantum Hall effect at $\nu = 1$. In sharp contrast, in weakly tunneling samples near the phase boundary no such quenching is observed and the absorption remains finite to the lowest accessible temperatures. We emphasize that all samples discussed here exhibit strong $\nu = 1$ quantum Hall states in transport.

2. Experiment and discussion

Direct transmission spectroscopy concentrated on two samples: Sample A consists of two identical 180A GaAs quantum wells separated by a 79A $Al_{0.1}Ga_{0.9}As$ undoped barrier layer. The electron density is $6.3 \times 10^{10}\,cm^{-2}$, the mobility is $10^6\,cm^2/V\,s$, and $\Delta_{SAS} = 0.7$ meV at $B = 0$. Sample B consists of two identical 180A GaAs quantum wells separated by a 31A undoped $Al_{0.3}Ga_{0.7}As$ barrier. Its density is $1.3 \times 10^{11}\,cm^{-2}$, the mobility $10^6\,cm^2/V\,s$, and the tunneling gap is $\Delta_{SAS} = 0.4$ meV. We have also performed simultaneous transport and transmission spectroscopy, confirming not only the carrier density, but also the presence of a gap in the charged excitations at $\nu = 1$.

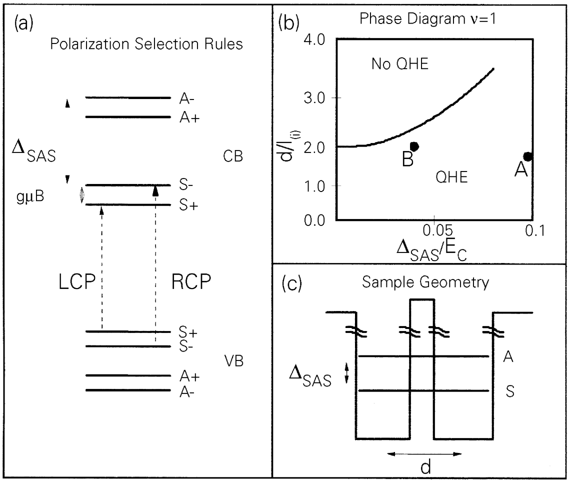

Fig. 1. (a) Polarization selection rules for inter-band absorption at $\nu = 1$. The dashed lines correspond to the two lowest-energy transitions in the left- and right-circular polarization (LCP and RCP); (b) phase diagram of in the DQW structure constructed by Murphy. The x-axis measures the tunneling gap Δ_{SAS} in units of the Coulomb energy, and the y-axis scale measures the ratio of intra-layer to inter-layer Coulomb interactions; (c) schematic of DQW structure used in these studies with the symmetric–antisymmetric gap.

Polarization selection rules for inter-band absorption at $\nu = 1$ are shown in Fig. 1a. In a single particle picture, the lowest-energy transition in LCP has its final state as the symmetric spin-up state of the LLL. Similarly in RCP, the final state is the symmetric spin-down state of the LLL. Fig. 1 also shows an approximate energy level configuration for our samples as well as their positions on the $\nu = 1$ QHE phase diagram. Fig. 2 displays the absorption in LCP into the LLL in sample A, whose tunneling gap of $\Delta_{SAS} = 0.7$ meV puts it deep into the single-particle regime and so should form a nearly fully pseudospin polarized ground state at $\nu = 1$. In the optical transmission data, the lowest-energy transition is strongly quenched as E_F passes through $\nu = 1$. This quenching is interpreted as the optical signature of a ferromagnetically aligned ground state and is reminiscent of the quenching seen in the single-layer system where the ground state is fully spin polarized at $\nu = 1$ [2]. The absorption minimum shows that the lowest-energy transition in LCP is sensitive to the ground state occupation of the symmetric spin-up level at $\nu = 1$.

Fig. 3 shows a set of spectra of the absorption for sample B in LCP at $T = 0.53$ K. Sample B has a much smaller tunneling gap ($\Delta_{\mathrm{SAS}} = 0.4$ meV, see Fig. 1) and so should be in the regime where interaction effects dominate. In striking contrast to sample A, the absorption at $\nu = 1$ for sample B shows no quenching of the lowest-energy transition, implying the existence of a finite density of available states in the spin-up electron level at $\nu = 1$.

Similarly intriguing behavior is seen in the temperature dependence of the absorption in sample B. The observation of non-zero absorption persists to the lowest accessible temperature of $T = 0.5$ K, illustrated in Fig. 4. The absorption changes dramatically as the temperature is reduced below $T = 1$ K, anomalously increasing at low temperatures, precluding a simple interpretation based on the thermal population of single-particle excitations. Large-temperature-dependent changes in the absorption are quite unusual, as previous measurements on many single [2] and double well samples have

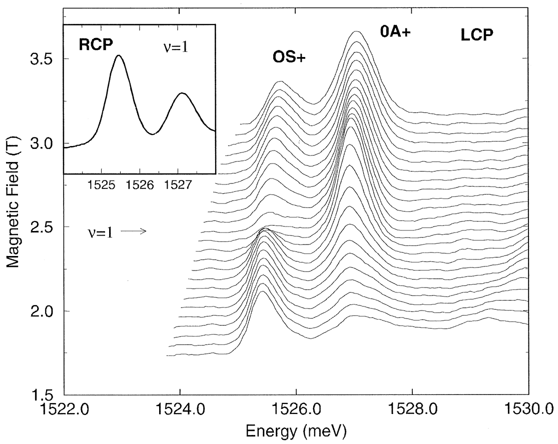

Fig. 2. Low-energy absorption in LCP at $T = 0.53$ K of sample A. The transition labeled 0A+ corresponds to absorption into the antisymmetric, spin-up state. Note the strong quenching of the lowest-energy transition exactly at $\nu = 1$. The inset displays the absorption in RCP at $\nu = 1$ and highlights the distinctly different behavior observed in the two polarizations. The ratio of 20 : 1 in absorption between RCP and LCP at 1525.5 meV indicates that the optical selection rules shown in Fig. 1 are active.

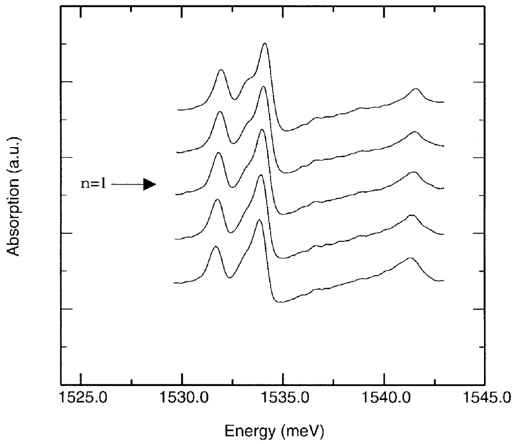

Fig. 3. Absorption in LCP for sample B at $T = 0.53$ K. The spectra are at the filling factor $\nu = 1$ with field steps of 0.05 T. Note, in sharp contrast to sample A, the lack of quenching of the lowest-energy transition at $\nu = 1$.

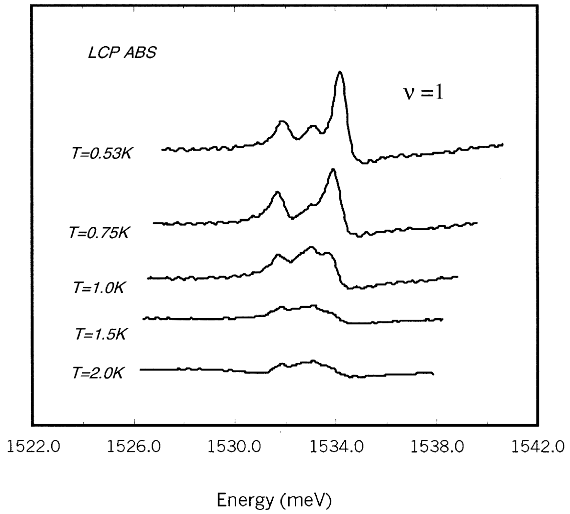

Fig. 4. Individual absorption spectra in LCP at $\nu = 1$ for sample B taken at various temperatures. The spectra change dramatically between 2 and 1 K, suggesting a rapidly evolving ground-state. Below $T = 0.8$ K the lowest-energy transitions appear activated.

shown no significant changes below 1 K. Again we emphasize that at these temperatures, sample B displays a well-developed quantum Hall state in transport.

Current theoretical work in the double layer system has focused on incomplete pseudospin polarization of the ground state at $\nu = 1$, attributed to the reduction in symmetry caused by the inter-layer Coulomb interactions [3–6]. To our knowledge, little work has been done exploring the combined roles of pseudospin and real spin at $\nu = 1$. Our data would seem to imply some unanticipated behavior in the spin degree of freedom for samples close to the $\nu = 1$ bi-layer QHE phase boundary yet within the quantum Hall regime. In lieu of a more complete theoretical understanding of our data, we note that sample B is close to the boundary of a quantum phase transition between compressible and incompressible states. Quite generally, a quantum phase transition is associated with long time scale fluctuations of the ground state configuration. Given sample B's proximity to the boundary, it is possible that the fluctuations at $\nu = 1$ are long on the time scale of our optical probe and thus absorption may be sensitive to these excursions from full polarization. We speculate that the observed lack of quenching of absorption exhibited in sample B may be associated with an impending phase transition to the compressible state. Of course, further experimental and theoretical justification is needed, not least of all a mechanism for the loss of spin polarization. Presently experiments are underway to explore samples in the compressible phase.

3. Conclusions

Absorption spectroscopy has been shown to be a powerful tool for the investigation of the double layer electron system at $\nu = 1$. For the first time we have been able to experimentally distinguish between regimes in which single-particle effects are paramount and those in which many-body interactions dominate. Our data in a weakly tunneling sample, while intriguing, remain unexplained. It suggests that correlations may be playing an unanticipated role in the formation of the quantum Hall ground state at $\nu = 1$.

Acknowledgements

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