

Chapter 1

Introduction

*This work contains many things which are new and interesting.
Unfortunately, everything that is new is not interesting, and
everything which is interesting, is not new.*

Lev Landau, not in reference to this book

Motivation

Some of the most intriguing physical phenomena, like superconductivity, superfluidity or Bose-Einstein condensation, are many-body effects. Here the interaction of the particles that constitute the physical system can change the system's behavior dramatically. Many of these effects have been discovered unintentionally in experiments which were conducted for example at very low temperatures and in very pure or very regular systems. Under such conditions, interaction effects that otherwise do not play a role and which often were not anticipated, become relevant.

Two-dimensional electron gases (2DEGs) are the ideal system for the experimentalist studying many-body effects in solid state physics. These systems are exceptionally pure and can be cooled to temperatures below 10 mK with state-of-the-art experimental setups. The fractional quantum Hall (FQH) effect is a many-body effect that has been discovered under these conditions. Electrons in a two-dimensional system exposed to a strong magnetic field interact with each other via the Coulomb interaction. It turns out that under certain conditions electrons form a collective ground state, described by a many-body wavefunction proposed by Laughlin [1]. The interacting electrons in this state can be understood as new quasiparticles, so-called composite Fermions [2]. In this description, they are only weakly interacting and have different physical properties than the original electrons. For example, the charge of the quasiparticles no longer corresponds to the original electron charge, but is only a fraction of it. Another far-reaching consequence of the correlations in a two-dimensional system is that composite particles do not behave as Fermions or Bosons. While a particle exchange of Fermions or Bosons changes the phase of the wavefunction by 0 or π , it can be any value for the quasiparticles of the fractional quantum Hall effect, making them “anyons”.

With the chase for new physics, samples have been further improved, revealing new interesting phenomena. One of the most remarkable subsequent discoveries was the $\nu=5/2$ state [3], which could no longer be understood in the framework developed for the ordinary FQH effect. A possible explanation for this groundstate suggests a BCS-like p -wave pairing of composite Fermions [4]. However, alternative less exciting explanations exist (see Sect. 3.6). The p -wave paired Moore-Read Pfaffian groundstate would possess another property, which has tremendously increased the interest in the $\nu=5/2$ state: it is believed to exhibit non-Abelian anyonic excitations. In a very simplified picture, this can be understood in the following way [5]: given an ensemble of N quasiparticles, an exchange of two quasiparticles transforms the total wavefunction to a different final state. The system is said to be non-Abelian, if performing exactly the same exchange operations in a different sequence leads to a different final state. By exchanging quasiparticles in a particular sequence, this might allow to apply a desired unitary transformation to the wavefunction, which could for example be used for quantum computation. Here, the exact trajectories on which the quasiparticles are exchanged are irrelevant and the system is protected from decoherence. Such a system is said to be “topologically protected”.

Though numerical and first experimental results favor the non-Abelian candidates for $\nu=5/2$, the definite proof is still missing. Also the nature of most of the other FQH states in the second Landau level (LL), like the $\nu=7/3$ and $\nu=8/3$ FQH states is not fully clarified yet. Given the large theoretical effort that is invested to explore the potential properties of these states, answering the open questions is one of the most important experimental tasks in the quantum Hall research community.

However, even without non-Abelian statistics, the FQH states in the second LL contain interesting many-body physics and are worth studying. The physics in the second Landau level is not only influenced by FQH states, but also by electron crystal phases which compete with the FQH states. The properties of those states are still largely unexplored and require further experimental study.

Impact of this work and outlook

An important goal of the experiments presented in this book was to investigate the properties of the FQH states in the second LL, especially the $\nu=5/2$ state. Our work intends to advance towards the realization of an interference experiment that clarifies the nature of the $\nu=5/2$ state and its potential suitability for quantum computing.

This book is the result of the first Ph.D. project conducted on the $\nu=5/2$ state in the Ensslin group at ETH Zürich by Stephan Baer. Hence we describe the experimental tasks, necessary for starting this project. For example, it was necessary to improve a dry dilution refrigerator setup for low electronic temperatures and a new low temperature cabling, filtering setup and silver cold finger had to be designed and built. Furthermore the sample processing had to be carefully checked and optimized, in order to avoid a degradation of the quality of the 2DEGs. Due to a close collaboration with the Wegscheider group, we could identify and characterize wafers that exhibit a pronounced $\nu=5/2$ state and which were suitable for the experiments conducted by us. By accomplishing these tasks we were finally able to observe the most fragile FQH states and could reach an electronic temperature of approximately

12–13 mK at a cryostat temperature of approximately 9–10 mK. Compared to the best electronic temperatures of around 50 mK that have been reached in the Ensslin group before, this is a large improvement. This preliminary work paves the way for future FQH experiments at very low temperatures in the Ensslin group. Starting from the prototype cabling and filtering employed by us, cold filtering techniques have been further improved. In the Ensslin group’s new cryostat with a base temperature of less than 3.5 mK, these developments might allow the study of even more fragile FQH states, like for example the $\nu = 12/5$ state.

Quantum point contacts (QPCs) allow a local manipulation of FQH states and are a basic building block for interferometers that try to investigate the $\nu = 5/2$ state. We have investigated the transport properties of QPCs fabricated on high-mobility electron gases. Finite-bias measurements have allowed us to investigate the confinement potential and its influence on the QPC transmission in magnetic fields. Here correlation effects show up in the transport. They arise from an interplay of the FQH states with localized states, which are described by single- or many-electron physics. In the FQH regime, disorder has a large influence on the transmission and we observe effects related to the localization of fractionally charged quasiparticles in the constriction. We have investigated the transmission properties of QPCs, which is necessary in order to be able to correctly interpret tunneling and interferometer experiments using QPCs, especially at $\nu = 5/2$.

Gating high-mobility 2DEGs is experimentally challenging and requires optimizing the gating procedure to the doping scheme of the heterostructure. By doing this, we succeeded to define QPCs, with a perfect transmission of the $\nu = 5/2$ state. We have demonstrated that this state can survive fully gapped in a top-gate defined interferometer, with an energy gap exceeding 200 mK. This is a crucial prerequisite for interference experiments at this filling factor. To our knowledge, this has not been clearly demonstrated before.

Using the gating techniques, we were able to define a QPC in a weak backscattering regime, where quasiparticle tunneling in the FQH states at $\nu = 5/2$, $7/3$ and $8/3$ could be observed. Previous experiments were only conducted with a single sample and were not fully conclusive regarding the question whether the tunneling properties at $\nu = 5/2$ favor an Abelian $(3,3,1)$ -state or the non-Abelian Anti-Pfaffian or $SU(2)_2$ -states. Hence, repeating those experiments with a different sample, fabricated with a different growth technique was desirable. Furthermore, a correct interpretation of the experiment in terms of the weak tunneling theory might depend sensitively on the experimental situation, like the backscattering strength and the local filling factor. We have addressed these open questions in detail and found that the Abelian $(3,3,1)$ - and $(1,1,3)$ -states describe our data best. Though this result is for example inconsistent with numerical findings, the quality of agreement of our data and theoretical predictions for the $(3,3,1)$ - and $(1,1,3)$ -states is astonishing. The nature of the $\nu = 8/3$ and $7/3$ states is not fully clear and non-Abelian candidate states have also been proposed here. We present the first systematic investigation of these states in a tunneling experiment. We find that the $\nu = 8/3$ state is best described by a particle-hole conjugate Laughlin state. This finding is not only relevant for $\nu = 8/3$, but is also an important crosscheck for the tunneling experiments that have investigated the $\nu = 5/2$ state. Our

quasiparticle tunneling experiments will be supplemented by further experiments at $\nu = 1/3$ and $\nu = 2/3$, which are currently being performed in the Ensslin group. These studies might reveal whether additional interaction effects which have not been taken into account in the theory modify the quasiparticle tunneling signatures.

In addition to the QPC measurements, we have performed transport measurements of large quantum dots and interferometers in magnetic fields. We have optimized charge detection techniques, which allow a time-resolved single-electron charge detection on micron-sized quantum dots, which are suitable for interference experiments in the quantum Hall regime. In order to perform charge detection on such large QDs, the sensitivity had to be greatly enhanced. We have shown how this can be accomplished using localized states. These optimized charge detection techniques might be employed in the future to study the behavior of Coulomb dominated Fabry-Pérot interferometers in the FQH regime. Here, (time-resolved) charge detection techniques might allow to study quasiparticle charges and the inner structure of edge states, which are only accessible by direct transport in very special cases. Subsequently, we have investigated such a special case: here, the transport properties of a single QD were modified due to the presence of different compressible and incompressible regions in the dot. The transport behavior of the system could be described in analogy to the physics of a double quantum dot. Our results show that the inner structure of a QD can strongly influence the charging spectrum, which is relevant for Coulomb blockade experiments trying to investigate the statistics of the $\nu = 5/2$ edge excitations. Finally, transport in top-gate defined interferometers has been investigated. Here we have used different high-mobility 2DEGs that employ different doping techniques. We have investigated the experimental problems that arise, for example due to the lack of stability of the structures. We have demonstrated how a fully gapped $\nu = 5/2$ state can be confined in a top-gate defined interferometer without destroying the quantization, by careful choice of the 2DEG in combination with gating and illumination techniques. This is one of the experimentally most challenging prerequisites for the implementation of an interference experiment at $\nu = 5/2$ and has to our knowledge not yet been clearly demonstrated in literature. Unfortunately, no interference could be found at $\nu = 5/2$. This was mainly attributed to an inappropriate QPC geometry. Implementing an optimized interferometer geometry with the techniques described by us, might in the future allow interference experiments at $\nu = 5/2$.

The physics of the second LL is not only influenced by FQH states, but also by density modulated phases corresponding to the reentrant integer quantum Hall (RIQH) effect. A better understanding of the density-modulated phases might also improve our understanding of the physics of the second Landau level as a whole. Hence we have investigated the RIQH phases in non-equilibrium transport. Due to their extreme fragility and high requirements to the sample quality, only few research groups were able to investigate those states. Because of this, many properties of these phases are still unknown and are still under experimental study. Our results suggest that either these phases are not electron-hole symmetric as expected from theory or that they possibly are of a more complicated nature than anticipated. As these phases

reside in the same LL as the $\nu=5/2$ state, such a particle-hole asymmetry might be of relevance for the physics at $\nu=5/2$ and the groundstate that is formed at this filling factor.

Organization of this book

This book is structured in five parts:

Part I gives an introduction to two-dimensional electron gases, the quantum Hall effect and edge states. We discuss the possibility of non-Abelian statistics and how this could be probed with interference experiments. Finally, we give a short overview of experiments at $\nu=5/2$ by other authors and discuss their relevance for our results and whether they are compatible with our findings.

Part II describes how the measurement setup and samples were optimized, which in the end allowed us to perform experiments with the most fragile FQH states.

Part III discusses the QPC experiments: we start with investigating transport at zero magnetic field and the QPC confinement potential. Then we turn to the question of the magnetic field transmission of QPCs and how to observe a $\nu=5/2$ state in a QPC. Finally, we discuss the quasiparticle tunneling experiments in the second LL.

Part IV shows the results of quantum dot and interferometer experiments. After a discussion of how charge detection techniques can be pushed towards the technical limit, we investigate a quantum dot, where the transport properties are strongly modified due to the presence of compressible and incompressible regions inside the dot. Then we discuss progress towards an interference experiment at $\nu=5/2$.

Part V summarizes the non-equilibrium transport measurements in the reentrant integer quantum Hall phases of the second Landau level.

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