Spin Phase Transitions in the FQHE: An NMR Study

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The spin degree of freedom in the fractional quantum Hall effect (FQHE) has produced a widespread of interesting phenomena, such as phase transitions between ground states with different spin configurations, elementary spin excitations and unanticipated interaction effects among electron spins and nuclear spins[2-4]. In the early days of the FQHE, electrons were thought to be completely polarized in the lowest Landau level, so that the spin degree of freedom is effectively frozen out. However, numerous experimental techniques have now shown that spin related effects play an essential role in our understanding of the FQHE. In this work, we focus on transitions between two ground states of different spin polarization at filling factor $\nu = 2/3$.

Spin transitions in the FQHE can be elegantly understood in the composite fermion (CF) picture[1]. In this model, the FQHE of electrons becomes the IQHE of noninteracting quasiparticles referred to as composite fermions. These quasiparticles can be viewed as electrons with an even number of magnetic flux quanta attached. They only experience an effective magnetic field B_{eff}. For example, filling factor $\nu_e = 2/3$ of electrons is equivalent to $\nu_{CF} = 2$ of composite fermions. In this case two CF Landau levels are filled, either having the same or opposite spin orientation. A transition from an unpolarized $P = 0$ to a fully polarized $P = 1$ state occurs when the CF cyclotron energy equals the Zeeman splitting. The transition is accompanied by the appearance of a small peak in the longitudinal resistance R_{xx}[2]. This peak is believed to be caused by scattering at the domain walls between regions with the two polarization values. At higher currents, the small transition peak develops into a huge peak known as the huge longitudinal resistance (HLR)[3]. Since the time it takes for the HLR to reach equilibrium is of the order of minutes, the involvement of the nuclear system is evident. Resistively detected (RD)NMR experiments demonstrate qualitatively the importance of the nuclear system in the appearance both of the HLR and the small resistance peak.

Electrons and nuclei interact via the hyperfine interaction given by the following Hamiltonian: $H_{HF} = \sum_{i;j} A\mathbf{I}_i \cdot \mathbf{S}_j$, where $A = \frac{8}{3}\pi g_0 \mu_B g_N \mu_N |\psi(0)|^2 \langle I \rangle$ is known as the hyperfine constant and $\mathbf{I}$ and $\mathbf{S}$ are the nuclear and electron spins respectively. From this equation, we can see that mostly s-type electrons take part in the interaction, since these have a non-zero probability of being localized at the nuclear sites. Whenever the nuclei are polarized, they create a local nuclear magnetic field B_N, which acts back on the electron spin, and changes its Zeeman energy E_Z. This phenomenon, known as the Overhauser effect, can be seen in transport experiments since the position of the phase transition shifts to a different value of the external magnetic field. Likewise, polarized electrons create a local magnetic field acting on the nuclear spins, causing the Knight shift of the NMR resonance frequency. This Knight shift is proportional to the electron spin polarization: $P(\nu, T) = K_s(\nu, T)/K_s(P = 1)$. Therefore NMR has proved to be an important technique to measure the electronic spin polarization of a 2 dimensional electron gas (2DEG). However, in such a system, the small number of nuclei makes it extremely difficult to carry out conventional NMR experiments. Two of the methods that have been developed to overcome this problem are optically pumped NMR (OPNMR) and the use of multiple quantum wells[4]. Even though these methods have increased the sensitivity of magnetic resonance by several orders of magnitude, they have some major drawbacks. For example in the OPNMR experiments, the nuclei must be dynamically pumped, changing the equilibrium state of the system. In the case of multiple quantum wells, only samples of lower mobilities are available and additionally the density cannot be varied by means of a gate.

Here, we present a novel method of combining RDNMR and conventional NMR experiments in order to obtain the electron spin polarization in a single quantum well. With RDNMR we observe the changes in R_{xx}, at the small current and large current (HLR) transition peaks at filling factor $\nu = 2/3$. Conventional NMR is carried out for the substrate nuclei in order to obtain a reference signal for the Larmor frequency. The difference in frequencies between the RDNMR and NMR signals is the Knight shift, which is proportional to the electron spin polarization.

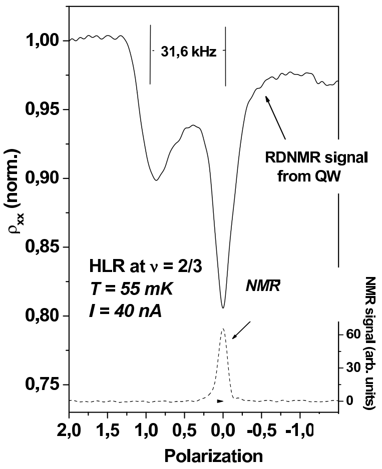

Figure 1: RDNMR spectrum of a 15 nm QW on the HLR transition at filling factor $\nu = 2/3$. The dashed line shows NMR of the substrate.

Figure 1 shows a typical RDNMR spectrum on the HLR peak. The measurements were obtained as follows: The gate voltage was swept around filling factor 2/3 until the spin unpolarized-polarized transition peak at a high current was reached. Then, both the gate and the B-field were kept constant and an HF signal was swept, monitoring the changes in R_{xx}. From the solid line, we can clearly see two lines in the RDNMR spectrum. By taking a reference signal from the substrate, we can mark the resonance frequency without a shift and observe that one of the lines of the RDNMR spectrum lies exactly at the position of the reference, while the other is shifted by $\sim$ 31.6 kHz. By using a calibration curve of Knight shift vs. density measured from a fully polarized system at $\nu = 1/2$, we can renormalize the x-axis from a frequency to a polarization axis. We can now assign a polarization to both of these lines and identify domains of $P = 0$ and $P = 1$ at the transition. This is the first spectroscopic evidence of domain formation at the transition. Experiments carried out at filling factors $\nu = 3/5$ and $\nu = 4/7$ reveal transitions from $P = 1/3$ to $P = 1$ and $P = 1/2$ to $P = 1$ respectively, as expected from the composite fermion theory.

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