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Resistively Detected NMR Study of Correlated Electrons in a GaAs Quantum Well: Fractional Quantum Hall States and More

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Abstract

Nuclear magnetic resonance (NMR) spectroscopy performed in the millikelvin temperature regime on a high-mobility two-dimensional electron system (2DES) confined to a GaAs quantum well and subjected to a strong perpendicular magnetic field is presented. Resistively detected NMR (RD-NMR) technique allows us to selectively probe ^{75}As nuclei in contact with the 2DES and thereby to deduce the spin polarization of the 2DES from the measured Knight shift. Measurements for various fractional quantum Hall liquid phases reveals the dominant role of Coulomb interaction and its marked dependence on the Landau orbital index in determining the spin polarization. Furthermore, it is shown that NMR can be a sensitive probe of not only the spin, but also the charge degree of freedom in the electron system. This becomes relevant when the electron system breaks the in-plane translational symmetry and solidifies into a periodic lattice (Wigner solid) at low partial filling, where striking anomalies in the Knight shift and spectral lineshape appear. Numerical simulations incorporating a spatially varying density landscape resulting from the formation of a Wigner solid reproduce the observed anomalies remarkably well.

1. Introduction

When the motion of electrons is restricted to a two-dimensional plane under a strong perpendicular magnetic field, the energy spectrum of the electrons is quantized into equally spaced discrete levels (Landau levels; LLs) with a macroscopic degeneracy proportional to the applied field B. In high-mobility samples with low disorder, the macroscopic degeneracy of the LLs is retained, which leads to the emergence of a variety of correlated phases at low temperatures, as exemplified by the fractional quantum Hall liquid phases, driven by the Coulomb interactions.

LLs have energies $(N + 1/2)\hbar\omega_c$, where N (= 0, 1, 2, ...) is the Landau orbital index and $\omega_c = eB/m^*$ is the cyclotron frequency (m^*: effective mass, $\hbar$: Planck's constant h divided by 2π). Each LL is further split into spin-up and spin-down levels separated by the Zeeman energy $E_Z = |g|\mu_B B$, where $\mu_B = e\hbar/2m_e$ is the Bohr magneton (m_e: electron mass in vacuum) and g is the g-factor. The ratio of the Zeeman energy to the Landau level separation $(m^*/m_e)|g|/2$, which is unity for electrons in vacuum, is significantly reduced in GaAs, by a factor of ~70 owing to the small effective mass $m^* = 0.067m_e$ and the small g-factor ($g = -0.44$). Consequently, spin remains an active degree of freedom even in high magnetic fields, as we show in this paper.

This paper presents nuclear magnetic resonance (NMR) spectroscopy in the millikelvin temperature regime performed on a high-mobility two-dimensional electron system (2DES) in a GaAs quantum well under high magnetic fields. The spin polarization of the 2DES deduced from the measured Knight shift demonstrates the dominant role of the Coulomb interaction. Furthermore, it is shown that NMR can be a sensitive probe of not only the spin, but also the charge degree of freedom in the electron system. This is demonstrate in the so-called Wigner solid regime, where the 2DES breaks the in-plane translational symmetry and solidifies into a periodic lattice.

2. Resistively detected NMR

NMR spectroscopy is one of the most powerful and sophisticated analytical tools for investigating the electronic and structural properties of matter. It exploits the resonant absorption of electromagnetic waves by nuclei placed in a strong magnetic field. By virtue of the hyperfine interaction that couples the electron spins and the nuclear spins, NMR provides information on the electron spins. When the electron system has non-zero spin polarization, it acts as an effective magnetic field exerted on the nuclear spins, which shifts the nuclear resonance frequency by a small amount (Knight shift) proportional to the electron spin polarization. Thus, the electron spin polarization can be deduced from the Knight shift of the nuclei placed in contact with the 2DES. All three nuclides, ^{69}Ga, ^{71}Ga, ^{75}As, constituting the GaAs quantum well, where the 2DES resides, have nuclear spin $I = 3/2$ and can serve as NMR probes.

The difficulty of NMR is the low signal level, which can be overcome by the technique called resistively detected NMR (RD-NMR). Instead of probing inductive signals via a pickup coil, in RD-NMR we measure the change in the electrical resistance of the sample that occurs when the applied radio-frequency (rf) wave matches the resonance frequency of the nuclei. This enables us to perform

NMR on a single sheet of a 2DES. However, since the RD-NMR signal relies on the hyperfine coupling, which transforms the nuclear spin polarization into the effective Zeeman field experienced by the electrons, it is applicable only to those electronic states that are sensitive to a tiny change in the electronic Zeeman energy.

We overcome this limitation by using a method which we call "gate-controlled RD-NMR" [1, 2]. In this method, we use a gate voltage to switch between two different electronic states, one for rf irradiation and the other for the resistive readout, which are specified by the filling factor ν and ν_{read}, respectively. (The filling factor, defined by $\nu = nh/eB$, where n is the electron density and e is the elementary charge, represents the number of occupied spin-split LLs.) That is, we measure the change in the longitudinal resistance R_{xx} of the state ν_{read} that results from the rf irradiation on the state ν. Although we measure R_{xx} of the state ν_{read}, the spectral information contained in the resultant NMR spectrum reflects only the electronic properties of the state ν. This allows us to obtain RD-NMR spectra for any electronic state accessible via gate voltage. For the resistive readout, we used the state at $\nu_{read} = 0.59$; in this range of filling factor, the electronic system is very sensitive to a small change in the Zeeman energy [3].

3. Experiment

The sample used in this study was a 100-μm-wide Hall-bar device fabricated from a heterostructure wafer containing a 27-nm-wide GaAs quantum well with $Al_{0.25}Ga_{0.75}As$ barriers grown by molecular beam epitaxy. Modulation doping with Si on the front side of the quantum well at a setback of 90 nm provided the 2DES with density $n = 1.55 \times 10^{11}$ cm^{-2} and mobility $\mu = 5.8 \times 10^{6}$ cm^2/Vs. A degenerately Si-doped GaAs buffer layer 1 μm below the 2DES served as a back gate [4], which allowed us to tune n over a wide range from 0.5×10^{11} to 4.2×10^{11} cm^{-2}. The mobility exceeded 1.0×10^{7} cm^2/Vs for $n \geq 2.8 \times 10^{11}$ cm^{-2}, reaching a maximum value of 1.15×10^{7} cm^2/Vs at $n = 3.9 \times 10^{11}$ cm^{-2}. To observe fragile fractional quantum Hall states, it is essential to control the disorder potential due to the remote ionized impurities in the Si doping layer. This was achieved by optimizing the Al composition in the barrier and the Si doping density [5] while ensuring the absence of parallel conduction or gate instability.

The sample was cooled in the mixing chamber of a dilution refrigerator with a base temperature of 10 mK. A three-turn coil was wound around the sample and connected to an rf generator. RD-NMR spectra of ^{75}As nuclei were measured at a fixed magnetic field of 6.4 T. The spectra taken at $\nu = 2$, which is spin unpolarized and thus induces no Knight shift, was used to obtain the reference for the bare resonance frequency of the ^{75}As nuclei. RD-NMR spectra were measured for various filling factors ranging from $\nu = 0$ to 8/3, accessed via a back-gate voltage. Electrical measurements are performed using a standard lock-in technique.

4. Result

Measurements at various filling factors at a fixed magnetic field reveal a contrasting behavior of the first and second LLs [2]. In the first LL, the spin polarization oscillates with ν, reflecting the properties of each fractional quantum Hall state and intervening compressible states. In contrast, the second LL remains fully polarized independent of ν, including not only the fractional quantum Hall states at ν = 5/2, 7/3, and 8/3 but also the compressible states between them. These results clearly demonstrate that spin is an active degree of freedom, and the Coulomb interaction plays a dominant role in determining the spin polarization. Our data also highlight the contrasting behavior of the first and second LLs, which points to the marked dependence of the Coulomb interaction on the Landau orbital index.

The RD-NMR spectra for the states with finite spin polarization have spectral lineshapes characterized by a sharp low-frequency onset and a long high-frequency tail. It is shown that this spectral lineshape is a result of the fact that the nuclear spins are a local probe and their Knight shift reflects the local electron density that varies along the direction normal to the quantum well. Simulations taking account of the subband wave functions of the state of interest and that used for the readout reproduce the observed lineshapes very well.

Furthermore, at low partial filling, we observe striking anomalies in the Knight shift and spectral lineshape that cannot be fitted with the model assuming a uniform 2DES. Numerical simulations incorporating a spatially varying density landscape resulting from the formation of a Wigner solid reproduce the observed anomalies remarkably well. These results demonstrate that NMR can be a sensitive probe of not only the spin, but also the charge degree of freedom in the electron system.

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