NMR Probing of the Spin Polarization of the $\nu = 5/2$ Quantum Hall State

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Resistively detected nuclear magnetic resonance is used to measure the Knight shift of the ^{75}As nuclei and determine the electron spin polarization of the fractional quantum Hall states of the second Landau level. We show that the 5/2 state is fully polarized within experimental error, thus confirming a fundamental assumption of the Moore-Read theory. We measure the electron heating under radio frequency excitation and show that we are able to detect NMR at electron temperatures down to 30 mK.

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The physics of interacting electrons at the half integer filling factor has intrigued researchers over the past two decades. It was found that the behavior at the first Landau level can be understood in terms of noninteracting composite fermions at zero magnetic field [1]. Numerous experimental findings confirm this picture and establish the formation of a nongapped state at $\nu = 1/2$. The behavior in the second Landau level is, however, fundamentally different. Early experiments, dating back to the late 1980s, show the formation of a fractional quantum Hall (FQH) state at $\nu = 5/2$ [2,3]. This observation has challenged the composite fermion theory and triggered an intense theoretical effort. Early on, Moore and Read (MR) have suggested that a weak residual attractive interaction in the second Landau level gives rise to pairing of the composite fermions and to the formation of a gapped state [4]. One of the exciting aspects of MR theory is the predicted excitation spectrum of the $\nu = 5/2$ state, which should consist of quasiparticles that obey non-Abelian braiding statistics. It was shown that this property may turn the 5/2 state into a platform for quantum computing by means of topological manipulations [5].

The examination of MR theory has become the focus of intensive experimental effort in recent years. A major support for its validity has been provided by the measurement of the quasiparticle charge, found to be $e/4$, in agreement with the prediction of the MR theory [6,7]. However, this finding is also consistent with other competing theories [1], and further experimental support is needed. The determination of the electron spin polarization can provide this needed support. A central assumption of the MR theory is that the electrons in the second Landau level are fully polarized and can, therefore, form pairs with p-type symmetry. Hence, confirming this point would provide a strong experimental evidence for the validity of the MR theory. Unfortunately, the experiments realized so far to probe the polarization at $\nu = 5/2$ have led to ambiguous results: Tilted field experiments have shown that the $\nu = 5/2$ gap decreases with the tilt angle [8,9], which could be interpreted in favor of a spin depolarized ground state. However, this behavior may also originate from the destruction of the 5/2 state induced by the orbital coupling to the parallel magnetic field [10–12]. Optical measurements also provided indications, which supported an unpolarized ground state. Raman experiments have shown diminishing of the spin flip mode and were interpreted as evidence for a partially polarized second Landau level [13]. Recently, we reported the results of photoluminescence (PL) measurements [14] that show a dip in the Zeeman splitting in the vicinity of $\nu = 5/2$ and can be interpreted as due to a spin unpolarized ground state. These experimental findings are in contrast with the results of numerical simulations, which show that the ground state should be spin polarized [10]. There are also transport data which support a spin polarized state, e.g., the observation of $\nu = 5/2$ at high magnetic fields [15] and resistively detected NMR measurements performed at a relatively high excitation power [16]. This controversy calls for further experimental work using a different experimental technique [17].

In this work, we use resistively detected nuclear magnetic resonance (NMR) to measure the Knight shift of the ^{75}As nuclei and determine the electron spin polarization of the FQH states of the second Landau level. We monitor the electron heating under radio frequency (rf) excitation and show that we are able to detect an NMR signal at electron temperatures down to 30 mK. We find that the FQH states in the second Landau level, and, in particular, the 5/2 state, are preserved under rf excitation. We show that the 5/2 state is fully polarized, thus confirming a fundamental assumption of the MR theory.

The NMR technique is a powerful tool to measure the electron spin polarization. It is based on the coupling of the electron and nuclei spins via the hyperfine interaction. In the presence of an external magnetic field, the nuclei acquire an average polarization $\langle I \rangle$ and create a local magnetic field $B_N \propto \langle I \rangle$ (Overhauser effect). B_N acts exclusively on the electronic spin and has no influence on the orbital motion of the electrons, so that the filling factor remains unchanged. The polarized electrons also create a local magnetic field B_e acting on the nuclear spins. This field reduces the Larmor resonance frequency of the nuclei by $K_S \propto n_e P$, an effect known as the Knight shift, where n_e is the local electron density and P is the electron spin polarization. Obtaining the signal from a 2D electron gas is, however, an experimental challenge, since the number of nuclei in a single quantum well is much smaller than the total number of nuclei in the bulk of the sample, and several techniques have been implemented to overcome this difficulty [18], [19]. A particularly useful technique, which generates a signal that is specific to the electrons in the well, is the resistively detected NMR [20,21]. This technique relies on the dependence of the longitudinal resistance R_{xx} on the Zeeman energy gap, which can be written as $E_Z = g\mu_B(B + B_N)$. By applying a radio frequency at the Larmor resonance frequency, it is possible to depolarize the nuclear spins, reduce the amplitude of B_N, and consequently decrease E_Z. This, in turn, results in a slight change of R_{xx}, typically of the order of a few percent.

Attempts to directly implement this technique to measure the electron spin polarization at $\nu = 5/2$ have failed; no detectable change of R_{xx} was measured throughout the quantum Hall plateau. Indeed, tilted field measurements show that the longitudinal resistance at this filling factor has a very weak dependence on E_Z [9]. One can, however, measure the Knight shift at 5/2 by quickly switching to another filling factor at which R_{xx} exhibits a strong dependence on E_Z. This idea relies on the long relaxation time of the nuclei which decay back to their original polarization on a time scale from a few tens of seconds to many minutes. It was implemented in Ref. [16] by applying short rf pulses when the system is at $\nu = 5/2$. We noticed, however, that applying these rf pulses causes a nonresonant transient response due to the heating of the electronic system and greatly degrades the signal to noise ratio for the detection. For this reason, we have developed a technique where a low rf power is *continuously* applied. The improved signal to noise ratio allows us to work at much lower rf power and, therefore, lower electronic temperature than the pulsed NMR technique of Ref. [16]. As will be shown, this reduction in the rf power is critical for the measurement.

The exact sequence used is shown in Fig. 1(a). To excite the system, the filling factor is first set to the excitation point (e.g., $\nu = 5/2$). After a short waiting time ($\simeq$ 30 ms), the radio frequency is abruptly changed during the excitation time τ_{exc}, without changing the rf power. Then, the filling factor is set to the detection point ($\nu \simeq$ 2.16); simultaneously, the radio frequency is set to an off-resonance value, and R_{xx} is measured for a time interval of τ_{det}. This sequence is repeated many times while varying the excitation radio frequency so as to sweep through the resonance. A few important considerations should be mentioned here.

(i) The sample we used is the *same* we used in our previous work, in which we measured the PL [14], and has a 4 nm PdAu top gate.

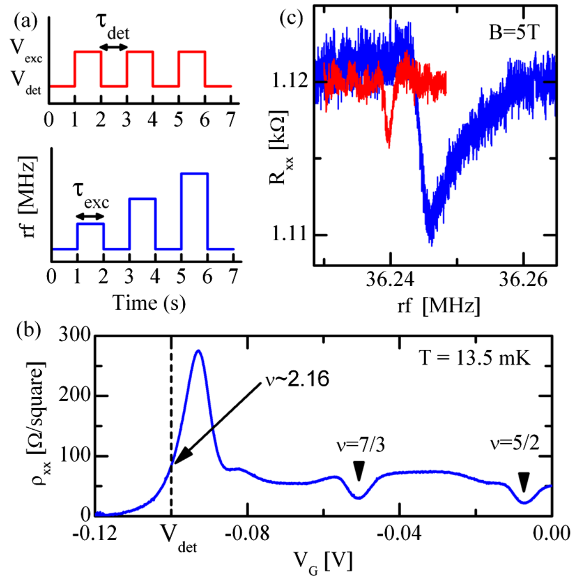

FIG. 1 (color online). (a) The NMR excitation and detection protocol as described in the text. (b) R_{xx} as a function of gate voltage showing the detection point. (c) R_{xx} versus applied radio frequency with a power of -5 dBm; under excitation at $\nu = 5/2$ and detection at $\nu = 2.16$ (red line) and a scan at the detection point (blue line). All measurements in this Letter are performed at $B = 5$ T. Note that we have a remanent field of -27 mT, which reduces the effective magnetic field to 4.973 T [23].

(ii) The detection point should be close enough to the filling factor under consideration to avoid irreversible deterioration of the quality of the FQH states that occurs under strong gating. We have selected to work at the high end of the $\nu = 2$ plateau, at $\nu \simeq 2.16$ [Fig. 1(b)]. In this region, R_{xx} exhibits a significant dependence on the Zeeman energy, and the NMR signal can be easily observed in a standard continuous wave experiment.

(iii) One should provide means for fast nuclear repolarization between frequency scans. This is effectively done by ramping the magnetic field to $\sim$11 T, at the end of each scan.

(iv) We found that the ramping of the field can induce a change of the value of the Larmor frequency of $\simeq 1$ kHz. Hence, it is essential to *always* have a point to which each scan can be compared. This is done by performing a measurement at the detection point at the end of each scan. This procedure sets a limit on the precision of measuring the Knight shift to be 300 Hz.

Figure 1(c) demonstrates the implementation of this technique. The red curve shows the R_{xx} signal under excitation at 5/2 and detection at 2.16. It is seen that a well-resolved dip with an amplitude of 4Ω appears at 36.24 MHz. The blue curve is a scan obtained by performing a regular resistively detected NMR measurement at the detection point ($\nu = 2.16$). The fact that the 5/2 dip appears at lower frequency than the signal at $\nu = 2.16$ is significant, and a qualitative conclusion can already be drawn. Since the electron polarization can only reduce the Larmor frequency ($K_S \leq 0$), it follows that the $\nu = 5/2$ FQH state cannot be fully depolarized.

Before presenting a quantitative analysis of the shift and its implications, one should verify that the observed polarization is not due to heating of the electrons by the rf power and that the FQH state still exists. Figure 2(a) shows the longitudinal resistance of the sample as the rf power is reduced, from 1 down to −14 dBm. It is seen that the resistance at 7/3 and 5/2 increases as the rf power is increased until the minima become barely visible at 1 dBm. To obtain a calibration of the electron temperature, we measured the dependence of ρ_{xx} on the bath temperature at several filling factors without rf excitation. We show in Fig. 2(b) the behavior at $\nu = 5/2$. This allows us to obtain a calibration curve of the electron temperature as a function of the rf power [Fig. 2(c)]. It is seen that at 0 dBm the electrons are heated up to 100 mK. At the lowest rf powers, the curve deviates from a linear dependence (solid line). At this regime the electron temperature is limited by the applied current (30 nA), and reducing it to 5 nA allows us to bring the electron temperature down to 33 mK. The residual heating by the rf power is demonstrated in Fig. 2(a); the lowest curve is taken without rf power and it is seen that its resistance is only slightly below that measured at −14 dBm.

To evaluate the effect of the residual heating of the electrons, one needs to estimate the 5/2 gap. The dotted line in Fig. 2(b) is a fit to $\rho_{xx} = \rho_0 + \rho_1 \exp[-\Delta/2T]$. Here $\rho_0 = 22\Omega$ is the lowest value of ρ_{xx} at zero temperature which is different than zero for this sample, $\rho_1 = 120\Omega$, and $\Delta \simeq 300$ mK. We can therefore conclude that the region below −5 dBm corresponds to the activation region, and by reducing the rf power we can determine the behavior of the spin polarization down to $T/\Delta \simeq 0.1$.

Figure 3 shows the change in resistance, ΔR, as a function of radio frequency $f - f_0$ at four filling factors: 5/3, 7/3, 5/2, and 8/3, where f_0 is the resonance frequency at $\nu = 2$. Since the $\nu = 2$ state is clearly depolarized, it will have a resonance frequency f_0 i.e., the bare (unshifted) Larmor frequency. On the other hand, the fractional quantum Hall state at $\nu = 5/3$ is the electron-hole symmetric state of $\nu = 1/3$ and is known to be fully spin polarized [22]. As we were unable to measure a convincing signal at $\nu = 2$ with our technique at low power, a calibration procedure was performed at higher rf power by using a pulsed NMR method similar to Ref. [16]. In this procedure we measured the signal at $\nu = 5/3$ to obtain the maximum possible Knight shift corresponding to a full degree of polarization. As $\nu = 5/3$ is also detected in the low power measurements, this provides a direct calibration for f_0 in our measurements [23]. Additionally, this calibration was confirmed by measurements at $\nu = 2/3$, which can serve as a reference for both fully polarized and unpolarized states due to the formation of domains [24].

From our measurements we obtain a different K_S equal to 5650 ± 75, 7750 ± 175, and 10175 ± 150 Hz for $\nu =$ 7/3, 5/2, and 8/3, respectively. In the inset in Fig. 3, we

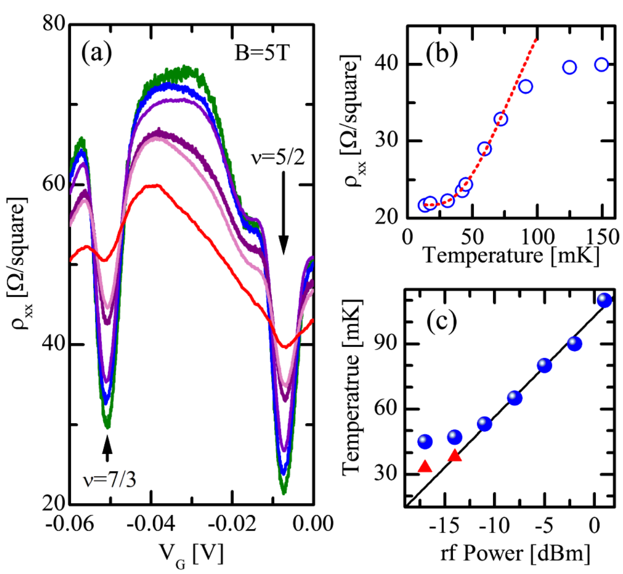

FIG. 2 (color online). (a) Resistivity ρ_{xx} at $B = 5$ T versus gate voltage V_G for various rf powers: +1, −2, −8, −11, and −14 dBm. The green curve is ρ_{xx} at $T = 13.5$ mK without rf power. (b) ρ_{xx} at filling factor $\nu = 5/2$ versus the electron temperature. The dotted red line is a fit to $\rho_{xx} = \rho_0 + \rho_1 \exp[-\Delta/2T]$ giving $\Delta \simeq 300$ mK. (c) Electron temperature versus rf power. Below −14 dBm, the temperature is limited by the current $I = 30$ nA. The red triangles correspond to $I = 5$ nA.

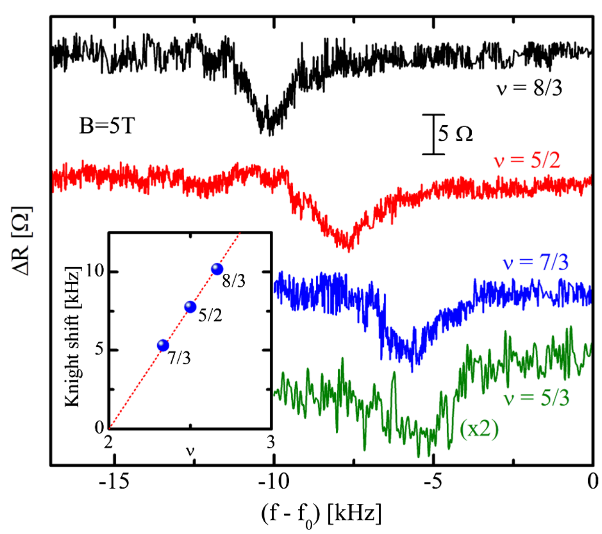

FIG. 3 (color online). Change of the longitudinal resistance ΔR as a function of radio frequency $(f - f_0)$, where f_0 is the resonance frequency at $\nu = 2$. The rf power is here −11 dBm. Inset: Knight shift as a function of the filling factor. The red dotted line corresponds to full electron polarization according to the shift obtained at $\nu = 5/3$.

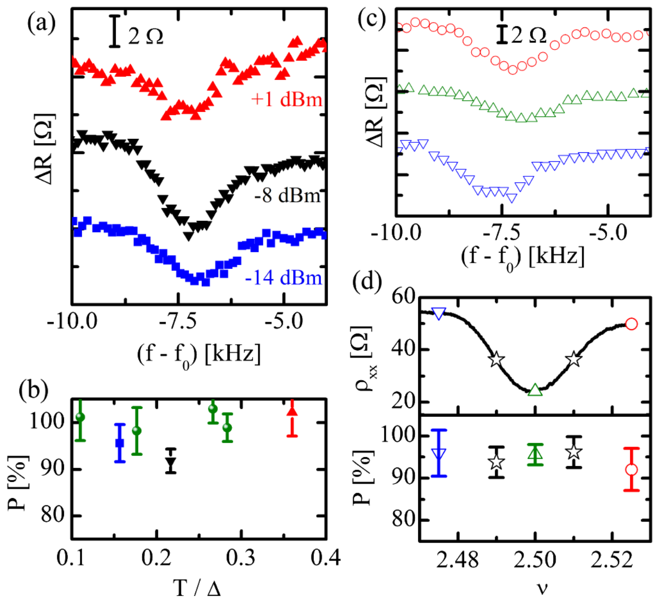

FIG. 4 (color online). (a) NMR signal at $\nu = 5/2$ for different rf powers. (b) Electron spin polarization at $\nu = 5/2$ as a function of T/Δ. To further reduce the heat load on the sample at the lowest rf powers, the current is reduced to $I = 1$ nA during the excitation phase. NMR signal (c) and the resistivity together with the electron spin polarization (d) in the vicinity of $\nu = 5/2$ at rf power -14 dBm. Note the correspondence of the symbols in (a)–(b) and in (c)–(d).

plot K_S as a function ν; remarkably, we find that they reside on a straight line, implying the same degree of spin polarization. The red line corresponds to the extrapolated value of the Knight shift for a fully polarized state according to its value at $\nu = 5/3$. We can, thus, conclude that the electrons at the second Landau level are fully polarized at the three filling factors 7/3, 5/2, and 8/3.

The full polarization at 5/2 is robust and persists throughout the temperature range that we have studied and throughout the Hall plateau, as demonstrated in Fig. 4. Figure 4(a) shows ΔR as a function of frequency for three rf powers: 1, -8, and -14 dBm, which correspond to electron temperatures of 110, 65, and 35 mK, respectively. It is readily seen that the resonance frequency does not change and the spin polarization remains constant at $0.1 < T/\Delta < 0.35$ [Fig. 4(b)]. Figures 4(c) and 4(d) show a measurement at -14 dBm in the vicinity of $\nu = 5/2$; no depolarization is observed within the 5% precision of our measurement.

Our results confirm the assumption of the MR theory that the electrons are fully polarized in the ground state. However, they seem to be in stark contradiction with the results of the photoluminescence measurements [14], which were conducted on the same sample. We note that the two measurements probe different aspects of the FQH state. The NMR measurement probes the spin polarization through its effect on the longitudinal resistance. Since the change in R_{xx} is related to tunneling through saddle points between edges at the two sides of the sample [25,26], the effect is global and is related to the average spin polarization of the whole sample. The PL measurement, on the other hand, is local in nature and samples the immediate neighborhood of the photoexcited valence hole. The results of the PL measurement imply that this local environment is depolarized. Recently, it was suggested that at $\nu = 5/2$ Skyrmions, which consist of two quasiparticles with opposite spin, tend to form in local minima of the disordered potential (formed by well width disorder or remote impurities) [27]. One can therefore imagine two possible scenarios that might explain the origin of the observed depolarization in the optical experiments. The first is that the holes are attracted to the same local minima at which Skyrmions are formed. The second is that the potential of the valence band hole, which induces a potential minima, could help forming a Skyrmion, essentially playing the same role as the disorder in Ref. [27]. In both cases, the immediate environment of the valence hole is unpolarized. We note that this is a unique property of the 5/2 state, and in this sense the optical measurement probes the Skyrmion formation.

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