NMR Determination of 2D Electron Spin Polarization at $\nu = 1/2$

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Using a "standard" NMR spin-echo technique we determined the spin polarization $\mathcal{P}$ of two-dimensional electrons, confined to GaAs quantum wells, from the hyperfine shift of Ga nuclei located in the wells. Concentrating on the temperature ($0.05 \lesssim T \lesssim 10$ K) and magnetic field ($7 \lesssim B \lesssim 17$ T) dependencies of $\mathcal{P}$ at Landau level filling factor $\nu = 1/2$, we find that the results are described well by a simple model of noninteracting composite fermions, although some inconsistencies remain when the two-dimensional electron system is tilted in the magnetic field.

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The fractional quantum Hall effect (FQHE), observed in low-disorder two-dimensional electron systems (2DESs) at low temperature T and high magnetic field B, is one of the most fascinating problems involving strongly correlated fermions. Recently, considerable attention has been focused on the FQHE ground states near half-integer Landau level filling factors ($\nu = 1/2, 3/2, \ldots$), where a large body of experimental and theoretical results can be cast in a surprisingly simple picture of *noninteracting* composite fermions (CFs) with the same charge and spin as electrons [1–3]. The simplest realization of a CF is at $\nu = 1/2$ where electrons bind two flux quanta of a fictitious Chern-Simons gauge field [3].

An important issue in the physics of CFs is the spin polarization of the 2DES at half-integer fillings. Before the remarkable success of the CF model, theoretical [4] and experimental [5] results pointed to the possibility of FQHE states with reversed spins at various fillings ($\nu = 2/3, 2/5, \ldots$). In an effort to understand the spin configurations of these states within the CF picture and, particularly, the spin polarization of the 2DES close to $\nu = 1/2$, Park and Jain [6] introduced a new parameter, the CF *polarization mass* m_p^*, which is proportional to the ratio of the cyclotron and Coulomb energies. These authors obtained an estimate for m_p^* at $\nu = 1/2$:

$$m_p^*/m_e \cong 0.60\sqrt{B_\perp}\,, \qquad (1)$$

where $B_\perp$ (in tesla) is the component of B perpendicular to the 2DES plane [7,8]. The parameter m_p^*, combined with a parabolic dispersion law for CFs at $\nu = 1/2$, uniquely determines the spin polarization $\mathcal{P}$ at any given T and B. Here we report direct measurements of the 2DES spin polarization as a function of T and B, and use our data to critically test the applicability of the noninteracting CF model and m_p^*. We find that the data are in excellent agreement with predictions of Ref. [6], except when the 2DES is tilted in B.

Nuclear magnetic resonance (NMR) is a sensitive technique for the experimental determination of the spin polarization of two-dimensional (2D) electrons [9,10]. Prior to this work, however, only the use of optically pumped NMR (OPNMR) was reported [9,10]. The reason is that the number of active nuclei in a typical 2D system is usually too small to generate a useful signal for "standard" NMR techniques. One way to increase the signal is by optical pumping: polarized electrons are excited in the conduction band by illuminating the sample with circularly polarized light and the strong hyperfine coupling ensures the transfer of this polarization to the nuclei. However, this also implies that in OPNMR experiments the electronic system is observed while nuclei are strongly polarized, well beyond their small equilibrium value. We demonstrate here that the *standard* pulsed NMR technique, applied to the Ga nuclei in GaAs/AlGaAs multiple-quantum well heterostructures does indeed provide measurable signal for $T \lesssim 10$ K. The NMR signal was observed on samples consisting of 200 quantum wells (QWs) using a state-of-the-art laboratory-built pulsed NMR spectrometer. The method we employ avoids any eventual perturbation of the system by optical pumping and the experimental setup is greatly simplified, making possible, e.g., the use of a ^{3}He/^{4}He dilution refrigerator.

Two heterostructures, M242 and M280, each composed of 100 GaAs QWs, separated by AlGaAs barriers which are Si doped near their centers, were used in this study. Sample M242 (M280) has 250 Å (300 Å) wide QWs, 1850 Å (2500 Å) thick $Al_{0.3}Ga_{0.7}As$ ($Al_{0.1}Ga_{0.9}As$) barriers, and density $n = 1.4 \times 10^{11}$ cm^{-2} (8.5×10^{10} cm^{-2}). Transport measurements on these heterostructures attest to their very high quality as they exhibit well developed FQHE states, including higher order states such as the one at $\nu = 2/5$ [11]. From each heterostructure, we cut two ≈26 mm^2 pieces and placed the two pieces together into the radio-frequency coil, so

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that experiments were done on effectively 200 QWs. For $T \gtrsim 1.5$ K, the NMR signal was recorded as a function of both B and tilt angle θ between B and the normal to the plane of the 2DES. For very low-T measurements, the radio-frequency coil was mounted into the mixing chamber of a ^{3}He/^{4}He dilution refrigerator, and measurements were performed as a function of T at fixed θ and B.

To distinguish between the contributions of Ga nuclei in QWs and barriers and to eliminate the signal from the substrate, we exploited the difference in their nuclear spin-lattice relaxation rates ($1/T_1$) [9]. The NMR pulse sequence is described in Fig. 1a: the nuclear magnetization was first set to zero by a comb of $\pi/2$ pulses. After the magnetization has recovered during time t_R, its value was measured by a spin-echo sequence ($\pi/2$-τ-π-τ-echo) [12]. The NMR spectra were obtained by Fourier transforming the spin echo (Figs. 1b and 1c). The hyperfine shift K_S of Ga nuclei located in the QWs is here defined as the frequency shift of the NMR line attributed to the QWs with respect to the barriers' line. This resonance shift is caused by the hyperfine interaction between nuclei and 2D electrons (dominated by the Fermi contact term) [9,10,12]. Note also that our QWs' NMR line is split by a small and well defined quadrupole coupling which is clearly resolved at high temperatures (Fig. 1b), confirming the high homogeneity of the 2DES.

Before focusing on the spin polarization at $\nu = 1/2$ we first discuss the results at $\nu = 1/3$. Previous OPNMR experiments [10] revealed a completely spin polarized FQHE ground state at $\nu = 1/3$. The low T ($\mathcal{P} = 1$) limit of OPNMR K_S data at $\nu = 1/3$, measured for several samples, was successfully used to determine the intrinsic hyperfine shift of Ga nuclei in the center of each QW [$K_{S\text{int}} = K_S + 1.1 \times (1 - \exp(-K_S/2.0))$] and to establish the relationship $K_{S\text{int}} = A_c \mathcal{P} n/w$, which defines the hyperfine coupling $A_c = (4.5 \pm 0.2) \times 10^{-13}$ cm^3/s (w is the QW width) [10]. Applied to our samples, these expressions yield the reference "full polarization" values $K_{S\text{int}}^{\mathcal{P}=1} \approx 12.7$ kHz for M280 and $K_{S\text{int}}^{\mathcal{P}=1} \approx 25.2$ kHz for M242 [13]. Figure 2 shows that the latter value is consistent with our very low-T data. The T dependence of these data is fitted to $K_{S\text{int}}^{\text{sat}}(\nu \cong 1/3) \tanh(\Delta_{1/3}/4k_BT)$, yielding $K_{S\text{int}}^{\text{sat}}(\nu \cong 1/3) = 21 \pm 2.5$ kHz and $\Delta_{1/3} = 1.7\Delta_Z$, in agreement with the OPNMR result $\Delta_{1/3} = 1.82\Delta_Z$ [10] and theoretical estimates $\Delta_{1/3} \approx 2\Delta_Z$ [14]. Here $\Delta_Z = |g|\mu_B B$ is the Zeeman energy, μ_B is the Bohr magneton, and $g = -0.44$ is the electron g factor in bulk GaAs.

In Fig. 3 we present the T dependence of the 2DES spin polarization at $\nu = 1/2$ at different B for our two samples. The right axes give the measured $K_{S\text{int}}$, while the deduced spin polarization, defined as $\mathcal{P}(T) = K_{S\text{int}}(T)/K_{S\text{int}}^{\mathcal{P}=1}$, is indicated on the left axes. Concentrating on the $\theta = 0°$ data (filled circles), we note that $K_{S\text{int}}$ for the high density 2DES (M242) at $B = 11.4$ T reaches the full polarization value as $T \to 0$, implying that the ground state of the 2DES is fully spin polarized at $\nu = 1/2$. On the other hand, M280 data at $B = 7.1$ T reveal that the low-T $K_{S\text{int}}$ saturates at 9.5 ± 1 kHz, below the expected $K_{S\text{int}}^{\mathcal{P}=1} \approx 12.7$ kHz for this sample. The ground state in

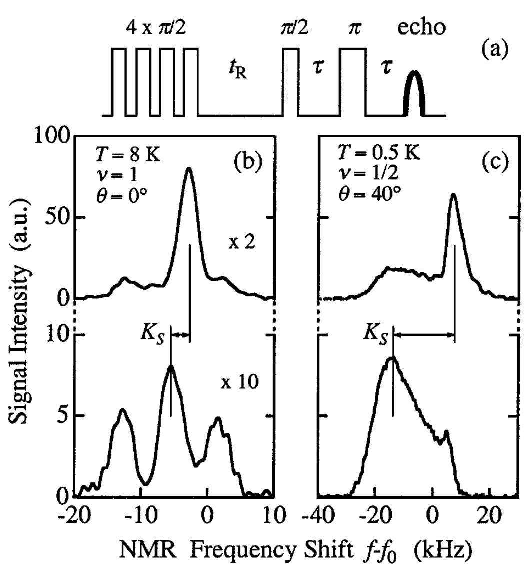

FIG. 1. (a) Pulse sequence used to detect the NMR spectra. ^{71}Ga NMR spectra taken on M242 at (b) $f_0 = 73.915$ MHz with $t_R = 256$ s (top) and 2 s (bottom) and at (c) $f_0 = 192.052$ MHz with $t_R = 128$ s (top) and 32 s (bottom). For short recovery times (lower spectra) the contribution is essentially from nuclei in QWs, while for longer times (upper spectra) barriers' signal becomes stronger than the one from QWs.

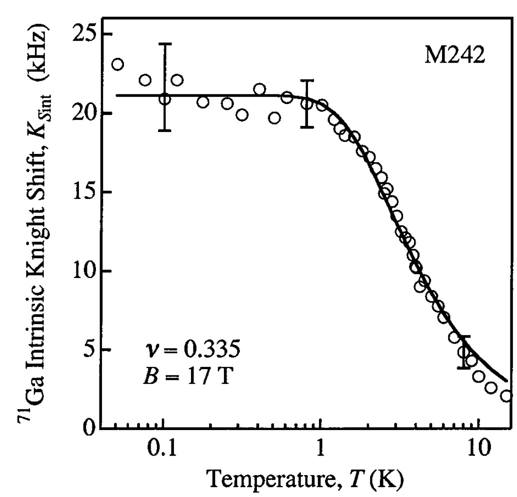

FIG. 2. ^{71}Ga intrinsic hyperfine shift ($K_{S\text{int}}$) vs T for M242 at $\theta = 0°$ and $B = 17$ T ($\nu = 0.335$). The solid curve is a fit to the data (see text). Note that the data points at low T have a larger and asymmetric error bar, showing possible greater consistency with $K_{S\text{int}}^{\mathcal{P}=1} \approx 25.2$ kHz. In our experiments, there are two factors which introduce errors near $\nu = 1/3$ and underestimate K_S at low T. While the broadening of the QWs resonance line is responsible for the larger uncertainty, the asymmetry in the error bar is due to the excessively long t_R necessary for the observation of the saturated peak position of the barriers.

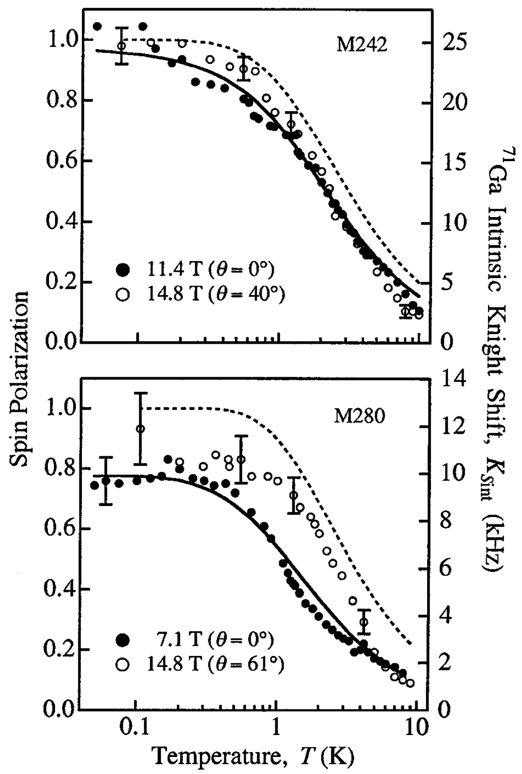

FIG. 3. $\mathcal{P}$ (left axes) and $K_{S\text{int}}$ (right axes) vs T at $\nu = 1/2$ for M242 (top panel) and M280 (bottom panel). The filled circles represent $\theta = 0°$ data and the unfilled circles represent $\theta \neq 0°$ data. In both panels the solid curves represent best fits of Eq. (2) to the $\theta = 0°$ data; these fits give $m_p^*/m_e = 2.2 \pm 0.2$ for M242 and $m_p^*/m_e = 1.7 \pm 0.2$ for M280. The dotted curves represent predictions of Eq. (2) for $B = 14.8$ T and using $m_p^* = 2.2 m_e$ (M242) and $m_p^* = 1.7 m_e$ (M280).

M280 therefore appears to be only *partially* spin polarized at $\theta = 0°$.

In the remainder of the paper we discuss how these conclusions, as well as the T dependencies reported in Fig. 3, compare to the noninteracting CF model of Ref. [6]. However, without referring to any model, we can already infer useful information from the data presented so far by considering the Zeeman energy normalized to the Coulomb energy (Δ_C) for the two samples. Here $\Delta_C = e^2/\epsilon l_B$, $\epsilon \approx 13$ is the static dielectric constant of GaAs, and $l_B = \sqrt{\hbar/eB_\perp}$ is the magnetic length. The Δ_Z/Δ_C ratio is 0.019 for M242 at $B = 11.4$ T and 0.016 for M280 at $B = 7.1$ T, implying that the 2DES becomes fully spin polarized for Δ_Z/Δ_C above a critical value which lies between 0.016 and 0.019. This conclusion is consistent with magneto-optics data [15] which yielded a critical value of 0.018 for the full spin polarization at $\nu = 1/2$.

We now attempt to understand the T dependence of $\mathcal{P}$ based on a simple model of noninteracting CFs. We assume that, consistent with previous work [1], CFs have a g factor roughly the same as electrons and consider parabolic bands occupied by n CFs with mass m_p^*. Hence, the density of states $D_\pm(E)$ (for spin-up and spin-down CFs) is $D_\pm(E) = D\vartheta(E \pm \Delta_Z/2)$, where $D = m_p^*/(2\pi\hbar^2)$ and ϑ is the step function. Making use of Fermi-Dirac distribution we find

$$\mathcal{P}(T,B) = \frac{D}{n}\left[\Delta_Z - 2k_BT \times \tanh^{-1}\left(1 + \frac{\exp(\frac{n}{Dk_BT})}{\sinh^2(\frac{\Delta_Z}{2k_BT})}\right)^{-\frac{1}{2}}\right]. \quad (2)$$

Depending on the strength of the magnetic field, this model predicts either partially or completely polarized Fermi sea of CFs in the $T \to 0$ limit, i.e., $\mathcal{P}(T = 0) = \min\{D\Delta_Z/n, 1\}$. Note that according to Eq. (2), $\mathcal{P}$ at a given T and B depends *only* on m_p^*. Taking m_p^* as a fitting parameter, in Fig. 3 we show the best fits of Eq. (2) to the $\theta = 0°$ data by solid curves. These curves indeed provide a reasonable description of the data. Moreover, the deduced m_p^* values ($2.2 m_e$ at $B = 11.4$ T and $1.7 m_e$ at $B = 7.1$ T) are found to be in excellent agreement with the polarization mass predicted by Eq. (1): $m_p^*/m_e = 2.0$ and 1.6 at $B = 11.4$ T and $B = 7.1$ T, respectively. This agreement is quite remarkable as it implies that m_p^* given by Eq. (1) together with the simple model leading to Eq. (2) give a very good account of the $\theta = 0°$ data without any adjustable parameters.

Next, we present our study of $\mathcal{P}$ in tilted magnetic fields (Figs. 3 and 4). Unfilled circles in Fig. 3 show $\nu = 1/2$ data at $\theta = 40°$ (M242) and $\theta = 61°$ (M280), taken as a function of T at $B = 14.8$ T. The data for both samples have a qualitatively similar behavior: the polarization at $\theta \neq 0°$ is larger than at $\theta = 0°$ for low and intermediate T while at highest T the measured polarization falls below the $\theta = 0°$ values. In Fig. 4 we present data, taken at $T \approx 1.5$ K, showing the dependence of $\mathcal{P}$ on B for both M242 and M280. Here the spin polarization exhibits a monotonic increase with B.

To compare these data with the predictions of the noninteracting CF model, we show in Figs. 3 and 4 plots of $\mathcal{P}(T,B)$ according to Eq. (2). Note that here there are no

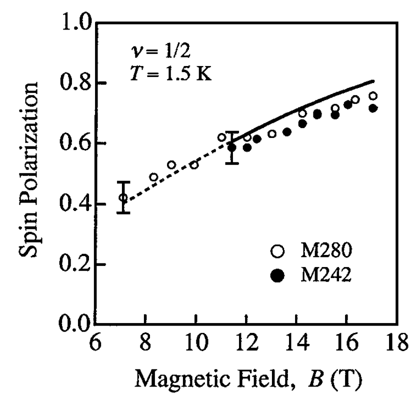

FIG. 4. $\mathcal{P}$ vs B at $\nu = 1/2$ and $T \approx 1.5$ K for M242 (•) and M280 (∘). The dotted and solid curves represent predictions of Eq. (2). The solid curve was computed with $m_p^* = 2.2 m_e$ (M242), and the dotted one with $m_p^* = 1.7 m_e$ (M280).

adjustable parameters as we used the m_p^* values obtained from the fits to the $\theta = 0°$ data. We recall that the only parameter in Eq. (2) that depends on the total magnetic field is Δ_Z. The calculated $\mathcal{P}$ (dotted curves in Fig. 3) overestimates the measured $\mathcal{P}$ over the entire T range [16]. The data taken on the high-density sample are in qualitative agreement with theory: in the low and intermediate T range both the measured and calculated $\mathcal{P}$ lie above the $\theta = 0°$ data. On the other hand, the measured $\mathcal{P}$ on the low-density sample is modestly consistent with the noninteracting CFs model as it notably falls below the calculated $\mathcal{P}$ at very low T. The data of Fig. 4, at first sight, appear to be in reasonable agreement with Eq. (2). But it is likely that this agreement is fortuitous, as it occurs at a particular intermediate temperature. Note also that in Fig. 4 the difference between the calculated curves and the data becomes larger at higher B (larger tilt angles). These observations suggest that the simple CF model leading to Eqs. (1) and (2) is not directly applicable at large θ. The deformation of the 2DES wave function at large θ may be partly responsible for this discrepancy, although we cannot rule out other possibilities.

In conclusion, we demonstrated the feasibility of the standard NMR experiments to investigate the spin polarization of the 2DES in the quantum limit. Our results in perpendicular magnetic field provide experimental support for the simplest model of $\mathcal{P}(T, B)$ at $\nu = 1/2$, based on the assumption of a parabolic dispersion law of CFs with an effective mass m_p^*.

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Note added.—As this manuscript was being completed we became aware of similar work [17] investigating the spin polarization and T_1 at $\nu = 1/2$ by OPNMR. While our conclusions are consistent with those reached from OPNMR K_S measurements, the T dependence of T_1, taken together with OPNMR K_S data, seems to support a more complex picture of strongly interacting CF.

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