Spin polarization of composite fermions and particle-hole symmetry breaking

Yang Liu,1 S. Hasdemir,1 A. Wójc,2 J. K. Jain,3 L. N. Pfeiffer,1 K. W. West,1 K. W. Baldwin,1 and M. Shayegan1
1Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA
2Institute of Physics, Wrocław University of Technology, 50-370 Wrocław, Poland
3Department of Physics, 104 Davey Lab, Pennsylvania State University, University Park, Pennsylvania 16802, USA
(Received 9 June 2014; revised manuscript received 23 July 2014; published 8 August 2014)

We study the critical spin-polarization energy (αc) above which fractional quantum Hall states in two-dimensional electron systems confined to symmetric GaAs quantum wells become fully spin polarized. We find a significant decrease of αc as we increase the well width. In systems with comparable electron layer thickness, αc for fractional states near Landau level filling ν = 3/2 is about twice larger than those near ν = 1/2, suggesting a broken particle-hole symmetry. Theoretical calculations, which incorporate Landau level mixing through an effective three-body interaction, and finite layer thickness capture certain qualitative features of the experimental results.

DOI: 10.1103/PhysRevB.90.085301
PACS numbers: 73.43.Fj, 73.21.Fg, 73.43.Nq, 73.43.Qt

A hallmark of an interacting two-dimensional electron system (2DES) subjected to a strong perpendicular magnetic field (B) is the fractional quantum Hall states (FQHs) which are observed predominantly at odd-denominator Landau level (LL) fillings ν [1,2]. They stem from the strong Coulomb interaction energy between electrons, VC = e2/4πεε0, and signal the formation of incompressible electron liquid states with strong short-range correlations (ς is the dielectric constant and ε0 = 1/4πε is the magnetic length). The composite fermion (CF) theory, in which two magnetic flux quanta are attached to each electron, maps the interacting electrons to a system of nearly noninteracting CFs [2–4], and explains many properties of FQHs. For example, CFs have their own discrete, magnetic-field-induced, orbital energy levels, the so-called A levels, whose filling factor is denoted by νCF. The integer quantum Hall states of CFs at νCF manifest as FQHSs of electrons at filling ν = νCF/(2νCF + 1) and 2 − νCF/(2νCF + 1).

The CFs also have a spin degree of freedom. In 2DESs confined to GaAs, because of the small Landé g factor (g* = −0.44), the Zeeman energy (Ez) is in fact comparable to the CF A-level separation, which is equal to a small fraction of VC. Thus, CFs might be partially spin polarized when Ez ≪ VC, and become fully spin polarized only if Ez/VC is larger than a ν-dependent critical value αC ≥ 0.02 which should be intrinsic to the 2DES and independent of the sample quality [5,6]. Moreover, in an ideal 2DES with zero layer thickness and no LL mixing, the FQHSs that have the same νCF, e.g., ν = 2/3 and 4/3 (νCF = −2), are expected to have the same αC because of particle-hole symmetry ν ↔ (2 − ν) [2]. Experimentally, the spin polarization of CFs has been probed through measurements of transitions of FQHSs in both transport and optical studies [7–21]. In these studies, Ez/VC is increased by either increasing the 2DES density or adding a parallel magnetic field. However, systematic measurements of αC on samples with controlled parameters, such as layer thickness, are scarce [21].

Here we report measurements of αC for 2DESs confined to GaAs quantum wells (QWs) and with carefully controlled, symmetric charge distributions [22]. Moreover, in our experiments, to avoid charge distribution distortions that occur when a strong parallel magnetic field is introduced, we apply only perpendicular magnetic fields, and tune the ratio Ez/VC at a fixed ν via changing the 2DES density. Our systematic measurements reveal that αC strongly depends on the charge distribution thickness. The thicker the 2DES, the smaller αC. We also find that, for a given electron layer thickness, normalized to ε0, αC is much larger for the FQHSs around ν = 3/2 compared to their particle-hole counterparts around ν = 1/2, implying that particle-hole symmetry is broken.

While the difference between the FQHSs near ν = 1/2 and 3/2 has been noticed before (see, e.g., Refs. [14,20]), it was not clear how much of the difference had to do with finite layer thickness and how much with LL mixing. We settle this issue by a systematic study of the width dependence of the transitions, which allows us to compare fractions ν and 2 − ν at the same effective thickness (width of the wave function measured in units of the magnetic length). We present calculations including LL mixing through an effective three-body interaction, which affects fractions ν and (2 − ν) differently and thus breaks the particle-hole symmetry. Our quantitative calculations show that, while the effect of LL mixing is typically small on the energy of any given FQHS, it has a substantial effect on the rather small energy differences that determine αC. The spin transitions can thus serve as a sensitive probe into the physics of LL mixing. We would like to emphasize that although the particle-hole symmetry breaking by the effective three-body interaction has been studied theoretically in conjunction with the ν = 5/2 FQHS [23–26], no quantitative comparisons with any experimental observables have been reported yet, to our knowledge.

We made measurements on 2DESs confined to 31- to 65-nm-wide GaAs QWs flanked by undoped AlGaAs spacer layers and Si δ-doped layers, which were grown by molecular beam epitaxy. The 2DESs have densities (n) ranging from 3.5 to 0.34, in units of $10^{11}$ cm$^{-2}$ which we use throughout this paper, and very high mobilities, $\mu > 1000$ to 250 m$^2$/V s. Each sample is a $4 \times 4$ mm$^2$ cleaved piece, with alloyed InSn contacts at its four corners. We fit the samples with an In back gate and Ti/Au front gate. By carefully applying the front- and back-gate voltages, we can change $n$ while keeping the QW symmetric. The measurements were carried out at temperature $T \simeq 30$ mK, and using low-frequency (<40 Hz) lock-in.
techniques. We injected a very low measurement current ~10 nA to avoid polarizing the nuclear spins which might introduce an effective nuclear field to our 2DES thus affecting the electron Zeeman splitting [15–18]. We also checked the up and down magnetic field sweeps to ensure the absence of any noticeable hysteresis.

In Fig. 1, we present longitudinal magnetoresistance (Rxx) traces for 2D electrons confined to a 65-nm-wide, GaAs QW near ν = 3/2. The density for each trace is indicated (in units of 10¹¹ cm⁻²), and traces are shifted vertically for clarity. Top inset shows the (B = 0) calculated charge distributions at n = 0.73, 1.40, and 1.94×10¹¹ cm⁻². Spin transitions of FQHSs, seen as a weakening or disappearing of Rxx minima, are marked with arrows.

FIG. 1. (Color online) Rxx traces for 2D electrons confined to a 65-nm-wide, GaAs QW near ν = 3/2. The density for each trace is indicated (in units of 10¹¹ cm⁻²), and traces are shifted vertically for clarity. Top inset shows the (B = 0) calculated charge distributions at n = 0.73, 1.40, and 1.94×10¹¹ cm⁻². Spin transitions of FQHSs, seen as a weakening or disappearing of Rxx minima, are marked with arrows.

In Fig. 2 we summarize the measured nC in the 65-nm QW for each FQHS as it becomes fully spin polarized (closed square symbols). The black dotted line represents the phase boundary above which all the FQHSs in this sample are fully spin polarized. It is clear in Fig. 2 that nC for this QW increases as |1/νCF| decreases, resulting in a “tent”-like shape for the phase boundary, with a maximum at ν = 3/2 (νCF = ∞). This behavior has been observed previously for the spin [11,14] or valley polarization [27] of the FQHSs, and is also predicted theoretically [5]. Below this boundary, FQHSs can show several transitions as the CFs become progressively more polarized with increasing E_Z/E_C [11]. An example of such multiple transitions is seen in Fig. 1, where we identify two transitions for the ν = 9/7 FQHS (νCF = 5/3) at densities n = 1.17 and 1.55, the latter corresponding to nC for the transition to a fully spin-polarized state. Note in the Fig. 2 plot that this nC is higher than nC for the ν = 4/3 FQHS, suggesting that a second tent develops around the even-denominator filling ν = 5/4. The FQHSs seen at fractional νCF correspond to higher-order CFs, and we will discuss their spin transitions elsewhere.
We performed similar experiments on the 31- and 42-nm QWs, and summarize the measured $n_C$ in Fig. 2. Clearly, $n_C$ strongly depends on the QW well width. For example, the $\nu = 7/5$ state becomes fully spin polarized when $n \gtrsim 1.25$ in the 65-nm QW, while it remains partially polarized until $n$ reaches $\approx 2.05$ in the 42-nm-QW or $\approx 3.19$ in the 31-nm QW. For the 42-nm QW, we measured $n_C$ in two different wafers with very different as-grown densities, 1.8 and 2.9, whose densities can be tuned from 1.4 to 2.0 and 2.0 to 3.0, respectively. The fact that both samples have very similar $n_C$ at $\nu = 11/7$ confirms that, for a symmetric GaAs QW with a given well width, $n_C$ for a particular FQHS spin-polarization transition is indeed an intrinsic property of the 2DES.

Figure 3 summarizes $\alpha_C$ deduced from Fig. 2 data. In Fig. 3, we also include $n_C$ reported for a GaAs/AlGaAs heterojunction sample [11]. The heterojunction sample has a very small layer thickness, typically $\approx 0.1l_B$, and is closer to an ideal, zero-thickness 2DES. It has a larger $\alpha_C$ and, in Ref. [11], an additional parallel magnetic was applied to enhance $E_Z$ and reach the transition to full spin polarization. In Fig. 3 it is clear that $\alpha_C$ decreases significantly as the 2DES layer thickness increases. As we discuss below, this strong thickness dependence of the phase boundary stems from the softening of the Coulomb interaction when the electron layer thickness becomes comparable to or larger than $l_B$.

An accurate assessment of the finite-layer-thickness effect requires taking the shape of charge distribution into account. For a semiquantitative discussion we use the simple parameter $\lambda/l_B$, where $\lambda$ is the standard deviation of the electron’s transverse position, as a measure of the thickness. To determine $\lambda$, we performed calculations of the charge distribution (at $B = 0$) by solving the Schrödinger and Poisson equations self-consistently and show examples of the resulting charge distributions above Fig. 4. Note that when the QW width is large, the 2DES has a bilayerlike charge distribution at high densities but in all cases $\lambda$ has a well-defined value. In Fig. 4, we plot our measured $\alpha_C$ as a function of $\lambda/l_B$ for the $\nu = 7/5$ FQHS. For the heterojunction sample, which has a very thin layer thickness, $\lambda/l_B \approx 0.1$, while in our QW samples, $\lambda$ is comparable to $l_B$. Figure 4 reveals that $\alpha_C$ for the $7/5$ FQHS monotonically decreases from about 0.03 in the heterojunction sample ($\lambda/l_B \approx 0.1$) to about 0.012 in the 65-nm-wide QW ($\lambda/l_B \approx 1.1$). The same trend is also seen for the other FQHSs.

In Figs. 2 and 3, we include the measured $n_C$ and $\alpha_C$ for several FQHSs near $\nu = 1/2$, namely, those at $\nu = 2/3, 3/5, 4/7, 5/9, 4/9$, and $5/11$. The data were taken in another 65-nm QW with a very low as-grown density of 0.34. The charge distribution in this low-density sample is single-layer-like and thinner than the higher density 65-nm-QW sample (see Fig. 4, top panel), so that there is less softening of the Coulomb interaction. However, instead of having a larger $\alpha_C$ compared to their particle-hole counterparts near $\nu = 3/2$, the FQHSs near $\nu = 1/2$ have about 20% smaller $\alpha_C$ (see Fig. 3). In a more quantitative comparison, when we normalize $\lambda$ to $l_B$, this discrepancy becomes even larger. This mismatch is seen vividly in Fig. 4 where we plot $\alpha_C$ for the $\nu = 3/5$ FQHS measured in heterojunction samples [10,14], and in two QWs with $W = 60$ and 65 nm. Since the $\nu = 3/5$ and 7/5 FQHSs both correspond to $\nu^{CP} = -3$, they are expected to have the same $\alpha_C$ if particle-hole symmetry holds. However, as seen...
in Fig. 4, $\alpha_C$ for $v = 3/5$ is less than half of $\alpha_C$ for $v = 7/5$ at the same $\lambda/l_B$, implying that particle-hole symmetry is broken. A difference between the spin-polarization energies for FQHSs near $v = 1/2$ and $3/2$ was also suggested in optical measurements [14]. We add that a significant difference was observed for the valley-polarization energies of the FQHSs at $v = 2/3$ and $4/3$ in 2DESs confined to AlAs QWs, and was attributed to a breaking of particle-hole symmetry, possibly because of LL mixing [28].

Next we present results of our theoretical calculations. To include the effect of finite $W$, we took $\cos^2(\pi z/W)$ as the shape of the density profile in the transverse direction, for which $\lambda \approx 0.18W$. Note that this simple model disregards the double-humped density profile for large $W$ and $n$ (see Fig. 4, top panel). We obtain the energies of the fully and partially spin-polarized states at different $\nu$ by extrapolating the finite system results to the thermodynamic limit; the resulting $\alpha_C$ is shown in Fig. 4 (solid black curve) for $\nu = 3/5$ or $7/5$. It reproduces the overall trend of decreasing $\alpha_C$ with increasing $\lambda/l_B$, as expected from a softening of the Coulomb interaction due to the finite width. A quantitative discrepancy remains, however, the sign of which depends on $\nu$.

We then include the effect of LL mixing. LL mixing modifies the two-body interaction, while also producing an effective three-body interaction (in a model that projects modifies the two-body interaction, while also producing an $\alpha$ are obtained perturbatively in $\pi z/W$, due to the finite width. A quantitative discrepancy remains, however, the sign of which depends on $\nu$.

Furthermore, an irregular size dependence makes the extrapolation to the thermodynamic limit unreliable, suggesting the need for larger systems and perhaps also for pseudopotentials beyond $m = 3$. As a result, we are not able to ascertain reliably the correction to $\alpha_C$ for $7/5$ that can be compared semi-quantitatively to experiments; nonetheless, our calculations clearly demonstrate that LL mixing causes at $7/5$ an increase in $\alpha_C$, in agreement with the experimental observation. We studied other states near $\nu = 1/2 (2/3, 3/2, 7/2, 3/3)$ and $\nu = 3/2 (8/5, 11/7, 4/3)$ and found a behavior similar to $3/5$ and $7/5$. Our results imply that LL mixing causes a significant renormalization of the polarization mass of CFs (for a fixed $\lambda/l_B$), increasing it in the vicinity of $\nu = 1/2$ but lowering it near $\nu = 3/2$.

In summary, our systematic study of 2DESs confined to symmetric GaAs QWs reveal that the critical Zeeman energies where FQHSs become fully spin polarized depend substantially on finite layer thickness and, more importantly, on LL mixing, which breaks particle-hole symmetry. Our results thus provide fundamental insight into the nature of the three-body interaction terms induced by LL mixing.

We acknowledge support from the DOE BES (Grant No. DE-FG02-00-ER45841) for measurements, and the Gordon and Betty Moore Foundation (Grant No. GBMF2719), the Keck Foundation, and the NSF (Grant No. DMR-1305691 and MRSEC Grant No. DMR-0819860) for sample fabrication. The experiments were partly performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-1157490, by the State of Florida, and by the DOE. For our theoretical work, we acknowledge the DOE Grant No. DE-SC0005042 for J.K.J., and the Polish NCN Grant No. 2011/01/B/ST3/04504 and EU Marie Curie Grant No. PCIG09-GA-2011-294186 for A.W. The computations were performed using computing facilities of the Cyfronet and WCSS, both parts of PL-Grid Infrastructure. We thank S. Hannahs, E. Palm, J. H. Park, T. P. Murphy, and G. E. Jones for technical assistance, and M. R. Peterson for sharing with us his unpublished results.


[22] In our QW samples, $\alpha_c$ shows a nontrivial dependence on the symmetry of the charge distribution, which needs to be studied carefully in the future.


[29] We use $V_{1/2,3}^{(3)} = 0.0423$ for $\lambda = 0$ (M. R. Peterson, private communication) and assume that its magnitude scales with $\lambda$ in the same fashion as $V_{3/2,3}^{(3)}$. 085301-5