Experimental Evidence for a Spin-Polarized Ground State in the $\nu = 5/2$ Fractional Quantum Hall Effect

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(Received: November 15, 2001; Revised: January 24, 2002; Published online: February 14, 2002)

We study the $\nu = 5/2$ even-denominator fractional quantum Hall effect (FQHE) state at Landau level filling factor $\nu = 5/2$ remains mysterious. Results of recent ultra-low-temperature experiments leave no doubt that this even-denominator state is a true FQHE with vanishing resistivity and Hall plateau formation. Such an even-denominator state does not fit the normal odd-denominator rule of the FQHE and requires other or additional electron correlations. An early, so-called Halpern-Brezin-Halpern (HR) model arrives at a spin-unpolarized trial wave function.

Eisenstein et al. tested the spin-polarization of the $\nu = 5/2$ state by tilted magnetic field experiments in a traditional, fixed-density sample. While the orbital motion of the electrons and hence their correlation energy ($E_o$) is subject only to the perpendicular component of the magnetic ($B$) field, the Zeeman energy ($E_z$) depends on the total $B$-field. Varying angle and $B$-field, the specimen can be kept in the $\nu = 5/2$ state while the Zeeman energy is raised. Such a procedure should leave a spin-polarized state intact, but should be detrimental to a spin-unpolarized state, once the Zeeman energy cost surmounts the gain in correlation energy. In the experiment the strength of the $\nu = 5/2$ state decreased quickly upon tilting and the state disappeared totally at $\theta \approx 50^\circ$. This was taken as evidence of a spin-singlet state at $\nu = 5/2$.

In recent years, with the advent of the composite fermion (CF) model, there has been a renewed interest in the $\nu = 5/2$ state. Moore and Read (MR) proposed a ground state of $p$-wave paired CF’s. Unlike the HR state, the MR state is spin-polarized. It is now being argued that the earlier disappearance of the $\nu = 5/2$ state under tilt may be the result of the compression of the wave function due to the in-plane component of the $B$-field. This reduction of the $z$-extend of the wave function affects electron correlation and is the cause for the gap collapse, rather than the increased Zeeman energy. Indeed, recently two tilted field experiments showed that the added in-plane magnetic field not only destroys the FQHE at $\nu = 5/2$ but also induces an electronic transport anisotropy. Theoretical modeling suggests that this is due to a phase transition from the MR pairing state to an anisotropic state and unrelated to any spin-effect. Hence, the spin-polarization of the $\nu = 5/2$ FQHE remains unresolved and there is presently little experimental input into the debate over the nature of the even-denominator FQHE state.

Here we pursue the spin-polarization of the $\nu = 5/2$ state in analogy to the tilted field experiments by investigating the competition between $E_o$ and $E_z$. Rather than tuning their ratio in a fixed density specimen by tilt, we keep the $B$-field perpendicular to the 2DES and employ a variable density specimen. Since for a fixed filling factor, such as $\nu = 5/2$, $E_z \propto n^{1/2}$, whereas $E_z \propto n$, increasing electron density modifies the ratio of $E_z$ to $E_c$. This approach is equivalent to tilting the sample, but it cannot cause a tilted-field induced phase transition. In our density-dependent experiment on the $\nu = 5/2$ state we observe a strong minimum in diagonal resistance and a developing Hall plateau even at very high electron densities, equivalent to $B$-fields as high as 12.6T. Furthermore, the strength of the energy gap varies smoothly with $B$-field. We interpret these observations as evidence for a spin-polarized ground state at $\nu = 5/2$. To perform these experiments we fabricate a HIGFET (heterojunction insulated gate field-effect transistor), in which the 2DES density can be tuned from $n = 0$ to $7.6 \times 10^{11} \text{ cm}^{-2}$ with a peak mobility $\mu = 5.5 \times 10^6$ cm$^2$/Vs.
dependence of density

highest gate-voltages and, hence, highest electron densi-

ties. In all specimens we observed qualita-
tively the same results. In this letter, we present ex-
perimental data from the specimen, which allowed for the
highest gate-voltages and, hence, highest electron densi-
ties.

The right inset of Fig. 1 shows the strictly linear de-

bility as high as $\mu$ cm$^{-2}$/Vs at $n = 3.0 \times 10^{11}$ cm$^{-2}$. The high-density limit is set by the breakdown voltage of the HIGFET and for densities much lower than $n = 3.0 \times 10^{11}$ cm$^{-2}$ the $\nu = 5/2$ state becomes weak. In Fig. 2(a)-2(c), we show the diagonal resistance $R_{xx}$ in the interval $3 > \nu > 2$ at three selected densities, $n = (3.0, 5.3, 7.6) \times 10^{11}$ cm$^{-2}$. In all cases there exists a strong minimum in $R_{xx}$ at $\nu = 5/2$. This indicates the existence of a $\nu = 5/2$ FQHE state over the whole range of density from $n = 3.0$ to $n = 7.6 \times 10^{11}$ cm$^{-2}$. The $\nu = 5/2$ FQHE state at 12.6T in Fig. 2(c) represents, to our knowledge, by far the highest $B$-field at which this state has ever been observed.

Since we are limited to standard dilution-refrigerator temperatures of $T > 30mK$, $R_{xx}$ never vanishes in our HIGFET data, in contrast to our previous ultra-low tem-

perature measurements. For this reason we cannot de-
termine the energy gap, $\Delta$, from activation energy mea-
surement. In order to quantify our results we employ an earlier method to attribute a strength, $S$, to the $R_{xx}$ minimum. $S$ is defined as the ratio of the depth of the minimum to the average around $\nu = 5/2$, $S = R_{5/2}/R_{ave}$ (see inset Fig. 3(a)). $S$ varies exponentially in temperature, $S \propto \exp(-\Delta_{quasi}/2kBT)$ and defines a quasi-energy gap, $\Delta_{quasi}$. Since $S$ measures a quantity very similar to $R_{xx}$ and is proportional to it, at least at higher temperatures, we can take $\Delta_{quasi}$ to be very similar to $\Delta$.

Fig. 3(a) shows the strength, $S$, of the $\nu = 5/2$ state versus inverse temperature $(1/T)$ for three selected den-
sities. For $n < 3.0 \times 10^{11}$ cm$^{-2}$ the $\nu = 5/2$ becomes too weak to be quantifiable in terms of $S$. On this semilog plot the data follow a linear relationship and $\Delta_{quasi}$ is readily deduced. Fig. 3(b) shows the value of $\Delta_{quasi}$ at $\nu = 5/2$ filling (solid dots) versus $B$-field. $\Delta_{quasi}$ hovers around 150mK and there is little variation over this magnetic field range. Our previous, ultra-low temperature measurement on a fixed density $(2.3 \times 10^{11}$ cm$^{-2})$ spec-
imen yielded an activation energy of $\Delta = 110$mK. A comparison between both data indicates that the value of the $\Delta_{quasi}$ is a good approximation to $\Delta$. In Fig. 3(b) $\Delta_{quasi}$ increases slightly from the smallest $B$-field to about 9T, whereupon it decays somewhat to higher fields. The dependence is smooth and no indication for any sharp transition is apparent.

From the data of Fig. 3(b) we conclude that it is unlikely that the $\nu = 5/2$ state is spin-unpolarized. At 12.6T the Zeeman energy amounts to $E_z \sim 3K$, which is more than a factor of 15 larger than the biggest energy gap ever measured for any $\nu = 5/2$ state, which typically vary from 100-200mK. The overwhelming strength of the Zeeman energy should have overcome any correlation-
induced spin-reversal and should have destroyed such a spin-unpolarized FQHE state. The smooth field-depen-
dence of $\Delta_{quasi}$ in Fig. 3(b) also indicates that no phase transition occurs in the $\nu = 5/2$ state over this field range. Therefore the polarization of the spin system re-
 mains unchanged, implying a spin-polarized state for the entire range of Fig. 3(b). For comparison we plot in the same figure the $\Delta_{quasi}$ of the $\nu = 8/5$ state, measured in the same specimen. The well-studied transition from a spin-unpolarized to a spin-polarized state expressed itself as a strongly reduced energy gap at $\sim 7.5T$ in contrast to the smooth variation of the gap at $\nu = 5/2$.

The above qualitative argument can be quantified with the help of Fig. 4. Here we plot the dependence of $E_c = \alpha e^2/\ell_B$ and $E_z = g \mu_B B$ versus $B$-field with $I_B = (\hbar c/eB)^{1/2}$ being the magnetic length, $\epsilon = 12.9$ the dielectric constant of GaAs, and $\mu_B$ the Bohr mag-
neton. We use $g = 0.44$ for the $g$-factor in GaAs and $\alpha = 0.02$ from a numerical calculation of Morf. For a spin-unpolarized state one would take the energy gap to be $\Delta = E_c - E_z$ which is represented by the difference between $E_c$ and $E_z$ in Fig. 4. $E_c$ equals $E_z$ at a critical $B$-field of $B_{crit} \sim 11T$. For higher fields the Zeeman energy exceeds the correlation energy and, in a simple model, one would expect a spin-unpolarized state to be no longer stable. With the usual uncertain-
ties in the theory and the simple nature of our model 12.6T is insufficiently far from this $B_{crit} \sim 11T$ to to-
tally rule out a spin-unpolarized ground state on this ba-
sis. However, theoretical energy gaps always exceed ex-
perimentally measured energy gaps. The reason is prob-
ably an inherent level broadening, $\Gamma$, due to disorder, which subtracts from the theoretical gap. From vari-
ous experiments this broadening is believed to be $\sim$0.5-1K for the standard high-mobility specimens and roughly magnetic-field independent within a given speci-
men. Such a broadening shrinks the range of observable gaps as indicated in Fig. 4. We have chosen $\Gamma = 0.6K$, which best reflects the value of $\Delta \sim 0.1-0.2K$ measured in most samples in the range of 3-5T. This reduces $B_{crit}$ to less than 7T, considerably lower than our highest value of 12.6T. Alternatively, in order to reflect the experimen-
eral values of $\Delta \sim 0.1-0.2\text{K}$ measured in most samples in the range of 3-5T the theoretical value for $\alpha$ may be an overestimate and consequently $\Gamma$ may be smaller than $\Gamma \sim 0.6\text{K}$. Yet, inspection of Fig. 4 shows that any such variation would only reduce the upper critical field. A theoretical value larger than $\alpha = 0.02$ is very unlikely, contrary to the trends in the experimental data and contrary to the results of other few particle numerical calculations [34]. On the basis of these comparisons one can be very confident, that the $\nu = 5/2$ FQHE state is spin-polarized over the entire density range over which it has been experimentally observed.

There remain some observations that need to be addressed. The gap of a spin-polarized system should follow the correlation energy $E_c \propto n^{1/2} \propto B^{1/2}$. The data of Fig. 3(b) initially show such a gradual increase but eventually turn around at $B \sim 9T$. The origin of this behavior is unclear, but is probably related to the increasing confinement of the electrons against the interface due to the rising gate voltage. Electron scattering from residual interface roughness increases, leading to an increase in $\Gamma$ and a deceasing energy gap for higher gate voltages and higher electron densities. (Note that such an $n$-dependent $\Gamma$ would further reduce $B_{\text{crit}}$ in Fig. 4). The decrease is not related to the population of a second subband as seen in the $B = 0$ mobility data in Fig. 1, although both occur at similar densities. In the range of the $\nu = 5/2$ state Landau quantization is operative and a simple, $B = 0$ intersubband scattering model is no longer valid. Furthermore, a comparison between Landau level splitting ($\sim 22\text{meV}$) and electrical subband splitting ($\sim 19\text{meV}$) at 12.6T indicates that the $\nu = 5/2$ state resides in the second Landau level of the lowest electrical subband, as in all previously studied, fixed-density specimens. The absence of any discontinuity of $\Delta_{\text{quasi}}$ in Fig. 3(b) indicates that this condition persists over the whole density range investigated. In any case, the existence of a $\nu = 5/2$ FQHE state, residing in the lowest Landau level of the second electrical subband is, a priori, very unlikely. Such a state is equivalent to $\nu = 1/2$, where CF’s form a fermi sea and not a CF-paired FQHE state.

In summary, in a variable-density specimen we observe a $\nu = 5/2$ FQHE state at a magnetic field as high as 12.6T. The high Zeeman energy at this $B$-field and a detailed comparison with a universal model calculation exclude a spin-uncalibrated ground state. The quasi-energy gap of the $\nu = 5/2$ FQHE varies smoothly over the whole density range from $n = 3.0$ to $7.6 \times 10^{11} \text{cm}^{-2}$, which excludes a transition between spin-polarizations. From these findings we conclude that the even-denominator $\nu = 5/2$ FQHE is spin-polarized, consistent with a Moore-Read paired CF state.

We would like to thank E. Palm and T. Murphy for experimental assistance. A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-9527035 and by the State of Florida. D.C.T. and W.P. are supported by the AFOSR, the DOE, and the NSF.

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FIG. 1. Electron mobility as a function of density, n. The left inset depicts the layer structure of the HIGFET. The right inset shows n versus V_g for the HIGFET. The solid circles (●) are experimental data.

FIG. 2. Magneto-resistance around \( \nu = 5/2 \) at three densities at \( T \sim 50 \text{mK} \). A low-frequency (\( \sim 7\text{Hz} \)) lock-in technique with excitation current \( I = 10 \text{nA} \) is used. The vertical lines mark the positions of the FQHE states at \( \nu = 8/3, 5/2, \) and 7/3.

FIG. 3. (a) Arrhenius plot for \( R_{5/2}/R_{\text{ave}} \) at three densities, in units of \( 10^{11} \text{cm}^{-2} \). (b) (●) Smooth variation of quasi-energy gap of the \( \nu = 5/2 \) FQHE state as a function of magnetic field (i.e. electron-density). (○) Collapse of the \( \nu = 8/5 \) quasi-energy gap due to the well-documented transition in its spin-polarizations.
FIG. 4. Model calculation of the energy gap at $\nu = 5/2$ as a function of magnetic field. The solid line is the Coulomb energy $e^2/\varepsilon l_B$, the dashed line is the Zeeman energy $g\mu_B B$, and the dotted line is the sum of Zeeman energy and disorder broadening, $\Gamma$, of CF’s. For discussion see text.