Experimental studies of the fractional quantum Hall effect in the first excited Landau level

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We present a spectrum of experimental data on the fractional quantum Hall effect (FQHE) states in the first excited Landau level, obtained in an ultrahigh mobility two-dimensional electron system and at very low temperatures, and report the following results. For the even-denominator FQHE states, the sample dependence of the $\nu=5/2$ state clearly shows that disorder plays an important role in determining the energy gap at $\nu=5/2$. For the developing $\nu=19/8$ FQHE state, the temperature dependence of the R_{xx} minimum implies an energy gap of $\sim$5 mK. The energy gaps of the odd-denominator FQHE states at $\nu=7/3$ and 8/3 also increase with decreasing disorder, similar to the gap at 5/2 state. Unexpectedly and contrary to earlier data on lower mobility samples, in this ultrahigh quality specimen, the $\nu=13/5$ state is missing, while its particle-hole conjugate state, the $\nu=12/5$ state, is a fully developed FQHE state. We speculate that this disappearance might indicate a spin polarization of the $\nu=13/5$ state. Finally, the temperature dependence is studied for the two-reentrant integer quantum Hall states around $\nu=5/2$ and is found to show a very narrow temperature range for the transition from quantized to classical value.

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I. INTRODUCTION

Since the discovery of the fractional quantum Hall effect (FQHE) state at Landau level filling $\nu=1/3$,[1,2] many FQHE states have been discovered[3–5] in the lowest ($N=0$) Landau level. In Table I, we have listed, to our best knowledge, all odd-denominator FQHE states that have been identified in this Landau level (boldface and lightface fonts). Remarkably, almost all these FQHE states, more than 90% (boldface font), can be mapped onto an integer quantum Hall effect (IQHE) state of composite fermions (CFs).[6–12] The remaining fractions (lightface font) which cannot be mapped onto IQHE states of CFs, are viewed as FQHE states of CFs,[13] demonstrating the importance of residual interaction between CFs.

No FQHE states have been observed in high Landau levels ($N\geqslant 2$). The additional nodes in the electron wave function in these Landau levels effectively suppress the short range electron-electron interaction and, as a result, unidirectional electron density wave state (also called "stripe phases") and Wigner-solid states of electron clusters (also termed "bubble phases") win out over the FQHE states as the ground state. When the electron temperature is raised, a melting transition from the correlated electron solid to a correlated electron liquid is observed, and evidence of FQHE states is seen at two very high Landau fillings, $\nu=21/5$ and 24/5 (underlined italic, boldface font).[14]

In the first excited ($N=1$) Landau level, which is the focus of this paper, the FQHE has been observed at even-denominators $\nu=5/2$, 7/2, and 19/8 (italic, lightface font), as well as at several odd-denominator fillings (italic black font).[15–21] Compared to the $N=0$ Landau level, the FQHE states in the $N=1$ Landau level are quite unusual. Most of them cannot be viewed as the IQHE states of CFs. The most bizarre among them and the most studied is the state at $\nu=5/2$.[22] This state does not follow the odd-denominator rule set by the initial Laughlin wave function, and today is believed to be due to paring of CFs.[23–32] In loose analogy to the formation of Cooper pairs in superconductivity,[33] this pairing of CFs creates a gapped, BCS-like ground state at $\nu=5/2$, which displays the FQHE.

TABLE I. List of FQHE states discovered to date. States with (?) have been observed as particular features in R_{xx} and/or R_{xy}, but the accuracy of their quantization has not been established.

1/3	**1/5**	**1/7**	**1/9**	**2/11**	**2/13**	**2/15**	**2/17**	**3/19**	**5/21**	**6/23**	**6/25**
2/3	**2/5**	**2/7**	**2/9**	**3/11**	**3/13**	**4/15**	**3/17**	4/19	**10/21**		
4/3	**3/5**	**3/7**	**4/9**	4/11	4/13	**7/15**	**4/17**	**5/19**			
5/3	**4/5**	**4/7**	**5/9**	**5/11**	5/13	**8/15**	5/17	**9/19**			
7/3	**6/5**	**5/7**	**7/9**	**6/11**	**6/13**	**11/15**	6/17	**10/19**			
8/3	**7/5**	**9/7**	**11/9**	7/11	**7/13**	**22/15**	**8/17**				
	8/5	**10/7**	**13/9**	**8/11**	**10/13**	**23/15**	**9/17**				
	9/5	**11/7**	**14/9**	**14/11**	**19/13**						
	11/5	**12/7**	***25/9***	**16/11**	**20/13**						
	12/5	***16/7***		**17/11**							
	13/5 (?)	***19/7***									*5/2*
	14/5										*7/2*
	14/5										*7/2*
	16/5										*3/8(?)*
	19/5										*5/8(?)*
	21/5										*19/8*
	24/5										*3/10(?)*

Besides the even-denominator FQHE states, the odd-denominator FQHE states of the $N=1$ Landau level are of interest as well. As compared to the lowest Landau level, fewer odd-denominator FQHE states are observed in the $N=1$ Landau level, and their physical origin is yet to be firmly established. For all these reasons, the physics underlying the $N=1$ FQHE states remains of great interest.[34–40] In particular, the proposal of using the conjectured non-Abelian quasiparticles of the $\nu=5/2$ FQHE states for topologically protected, fault tolerant quantum computation has created considerable excitement.[41,42] On the experimental side, results on the FQHE states in the $N=1$ Landau level have been scarce due to the extraordinary requirements on high sample quality and low electron temperature. In this paper, we present recent data, obtained in a specimen of ultrahigh electron mobility and recorded at very low temperature, which provide insight into the properties of the correlated states in the $N=1$ Landau level.

The paper is structured as follows. Section II details the sample parameters and experimental techniques. Section III presents the main experimental results and discussions. Summaries and the discussion of open issues are provided in Sec. IV.

II. SAMPLE AND EXPERIMENTAL TECHNIQUES

The specimen is a quantum well, symmetrically doped on both sides at a setback distance of 100 nm. The well width is 30 nm. The electron density, $n=3.1\times10^{11}$ cm^{-2}, and mobility, $\mu=31\times10^{6}$ cm^{2}/V s, were established after illuminating the specimen with a red light emitting diode (LED) at low temperature (T). The two-dimensional electron density differed by 1%–5% from one cool down to another. Within any given cool down, the electron density stabilized only after being kept cold ($T<0.3$ K) for ~24 h. All data were taken after this interval.

Ultralow T measurements were carried out in the same demagnetization refrigerator as in Ref. 16. Specially designed sintered silver heat exchangers were used to cool the two-dimensional electron system (2DES). The fridge temperature was monitored by a cerium magnesium nitrate thermometer, a ^{3}He melting curve thermometer, and a Pt-NMR thermometer. All measurements were performed in an ultraquiet environment, shielded from electromagnetic noise. Standard low-frequency technique (~7 Hz) was utilized to measure the magnetoresistance R_{xx} and the Hall resistance R_{xy}, with an excitation current of 1 nA.

During the course of the experiments, we found the sample state to be very sensitive to its cooling and illumination history. Several different illumination protocols were tested, such as illuminating the sample continuously from room temperature and stopping at 10, 4.2, and 1.2 K or cooling the sample in the dark and then illuminating it at 10, 4.2, and 1.2 K for 30 min. The cleanest R_{xx} and R_{xy} features were obtained by cooling the sample in the dark and then illuminating it at 4.2 K for 30 min, at an LED current of 30 μA.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Disorder in the $\nu=5/2$ fractional quantum Hall effect state

The first even-denominator FQHE state at $\nu=5/2$, discovered in 1987 (Ref. 15) and unequivocally demonstrated to be quantized in 1999,[16] remains enigmatic. Not following the initial "odd-denominator" rule of the lowest Landau level, its underlying physics has been hotly debated. At present, theory seems to gravitate toward it being a condensed state of CF pairs[22–32] with quasiparticle excitations of non-Abelian statistics,[42] the so-called "Pfaffian state." This has led to an emerging effort to exploit this system for quantum computation.[41,42] However, on the experimental side, neither

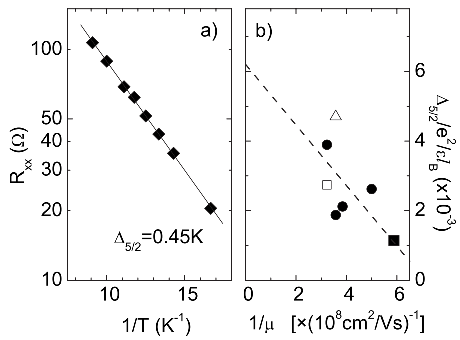

FIG. 1. (a) Arrhenius plot for the R_{xx} minimum at $\nu=5/2$. The line is a linear fit. (b) Normalized energy gap $\Delta^{\text{norm}}=\Delta_{5/2}/e^2/\varepsilon l_B$ for five samples of different mobilities. Results from Ref. 17 (open square) and Ref. 20 (open triangle) are included. The line shows a linear fit to the data points.

CF pairing nor the bizarre statistics of its quasiparticles has been demonstrated yet.

At this stage, we only have comparisons between measured and calculated energy gaps to support (or reject) the notion of a paired CF ground state at $\nu=5/2$. All previous data show an energy gap[16–18,20,43] that is much smaller than the theoretical value.[26,27] For example, a 2DES of mobility $\mu=17\times10^6$ cm^2/V s showed an energy gap of ~0.1 K (Ref. 16) which is over 1 order of magnitude smaller than the theoretical value.[26,27] In order to reconcile this difference, an *ad hoc* disorder broadening of ~2 K must be assumed,[16] which, taking up 95% of the gap, is rather unphysical and exceeds a broadening estimated from the mobility by a factor of 300. Thus, the role of disorder in determining the size of the many-body energy gap at 5/2, or in general, the stability of the 5/2 state, remains to be understood.

In the present high quality sample, the $\nu=5/2$ state is particularly strong. In fact, R_{xx} remains very small even at a temperature of ~50 mK. An energy gap of $\Delta_{5/2}\sim0.45$ K is deduced from the Arrhenius plot of Fig. 1(a) using $R_{xx} \propto \exp(-\Delta_{5/2}/2K_BT)$. This large value in a high quality specimen emphasizes the importance of residual disorder for determining the size of the $\nu=5/2$ gap.

To quantify the role of disorder, we have measured the energy gap at $\nu=5/2$ in a series of high quality samples. Table II lists the sample parameters. Figure 1(b) shows the energy gap $\Delta^{\text{norm}}=\Delta_{5/2}/e^2/\varepsilon l_B$, normalized to the strengths of the electron-electron interaction $e^2/\varepsilon l_B$, as a function of

TABLE II. Parameters of five ultrahigh mobility specimens—density, mobility, and energy gap at $\nu=5/2$.

Sample No.	Density (10^{11} cm^{-2})	Mobility (10^6 cm^2/V s)	Energy gap at $\nu=5/2$ (K)
A	3.1	31	0.45
B	3.2	28	0.22
C	2.3	26	0.24
D	3.0	20	0.26
E	2.2	17	0.11

$1/\mu$, which is proportional to $1/\tau$ and hence proportional to a lifetime broadening. In these equations, e is the electron charge, $\varepsilon=12.8$ is the dielectric constant of GaAs, and $l_B=(\hbar/eB)^{1/2}$ is the magnetic length. This plot also includes results obtained by Eisenstein *et al.*[17] and by Choi *et al.*[20] Though there is appreciable scatter in the data, clearly Δ^{norm} increases with decreasing disorder. A linear fit gives an energy gap for vanishing disorder of $\Delta_{5/2}\sim0.006$–$0.007e^2/\varepsilon l_B$.

A coefficient of 0.006–0.007 is within a factor of 2–3 of a recent theoretical calculation of $\Delta_{5/2}/e^2/\varepsilon l_B\sim0.016$.[44] Considering that the calculation[44] was carried out employing the parameters of the sample we are presenting here, and that the finite thickness of the 2DES and Landau level mixing effects[45,46] had been taken into account, this remaining difference of a factor of 2–3 seems to suggest that there exists an interplay between disorder and electron-electron interaction that goes beyond a simple level broadening. In this regard, we note that experimental energy gaps can differ significantly between very similar sample structures. For example, the sample structure, electron density, and mobility are very similar in Ref. 17 and in this work, and yet the gap data differ by 50% (Ref. 17: 0.3 K; this work: 0.45 K). This large difference suggests that mobility is not the best measure to quantify disorder in these samples and the extrapolation in Fig. 1(b) is not reliable. Other sample parameters, such as the larger scale distribution of disorder distribution, may also play a significant role.

Alternatively, the 5/2 state may not be of the Pfaffian type. In fact, a so-called "anti-Pfaffian" state was recently proposed as an alternative candidate for the ground state at $\nu=5/2$.[47,48] An energy gap has not been calculated yet for this state, but it may turn out to be closer to experiment, providing some hint as to the true correlation at 5/2.

B. Even-denominator fractional quantum Hall effect state at $\nu=19/8$

The observation of an even-denominator FQHE state at $\nu=19/8$ was first reported in Ref. 18. This state is very fragile, occurs only in very high quality samples and at very low temperatures. No other observation of the $\nu=19/8$ state has been made; therefore, its parameters in the present specimen are important to report.

Figure 2(a) shows the value of R_{xx} at the minimum of the $\nu=19/8$ state as a function of $1/T$. The data show considerable scatter at higher temperatures (T higher than ~20 mK) and develop an activated behavior at lower temperatures. The scatter of the data and the limited range of R_{xx} variation reflect the fragility of the state. A linear fitting at low temperatures [see Fig. 2(a)] yields an energy scale of ~5 mK. Considering the limited temperature range and small change in R_{xx}, the obtained ~5 mK most likely is not the true energy gap at $\nu=19/8$. Yet, higher quality specimens and lower temperatures seem to be required to address this shortcoming.

To quantify the development of the state at $\nu=19/8$ and convince ourselves further that it represents a FQHE, we compare in Fig. 2(b) the derivative of R_{xy} at $\nu=19/8$ and at $\nu=12/5$ as a function of T. The data are reproduced from

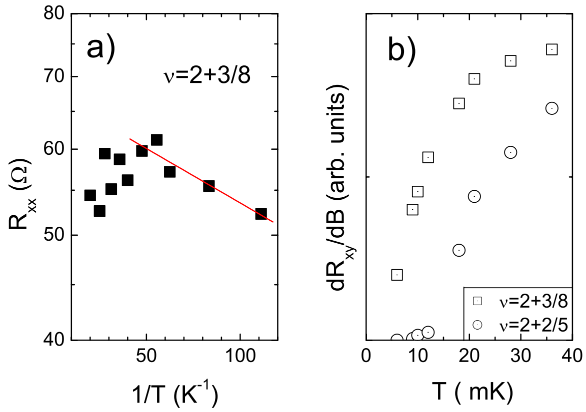

FIG. 2. (Color online) (a) Temperature dependence of the R_{xx} minimum at $\nu=19/8$. The line is a linear fit. (b) Temperature dependence of the derivative of the Hall resistance R_{xy} at $\nu=19/8$ and 12/5. This plot is reproduced from Ref. 18, with an extra data point at $T=6$ mK.

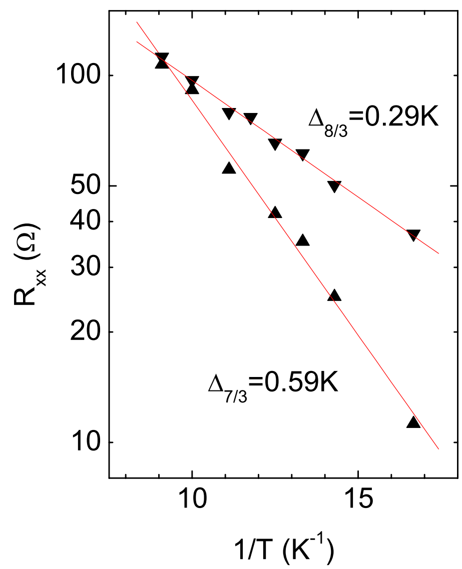

FIG. 3. (Color online) Arrhenius plot for the R_{xx} minima at $\nu=8/3$ and 7/3. Lines are linear fits.

Ref. 18, with the addition of our most recent data point at $T\sim6$ mK. Both fractions show very similar behavior, moving from their classical high temperature dR_{xy}/dB value toward the vanishing slope of a quantum Hall plateau at low temperatures. The $\nu=12/5$ state reaches this vanishing value, whereas the $\nu=19/8$ state falls slight short. Extrapolating toward $dR_{xy}/dB=0$, it appears that a temperature of $\sim$2–3 mK is required to reach a flat Hall plateau, which is consistent with the $\sim$5 mK energy scale obtained from the T dependence of R_{xx} minimum in Fig. 2(a).

At present, the origin of the $\nu=19/8$ FQHE state is unknown. We speculate that it may also be a paired CF state, similar to the state at $\nu=5/2$ state. If this were the case, the mental sequence of creating the $\nu=19/8$ (=2+3/8) state would be to first map the partially filled 3/8 state onto the $\nu^*=3/2$ state of CFs with two attached flux quanta (or ^{2}CFs), where ν^* is the effective filling factor of ^{2}CFs. Then, two additional flux quanta are attached to the ^{2}CFs in the top, half-filled CF Landau level, thus, transforming the ^{2}CFs to ^{4}CFs. Ultimately pairing of ^{4}CFs would give rise to the FQHE at $\nu=19/8$. Following this rationale, FQHE states may also exist at $\nu=9/4$ or 11/4. However, as will be shown in the following section, the $\nu=9/4$ and 11/4 states are composite fermion Fermi sea state. The reason for a different behavior at $\nu=19/8$ and $\nu=9/4$ or 11/4 may result from fact that at $\nu=19/8$, there is one fully filled CF Landau level beneath, whereas at $\nu=9/4$ and 11/4, no such fully filled CF Landau level exists. Consequently, the 19/8 CF state reflects more closely the 5/2 electron state, which is a FQHE, whereas the $\nu=9/4$ and 11/4 CF states reflect the 1/2 electron state, which is a CF Fermi sea state. As a final note, we add that a FQHE state has been observed recently at $\nu=3/8$ in the lowest Landau.[13] Several proposals as to the origin of this state have been set forward,[49–53] including p-wave pairing of CFs in the spin reversed sector[49] and clustering of composite bosons.[52] It must be left for the future experiments to determine whether there is a connection between $\nu=3/8$ and $\nu=19/8$.

C. Odd-denominator fractional quantum Hall effect states in the $N=1$ Landau level

The origin and the stability of most of the odd-denominator FQHE states in the $N=1$ Landau level remains a largely unresolved issue.[34–40] Compared to the lowest Landau level, much fewer odd-denominator FQHE states are observed in this Landau level. In fact, to date, only four, at $\nu=7/3$, 8/3, 12/5, and 14/5, are firmly established. The states at $\nu=14/5$ and 11/5 are generally believed to be of the Laughlin type.[34] The origin of the states at $\nu=7/3$ and 8/3, on the other hand, remains unclear. Earlier on, a Laughlin-type FQHE state was ruled out for these states based on small, finite size, few particles calculations.[34,54] Later calculations, with larger numbers of particles, seem to allow for a Laughlin-type sate at these filling factors.[35] This particle number dependence differs from the stability of the 1/3 state in the lowest Landau level, which is the original Laughlin state and shows incompressibility at all sizes of systems.[55]

In the $\nu=12/5$ state, a so-called parafermionic state[37] might be realized. Yet, it remains puzzling why there is no signature of a FQHE state at $\nu=13/5$, the particle-hole conjugate state of the $\nu=12/5$ state. In this section, we will present temperature dependent data at $\nu=7/3$ and 8/3 and discuss the absence of the $\nu=13/5$ state.

Figure 3 shows R_{xx} at $\nu=7/3$ and 8/3 as a function of $1/T$. The derived energy gaps are $\Delta_{7/3}=0.59$ K and $\Delta_{8/3}=0.29$ K. The relationship of $\Delta_{7/3}\sim2\Delta_{8/3}$ is unexpected, although this ratio has now been observed in two samples of very different electron density and mobility.[16] Theoretically, on the other hand, these two states are treated as electron-hole mirrors and their energy gap is therefore expected to be the same at the same B field [which roughly holds, since $(8/3)/(7/3)\sim1$]. Recent experiment performed by others on similarly high quality samples, indeed, shows activation energy gaps that are similar for 7/3 and 8/3.[20] One needs to await further low temperature data to reexamine the gap at the thirds in the first excited Landau level.

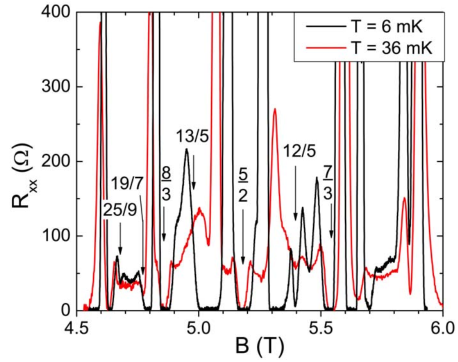

FIG. 4. (Color online) R_{xx} between $\nu=2$ and 3 at two temperatures $T\sim6$ and 36 mK. Landau level fillings are marked by arrows.

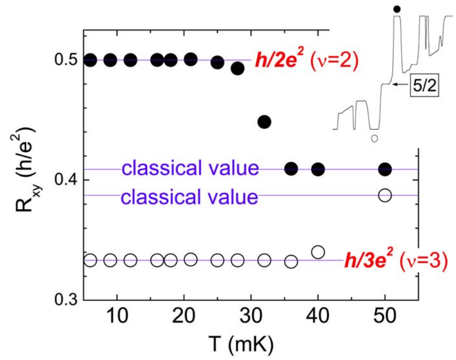

FIG. 5. (Color online) Temperature dependence of R_{xy} of the two RIQHE states around $\nu=5/2$. The horizontal lines mark the values of nearby integer Hall plateaus and the corresponding classical Hall values.

Signs of developing FQHE states are also observed at $\nu=25/9$ and, at higher temperatures, at $\nu=19/7$ (as shown in Fig. 4). The sequences around $\nu=11/4$ $(2+3/4)$, from $14/5$ $(2+4/5)$ to $25/9$ $(2+7/9)$ on the lower magnetic field (B) field side, and from $\nu=8/3$ $(2+2/3)$ to $\nu=19/7$ $(2+5/7)$ on the higher B field side, resemble those in the lowest Landau level around $\nu=3/4$. From this observation, together with an unquantized transport behavior at $\nu=11/4$, one may conclude that the state at $\nu=11/4$ is also a CF Fermi sea state. The same probably holds at its electron-hole symmetric filling factor of $\nu=9/4$.

Surprisingly, in this ultrahigh quality sample, the $\nu=13/5$ state is totally missing, while its particle-hole conjugate state at $\nu=12/5$ shows a fully developed FQHE. This is not universally observed, since in previous data, both fractions showed comparable strength.[16] To emphasize this absence of 13/5 in the present data, we show in Fig. 4 R_{xx} at two temperatures: $T\sim6$ and 36 mK. At $T\sim6$ mK, for the $\nu=12/5$ state, R_{xx} is very small and $\sim5\ \Omega$ and R_{xy} (not shown here) is precisely quantized to better than 0.02%, using R_{xy} at $\nu=5/2$ as a reference. At $T=36$ mK, R_{xx} rise to $\sim56\ \Omega$ and exhibits thermally activated behavior in between (not shown). At $\nu=13/5$, on the other hand, there is no evidence of a FQHE state at neither temperature.

The slight difference in B field at $\nu=12/5$ and $\nu=13/5$ can hardly explain the absence of the 13/5 state, given that the activation energy at $\nu=12/5$ is as large as 70 mK.[18] Alternatively, the $\nu=13/5$ state may be affected by the existence of the neighboring reentrant integer quantum Hall state (RIQHE) at $\nu\sim2.56$. However, signs of a weaker FQHE state usually are observable at higher temperatures when the earlier overpowering state subsides in strength. This is not the case here, as can be seen in Fig. 4, at $T\sim36$ mK, where, in spite of the weakness of the RIQHE, there is no sign of a $\nu=13/5$ FQHE state, while $\nu=12/5$ is well developed. Toward a third explanation, we recall the existence of a $\nu=13/5$ state, as strong as the $\nu=12/5$ state, in previous experiment,[16] in a specimen of smaller electron density and thus at smaller B field, which favors spin flips. The absence or presence of a $\nu=13/5$ state may therefore be spin related, with a transition from a spin unpolarized (or partially polarized) at small B fields to a spin-polarized state around $B\sim5$ T. Of course, there are other effects that may lead to the breaking of particle-hole symmetry and thus to a disappearance of the $\nu=13/5$ state, such as Landau leveling mixing or finite thickness.[56] Indeed, the sample of Ref. 16 is a single heterojunction, while the sample of Ref. 18 is a quantum well, and this may affect which of these weak FQHE states can be observed.

D. Temperature dependence of the reentrant integer quantum Hall effect states around $\nu=5/2$

In the $N=1$ Landau level between $\nu=2$ and 3, aside from the FQHE states, another distinguishing feature is the so-called reentrant IQHE state at Landau level fillings $\nu\sim2.30$, 2.44, 2.56, and 2.70. At these values, R_{xx} becomes vanishingly small at very low temperatures and R_{xy} abruptly changes from the classical Hall value and assumes a quantized plateau with the value of the closest IQHE state. Though its origin is still unresolved, the connection between this reentrant phase and the bubble phases in the third and higher Landau levels[57–59] has been suggested.[52,60,61] Recently, it was shown that these RIQHE states are very sensitive to an in-plane magnetic field and disappear very quickly within a few degrees of tilt of the B field.[19] This transport behavior was interpreted as a tilt-induced melting of the bubble phase.[19] To complete our study of the first excited Landau level presented in this paper, we add here some data on the melting behavior, by raising the temperature, of the two RIQHE states around $\nu=5/2$.

Figure 5 shows the values of R_{xy} for the RIQHE versus temperature. Both show a very similar behavior: R_{xy} remains quantized to an integer value at very low temperatures, increases very quickly within a small temperature range, and assumes their respective classical values thereafter. The temperature range where R_{xy} varies quickly is different for these two RIQHE states. For the $\nu\sim2.44$ state on the higher B field side, it ranges from 25 to 35 mK, while for the state at $\nu\sim2.56$ on the lower B field side ranges from 35 to 50 mK. Over the same temperature range, the 5/2 state remains a good quantum Hall state.

This abrupt T dependence of R_{xy} in the RIQHE has been observed earlier,[19] and it was attributed to the melting of an assumed, underlying bubble phase whose energy scale is expected to scale as $e^2/\varepsilon l_B$. Therefore, invoking again electron-hole symmetry, one would expect the RIQHE at $\nu\sim2.44$ to be more stable than the RIQHE state at $\nu\sim2.56$. Yet, we observe exactly the opposite. Here too, we have no basis to explain the apparent contradiction, but bring up the recently promoted Pfaffian and anti-Pfaffian phases[47,48] that might play a role, both of which break electron-hole symmetry and affect features around $\nu=5/2$ depending whether they occur on the electron or hole side of 5/2.

IV. SUMMARIES AND OPEN QUESTIONS

In an ultrahigh mobility two-dimensional electron system, at ultralow temperatures, we observe a very complex electronic transport behavior in the first excited Landau level. In detail, the $\nu=5/2$ state is very strong in this specimen and its energy gap is 0.45 K. Residual disorder has an important impact on the value of the energy gap at $\nu=5/2$. For another even-denominator FQHE state at $\nu=19/8$, an energy scale of $\sim$5 mK is deduced for its gap. This small energy scale attests to the need of still lower electron temperature and/or high sample quality for the $\nu=19/8$ FQHE state to be fully developed. As for the odd-denominator FQHE state, we measured the energy gap at $\nu=7/3$ and 8/3. Like the 5/2 state, their energy gaps increase with decreasing disorder. The state at $\nu=12/5$ is developed into a full FQHE state, however, its particle-hole conjugate state, the $\nu=13/5$ state, is entirely missing in this ultrahigh quality 2DES. We speculate that this disappearance might be related to the spin polarization of the $\nu=13/5$ state. For the two-reentrant integer quantum Hall states around $\nu=5/2$, we observe a temperature scale that is opposite to the expected behavior, which is puzzling and may be related to the recently proposed Pfaffian and anti-Pfaffian states.

Of all the electronic states in the first excited Landau level, the state at $\nu=5/2$ remains the most exciting, but also quite enigmatic. Based on the p-wave pairing within the CFs model, the $\nu=5/2$ state is expected to be spin polarized. Even this relatively simple property is not totally substantiated experimentally. So far, we only have indirect evidence of a spin-polarized 5/2 state from a tilted B field induced anisotropy.[30,62,63] The density dependence of the $\nu=5/2$ gap could shine light on the spin polarization, as with increasing density and hence increasing B, a collapse of the gap due to a spin transition may be observed or be absent. A previous such measurement[64] did not observe a spin transition and hence favored the existence of a spin-polarized state in support of the CF pairing model and the Pfaffian state. While this experiment employed a relatively low quality heterojunction insulated gate field effect transistor (HIGFET), in which the $\nu=5/2$ state was not fully developed, it would be desirable to revisit this question in a future, high quality HIGFET. The resistively detected NMR technique has proven to be a very powerful tool in directly measuring the spin polarization of FQHE states.[65] This same technique has been contemplated for studying the 5/2 spin state. However, rf heating of the specimen has so far prevented any conclusion as to the spin. While the Pfaffian state remains the front runner in explaining the existence of the state at $\nu=5/2$, an anti-Pfaffian state was proposed recently as an alternative candidate.[47,48] Yet, their spin polarization is not a tool to discriminate between both.

The spin polarization of the 7/3 and 8/3 states in the $N=1$ Landau level so far is largely unpursued. Naively, extrapolating from the lowest Landau level, one might expect that the 7/3 state is spin polarized, whereas the 8/3 state is unpolarized. However, at least one theoretical paper[66] predicts that, contrary to our intuition, the $\nu=8/3$ state is also spin polarized. Experimentally, the recent study at ultralow temperature showed a surprisingly complex tilted magnetic field dependence of the 7/3 and 8/3 states.[19] These third states in the $N=1$ Landau level may be much more complex than expected.

The disappearance of the $\nu=13/5$ state continues to be puzzling. Whether its disappearance is a result of a spin transition at the particular B field of our present experiment is unclear here too. Spin may be a primary ingredient.

The exciting even-denominator state at $\nu=19/8$ needs further confirmation. At this point, it is still shy of showing the ultimate characteristics of a true FQHE state. To this end, higher sample quality and lower electron temperature are needed.

In general, it appears that spin may be the essential ingredient for the behavior of many states in the $N=1$ Landau level. The occurrence of the related features at typically lower B field than the equivalent states in the lowest Landau level makes such a conjecture quite likely. Imaginative new experimental techniques as well as yet higher quality specimens seem to be required to further assess electron-electron correlation in this first excited Landau level.

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