Spin excitations in the Fractional Quantum Hall regime at $\nu \lesssim 1/3$

Y. Gallais$^a$, T.H. Kirschenmann$^a$, C.F. Hirjibehedin$^a$, I. Dujovne$^a$, A. Pinczuk$^{a,b}$, L.N. Pfeiffer$^b$ and K.W. West$^b$

$^a$Departments of Physics and of Applied Physics, Columbia University, New York, NY 10027, USA

$^b$Bell Labs, Lucent Technologies, Murray Hill, New Jersey 07974, USA

Abstract

We report inelastic light scattering experiments in the fractional quantum Hall regime at filling factors $\nu \lesssim 1/3$. A spin mode is observed below the Zeeman energy. The filling factor dependence of the mode energy is consistent with its assignment to spin flip excitations of composite fermions with four attached flux quanta ($\phi=4$). Our findings reveal a composite fermion Landau level structure in the $\phi=4$ sequence.

Key words: EP2DS-16 composite fermions, spin excitations, inelastic light scattering

PACS: 74.40.Xy, 71.63.Hk

1 Introduction

In the composite fermion (CF) picture of the fractional quantum Hall (FQH) effect, fundamental interactions are taken into account at the mean field level by mapping the system of strongly interacting 2D electrons in magnetic field into a system of weakly interacting Composite Fermions (CF) moving in a reduced effective magnetic field [1]. The reduction in magnetic field follows from the binding of $\phi$ flux quanta to electrons, so that effective magnetic field experienced by CF quasiparticles is $B^*=\pm B/(\phi p \pm 1)$, where $p$ is an integer that enumerates members of a particular sequence and $\phi$ is a even integer that labels different sequences. In this picture, the FQH effect can be understood by the emergence of CF Landau levels with cyclotron frequency: $\omega_{CF} = \frac{eB^*}{cm}$.

1 Corresponding author. E-mail: yann@phys.columbia.edu
where \( m^* \) is an effective CF mass. Evidence for a spin split Landau level structure of CF for the \( \phi = 2 \) sequence has been provided by magnetotransport experiments in tilted magnetic fields at filling factors near \( \nu = 3/2 \) \cite{2} and by inelastic light scattering studies of spin excitations in the range \( 1/3 < \nu < 2/5 \) \cite{3}. For the \( \phi = 4 \) sequence (i.e. \( \nu \lesssim 1/3 \)), however, direct evidence for such CF Landau level structure is lacking. Studies of the \( \phi = 4 \) sequence are more difficult because of the higher magnetic fields that are required and, compared to the \( \phi = 2 \) sequence, the smaller energy scales in the excitations. Insight on the energy scales for excitations were revealed by activated transport measurements \cite{4} and by the recent observations of \( \phi = 4 \) quasiparticle excitations in light scattering experiments \cite{5}.

In this work, we present a resonant inelastic light scattering study of spin excitations for \( \nu \lesssim 1/3 \). The excitations are spin waves (SW) and spin-flip (SF) modes. The SF excitations involve a change in both the spin orientation and CF Landau level quantum number. We monitor the evolution of these spin excitations below and away from \( \nu = 1/3 \) when the population of the excited CF Landau level increases. Our results reveal the existence of spin split CF Landau levels in the \( \phi = 4 \) sequence. The SW-SF splitting is linear in magnetic field. This determination suggests an effective mass significantly larger than the activation mass of CF with \( \phi = 4 \).

2 Sample and Experiment

The 2D electron (2DES) system studied here is a GaAs single quantum well of width \( w = 330 \, \text{Å} \). The electron density at small magnetic fields is \( n=5.5 \times 10^{10} \, \text{cm}^{-2} \) and the low temperature mobility is \( \mu=7.2 \times 10^6 / \text{Vs} \). The sample is mounted in a backscattering geometry, making an angle \( \theta \) between the incident photons and the normal to the sample surface. The magnetic field perpendicular to the sample is \( B=B_T \cos \theta \), where \( B_T \) is the total applied field. The results reported here have been obtained at \( \theta = 50 \pm 2 \) degrees. Similar results have been seen at 30 degrees \cite{6}. The ingoing and outgoing polarizations were chosen to be orthogonal (depolarized spectra) since excitations which involve a change in the spin degrees of freedom are stronger in this configuration. The sample was cooled in a dilution refrigerator with windows for optical access. All the measurements were performed at the base temperature \( T=23 \, \text{mK} \) and the power density was kept below \( 10^{-5} \, \text{W/cm}^2 \) to avoid heating the electron system. The energy of the incident photons was tuned to be in resonance with the excitonic optical transitions of the 2DES in the FQH regime \cite{7,8,9}.
Fig. 1. Low energy spectra of spin excitations in the filling factor range $0.31 < \nu < 0.33$. The most intense peak is the long wavelength spin-wave at the Zeeman energy $E_z$ while the peak its low energy side is assigned to a spin-flip transition (see text and figure 2). The left inset shows the result of a two-gaussian fitting procedure for the two peaks to extract their respective energies. The right inset shows the backscattering configuration.

### 3 Results and discussion

Figure 1 shows the evolution of the low energy spectrum for $\nu \lesssim 1/3$. $\nu = 1/3$ corresponds to a perpendicular field of 6.5T and the filling factor range studied corresponds to the range $0.31 < \nu < 0.33$. Close to $\nu = 1/3$, the spectra are dominated by the long wavelength SW at the 'bare' Zeeman energy $E_z = g\mu_B B_T$, where $g=0.44$ is the Lande factor for electrons in GaAs and $\mu_B$ is the Bohr magneton. For filling factors away from $\nu = 1/3$ an excitation emerges.
Fig. 2. Structure of spin split CF Landau levels for \( \frac{2}{7} < \nu < \frac{1}{3} \) (\( \phi = 4 \)). Two \( ^4\text{CF} \) spin transitions are possible. The large \( q \) spin wave is at \( E^*_z = E_z + E^{\uparrow\downarrow} \) where \( E^{\uparrow\downarrow} \) is the spin reversal energy. The spin-flip excitation at \( E_{SF} \). The spin-flip excitation emerges when the \( |1, \uparrow\rangle \) level is populated.

On the low energy side of \( E_z \). We assign this excitation to a SF mode linked to transitions in the CF framework that involve the first excited CF Landau level as depicted in figure 2. At \( \nu = 1/3 \) the first CF Landau (\( |0, \uparrow\rangle \)) level is fully occupied while for \( \nu = 2/7 \) the first two CF Landau levels (\( |0, \uparrow\rangle \) and \( |1, \uparrow\rangle \)) are occupied. In between the two incompressible states, the first excited Landau level is partially populated and SF transitions between \( |1, \uparrow\rangle \) and \( |0, \downarrow\rangle \) starting from the partially filled level become possible. Thus the study of the SF excitations in the filling factor range \( 2/7 < \nu < 1/3 \) probe directly the CF level structure for \( \phi = 4 \). For small occupation of the \( |1, \uparrow\rangle \) excited level and when the coupling between the excited quasiparticle and its quasihole is negligible, the SF transition energy can be written as in the \( \phi = 2 \) case:

\[
E_{SF} = E_z + E^{\uparrow\downarrow} - \hbar \omega_c \tag{1}
\]

where \( E^{\uparrow\downarrow} \) is the spin reversal energy which is a measure of the residual interactions between \( \phi = 4 \) CF quasiparticles [11,10,12,13,3]. The energy \( E_{SF} \) was extracted for each filling factor by performing a simple analysis of the low energy spectra using a two-gaussian fitting procedure as shown in the inset of figure 1. Figure 3 displays the corresponding energies, \( E_z \) and \( E_{SF} \) as a function of filling factor. The strong dependence of \( E_{SF} \) confirms our assignment of the peak as excitation involving spin degrees of freedom. More importantly, the spacing between \( E_z \) and \( E_{SF} \) is not constant and decreases with the filling factor. From equation 1, we easily see that this spacing is directly related to the CF cyclotron energy so that the splitting between the two spin excitations is \( E_z - E_{SF} = \hbar \omega_c - E^{\uparrow\downarrow} \). The magnetic field dependence of the \( E_z - E_{SF} \) spacing is set by the effective field \( B^* \). For the \( \phi = 2 \) sequence, \( ^2\text{CF} \) emanate from the \( \nu = 1/2 \) state and the effective field has its origin at \( B_{1/2} \). For the \( \phi = 4 \) sequence however, \( ^4\text{CF} \) emanate from the \( \nu = 1/4 \) state and the origin is at \( B_{1/4} \) and the effective magnetic field should then decrease when going from
Fig. 3. Magnetic field dependence of the Zeeman ($E_z$) and spin-flip excitation energies for $0.31 < \nu < 0.33$. Also shown is the evolution of the splitting $E_z - E_{\text{SF}}$.

0.33 to 0.31. This is indeed consistent with our data and to the existence of $^4\text{CF}$ or $\phi = 4$ spin-flip excitations below $\nu = 1/3$. Our results support the CF Landau level picture shown figure 2 for the $\phi = 4$ sequence.

The linear decrease of $E_z - E_{\text{SF}}$ with the effective magnetic field makes very tempting the evaluation of an effective mass by using a slope that is simply given by $\frac{\hbar e}{m^* c}$ in the framework of equation 1 for $E_{\text{SF}}$. Our data between filling factors 0.33 and 0.31 give $m^* = 1.5(\pm 0.1) m_e$ where $m_e$ is the bare electron mass. Previous determinations using the activation gap values at $\nu = 2/7$, $3/11$ and $4/15$ on samples with similar densities yield values around $0.9 m_e$ [4]. We note that while our determination of $m^*$ is performed between $\nu = 0.33$ and $\nu = 0.31$, i.e. in between the incompressible states at $1/3$ and $2/7$, the effective mass determined via transport measurements comes from a linear scaling of the activation gap values at the incompressible states. The high effective mass obtained in our analysis may be linked to the onset of significant CF interactions in the partially populated CF Landau level. Additional insights can be obtained by tracking the evolution of the intensity of the SF excitation when the population of the first excited CF level increases. This is done in Fig. 4 where the integrated spectral weight of the SF excitation is plotted as a function of filling factor. As expected, the SF intensity increases when the
population of $|1, \uparrow\rangle$ increases but displays an intriguing saturation around below $\nu=0.32$. As already mentioned for the effective mass, the saturation may result from increasing impact of CF residual interactions. These interactions could possibly lead to further condensation into higher order CF in the partially populated level. Recent transport measurements have indeed shown the possible existence of such higher order states even for the $\phi=4$ sequence [14].

4 Conclusion

In this study, we have shown the existence of spin-flip excitations of $^4$CF quasiparticle below $\nu=1/3$. The results indicate the existence of a spin-split CF Landau level structure for the $\phi = 4$ sequence of the fractional quantum Hall effect that is similar to the one found for the $\phi = 2$ sequence. The evolution of the SF energy with effective magnetic field yields an effective mass of $1.5m_e$. The evolution of the SF intensity with filling factor might signal the onset of significant CF-CF interactions that could possibly lead to further CF condensation.

This work is supported by the National Science Foundation under Grant No. NMR-0352738, by the Department of Energy under Grant No. DE-AIO2-04ER46133, and by a research grant from the W.M. Keck Foundation.
References

[1] J.K Jain, Phys. Rev. Lett. 63, 199 (1989).

[2] R.R. Du, H.L. Störmer, D.C. Tsui, L.N. Pfeiffer and K.W. West, Phys. Rev. Lett. 70, 2944 (1993)

[3] I. Dujovne et al., Phys. Rev. Lett. 90, 036803 (2003).

[4] W. Pan et al., Phys. Rev. B 61, R5101 (2000).

[5] C.F. Hirjibehedin, A. Pinczuk, B.S. Dennis, L.N. Pfeiffer and K.W. West, Phys. Rev. Lett. 91, 186802 (2003).

[6] C.F. Hirjibehedin, Ph.D. Thesis, Columbia University (2004).

[7] B.B. Golberg, D. Heiman, A. Pinczuk, L. N. Pfeiffer and K.W. West, Phys. Rev. Lett. 65, 641 (1990).

[8] G. Yusa, H. Shtrikman and I. Bar-Joseph, Phys. Rev. Lett. 87, 216402 (2001).

[9] C.F. Hirjibehedin et al., Solid State Commun. 127, 799 (2003).

[10] J. Longo and C. Kallin, Phys. Rev. Lett. 47, 4429 (1993).

[11] A. Pinczuk et al., Phys. Rev. Lett. 68, 3623 (1992).

[12] T. Nakajima and H. Aoki, Phys. Rev. Lett. 73, 3568 (1994).

[13] S.S. Mandal and J.K. Jain, Phys. Rev. B 63, 201310 (2001).

[14] W. Pan et al., Phys. Rev. Lett. 90, 016801 (2003).