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Inelastic light scattering study of the $\nu=1$ quantum Hall ferromagnet

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We report on an inelastic light scattering study in the two-dimensional electron system at filling factor $\nu=1$. The energy and the inelastic cross section of the cyclotron spin-flip mode are analyzed. The exchange enhanced electronic g factor in the quantum Hall ferromagnet is measured. In addition to the magnetoplasmon and cyclotron spin-flip modes, inelastic scattering lines associated with spin-singlet and spin-triplet D^- complexes are observed. The inelastic light scattering is shown to probe the thermodynamics of the quantum Hall ferromagnet and gives insight into the formation of ferromagnetic order in two dimensions. It is established that at temperatures above the bare Zeeman energy, the ferromagnet breaks up into domains, whose size and number change with temperature. The experimental data allow us to construct a stability diagram of the $\nu=1$ quantum Hall ferromagnet in the temperature versus magnetic field plane.

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I. INTRODUCTION

At Landau level filling factor $\nu=1$, the two-dimensional electron system turns into an itinerant ferromagnet.[1] The low-energy electron-spin dynamics is governed by the Coulomb interaction between the electrons and the Zeeman coupling of the electronic spins to the external applied magnetic field. The simplest neutral excitations are spin excitons. A spin exciton is composed of an excited electron in the empty spin branch of the Landau level and a hole in the filled branch with opposite spin.[2] At zero momentum ($q=0$), the exciton has an energy equal to the bulk Zeeman gap, whereas the energy required to create a well separated electron-hole pair ($q\rightarrow\infty$) is determined by the exchange enhanced spin splitting. This splitting can be written as $g_{\text{eff}}(B)\mu_B B$, where $g_{\text{eff}}(B)$ is the enhanced or effective g factor and μ_B is the Bohr magneton.

The thermodynamics of this $\nu=1$ quantum Hall ferromagnet depends on the temperature, the Zeeman coupling strength, and the exchange interaction. At nonzero temperature, the thermal excitation of spin excitons may wash out ferromagnetic order. However, the finite Zeeman coupling cuts off the thermal excitation of long-wavelength spin excitons, and quantum Hall ferromagnetism is certainly expected to persist at temperatures well below the bulk Zeeman energy. It is unclear what happens in the opposite limit. Magnetotransport measurements suggest that ferromagnetic order survives even in the absence of Zeeman energy.[3] Nuclear magnetic resonance and optical absorption measurements of the magnetization of the two-dimensional (2D) electron system can also be interpreted this way.[4,5] These techniques are macroscopic in nature and hence are unable to distinguish between long and short-range spin correlated orders. As is known from physics of three-dimensional Heisenberg ferromagnets, the short-range spin-spin correlations are preserved well above the Curie temperature and continue to exist into the paramagnetic phase. In the two-dimensional case, short-range spin correlations are also predicted in the disordered $\nu=1$ quantum Hall state.[6] To distinguish the $\nu=1$ quantum Hall ferromagnetic phase from the other magnetic order, it would be highly desirable to design an experiment which probes the ferromagnetic order directly. In this paper, we show that inelastic light scattering can be utilized for this purpose. It also offers a direct route for the measurement of the magnitude of the exchange interaction in the ground state.

The paper is divided as follows. In the next section, we intend to discuss the physics of the cyclotron spin-flip mode and, in particular, its importance for studying spin correlations in the two-dimensional electron system. Some of this work was reported previously[7] but is included here in order to make the manuscript self-contained. In Sec. III, the experimental technique and the samples explored in the course of this work are described. Subsequently, the exchange interaction in the $\nu=1$ quantum Hall ferromagnet is addressed in Sec. IV. In Sec. V, we consider the D^- complexes, which reduce the spin polarization of the ground state of the two-dimensional system at filling factor $\nu=1$. Finally, Sec. VI is devoted to the thermodynamics of the $\nu=1$ ferromagnet. A temperature versus magnetic field stability diagram of this ferromagnetic state is presented.

II. EXCITATIONS IN THE $\nu=1$ QUANTUM HALL FERROMAGNET

Here, we compare the properties of the three lowest energy excitations in the $\nu=1$ quantum Hall ferromagnet: (1) the spin exciton, an excitation which preserves the orbital quantum number while the spin quantum number changes by 1; (2) the magnetoplasmon, an excitation which leaves the spin quantum number unaltered, but the orbital quantum

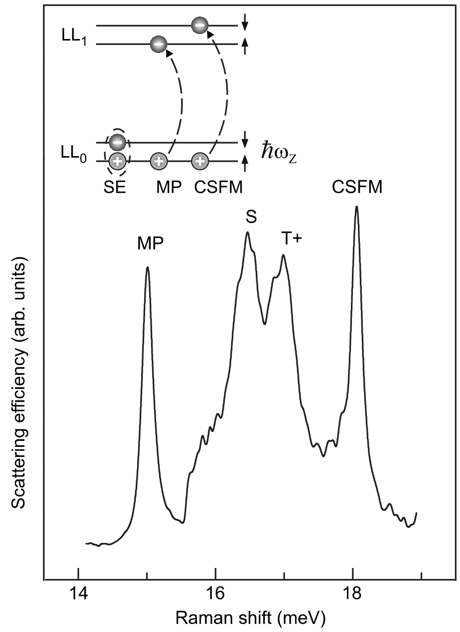

FIG. 1. An example of an inelastic light scattering spectrum at filling factor $\nu=1$ recorded at 8.5 T on a 25 nm wide quantum well sample. The features denoted as MP and CSFM correspond to the magnetoplasmon and the cyclotron spin-flip modes. The inset shows a cartoon of the three lowest energy excitations for the $\nu=1$ quantum Hall ferromagnet.

number is changed by 1; (3) the cyclotron spin-flip mode (CSFM), which involves a change in both the spin and orbital quantum numbers. These excitations are schematically illustrated in Fig. 1. The zero-momentum spin exciton and the magnetoplasmon were carefully investigated in electron-spin and cyclotron resonance experiments.[8] The cyclotron spin-flip mode, however, has attracted attention only recently. This mode seems to offer a number of advantages over the other two excitations when it comes to investigating the exchange interaction.[9–13] Homogeneous electromagnetic radiation incident on a translationally invariant electron system is unable to excite the internal degrees of freedom that determine the Coulomb interaction. The energy of the zero-momentum magnetoplasmon triggered by homogeneous radiation therefore does not contain any information about Coulomb interactions (Kohn theorem).[14] Similarly, for a system with rotational invariance in spin space, the Coulomb interaction does not contribute to the energy of the zero-momentum spin exciton (Larmor theorem).[15] In contrast, the zero-momentum cyclotron spin-flip mode includes an exchange contribution.[9,10,16,17] Its energy,

$$E_{CSFM}(q=0)=\hbar\omega_c+|g\mu_B B|+\Delta(q=0,B), \tag{1}$$

is composed of three terms: the cyclotron gap, the bulk Zeeman energy $g\mu_B B$, and a Coulomb energy term $\Delta(0,B)$ equal to the difference between the interaction energy of the ground state and the excited state with one spin flipped.[9,17] In inelastic light scattering, large momentum can only be transferred if impurities are involved, but then the transferred momentum remains unknown. Only small momentum can be transferred in a well-defined manner (small compared to the inverse of the magnetic length) and hence solely the measurement of the cyclotron spin-flip mode reveals clear-cut information about the Coulomb interactions.

Within the Hartree-Fock approximation, $\Delta(0,B)$ is closely related to the ground state exchange energy. A first order approximation in the ratio of the Coulomb energy E_C to the cyclotron energy E_c yields a value of $\Delta(0,B)$ equal to half of the ground state exchange energy for a two-dimensional electron system with zero width. The validity of the first order approximation has, however, been debated since the ratio E_C/E_c is not small in the experimental range of magnetic fields.[1] Hence, it has been important to take a closer look and investigate the significance of higher order corrections to the cyclotron spin-flip mode. It turns out that the magnitude of these higher order corrections can be estimated experimentally at electron filling factor $\nu=2$.[13] At this filling, the first order Coulomb corrections are absent as a result of symmetry and only higher order Coulomb corrections contribute to the energy of the cyclotron spin-flip mode. Previous measurements by some of us have shown that those corrections are negative, i.e., *the energy necessary to change both the orbital and spin quantum number of the electron system at* $\nu=2$ *is less than the energy necessary to change the orbital quantum number alone*.[7,13] The higher order Coulomb corrections measured at $\nu=2$ make up only 10% of the $\Delta(0,B)$ term measured at $\nu=1$.[7,13]

We note that the Hartee-Fock approach is not entirely correct even when only aiming for a first order description of the electron-electron interaction terms.[18,19] The cyclotron spin-flip mode has an energy that falls into that of the continuous spectrum of possible pair excitations which simultaneously involve a spin exciton and a magnetoplasmon with opposite momentum.[16] One may anticipate that the cyclotron spin-flip mode decays into such a pair of excitations. However, experimentally, such an instability is not observed. This can elegantly be explained. The cyclotron spin-flip mode cannot be reduced to a single exciton state. Instead, it is itself a superposition of the cyclotron spin-flip exciton and pair excitations formed out of spin excitons and magnetoplasmons. The cyclotron spin-flip mode is, in fact, a *stable many-exciton complex*. Many particle corrections increase the CSFM energy at $\nu=1$ by about 10% of the conventional Hartree-Fock value.[20] One sees that the positive many-particle corrections cancel out the negative second order corrections in the CSFM energy. Therefore, the standard Hartree-Fock approach gives a quite accurate description for the energy of the cyclotron spin-flip mode of the $\nu=1$ quantum Hall ferromagnet at the experimentally accessible magnetic fields, although this is somewhat fortuitous.[7,9]

III. EXPERIMENTAL TECHNIQUE

Our studies were carried out on single sided doped $Al_{0.33}Ga_{0.67}As/GaAs$ quantum wells (QWs) with quantum well widths of 20, 25, and 30 nm. The mobility of the samples varied between 5 and 20×10^6 cm^2/V s and the density ranged from 1 to 2.5×10^{11} cm^{-2}. The density was tuned continuously via the optodepletion effect and was obtained from magnetoluminescence measurements.[21] The inelastic light scattering experiments were carried out in a variable temperature insert at temperatures from 0.3 to 10 K with a multiple glass fiber arrangement.[10] One fiber was used for transmitting the coherent light of a Ti-sapphire laser with a wavelength above the fundamental band gap of GaAs and a power density of less than 0.1 W/cm^2 in order to excite the 2D electron system. The scattered light was collected with a second fiber placed at an angle to the surface normal. This angle determines the small momentum transfer during inelastic scattering. The collected light was dispersed in a T-64000 triple spectrograph and recorded with a charge-coupled device camera. The spectral resolution of the setup was equal to 0.04 meV. The resonant inelastic light scattering observed in the experiment is allowed due to the spin-orbit interaction in the valence band of the AlGaAs/GaAs quantum wells. When the exciting laser line has an energy close to the band gap of GaAs, the inelastic light scattering efficiency is composed of a set of narrow resonances as the laser excitation energy is tuned. These resonances are extremely narrow in high mobility samples. To avoid artifacts, we have therefore averaged a large number of measurements at different excitation energies close to the GaAs band gap.

IV. CYCLOTRON SPIN-FLIP MODE ENERGY OF THE ν=1 QUANTUM HALL FERROMAGNET

Here, we briefly address and summarize results on the exchange interaction for the $\nu=1$ quantum Hall ferromagnet.[7] Figure 1 depicts a typical inelastic light scattering spectrum at $\nu=1$. It consists of four spectral features. The two narrow lines are attributed to collective modes: the magnetoplasmon with an energy close to the cyclotron energy and the cyclotron spin-flip mode with an energy equal to the sum of the cyclotron energy and the Coulomb term $\Delta(0,B)$. The additional significantly broader spectral features originate from inelastic light scattering on electron impurity complexes. They will be discussed in Sec. V.

The energy of the cyclotron spin-flip mode shows excellent agreement in the magnetic field range from 1 to 10 T with a simulation based on a first order Hartree-Fock approximation. The magnetic field dependence is much weaker than the square root dependence one would expect from a simple dimensional analysis. The weak magnetic field dependence is due to Coulomb softening in the studied samples with finite quantum well widths. The nature of the Coulomb interaction alters as B increases. For small B fields when $l/l_B \ll 1$ (l is the full width at half maximum of the electron wave function and l_B is the magnetic length), the Coulomb interaction behaves effectively as for a 2D system with zero width. In the opposite limit when $l/l_B \gg 1$, the electrons may be thought of as long charged rods interacting via Coulomb forces. It considerably softens the Coulomb interaction. The interaction energy then only shows a logarithmic B-field dependence instead of a square root dependence. In the investigated samples, the effective QW width is equivalent to the interparticle distance at approximately 4 T. As a consequence, the Coulomb term $\Delta(0,B)$ barely changes for magnetic fields exceeding 4 T.

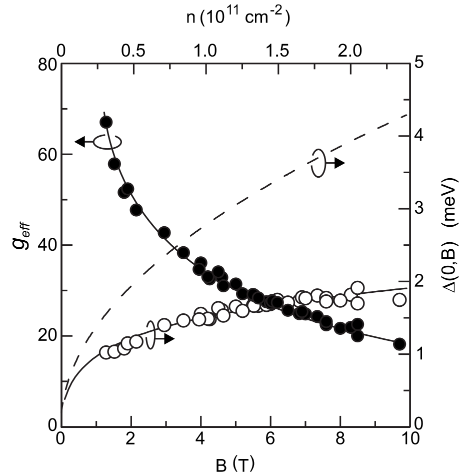

FIG. 2. Right axis: $\Delta(0,B)$ as a function of density (or equivalently B). Open circles are the values extracted from inelastic light scattering experiments. The dashed and solid lines are the results from a first order Hartree-Fock simulation for a 2D system with zero width (dashed line) and when the finite width of the confining potential is taken into account (solid line). Left axis: the exchange enhancement of the electron g factor as a function of density (or equivalently B) calculated from the experimental data points (solid circles). The line is a guide to the eyes.

From the $\Delta(0,B)$ value, the exchange enhanced g factor, g_{eff}, in the $\nu=1$ quantum Hall ferromagnet can be extracted (Fig. 2). The effective g factor can reach values as large as 60 at 1 T, whereas the absolute value of the bare electron g factor in GaAs is only 0.44. This enhancement is an order of magnitude larger, as has been reported from temperature dependent transport studies.[22–25] This large discrepancy between the inelastic light scattering and transport data has been assigned to the very different susceptibility of both techniques to the disorder potential.[7] In inelastic light scattering, the cyclotron spin-flip mode signal stems only from those regions of the sample which exhibit ferromagnetic order. The excitations of these ferromagnetically ordered regions are *spectrally separated* from all other excitations. In the next section, we discuss excitations from nonordered parts of the sample. They reduce the exchange enhancement observed in magnetotransport data which inevitably averages the behavior over the macroscopic sample scale.

V. D^- COMPLEXES OF THE ν=1 QUANTUM HALL FERROMAGNET

Apart from the magnetoplasmon and the cyclotron spin-flip modes, Fig. 1 shows two additional spectral features with some peculiar properties. In the highest mobility samples, the feature with the lowest energy, denoted as S, splits into three. It allows to unambiguously identify this line with excitations of a spin-singlet D^- complex. This complex is composed of two electrons with opposite spins and a positively charged impurity in the quantum well barrier.[26,27] In a strong magnetic field, the Coulomb potential of a positive charge attracts not one but rather two electrons with opposite spin to

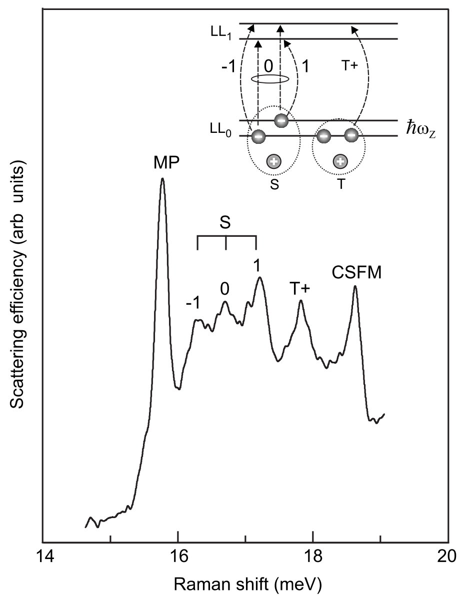

FIG. 3. Inelastic light scattering spectrum at 9 T ($\nu=1$) for a 25 nm wide quantum well. The cartoon at the top explains the origin of the S and T^{+} lines.

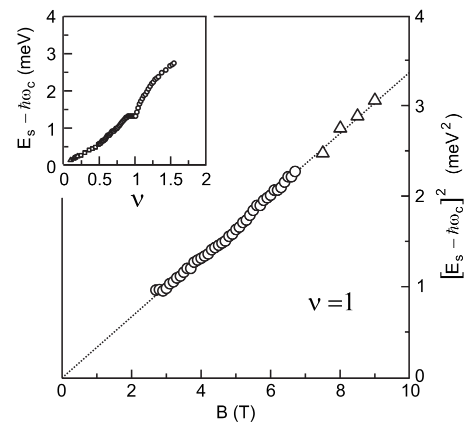

FIG. 4. Measured dependence of the difference between the central energy of the threefold split spin-singlet line (S) and the cyclotron energy (open symbols). The dotted line is a guide to the eyes. In the inset, the central energy of the spin singlet feature is plotted versus filling factor ν.

its surrounding since the gain of negative potential energy in the field of the donor outweighs the loss of the Zeeman and the exchange energies. Since this complex is charged, it repels the remaining electrons and they move further away from the D^{-} complex. The D^{-} complex surrounded by the resulting cloud of the positively charged background can be viewed as a single electron bound to a positively charged impurity (D^{0} complex) and a spin exciton bound to them. When one of the electrons composing the D^{-} complex is promoted to the next Landau level, its wave function spreads further from the D^{-} core. This prevents a rearrangement of the electron density around the complex. The Coulomb repulsion between the excited electron and the free electrons surrounding the complex causes a blueshift of the excitation transition energy.[26]

D^{-} complexes were investigated previously with far infrared absorption in samples with impurities which were introduced intentionally directly in the quantum well.[28–30] Here, similar complexes with positively charged impurities in the QW barrier are reported in a high purity 2D electron system. We observe all three spin components (denoted as S in Fig. 3) of the excitations in the spin-singlet D^{-} complexes (Fig. 3). The additional feature marked as (T^{+}) is attributed to the higher energy excitation in the spin-triplet D^{-} complex.[28] This is in contrast to the optical absorption results where, in general, the lowest energy (T^{-}) of the two possible transitions in the spin-triplet D^{-} complex is seen.[28,30]

The properties of the S and T^{+} lines are as follows. Neither of the two lines is sensitive to the momentum transferred in the course of the inelastic light scattering. Unlike the energy of the cyclotron spin-flip mode, the energies of both S and T+ lines are also not sensitive to a change of the quantum well width from 20 to 30 nm. This suggests that the electron-electron interaction within the D^{-} complex is much less influenced by the quantum well confinement potential. The energies of both lines exhibit a square root magnetic field dependence, which also points toward the irrelevance of Coulomb softening due to the finite width of the confinement potential. The D^{-} singlet line is also present at filling factors above and below $\nu=1$. Its energy varies linearly with the electron density from filling $\nu=0.1$ up to $\nu=2$ in agreement with theoretical simulations (Fig. 4).[29] For electron filling factors smaller than 1, this can be understood intuitively. The added holes tend to move close to the D^{-} spin-singlet complex, while the remaining electrons maximize their spatial separation and move away from the complex in order to decrease the electron-electron repulsion and minimize the total energy. The two spin-singlet electrons bound to the positively charged impurity become spatially isolated from the remaining electrons and the optical properties of the complex approach those of an isolated two-electron D^{-} singlet ion. Because of the available states in the lowest Landau level, the excitations of the D^{-} complex essentially occur at the cyclotron energy, whereas the Coulomb repulsion of the excited electron and of the free electrons vanishes.[10] The behavior of the T^{+} line is different. The T^{+} line is observed only in close proximity of electron filling factor 1. It disappears from the spectrum at $\nu>1$ in a similar fashion as the cyclotron spin-flip mode does.

The inelastic light scattering experiment unfortunately does not provide information about the number of impurity complexes that form in the electronic system. That would require knowledge about the scattering probability difference for impurity related excitations and collective excitations. Nevertheless, it is possible to estimate the density of charged impurities located in the quantum well barrier close to the 2DES from the observation that all of the two-dimensional electrons form isolated D^{-} complexes (ions) at $\nu\sim 0.1$ and $B\sim 10$ T.[10] Therefore a reasonable estimate for the upper limit of electron density bound in D^{-} complexes is $\sim 2\times 10^{10}$ cm^{-2} at 10 T. This estimate holds also at filling 1 since the scattering efficiencies for the singlet D^{-} complexes at filling factors $\nu=0.1$ and $\nu=1$ are comparable. We therefore conclude that, apart from the free 2D electrons, there exists *a macroscopic and spin depolarized electron subsystem at* $\nu=1$ with a singular excitation spectrum. Other experimental techniques often assume complete spin polarization at a certain filling factor for normalization purposes. These techniques are not able to detect this subsystem. Charged excitations present in a system composed of two subsystems, the D^- complexes and the free 2D electrons, may be an important ansatz for understanding the much lower than expected activation energies at $\nu=1$ in magnetotransport studies.[22]

The density of D^- complexes is nearly the same for the different samples that were investigated here. The estimated density is also close to the reported density of D^0X complexes, often referred to as localized trions, in undoped optically excited AlGaAs/GaAs quantum wells.[31] This further validates our estimation since both complexes have a common nature.

VI. THERMODYNAMICS OF THE ν=1 QUANTUM HALL FERROMAGNET

In this section, the temperature dependence of both the energy and the intensity of the cyclotron spin-flip mode of the $\nu=1$ quantum Hall ferromagnet will be discussed. While the energy of this mode carries information about the exchange interaction, the intensity is proportional to the scattering volume. A simultaneous investigation of both quantities is valuable to assess the area occupied by the ferromagnetic phase. Our measurements resemble in essence inelastic light scattering studies, as they have been performed for the zone center magnons in three-dimensional ferromagnets and antiferromagnets.[32]

Some key observations are visible in the inelastic light scattering spectra plotted in Fig. 5. At temperatures below $T_Z=\mu gB/k_B$, both energy and intensity of the cyclotron spin-flip mode barely change. We conclude that the area occupied by the ferromagnetic phase is preserved in this temperature range. At temperatures above T_Z, the intensity of the cyclotron spin-flip mode drops rapidly (Fig. 5). Apparently, the ferromagnetic order still exists but is now only present in some parts of the sample (domains). Within these domains, the energy of the cyclotron spin-flip mode is weakly blueshifted. This shift can most likely be ascribed to the spatial confinement within these ferromagnetic regions. Cyclotron spin-flip modes with momenta less than the reciprocal characteristic length scale of the domains can no longer proliferate.

The CSFM scattering efficiency is compared with the magnetization of the electron system obtained from nuclear magnetic resonance[4] and optical absorption techniques[5] at similar experimental conditions [Fig. 6(a)]. The magnetization carries information about the average spin polarization per electron. Similar to the scattering efficiency, the magnetization barely changes below T_Z. In this regime, the magnetization behavior is dominated by activated spin excitons and is calculated from

$$\frac{M(T)}{M_0} = 1 + Ck_BT\ln(1 - e^{\mu gB/k_BT}). \tag{2}$$

Here, M_0 is the magnetization at zero temperature and C is a parameter related to the mass of long-wavelength spin

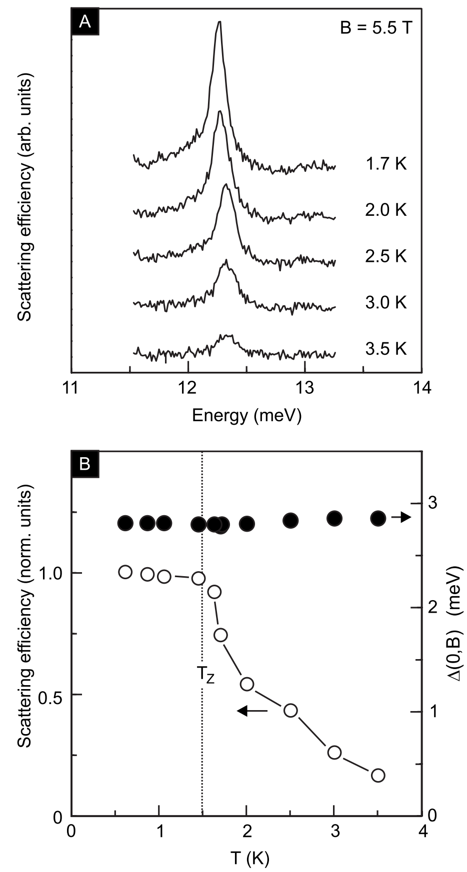

FIG. 5. (A) Changes as a function of temperature for the cyclotron spin-flip mode in the inelastic light scattering spectrum at $B=5.5$ T. (B) The scattering efficiency of the cyclotron spin-flip mode (open dots, left axis) and the Coulomb term $\Delta(0,B)$ (solid dots, right axis) as a function of temperature. The dashed line indicates $T_Z=\mu gB/k_B$. The bulk g factor in QWs is taken from Ref. 13.

excitons.[33,34] Equation (2) is valid when the number of spin excitons is much smaller than the number of electrons. Beyond this limit, the interaction among the spin excitons should be taken into account.[34] Their mutual interaction causes a strong deviation in the magnetization from the dependence described by Eq. (2). A continuum quantum field theory of a Heisenberg ferromagnet, in which the nearest neighbor exchange interaction strength is adjusted to yield the correct spin stiffness of the $\nu=1$ quantum Hall ferromagnet, predicts that this deviation starts to occur at T_Z.[35]

Figure 6(a) shows that the magnetization and inelastic light scattering data basically agree. Above a temperature T_f, which coincides approximately with T_Z, both the scattering efficiency and the magnetization decline rapidly from the dependence given by Eq. (2). The stronger reduction of the scattering efficiency in comparison with the magnetization can be explained in terms of short order spin-spin correlations. They produce a finite magnetization and tend to cause the formation of regions with ferromagnetic order. However, the fluctuations of the order parameter become so large that some of these ferromagnetic domains shrink to a size for which the momentum of the cyclotron spin-flip mode is no longer well defined. These domains do not contribute to the

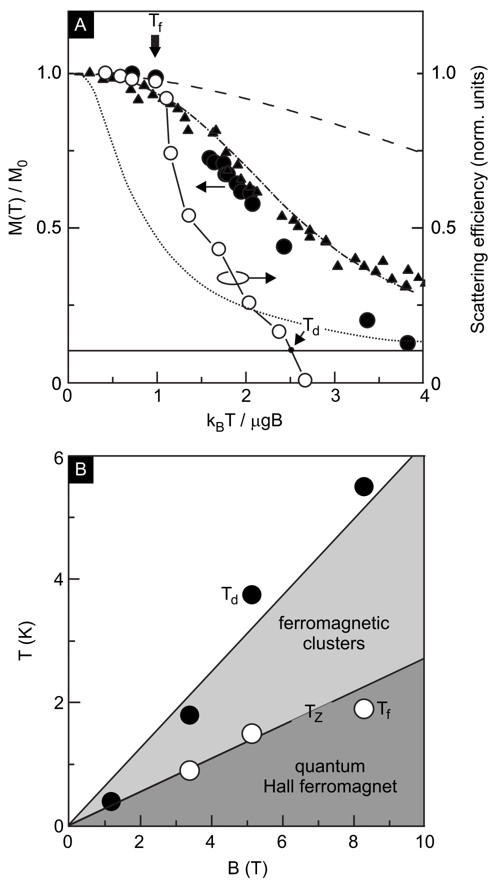

FIG. 6. (A) Temperature dependence of the inelastic light scattering efficiency for the cyclotron spin-flip mode (open circles) in comparison with the magnetization of the 2D electron system. The magnetization results were taken from nuclear magnetic resonance (Ref. 4) (solid circles) and optical absorption (Ref. 5) (triangulars) experiments in the literature. The solid lines are guides to the eyes. The dotted line shows the magnetization of noninteracting electrons obeying Fermi-Dirac statistics, while the dashed line presents the spin-exciton activated magnetization described by Eq. (2). The dash-dotted line is simulated within the $O(N)$ continuum quantum field theory of Heisenberg ferromagnets with adjusted nearest neighbor exchange interaction strength. The spin stiffness is calculated with the inclusion of finite width effects for the electron wave function in the growth direction. This wave function is obtained from a self-consistent solution of the one-dimensional Schrödinger and Poisson equations. (B) The stability diagram for the $\nu=1$ quantum Hall ferromagnet. T_f (open circles) and T_d (solid circles) are plotted as a function of the magnetic field. The regions with macroscopic ferromagnetic order and with only domains or clusters with ferromagnetic order are delineated by solid lines.

CSFM inelastic light scattering. We introduce a second characteristic temperature T_d at which the narrow inelastic light scattering line associated with the cyclotron spin-flip mode has dropped in intensity 1 order of magnitude compared to the low-temperature value. The area occupied by the ferromagnetic phase reduces accordingly. Above T_d, the ferromagnetic domains with well-defined CSFM are nearly absent.

In Fig. 6(b), the two characteristic temperatures T_f and T_d are plotted as a function of the magnetic field. This plot may be viewed as a stability diagram of the $\nu=1$ quantum Hall ferromagnet. The diagram shows unambiguously that for temperatures below the single particle Zeeman energy, macroscopic ferromagnetic order occurs. The ferromagnet breaks apart into domains as soon as the electron temperature exceeds T_Z. This finding is in line with a longstanding prediction for the instability of long-range ferromagnetic order in two dimensions.[36,37] We note that our experiments are unable to rule out the Stoner instability in two dimensions.[38] This instability is anticipated at electron densities on the order of $\sim 10^8$ cm^{-2}.[39] Measurements at these low electron densities are well beyond our reach. In addition, the density of the spin-singlet D^- complexes in the currently available GaAs/AlGaAs samples exceeds by more than an order of magnitude the Stoner critical density. The possibility of a Stoner instability in two dimensions therefore remains an open question.

In conclusion, we have carried out a detailed study of the $\nu=1$ quantum Hall ferromagnet with the help of inelastic light scattering. The cyclotron spin-flip mode was used to probe ferromagnetic order. The exchange interaction energy and the exchange enhanced electronic g factor were determined. Our data suggest that the ground state is not completely spin polarized even in the highest mobility samples. The absence of complete spin polarization is attributed to the presence of a macroscopic number of spin-singlet D^- complexes, which coexist with the ferromagnetic phase. The thermodynamics of the quantum Hall ferromagnet is governed primarily by the bulk Zeeman energy. At temperatures above the Zeeman energy, the ferromagnet breaks up into domains with ferromagnet order. Their size and number decrease with increasing temperature.

ACKNOWLEDGMENTS

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[1] For a review, see *Perspectives in Quantum Hall Effect*, edited by S. Das Sarma and A. Pinczuk (Wiley, New York, 1997).
[2] Yu. A. Bychkov, S. V. Iordanskii, and G. M. Eliashberg, JETP Lett. **33**, 143 (1981).
[3] D. K. Maude, M. Potemski, J. C. Portal, M. Henini, L. Eaves, G. Hill, and M. A. Pate, Phys. Rev. Lett. **77**, 4604 (1996).
[4] S. E. Barrett, G. Dabbagh, L. N. Pfeiffer, K. W. West, and R. Tycko, Phys. Rev. Lett. **74**, 5112 (1995).
[5] M. J. Manfra, E. H. Aifer, B. B. Goldberg, D. A. Broido, L. Pfeiffer, and K. West, Phys. Rev. B **54**, R17327 (1996).
[6] D. K. K. Lee, S. Rapsch, and J. T. Chalker, Phys. Rev. B **67**, 195322 (2003).

[7] A. B. Van'kov, L. V. Kulik, I. V. Kukushkin, V. E. Kirpichev, S. Dickmann, V. M. Zhilin, J. H. Smet, K. von Klitzing, and W. Wegscheider, Phys. Rev. Lett. **97**, 246801 (2006).
[8] T. Ando, A. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[9] A. Pinczuk, B. S. Dennis, D. Heiman, C. Kallin, L. Brey, C. Tejedor, S. Schmitt-Rink, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **68**, 3623 (1992).
[10] L. V. Kulik, I. V. Kukushkin, V. E. Kirpichev, J. H. Smet, K. v. Klitzing, and W. Wegscheider, Phys. Rev. B **63**, 201402(R) (2001).
[11] M. A. Eriksson, A. Pinczuk, B. S. Dennis, S. H. Simon, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **82**, 2163 (1999).
[12] L. V. Kulik, I. V. Kukushkin, V. E. Kirpichev, J. H. Smet, K. von Klitzing, V. Umansky, and W. Wegscheider, Physica E (Amsterdam) **12**, 574 (2002).
[13] L. V. Kulik, I. V. Kukushkin, S. Dickmann, V. E. Kirpichev, A. B. Van'kov, A. L. Parakhonsky, J. H. Smet, K. von Klitzing, and W. Wegscheider, Phys. Rev. B **72**, 073304 (2005).
[14] W. Kohn, Phys. Rev. **123**, 1242 (1961).
[15] M. Dobers, K. v. Klitzing, and G. Weimann, Phys. Rev. B **38**, 5453 (1988).
[16] C. Kallin and B. I. Halperin, Phys. Rev. B **30**, 5655 (1984).
[17] J. P. Longo and C. Kallin, Phys. Rev. B **47**, 4429 (1993).
[18] S. Dickmann and I. V. Kukushkin, Phys. Rev. B **71**, 241310(R) (2005).
[19] S. Dickmann, V. M. Zhilin, and D. V. Kulakovskii, JETP **101**, 892 (2005).
[20] S. Dickmann (private communication).
[21] I. V. Kukushkin and V. B. Timofeev, Adv. Phys. **45**, 147 (1996).
[22] A. Usher, R. J. Nicholas, J. J. Harris, and C. T. Foxon, Phys. Rev. B **41**, 1129 (1990).
[23] A. Schmeller, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **75**, 4290 (1995).
[24] V. T. Dolgopolov, A. A. Shashkin, A. V. Aristov, D. Schmerek, W. Hansen, J. P. Kotthaus, and M. Holland, Phys. Rev. Lett. **79**, 729 (1997).
[25] V. S. Khrapai, A. A. Shashkin, E. L. Shangina, V. Pellegrini, F. Beltram, G. Biasiol, and L. Sorba, Phys. Rev. B **72**, 035344 (2005).
[26] S. Holmes, J.-P. Cheng, B. D. McCombe, and W. Schaff, Phys. Rev. Lett. **69**, 2571 (1992).
[27] A. B. Dzyubenko and A. Yu. Sivachenko, Phys. Rev. B **48**, 14690 (1993).
[28] J.-P. Cheng, Y. J. Wang, B. D. McCombe, and W. Schaff, Phys. Rev. Lett. **70**, 489 (1993).
[29] P. Hawrylak, Phys. Rev. Lett. **72**, 2943 (1994).
[30] Z. X. Jiang, B. D. McCombe, and P. Hawrylak, Phys. Rev. Lett. **81**, 3499 (1998).
[31] D. M. Whittaker and A. J. Shields, Phys. Rev. B **56**, 15185 (1997).
[32] See, for example, P. A. Fleury and R. Loudon, Phys. Rev. **166**, 514 (1968), and references therein.
[33] S. M. Dikman and S. V. Iordanskii, JETP Lett. **63**, 50 (1996) [Pis'ma Zh. Eksp. Teor. Fiz. **63**, 43 (1996)].
[34] M. Kasner and A. H. MacDonald, Phys. Rev. Lett. **76**, 3204 (1996); M. Kasner, J. J. Palacios, and A. H. MacDonald, Phys. Rev. B **62**, 2640 (2000).
[35] N. Read and S. Sachdev, Phys. Rev. Lett. **75**, 3509 (1995).
[36] N. D. Mermin and H. Wagner, Phys. Rev. Lett. **17**, 1133 (1966).
[37] P. C. Hohenberg, Phys. Rev. **158**, 383 (1967).
[38] E. C. Stoner, Rep. Prog. Phys. **11**, 43 (1947).
[39] C. Attaccalite, S. Moroni, P. Gori-Giorgi, and G. B. Bachelet, Phys. Rev. Lett. **88**, 256601 (2002).