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Enhanced magnetization at integer quantum Hall states

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We report on enhancements in the magnetization of two-dimensional electron systems in the quantum Hall regime. The observed discontinuities in the magnetization exceed the predictions for interacting electrons calculated in the Hartree-Fock approximation where only the exchange enhancement of the energy gaps is taken into account. We attribute the further enhancement to many-body correlation effects, i.e., filling factor dependent screening within the screened Hartree-Fock approximation. With this, the discontinuities in the magnetization no longer reflect the discontinuities of the chemical potential, but its behavior in the vicinity of integer filling factors.

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The electronic properties of high-mobility two-dimensional electron systems (2DES), as realized in GaAs/AlGaAs heterostructures, are, in high magnetic fields, strongly affected by electron-electron interaction. In the integer quantum Hall regime this leads to a renormalization of the single-particle energy gaps. For the Zeeman gap the exchange enhancement has often been observed and is usually expressed in terms of an effective Landé-factor g^*.[1–5] For the Landau gap an enhancement has only rarely been reported.[5] The common methods are thermal activated magnetotransport, which probes the excitation dispersion relation for large k, and optical spectroscopy measuring the limit $k \rightarrow 0$. Both techniques map a nonequilibrium state of the 2DES, i.e., an excitation gap. In this paper, we present measurements of the magnetization, which probes the equilibrium properties, i.e., the thermodynamic ground-state of the electron system. It is an advantageous quantity to study many-particle renormalization effects. This has been predicted theoretically[6–8] and demonstrated experimentally by monitoring the magnetization of the correlated fractional quantum Hall ground states.[9]

In this work we focus our attention on the amplitude of the de Haas-van Alphen oscillations, i.e., the magnetization of the 2DES, in the integer quantum Hall regime. The observed signal strengths at integer filling factors are significantly more enhanced than predicted so far by the Hartree-Fock approximation (HFA)[6,8] and current-density functional theory,[7] and show a characteristic maximum at a moderate magnetic field. We suggest a new approach to calculate the magnetization using the screened HFA (SHFA) which takes into account some correlation effects in addition to exchange interaction.

We have performed magnetization studies on high-mobility modulation-doped 2DES in AlGaAs/GaAs heterostructures using a superconducting magnetometer. The sample was surrounded by an in-plane superconducting pickup loop configured as a first-order gradiometer and coupled to a low-noise superconducting quantum interference device (SQUID). The measurements were performed at *constant* magnetic field as a function of the carrier density N_S of the 2DES. For this, a metal gate was evaporated on top of the sample. By applying different gate voltages V_g and magnetic fields B up to 10 Tesla we could tune the filling factor $\nu = hN_S/eB$. With a phase-sensitive detection technique, modulating the carrier density, we measured the differential magnetization $\partial M/\partial N_S$ as a function of the carrier density at fixed magnetic field. The absolute magnetization M was obtained by integration and subtraction of a polynomial background. The setup and the measuring procedure are described in detail in Refs. 9 and 10. We here report on different samples from the same wafer which exhibit a high mobility of 2×10^6 cm^2/Vs after illumination for a carrier density of 0.97×10^{11} /cm^2 (sample #8896_6) and 0.89×10^{11}/cm^2 (sample #8896_7) at zero gate voltage. The gated areas were 10.2 mm^2 and 8.7 mm^2, respectively. The temperature was $T = 0.3$ K. In general, one has to be aware of nonequilibrium currents induced by modulation leading to signals which might mimic the equilibrium magnetization. We interpret our data in terms of equilibrium magnetization based on the following observations: All our data have been taken after illumination of the 2DES. This procedure has led to sharpened structures and has increased our signal strength. The behavior of eddy currents is known to be in contrast to that. They are suppressed by illumination.[4,11] Our signals survive at much higher temperatures than eddy currents which obey a strong temperature dependence.[12]

Figure 1 shows the integrated data, i.e., the absolute magnetization per electron, as a function of the filling factor ν adjusted via the dc gate voltage at different fixed magnetic fields $B = 1.0$, 1.6, and 2.0 T. We observe sawtoothlike de Haas–van Alphen oscillations with distinct jumps ΔM in the

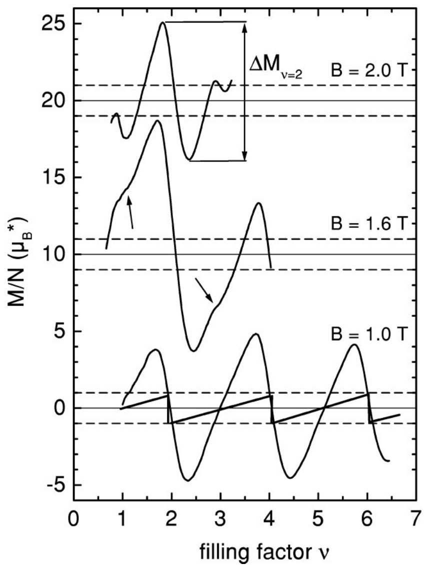

FIG. 1. Magnetization at different B as a function of ν. The thick line at $B=1.0$ T represents the single-particle picture with a discontinuity of 2 μ_B^* at even ν (disregarding spin-splitting) marked by the dashed lines. For clarity, an offset of 10 μ_B^* is added to each curve.

magnetization at even integer filling factors. Strikingly, the height of these jumps is significantly enhanced if compared to the predictions for noninteracting electrons, where oscillations between $\pm 1\mu_B^*$ (marked by the dashed lines) corresponding to $\Delta M = 2\mu_B^*$ per electron, are expected. $\mu_B^* = 1.38\times 10^{-22}$ J/T is the effective Bohr magneton in GaAs. At $B=1.6$ T we get a discontinuity of about 15 μ_B^* for $\nu = 2$ which exceeds the value for noninteracting electrons by a factor of 7.5.

Following the theory for noninteracting electrons and the HFA, ΔM is related to the discontinuity in the chemical potential $\Delta\chi$, i.e., the Landau energy gap at even and the Zeeman gap at odd filling factors, according to $\Delta\chi = \Delta M \cdot B$. At odd ν, it is common to express an enhancement of the energy gap in terms of an enhanced g-factor. In our data, spin splitting becomes visible already at $B=1.6$ T (indicated by arrows). At $B=2.0$ T, we find $\Delta M = 1.4\mu_B^*$ corresponding to $g^* \approx 22$ for $\nu = 1$.

The enhancements at even and odd ν deduced from our data are much higher than the values obtained by thermal activated magnetotransport measurements so far.[5] Surprisingly, the signal strengths at odd ν increase with increasing magnetic field whereas the signal strengths at even ν decrease at higher B. In order to elucidate this further, we evaluate the magnitude of the discontinuities ΔM at each fixed filling factor as a function of the magnetic field as depicted in Fig. 2 for two samples. Intriguingly, we observe a common behavior, and integer filling factors follow the same curve. Starting from zero signal strength at low magnetic fields, ΔM increases rapidly as a function of B, evolves a maximum and decreases again. Most astonishing is the high maximum of ΔM at moderate magnetic fields at even ν, which is significantly enhanced in comparison to noninteracting electrons (dashed line). For even ν, we derive a maximum enhancement of about 7.5 (compare Fig. 1). For $\nu = 1$, we observe a similar behavior with an onset at higher magnetic fields. The maximum is now at about 3 T. Here, the signal strength is enhanced up to a factor of 210. If expressed in terms of an effective g-factor this would correspond to the extraordinary high value of 90. Even within the HFA including the exchange enhancement (solid line for $\nu = 2$) we are not able to explain such high signal strengths.

Since we know from Ref. 9 that correlation effects are important to the magnetization one is tempted to assume that they might be the origin of these enhancements as well. We have therefore calculated ΔM in the SHFA following the approach of Ref. 13 as described briefly in the following.

At zero temperature, the magnetization can be calculated using the thermodynamic equation

$$M = -\left(\frac{\partial U}{\partial B}\right)\bigg|_N , \qquad (1)$$

where U denotes the total energy of the 2DES and N the number of electrons. If one restricts the calculations to the discontinuities, i.e., to integer filling factors, it is more convenient to express the derivative with respect to B in terms of the filling factor:

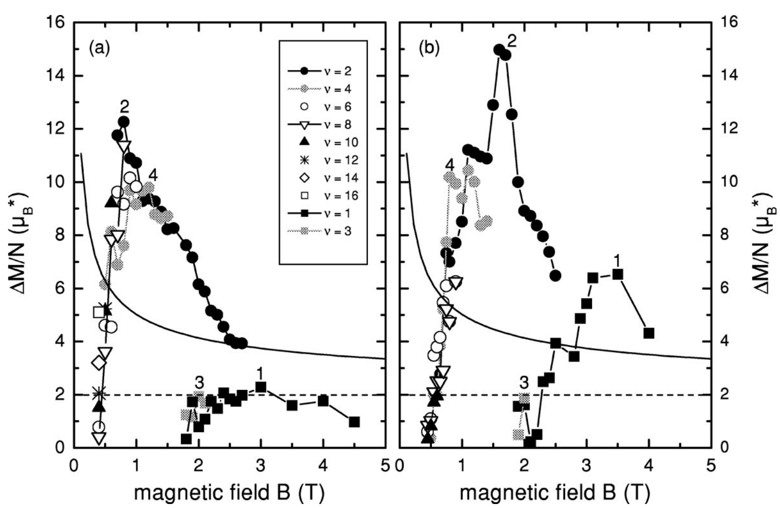

FIG. 2. ΔM at different fixed ν as a function of B for (a) sample #8896_6 and (b) sample #8896_7. Assuming an ideal 2DES, the dashed line is the result for noninteracting electrons, the solid line shows the behavior calculated for $\nu = 2$ with current density functional theory (Ref. 7) and HFA (Ref. 8). The accuracy of the theory (Ref. 8) is limited at small B with the strong signal increase.

$$M=\frac{\nu}{B}\left(\frac{\partial U}{\partial \nu}\right)\bigg|_N . \tag{2}$$

U can be obtained by a summation of the single-particle energies,

$$U=\frac{N}{\nu}\sum_{n\sigma}\nu_{n\sigma}\left(\epsilon_{n\sigma}^{(0)}+\frac{1}{2}\epsilon_{n\sigma}^{(int)}\right), \tag{3}$$

where $\nu_{n\sigma}$ is the (partial) filling factor of the single-particle states with Landau index n and spin projection $\sigma=\pm 1$, $\epsilon_{n\sigma}^{(0)}=(n+1/2-\sigma g m^*/4m)\hbar\omega_c$ are the spin-split Landau levels for noninteracting electrons (for GaAs $m^*=0.067m$ and $g=-0.44$), and $\epsilon_{n\sigma}^{(int)}$ denote the Coulomb component of the single-particle energies, $\epsilon_{n\sigma}=\epsilon_{n\sigma}^{(0)}+\epsilon_{n\sigma}^{(int)}$. (The factor 1/2 in Eq. (3) is for counting the pair interaction energy only once in the total energy.)

The discontinuities ΔM are always due to the terms containing

$$\frac{\partial \nu_{n\sigma}}{\partial \nu}=\delta_{nn_F}\delta_{\sigma\sigma_F}, \tag{4}$$

where n_F and σ_F are the labels of the Landau level where the Fermi energy is pinned. ΔM is caused by the variation of the total energy U when the Fermi energy jumps from the level $n_F\sigma_F=n_1\sigma_1$ to the level $n_F\sigma_F=n_2\sigma_2$ due to an infinitesimal variation of the filling factor. For the magnetization per electron we obtain

$$\frac{M}{N}=\frac{1}{B}\left[\sum_{n\sigma}\frac{\partial \nu_{n\sigma}}{\partial \nu}\left(\epsilon_{n\sigma}^{(0)}+\frac{1}{2}\epsilon_{n\sigma}^{(int)}\right)+\frac{1}{2}\sum_{n\sigma}\nu_{n\sigma}\frac{\partial \epsilon_{n\sigma}^{(int)}}{\nu}\right] + (\text{c.f.}), \tag{5}$$

where by (c.f.) we denote terms containing *continuous functions* of ν, which have thus no contribution to ΔM.

In the SHFA the interaction energy has the form

$$\epsilon_{n\sigma}^{(int)}=-\frac{e^2}{\kappa l}\sum_{n'}c_{nn'}(\nu)\nu_{n'\sigma}, \tag{6}$$

where $\kappa=12.4$ is the dielectric constant of the bulk semiconductor. The coefficients $c_{nn'}(\nu)$ are obtained by integrating the matrix elements of the Coulomb potential, Fourier transformed into $\tilde{v}(q)=2\pi/[q\varepsilon(q)]$. Here, the correlation effects are included through the screening of the exchange interaction. The static, filling factor dependent dielectric function of the 2DES, $\varepsilon(q)$, thus includes the spatial fluctuations of the 2DES via the wave vector q, but neglects the time-dependent fluctuations. The HFA is recovered by putting $\varepsilon(q)\equiv 1$. The final expression for the coefficients of Eq. (6) is[13,14]

$$c_{nn'}=\frac{n!\sqrt{2}}{n'!}\int_0^\infty dz\frac{e^{-z^2}z^{2(n'-n)}}{\varepsilon(z\sqrt{2})}[L_n^{n'-n}(z^2)]^2, \tag{7}$$

where $L_n^{n'-n}$ are the Laguerre polynomials and $c_{nn'}=c_{n'n}$. The qualitative variation of one coefficient around an integer filling factor is depicted in Fig. 3. In the HFA $c_{nn'}$ does not depend on the filling factor, and from Eq. (5) one obtains the magnetization discontinuity

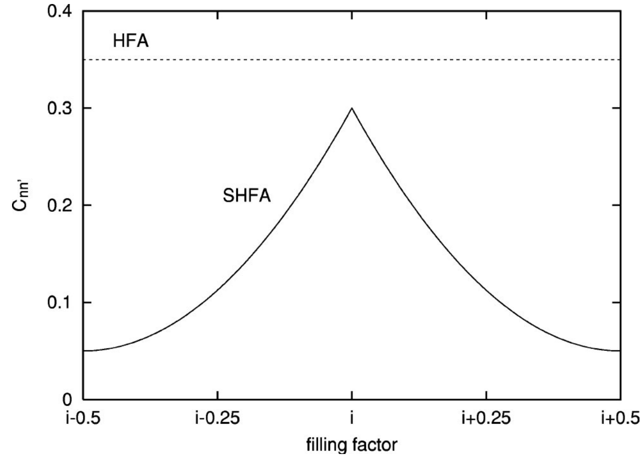

FIG. 3. Qualitative variation of one coefficient $c_{nn'}$ in the SHFA (solid line), when the filling factor varies around an integer value *i*. The dashed line shows the value in HFA.

$$\frac{\Delta M}{N}=\frac{\epsilon_{n_2\sigma_2}-\epsilon_{n_1\sigma_1}}{B}, \tag{8}$$

given by the energy gap between the adjacent Landau levels. Obviously, this result holds also for noninteracting electrons, when Eq. (8) becomes $\Delta M/N=2\mu_B^*(1-g^*m^*/2m)$ for even ν, and $\Delta M/N=\mu_B^* g^* m^*/m$ for odd ν.

In contrast to the HFA, here, in the SHFA, the screening leads to coefficients $c_{nn'}$ dependent on the filling factor, with a cusp at integer ν, as shown in Fig. 3. The screening is weak for integer ν, when there are no states at the Fermi level (and thus $\varepsilon(q)\approx 1$), and strong in the metal-like state, when ν is not integer (and thus $\varepsilon(q)\gg 1$). Hence, the derivative in Eq. (5) leads to a new magnetic contribution,

$$-\frac{1}{2B}\frac{e^2}{\kappa l}\sum_{nn'}\nu_{n\sigma}\nu_{n'\sigma}\frac{\partial c_{nn'}(\nu)}{\partial \nu}, \tag{9}$$

which depends on n_F. It is positive when ν is on the right side of the cusp, and negative on the left side. This yields a *positive* contribution to the magnetization discontinuity (cumulated from both Landau levels $n_1\sigma_1, n_2\sigma_2$) which is no longer directly related to the discontinuity of the chemical potential. The important result is that M reflects the complex renormalization of the many-body ground state due to correlations. In contrast to noninteracting electrons and to HFA the discontinuities ΔM are now significantly enhanced, whereas the discontinuity in the chemical potential remains nearly the same.

Figure 4 shows the numerical results for ΔM calculated by SHFA at even and odd ν. Much larger values than in HFA are obtained, which are of the same order of magnitude as observed in the experiment. In the numerical calculations we account for disorder effects, by considering a Gaussian broadening of the Landau levels defined by the disorder energy $\Gamma=\gamma\sqrt{B}$, where γ is constant and characteristic for each sample.

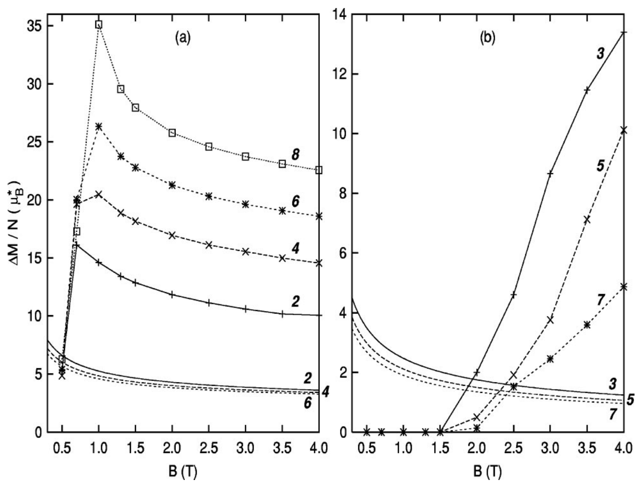

FIG. 4. ΔM at (a) even and (b) odd filling factors, calculated by SHFA, with a disorder parameter $\gamma = 0.5$ meV/$\sqrt{\mathrm{T}}$, shown by the lines with point symbols. The attached numbers are the filling factors. The solid and dashed lines below show the results in the HFA, with $\gamma = 0$, for $\nu = 2,4,6$, and $\nu = 3,5,7$.

Firstly, we are able to interpret the strong suppression of ΔM at low B for even filling factors, as a disorder effect. Reducing or increasing γ, the maxima of Fig. 4(a) move to the left and to the right, respectively. The common scaling for all the different ν at low magnetic fields reproduces our experimental observation. In addition, the calculations yield a decreasing signal strength with increasing magnetic field, reflecting the increase of the disorder energy Γ with B. Only the slope is smaller than observed in the experiment. Secondly, using the same γ, the maximum signal strengths at low even filling factors are quite close to the experimental data. Also, the maxima of ΔM occur at magnetic fields close to the experimental values. Hence, the SHFA explains the magnitude of ΔM, and the disorder broadening explains the shape of the curve, i.e., the maximum.

Another interesting aspect is the weak asymmetry between the maxima and the minima of the magnetization around integer filling factors, observable in Fig. 1. Within our model, we can explain it by the dependence of the cusps of $c_{nn'}$, Fig. 3, on the Landau levels n and n'. Therefore the magnetization enhancements for ν slightly above and below an even integer value, given by Eq. (9), are slightly different.

The numerical results however overestimate the magnetization discontinuities. One possible explanation may be that the static screening is in general too strong, and thus a model based on a dynamically (and thus a weaker) screened Coulomb interaction may give a better quantitative agreement.[15,16] Also the spin splitting is overestimated by the model. Here the disorder broadening also plays an important role, and our model might be too poor also in this respect. Slightly increasing the disorder parameter the calculated spin splitting is rapidly suppressed. It has been suggested that the real broadening of the energy levels might be smaller for the spin split levels.[5] However, the general trend of our available experimental data is remarkably reproduced by the calculations.

In conclusion, we have shown experimentally and theoretically that the magnetization of integer quantum Hall states is strongly enhanced due to many-particle interactions, i.e., exchange and correlation effects. We have presented a new theoretical approach to calculate the magnetization taking into account correlation effects, i.e., filling factor dependent screening, within the SHFA. An important result is that the discontinuities of the magnetization at integer filling factors are no longer proportional to the discontinuities of the chemical potential. This results in signal strengths much higher than predicted for noninteracting electrons and within the usual HFA, in good agreement with the experimental data. The features exhibit a characteristic dependence on the magnetic field which we have shown to be caused by disorder in the real sample.

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