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Filling-factor-dependent electron correlations observed in cyclotron resonance

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Cyclotron resonances of electron space-charge layers in GaAs were studied at ^{3}He temperatures covering a density regime from 2 to 13×10^{11} cm^{-2}. For densities higher than about 6×10^{11} cm^{-2} many-body influences are sufficiently reduced such that line splittings due to band-structure influences were involved. At integer filling factors the spin-up and spin-down electrons are not completely decoupled as predicted by theory. Inter Landau-level optical gaps are renormalized at odd fillings, and there is a correlation gap between spin- and charge-density excitations in the long-wavelength limit.

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The influence of many-body effects on the cyclotron resonance (CR) is a fascinating topic that still has not been settled properly. According to Kohn[1] the CR frequency of a translational invariant carrier system is not influenced by many-body effects. This is due to the fact that the exciting electric dipole field couples only to the center-of-mass motion of a one-component system leaving the internal forces unaffected. Under such circumstances the experiment reflects the single-particle CR position. Impurity or band-structure influences can break the translational invariance and reintroduce many-body effects as is well known from many experiments performed on space-charge layers in semiconductors.[2–8] One then faces a multicomponent system where the internal forces cannot be neglected.[9–14] Each component represents an oscillator with a characteristic single-particle frequency, and many-body effects couple the oscillators in a manner that has not been explored yet satisfactorily. In sufficiently high-mobility carrier systems impurity influences are suppressed, and the band-structure-mediated interaction coupling will dominate. Previously, this coupling was studied only on dilute electron space-charge layers in GaAs. A limit fairly well understood today. For samples with surface electron densities N_s of the order of 10^{11} cm^{-2} the coupling has not been explored yet. Due to a strong interaction influence previous experiments could not reveal split CR lines that are essential to analyze the coupling quantitatively. We report here a detailed CR investigation of high-mobility electron space-charge layers in GaAs that gives first insight in the band-structure-mediated interaction coupling at high densities. At integer filling factors $\nu=2\pi l^2 N_s$ [$l=(\hbar/eB)^{1/2}$] when a two-component electron system is present the spin-up and spin-down electrons are not decoupled. A result presently not matched by calculations. We also provide information on the inter-Landau-level optical gaps and the spin- and charge-density excitations in the long-wavelength limit.

We studied electron space-charge layers with mobilities in the million cm^2 V^{-1} s^{-1} range in modulation doped $Al_{0.3}Ga_{0.7}As$-GaAs single heterostructures and in 10 nm wide GaAs quantum wells covering a density regime from 2 to 13×10^{11} cm^{-2}. CR was studied in Faraday geometry in transmission with unpolarized far-infrared radiation with a set up incorporating a rapid-scan Fourier transform spectrometer, a 17 T magnet system and a ^{3}H insert. CR lines were obtained from the relative change in transmission $-\Delta T/T=1-T(B)/T(B_{\rm ref})$, where B and $B_{\rm ref}$ are the measurement and reference magnetic-field strengths, respectively.

Figure 1 provides an overview of resonances observed for a quantum well with $N_s=10.65\times10^{11}$ cm^{-2} at 1.4 K in a magnetic-field regime from 2.2 to 17 T. CR traces at integer filling factors are featured by bold lines. Pronounced CR splittings are observed at the odd filling factors $\nu=3$ and 5. At noninteger fillings a more or less asymmetric single line

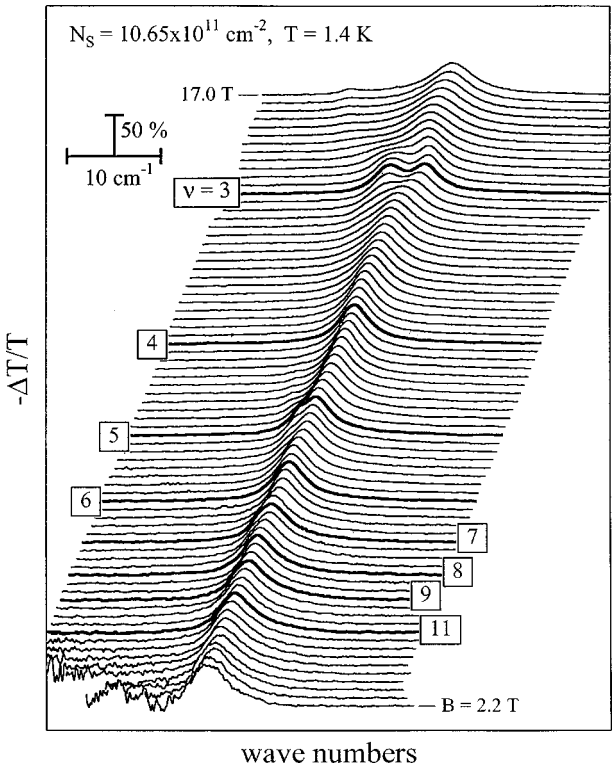

FIG. 1. Cyclotron resonances for a 10 nm wide GaAs quantum well with $N_s=10.65\times10^{11}$ cm^{-2} at 1.4 K in the magnetic-field regime from 2.2 to 17 T (field increment=0.2 T). At integer filling factors ν the traces are featured by bold lines.

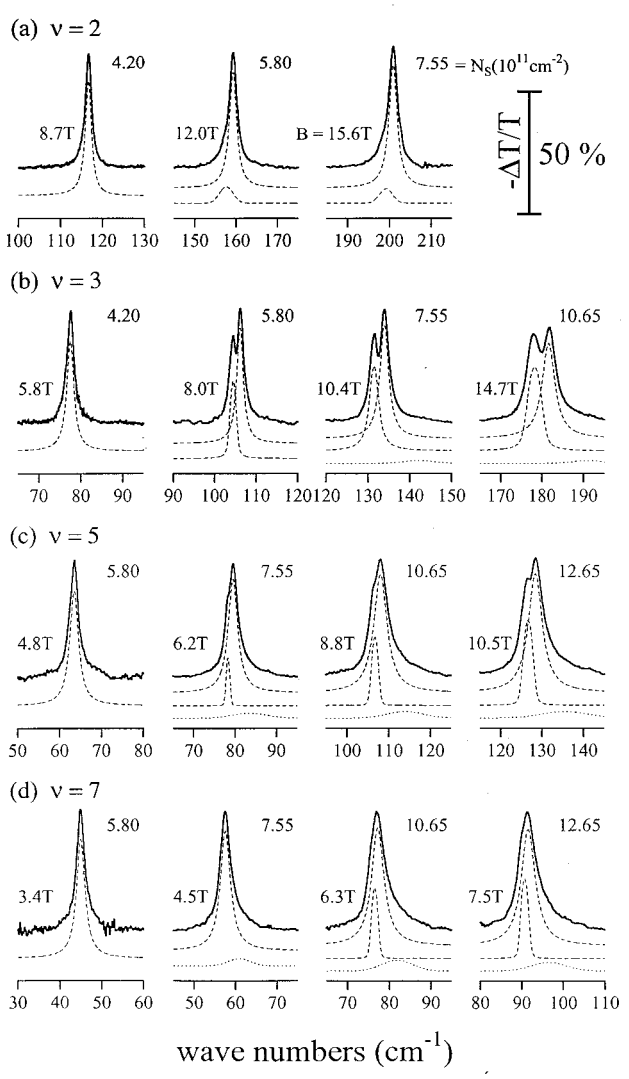

FIG. 2. Evolution of the CR line shape with density for (a) $\nu=2$, (b) 3, (c), 5, and (d) 7. The dashed and dotted lines are fits to the experiment as described in the text.

dominates. There is essentially no difference between measurements at 400 mK and 1.4 K, however, all splittings are quenched at higher temperatures. We like to note, that qualitatively similar line-shape variations could not be resolved for the electron systems with $N_s \leqslant 5.80\times10^{11}$ cm^{-2}. Even at the lowest temperatures an essentially symmetric single CR line was observed.

For $\nu=2$, 3, 5, and 7 the evolution of the CR line shape with N_s is shown in Fig. 2. Traces are for single heterostructures and quantum wells for the N_s regime below and above about 6.5×10^{11} cm^{-2}, respectively. For $\nu=2$ a symmetric single line at lower densities develops in an asymmetric one with low energy shoulder at higher densities. For the even fillings $\nu \geqslant 4$ no evolution of the line shape with N_s was observed. For all densities an essentially symmetric single line was present. At the odd fillings the changes in line shape with density are more dramatic. A well-resolved splitting is observed for $\nu=3$ and 5 increasing with N_s. A similar behavior is found also for $\nu=7$, however, the degree of splitting is less pronounced. At fixed integer ν the splitting increases with increasing N_s and the resonance with lower transition frequency gains in strength.

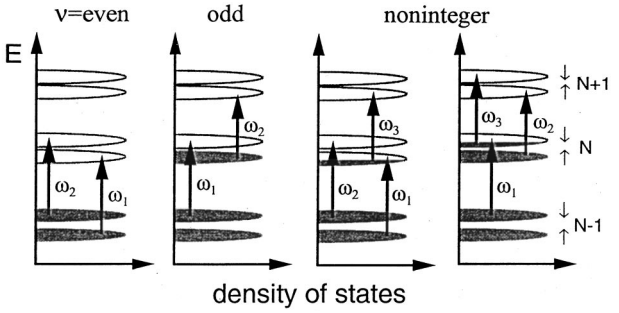

FIG. 3. Schematic sketch of the density of states for a two-dimensional electron system subject to a perpendicular magnetic field for integer and noninteger filling factors. The possible single-particle CR transitions with frequencies ω_i $(i=1-3)$ are indicated by arrows. N is the Landau-level quantum number and the small arrows indicate the spin orientation.

In Fig. 3 the allowed single-particle electrical dipole transitions at integer and noninteger fillings are depicted schematically. Three transitions are allowed at noninteger and two at integer fillings, which will have different transition frequencies in a nonparabolic system. Our assignment is chosen such that the frequencies ω_i $(i=1-3)$ decrease with increasing index i. At odd fillings the difference in the transition frequencies $\Delta\omega=\omega_1-\omega_2$ is essentially ruled by the difference in the Landau gaps, whereas at even fillings the difference in the comparatively smaller Zeeman-gaps counts. Qualitatively this can explain why we observe more pronounced line splittings at odd fillings. Since the difference in the gap sizes increases with B, which at fixed integer filling is proportional to N_s, one can also understand why the line splitting increases with increasing N_s. Eventually, at fixed N_s the reduction of the splitting with increasing odd filling is also in qualitative agreement with the expectation. However, the single-particle picture is not appropriate to analyze the experiment quantitatively. This becomes immediately evident if we compare the experimental oscillator strengths with the predicted ones. In single-particle approximation the oscillator strength of a CR transition $N\rightarrow N+1$ for spin-up or spin-down electrons is ruled by the expression $f=(N+1)(n_N-n_{N+1})/N_s$ where n_N and n_{N+1} are the populations of the initial and final steps, respectively. At even fillings initial and final states for both spin orientations are equally populated and the two transitions should have the same strength. The asymmetry of the lines observed in Fig. 2(a) for $\nu=2$ at the higher densities does not support this point of view. The asymmetry is a strong indication for the presence of two lines with different strengths. At odd fillings the relative strength of the spin-up to the spin-down transitions should scale according to $N+1/N=\nu+1/\nu-1$. Thus, the lower energy transition ω_2 should always be stronger than the higher one ω_1. In contrast, it is evident from Figs. 2(b) and 2(c) that the strength of the transition with lower frequency is mostly smaller than the one with higher frequency. The transition with lower frequency gains in weight

with increasing N_s, and can eventually exceed the strength of the transition with higher frequency as in the case in Fig. 2(b) for $B=14.7$ T. However, this simply indicates that the single-particle limit is approached.

The inadequacy of the single-particle picture to predict the oscillator strength provides a clear indication that the interaction coupling rules the experiment. The response theory for CR incorporating the coupling was developed previously.[7,8,10–12,14] If we restrict the discussion to the most simple case of a two-component system, i.e., integer fillings, then one has to solve the eigenvalue problem of the Hermitian 2×2 matrix

$$\begin{pmatrix} \omega_1+f_2\omega_I & -\sqrt{f_1f_2}\omega_I \\ -\sqrt{f_1f_2}\omega_I & \omega_2+f_1\omega_I \end{pmatrix}. \tag{1}$$

ω_i and f_i $(i=1,2)$ are, respectively, the single-particle transition frequencies and oscillator strength for the spin-up and spin-down electrons, and ω_I is the term that rules the coupling. In a Hartree-Fock treatment of the coupling the interaction vanishes at integer fillings.[12] This is due to the fact that the two-spin states are completely decoupled within this approximation. Only components with the same spin can interact. Also a finite-size study of a two-component system for the case $\nu=2$ could not reproduce a finite coupling.[14] Present theoretical treatments cannot account for the result of our experiment. It is necessary to go beyond existing theoretical approaches. With regard to the previous Hartree-Fock calculation, we will refer to the observed coupling of the spin-up and spin-down electrons as a correlation effect.

Though refined theoretical approaches are required to account for the coupling term, its experimental determination is straightforward. Solving the eigenvalue problem Eq. (1) predicts collective mode frequencies $(i=1,2)$:

$$\Omega_i=\omega_1+\frac{X-1-(-1)^i\sqrt{(1-X)^2+4X\rho}}{2}\Delta\omega \tag{2}$$

and oscillator strengths

$$F_i=\frac{\sqrt{(1-X)^2+4X\rho}+(-1)^i(X-1+2\rho)}{2\sqrt{(1-X)^2+4X\rho}}. \tag{3}$$

We used abbreviations $X=\omega_I/\Delta\omega$ and $\rho=f_2/(f_1+f_2)=1/2[(\nu+1)/2\nu]$ for even [odd] fillings. The prediction of the single-particle picture is recovered for $\omega_I=0$. We then have $\Omega_1=\omega_1$, $\Omega_2=\omega_2$, and $F_1/F_2=f_1/f_2=1$ for even and $F_1/F_2=f_1/f_2=(\nu-1)/(\nu+1)$ for odd fillings.

Oscillator strengths and resonance positions were analyzed by calculating the relative change in transmission $-\Delta T/T$ taking into account all dielectric layers of the samples and the contribution of the electron space-charge layer via a complex high-frequency conductivity. With the usual Drude-type high-frequency conductivity alone, which gives a Lorentzian line, a satisfactory fit of the line shapes was not possible. For best agreement also a contribution whose real part follows a Gaussian-type frequency dependence had to be considered. The result of the fitting procedure is shown in Fig. 2 by dashed lines.

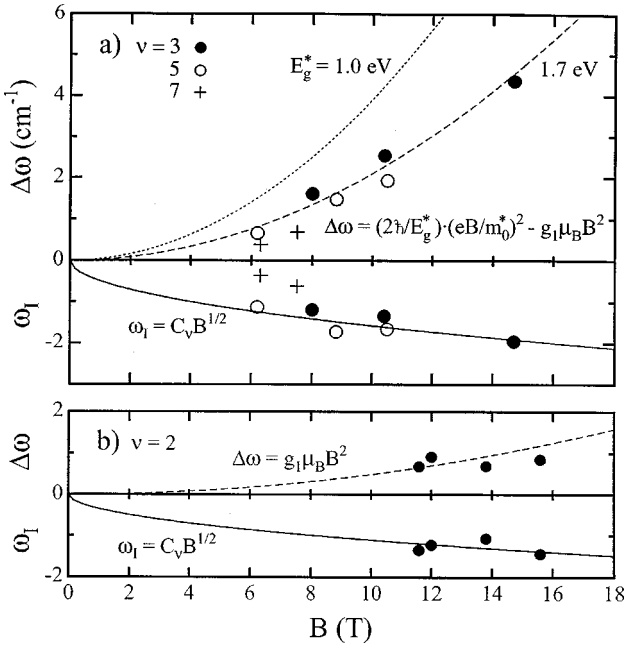

FIG. 4. Experimental $\Delta\omega$ and ω_1 values for the (a) odd fillings $\nu=3$, 5, 7 and (b) $\nu=2$. The solid, dashed, and dotted lines are calculated according to the given equations.

Comparing the experimental values to the predicted ones by Eqs. (2) and (3) we obtain the difference in the single-particle transition frequencies $\Delta\omega$ and the coupling frequency ω_I as shown in Fig. 4 for odd and even fillings. Note, that the interaction term is negative and follows a relation $C_\nu B^{1/2}$ with a filling-factor-dependent scaling factor C_ν. The square-root dependence in B is expected, since any interaction energy scales with the inverse of the magnetic length l in the strictly two-dimensional limit. We obtain $C_\nu \approx -0.5$ T$^{-1/2}$ cm^{-1} and -0.35 T$^{-1/2}$ cm^{-1} for the odd fillings $\nu=3$ and 5 and the even filling $\nu=2$, respectively. Within the experimental accuracy we cannot resolve a possible difference for $\nu=3$ and 5. The difference in the single-particle transitions $\Delta\omega$ increases proportional B^2. Such a dependence can be expected from the nonparabolicity of the GaAs conduction band. To first order in the nonparabolicity at even fillings $\Delta\omega$ is given by $g_1\mu_B B^2$, where g_1 is the nonparabolicity correction to the Landé g factor and μ_B is the Bohr magneton. The experimental data are well described by $g_1\approx0.0105$ T^{-1} determined previously for dilute quasi-two-dimensional electron systems[7,8] and bulk GaAs.[15] At odd fillings $\Delta\omega$ can be parametrized in the framework of the two-band model in the form

$$\left[\frac{2\hbar}{E_g^*}\left(\frac{e}{m_0^*}\right)^2-g_1\mu_B\right]B^2,$$

where m_0^* is the effective mass at the subband edge and E_g^* an effective gap between the conduction and valence band edges. Since far band contributions cannot be neglected for GaAs, the effective gap is smaller than the fundamental gap. The dotted line in Fig. 4(a) was calculated with $E_g^*=1.0$ eV, which is the appropriate value for bulk samples and suffi-

ciently dilute electron space-charge layers in GaAs. However, best agreement with the experiment is obtained with an effective gap value of 1.7 eV as shown with a dashed line. Obviously, in the high-density limit the difference in the inter Landau-level optical gaps is reduced compared to the dilute and bulk case. We attribute the reduction to a many-body induced renormalization of the inter-Landau-level optical gaps.

Equations (1)–(3) formally also describe the coupling of electrical dipole transitions in the dilute limit ($N_s < 10^{11}$ cm^{-2}), however, with different values for ω_I and ρ.[7,8] In the dilute limit the coupling term is positive. Most interestingly, there is a sign reversal of the interaction term if one switches between the high and low density limits. There is a vivid interpretation for ω_I. In the parabolic limit Eqs. (2) and (3) predict $\Omega_1 = \omega_1 = \omega_2$ with $F_1 = 1$ and $\Omega_2 = \omega_1 + \omega_I$ with $F_2 = 0$. If we consider a finite wave vector q parallel to the interface the excitations close to the cyclotron frequency can be classified as charge-density (CDW) and spin-density waves[10,11] (SDW). The CDW and SDW frequencies approach the cyclotron frequency in the $q \to 0$ limit for a parabolic system with the SDW not being dipole active. In our treatment of a parabolic system Ω_1 and Ω_2 represent, respectively, the CDW and SDW frequencies, however, their degeneracy is lifted in the $q \to 0$ limit. The mode energies differ by a correlation gap of size $\hbar\omega_I$. According to the sign of ω_I the CDW energy is larger than the SDW energy in the high density limit, whereas in the dilute limit we have a reversed situation. Due to band-structure influences both charge-density and spin-density excitations mix. Experimental evidence for the mixing can be derived from the line shape of the collective CR transitions shown in Fig. 2. The resonance with higher energy, which carries most of the strength, is essentially described by a Lorentzian line. In contrast, the resonance with lower energy and smaller strength could only be described well by considering a superposition of a Drude- and a Gaussian-type high-frequency conductivity. The Gaussian contribution increases with decreasing oscillator strength. We expect that transitions with reduced oscillator strength are likely to possess more spin-density character. CDW are influenced by an average scattering potential, since the electrons are locked together by an internal electric field generated by the spatial displacement with respect to a positive background. This scattering potential can, in principle, cause a frequency shift of the collective mode, however, no break-up in several collective excitations with different frequencies can occur. Thus, we expect only the homogeneous broadening for this type of excitation. In the case of SDW the electrons are coupled by the short-range exchange field and will pick up more local properties of the scattering potential. This excitation should be more sensitive to the inhomogeneous broadening.

For the quantum wells at $\nu \geqslant 3$ a third resonance had to be considered for best agreement with the experiment as is shown by dotted lines in Fig. 2. Those resonant structures are shifted considerably to higher energies with respect to the mean position of the CR line and are about an order of magnitude broader than the collective CR. At fixed density the separation with respect to the mean CR position increases and the strength decreases with increasing B. It could well be that we face here a scatterer-induced excitation to the roton-type minimum in the dispersion of the CDW.[16] The experimental shift agrees surprisingly well with the predicted shift $\Delta E \approx (0.1-0.2)e^2/4\pi\epsilon\epsilon_0 l$.

In summary, we studied the interaction coupling of CR transitions for high-density electron space-charge layers in GaAs. Line splittings that could be traced back to the nonparabolicity of the GaAs conduction band were observed for densities above about 5.8×10^{11} cm^{-2}. The split resonances represent mixed modes of CDW and SDW. There is strong evidence that the degeneracy of CDW and SDW of nonparabolic systems is lifted in the long-wavelength limit. At integer filling factors there is no complete decoupling of the spin-up and spin-down electrons as predicted by present theories. We hope that our experiment might initiate calculations to better account for the influence of the electron spin.

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