Coulomb Narrowing of the Quantum Cyclotron Resonance in a Nondegenerate Two-Dimensional Electron Liquid

E. Teske,[1] Yu. P. Monarkha,[1,2] M. Seck,[1,*] and P. Wyder[1]
[1]*Grenoble High Magnetic Field Laboratory, MPI-FKF and CNRS, BP 166, F-38042 Grenoble Cedex 9, France*
[2]*Institute for Low Temperature Physics and Engineering, 47 Lenin Avenue, 310164 Kharkov, Ukraine*
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We have observed a narrowing of the linear cyclotron resonance linewidth with an increase in the density of surface electrons on liquid helium in the electron-vapor atom scattering regime. The effect changes sign at densities $n_s > 1.7 \times 10^8$ cm^{-2}. The data are interpreted as a Coulombic effect on the Landau level width produced by a strong fluctuating electric field. [S0031-9007(99)08755-4]

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Cyclotron resonance (CR) studies in two-dimensional (2D) electron systems such as inversion layers on semiconductor surfaces and electrons bound at the free surface of liquid helium have been of great interest for many years [1,2]. Cyclotron resonance serves as a powerful probe for the effects of quantization of both out-of-plane and in-plane (orbital) motions on electron transport phenomena [3,4]. Two-dimensional electrons on a liquid helium surface are usually under extremely strong coupling conditions with respect to mutual Coulomb interaction: $e^2\sqrt{\pi n_s}/k_B T \gg 1$ (here n_s is the electron density). At such conditions a strong influence of electron-electron interaction on the CR linewidth and line shape is expected. In the ultraquantum limit for short-ranged scatterers, according to [1] , the linewidth is determined by the Landau level width itself. Therefore the CR may also serve as a probe for Coulombic effects on the Landau level width.

Experimental studies of the Coulomb effect on the static magnetoconductivity of surface electrons (SE) on liquid helium extensively carried out over the years [5,6] were shown to be in agreement with the theoretical concept of a quasiuniform many-electron fluctuating field E_f. However, the only direct study of the many-electron effect on the CR of SE [7] showed mysteriously a density dependence of the linewidth that is opposite to the theoretical predictions [8,9], putting in question the applicability of this concept.

The intriguing decrease of the CR linewidth with the electron density was predicted nearly two decades ago [8]. This effect caused by the many-electron fluctuating electric field E_f is expected to be quite universal: From a theoretical point of view, it does not depend much on a particular scattering mechanism and remains valid for the Wigner solid [9]. The CR data reported by that time [4] showed a slight decrease of the CR linewidth with the increase of the holding electric field $E_\perp = 2\pi e n_s$ at low temperatures $T < 0.8$ K, where electrons are scattered by capillary wave quanta (ripplons). Under these conditions the electron-ripplon coupling is also dependent on $E_\perp$ which interferes with the many-electron effect. At $T \sim 1.3$ K, where the main scatterers are helium vapor atoms, the opposite behavior was reported: The linewidth increases linearly with $E_\perp$ [4]. Later, a more detailed exploration of the low temperature regime with the electron density n_s being varied independently of the holding electric field $E_\perp$ showed no sign of the linewidth narrowing with n_s for the Wigner solid phase [7]. Additionally, the onset of the electron crystallization did not affect the CR data. In this experiment the linewidth appeared to increase linearly with density which is in conflict with existing theories and is similar to the behavior previously reported for the vapor scattering regime [4].

In our study of Coulombic effects on the CR from 2D electrons, we confine ourselves to the regime $T > 1.3$ K, where the scattering potential is of the most simple form $V \propto U_0 \delta(\mathbf{r}_e - \mathbf{R}_a)$, independent of the holding electric field, and the saturation condition $E_\perp = 2\pi e n_s$ can be employed for studying the density dependence of the CR. We also assume that the effect of narrowing of the CR linewidth is restricted to rather limited density and magnetic field ranges due to the interplay of parameters $eE_f l$, Γ_{SC}, and $\hbar\omega_c$. Here l is the electron magnetic length, ω_c is the cyclotron frequency, $\Gamma_{SC} = \hbar\sqrt{(2/\pi)\omega_c \nu_0}$ is the collision broadening of Landau levels according to the self-consistent Born approximation (SCBA) [1], and ν_0 is the collision frequency for $B = 0$. This makes it necessary to conduct measurements at rather low electron densities and strong magnetic fields, which requires some precautions with regard to the sensitivity of the experimental device when measuring at $T > 1.3$ K and low input powers. We pay additional attention to the power dependence of the experimental data, since we found that, at lower powers, the weak power broadening of the linewidth also observed in [3] turns into power narrowing and the extrapolation to zero power input cannot be used.

To summarize our results, we report the observation of strong narrowing of the linear CR linewidth with the increase of electron density in the range $10^7 < n_s < 10^8$ cm^{-2} for the electron-vapor atom scattering regime, which we ascribe to the Coulombic effect on the collision broadening of Landau levels. The power narrowing of the CR observed at certain conditions is also in accordance

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with the concept of the fluctuating many-electron field $E_f \propto n_s^{3/4}\sqrt{T_e}$ [8]. At $n_s > 1.7 \times 10^8$ cm^{-2}, the many-electron effect changes sign and an increase of the linewidth with n_s is observed in accordance with previous measurements [4]. We also calculate the Landau level width by taking into account fast drift velocities of the cyclotron orbits in a fluctuating electric field E_f and find good agreement with our measurements.

For the measurements of CR of SE on liquid helium, we used a microwave (MW) spectrometer working in the range of 40–60 GHz, originally built for electron spin resonance measurements [10]. The low-temperature part consists of a cavity in the form of an upright cylinder resonating in the TE_{011} mode, and operated in reflection. In the measurements reported here, the MW frequency was set at 40 GHz, which corresponds to the cavity having the following dimensions: height $=$ 7 mm and diameter $=$ 10.8 mm. The cavity is mounted in a cell partly filled with liquid helium, so that the liquid surface inside the cavity lies about 0.6–0.8 mm above the bottom plate. Electrons are produced by pulse firing a small filament and are confined at the helium surface by a negative voltage applied to the walls and the top plate of the cavity, while the bottom plate is kept at ground potential. To observe CR, a vertical magnetic field up to 2.5 T is produced by a superconducting magnet. The spectrometer employs a superheterodyne detection system with high sensitivity, which enables the power input in the electron system to be kept at an estimated level of below 10^{-18} W per electron to allow measurements without heating effects.

Typical CR curves of the linear regime are shown in Fig. 1 for two electron densities. The low density curve has a shape which fits to a Gaussian rather than to a Lorentzian which is in agreement with the theoretical curves calculated for nondegenerate electrons, according

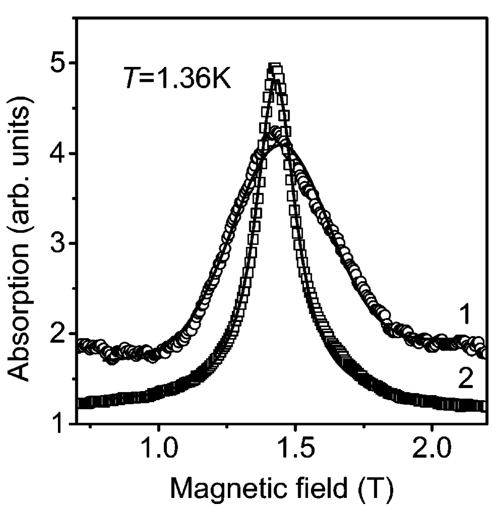

FIG. 1. Typical CR absorption curves, showing the Coulombic effect for SE. Solid curves represent fitting to Gaussian (curve 1, $n_s = 0.167 \times 10^8$ cm^{-2}) and Lorentzian (curve 2, $n_s = 1.68 \times 10^8$ cm^{-2}).

to the Ando CR theory [1]. With the increase of electron density the fluctuating field affects the line shape which is in qualitative accordance with the theoretical concept [11]. In the intermediate case, the line shape is somewhat of a mixture of Gaussian and Lorentzian. The high density limit curves are of pure Lorentzian shape.

It should be noted that under usual experimental conditions the mean potential energy of SE is much larger than $k_B T$ and it is difficult to rely on the results of the single-electron description. The important insight into the problem of strongly interacting 2D electrons in a normal quantizing magnetic field was made by Dykman and Khazan [8], who proved that the main many-electron effect arises from the fluctuating electric field E_f which can be considered approximately uniform. Acting on a particular electron, this field makes the electron spectrum continuous due to the well-known correction $eE_f X$ (here X is the orbit center coordinate). The final result of Refs. [8,11] for the CR linewidth $\gamma_{\rm CR}(E_f)$ of electrons interacting with short-ranged scatterers can be conveniently represented as $\hbar\gamma_{\rm CR}(E_f) \simeq a\Gamma_{\rm SC}^2/\Delta_f$. Here we introduced the typical electron energy in a fluctuating field $\Delta_f = eE_f l$, and the proportionality coefficient $a = \frac{3}{8}\sqrt{\pi/2}$. Since $E_f^{(0)} \equiv \sqrt{\langle E_f^2 \rangle} = 0.84\sqrt{4\pi k_B T_e n_s^{3/2}}$ [7], the linewidth should decrease strongly with electron density and T_e as $\gamma_{\rm CR} \propto 1/(n_s^{3/4}\sqrt{T_e})$.

The result of Ref. [8] should be restricted from both low and high density limits: $\Gamma_{\rm SC} \ll \Delta_f \ll \hbar\omega_c$. This condition is very difficult to realize for the vapor scattering regime. To extend the many-electron theory, taking into account collision broadening and mixing of Landau levels, we propose a different approach. We would like to point out that a quasiuniform fluctuating field E_f does not produce an additional broadening of Landau levels by itself, since the transcription into the frame moving along with the center of electron orbit $u_f = cE_f/B$ eliminates the field ($E_f' = 0$) and restores the purely discrete electron spectrum $\varepsilon_n = \hbar\omega_c(n + 1/2)$ (here $n = 0, 1, \ldots,$). Rather, it is the fast drift velocity of the electron orbit that changes the broadening induced by scatterers.

Instead of introducing the continuous spectrum, we describe the electron kinetics in local frames moving along with the center of each orbit, where the electron spectrum is discrete. The final result will be found by proper averaging over E_f. In this treatment, the main difference from the conventional SCBA is that the vapor atoms (impurities) are moving as a whole with the velocity $-\mathbf{u}_f$ with regard to an electron orbit. In the nonrelativistic theory, the transcription into a moving frame does not affect the momentum exchanged at a collision $\hbar\mathbf{q}$. But the important point is that, in the moving frames, the electron energy is not preserved at a collision, since the impurity hits the electron orbit with the velocity $-\mathbf{u}_f$. The additional energy exchange is usually described by the Doppler shift correction $\hbar\mathbf{q} \cdot \mathbf{u}_f$, which is estimated as Δ_f (we use $q \sim 1/l$ for the electron-atom scattering). When the energy exchange Δ_f becomes larger than the Landau level width, the scattering processes within a Landau level and their contribution to the imaginary part of the electron self-energy are reduced, since electrons have to scatter into an energy range with fewer or next-to-no states. This is the cause for the Coulomb reduction of the collision broadening. At higher n_s or at weak B, Δ_f can become of the order of $\hbar\omega_c$ or even larger, which gives rise to electron transitions between different levels and causes the mixing of Landau levels. The latter eventually changes the sign of the many-electron effect.

The general procedure of finding the Landau level broadening for a spectrum which is discrete in a frame moving with a constant drift velocity was described in [12]. As usual, the broadening of the nth Landau level is defined as $\Gamma_n = -2\,\mathrm{Im}\,\Sigma_n(\varepsilon_n)$, but now the electron self-energy $\Sigma_n(\varepsilon)$ is affected by the motion of scatterers (the frequency argument of the Green's function of scatterers contains the Doppler shift $\mathbf{q}\cdot\mathbf{u}_f$). Following [12], the self-consistent equation for the normalized broadening $g_n = \Gamma_n/\Gamma_{\mathrm{SC}}$ can be written as

$$g_n = \frac{1}{g_n}\,\chi_n(\lambda_f/g_n) + \frac{1}{2\lambda_f}\,C_n(x_f)\,,$$
$$\lambda_f = \Delta_f/\Gamma_{\mathrm{SC}}, \qquad x_f = \frac{1}{2}\,(\hbar\omega_c/\Delta_f)^2. \qquad (1)$$

Here $\chi_n(y)$ results from the imaginary part of the electron Green's function $\mathrm{Im}\,G_n(\varepsilon_n + \hbar\mathbf{q}\cdot\mathbf{u}_f)$ affected by the energy exchange, averaged over $\mathbf{q}$, and normalized. Assuming a Gaussian level shape, we find $\chi_0(y) = 1/\sqrt{1+4y^2}$. The second term of Eq. (1) (usually neglected in the SCBA) represents the effect of the mixing of Landau levels originating from $\mathrm{Im}\,G_{n'}(\varepsilon_n + \hbar\mathbf{q}\cdot\mathbf{u}_f)$ with all possible $n' \neq n$. This term becomes important if $\Delta_f \gtrsim \hbar\omega_c$ ($x_f \lesssim 1$). In the most important range $0.2 < x < 2.5$, $C_0(x)$ can be interpolated as $C_0(x) \simeq e^{-x}(x - 0.6 + 3/\sqrt{\pi x})$ with an accuracy of 2%.

When the mixing of Landau levels becomes important ($x_f \lesssim 1$), the parameter $\lambda_f \gg 1$, due to $\hbar\omega_c \gg \Gamma_0$. Therefore, in the general case, the solution of Eq. (1) for the ground Landau level can be analytically written as

$$g_0^2 = \sqrt{[1 + C_0(x_f)]^2 + 4\lambda_f^4} - 2\lambda_f^2\,. \qquad (2)$$

For both extreme limiting cases with regard to λ_f, Eq. (2) is consistent with existing theories. At $\lambda_f \ll 1$, we have the SCBA result $g_0 = 1$ (or $\Gamma_0 = \Gamma_{\mathrm{SC}}$) while, in the opposite limiting case $\lambda_f \gg 1$ at $C_0(x_f) \ll 1$, the Landau level broadening $\Gamma_0 \simeq \Gamma_{\mathrm{SC}}^2/(2\Delta_f)$, which is in accordance with the CR width γ_{CR} found in [8]. Under real experimental conditions the density dependence of Γ_n results from the interplay of parameters λ_f and x_f. For the averaged value $E_f = E_f^{(0)}$, typical density dependencies of the Landau level broadening are shown in the inset of Fig. 2 for two magnetic fields. According to the curve calculated for

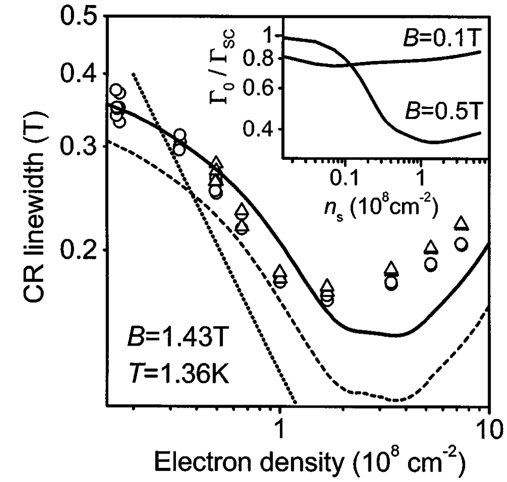

FIG. 2. CR linewidth vs n_s: Data was obtained by fitting to Gaussians (circles) and Lorentzians (triangles); the theory [8] (dotted line); our new theory for $w(E_f^{(0)})$ without any fitting (dashed line) and with Γ_{SC} adjusted to the data at $n_s \to 0$ (solid line). The inset shows $\Gamma_0/\Gamma_{\mathrm{SC}}$ vs n_s at $E_f = E_f^{(0)}$ and $T = 1.36$ K.

$B = 0.1$ T, which corresponds approximately to the MW frequencies (2 GHz) used in [7], the narrowing of Γ_0 is small and is shifted into the range of extremely low densities $n_s < 10^7$ cm^{-2}. At n_s and B employed in [7], Γ_n increases with n_s due to, at the least, the effect of mixing of Landau levels, which can be considered as a qualitative explanation of the unexpected results of this experiment. The decrease of Γ_0 with n_s becomes pronounced only at strong magnetic fields.

The linewidth data versus n_s are shown in Fig. 2. The dotted line shows the result of the Dykman and Khazan theory [8] for $\gamma_{\mathrm{CR}}(E_f^{(0)})$. The dashed curve represents the conventional Gaussian width parameter $w_0(E_f^{(0)}) = \Gamma_{\mathrm{SC}}\sqrt{g_0^2 + g_1^2}/\hbar$, according to Eq. (1). The decrease of the observed CR linewidth is in accordance (even quantitative) with the theoretical model. Still, there is an additional contribution to Γ_{SC} of the order of 10%–13% which is not described by the theoretical model. Since this quantity is found in the simplest approximation, we can adjust empirically Γ_{SC} to fit the data at the lowest n_s (solid curve). This improves the agreement in the range $n_s < 1.7 \times 10^8$ cm^{-2}, while beyond this density, additional effects have to be taken into account.

The contribution from the electron-ripplon interaction, which is negligible (less than 2%) for $n_s \leq 10^8$ cm^{-2}, was taken into account in Fig. 2 for the dashed and solid curves. To investigate the origin of the deviations at high densities, we increased $E_\perp$ at a fixed density and found no substantial change in the linewidth. This proves that these data depend on n_s and represent a many-electron effect. We attribute these deviations to the breakdown of the assumption of a quasiuniform field E_f. Indeed, according to [8], the fluctuating field can be considered as

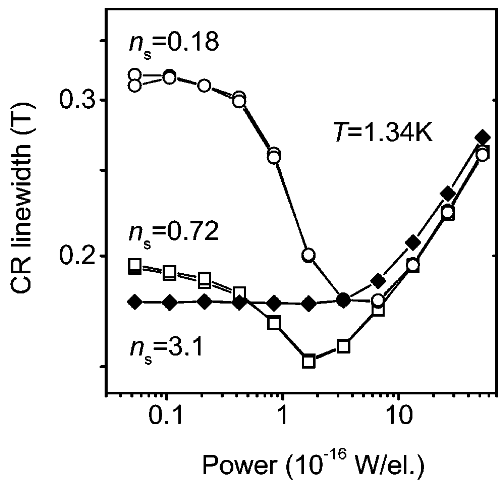

FIG. 3. CR linewidth data vs absorbed power for three n_s shown in units of 10^8 cm^{-2}. Lines connect data points for magnetic field sweeps up and down, respectively.

uniform only if $\Delta_f \ll k_B T$. For the conditions of Fig. 2 at $n_s > 2 \times 10^8$ cm^{-2}, the parameter $\Delta_f / k_B T \gtrsim 0.4$ and E_f cannot be treated as uniform any more.

The fluctuating field increases not only with n_s but also with the electron temperature, due to $E_f^{(0)} \propto \sqrt{T_e}$. At certain conditions, this can lead to a power narrowing of the linewidth, as is shown in Fig. 3. We observed the power narrowing at low electron densities $n_s < 1.7 \times 10^8$ cm^{-2}, while at higher n_s, there is only the power broadening. This behavior is consistent with the density dependence of the CR linewidth presented in Fig. 2. It is quite convincing that Figs. 2 and 3 represent the same effect observed due to varying E_f by changing n_e and T_e, respectively.

In conclusion, the observation of Coulomb narrowing of the CR linewidth reported here completes the set of basic many-body effects on quantum magnetotransport in a nondegenerate 2D electron liquid which follow from the concept of a quasiuniform fluctuating electric field. Two other effects (Coulomb reduction of the static magnetoconductivity and the sharp increase of σ_{xx}, restoring the Drude conductivity behavior) were reported in [5]. The transcription into frames moving along with the electron orbit center proposed here appears to be very fruitful for the description of the Coulombic effects at an arbitrary relation between Δ_f and Γ_{SC}. According to it, all of these effects represent a sort of inelastic effect caused by the fast motion of electron orbits in a fluctuating field. Coulomb narrowing of the Landau level width reflects the suppression of electron scattering within a Landau level, also reducing σ_{xx}, when the energy exchange $\Delta_f \gtrsim \Gamma_{SC}$. The same link exists between the effect of the mixing of Landau levels, increasing Γ_n, and the stimulation of electron scattering between different Landau levels, restoring the Drude conductivity behavior, when $\Delta_f \gtrsim \hbar\omega_c$. It should be noted that the many-electron decrease of the dc magnetoresistivity $\rho_{xx}^{(me)}$ exists, remarkably, even for the unchanged Landau level width ($\Gamma_0 = \Gamma_{SC}$), and has a very weak dependence on the real behavior of Γ_0 in a fluctuating field: $\rho_{xx}^{(me)} / \rho_{xx}^{(\mathrm{SCBA})} = \langle \Gamma_{SC}(\Gamma_0^2 + \Delta_f^2)/(\Gamma_0^2 + 2\Delta_f^2)^{3/2} \rangle_f$ [13] (here $\langle\,\rangle_f$ means an average over E_f). However, the CR linewidth study conducted here proves to be an excellent probe for the Landau level width affected by the internal forces of a 2D electron liquid.

*Present address: SIMEC GmbH, P.O.B. 100940, 01076 Dresden, Germany.

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