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Microwave study of surface electrons on helium films in a magnetic field

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We report preliminary results of a cyclotron resonance study of surface electrons (SE) on saturated helium films covering a PMMA substrate at $T > 1\,K$. The real and imaginary parts of the dielectric response $\epsilon\,(k, \omega)$ of the SE are measured at fixed k and ω in B-fields up to 10 T in a 12 GHz cavity. The cyclotron resonance of the SE is determined at different helium film thicknesses d_{He} and at various electron densities. At small d_{He} we find significant anomalies in the cyclotron resonance lineshape and position. As d_{He} increases the lineshape becomes progressively more symmetric and its peak moves towards the cyclotron field value expected for a free electron. To fit these data we have modified the classical Drude expression, introducing two different relaxation times for the low and high B-field regions. The phenomenological formulas fit the data quite well. A systematic theoretical analysis of these results is in progress.

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Cyclotron resonance (CR) measurements have been one of the first experiments carried out on surface electrons (SE) prepared on bulk helium and proved for the first time the two dimensional character of the SE[1,2]. Because of an electrohydrodynamic instability of the bulk helium surface, the electron density n is limited to values below $2.2 \times 10^9\,cm^{-2}$ and therefore the transition to a so called Wigner crystal occurs only at low temperatures

$T < 1\,K$[2]. In this temperature region, CR of SE on bulk helium has been measured at a frequency $\approx 2\,GHz$ but the onset of electron crystallization was not observed with CR[3].

This behaviour changes substantially when the SE are formed on films rather than on bulk helium. Because of the stabilization of the film caused by van der Waals forces, equilibrium electron densities near $10^{11}\,cm^{-2}$ can be reached[4]. In addition, the helium film thickness d_{He} becomes a new important parameter easily controllable in laboratory. By changing d_{He} it is possible to vary the effect of the screening of the inter-electronic Coulomb interaction on the electron crystallization. In particular, a large screening, which can be achieved on a thin film and/or on a highly polarizable substrate, implies an increase in the crystallization density of the SE crystal and a decrease in the density value where quantum melting of the crystal occurs with respect to the corresponding values on bulk helium[5,6]. At the same time, when d_{He} decreases the effect of the disorder caused by surface defects onto the SE behaviour increases, until a complete localization occurs[7].

In order to investigate the interesting properties of this system, a research program was started at the University of Konstanz a few years ago. Among the experimental techniques employed, the microwave cavity has proved to be a powerful tool in the study of high density systems of SE on helium films. With such a probe the screened phase diagram of the classical Wigner crystal has been mapped out in zero B-field[5] and a first hint of the crossing of the quantum melting line may have been observed[8]. Hereafter we report preliminary results of the first systematic CR study carried out on SE in the liquid and solid phases formed on helium films at $T > 1\,K$. The microwave cavity set-up used in this study has been described in details elesewhere [5]. A thin Si platelet, $5 \times 18\,mm$, spin coated with a thin PMMA layer ($d_s \approx 100\,nm$) was placed along the axis of a cylindrical cavity which was excited in the fundamental TM_{010} mode at a frequency $f \approx 12GHz$ when the sample was inside. An initial helium film of thickness d_{He} was prepared by keeping the level of liquid helium at a height H below the substrate. The distance H was determined by the frequency shift of the cavity when the liquid helium level was inside the resonator [5], and by the amount of ^4He gas dosed in when it was outside. The helium film was charged by firing a small tungsten filament while increasing the generally positive clamping voltage U applied to the Si platelet in small steps so that the electrons could not acquire sufficient energy to penetrate into the helium film. The resonator was inserted in a microwave transmission line with a feedback loop which locked the frequency of an X band generator onto the cavity resonance. The frequency stability was $\approx 3ppm$, that of the amplitude $\approx 0.3\%$. Both the resonance frequency and the transmitted power through the cavity were monitored during charging or during a B-field sweep. The total relative absorption α and susceptibility χ of the SE, that is the real and imaginary parts of the dielectric response of the SE respectively, were calculated from the resonance amplitude and frequency[5].

Figure 1 shows three charging runs measured at constant temperature and at three different B fields whose values were chosen near the cyclotron field of a free electron $B_c = \frac{2\pi f e}{m_e} = 0.42\,T$, where m_e is the free electron mass. Because of the uncertainty in the determination of d_{He}, the horizontal axis reports the applied clamping voltage U instead of the calculated electron density $n = \frac{\epsilon_0 \epsilon_s \epsilon_{He}}{e(\epsilon_{He} d_s + \epsilon_s d_{He})} U$. In any case, for the data reported in fig. 1, $dn/dU \approx 10^{10} cm^{-2} V^{-1}$. Charging starts at a slightly negative voltage $U_o \approx -0.5\,V$, which may be due to a contact potential between the Si platelet and the wire soldered to it or to electrostatic charging of the substrate during its handling. Similar offsets in the clamping voltage have been already reported in the literature[7].

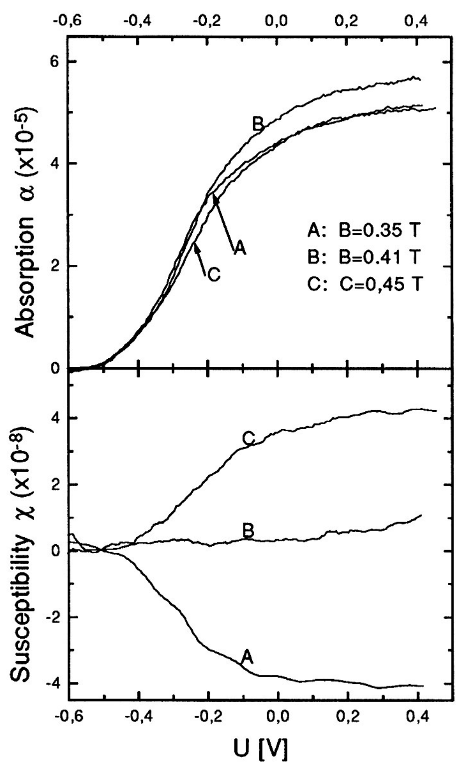

Fig. 1. Charging runs at different magnetic fields. $T = 1.4\,K$, $d_{He} = 300 Å$.

The 3 absorption curves are analogous to those already reported in zero field[5], namely an initial linear region, which is interpreted as the microwave response of a weakly correlated gas of SE obeying the Drude model, followed by a kink, which marks the onset of electron cristallization, and a less steep line, where the absorption is due to small crystallites not pinned to surface defects[5]. The sharpness of the kink depends on the quality of the surface. On smooth, clean substrates and/or on thick helium films this kink is very sharp. It becomes progressively more round as the influence of the surface defects increases because of surface contamination or use of thin helium films. In contrast, the susceptibilty curves are strongly affected by the presence of B. At $B \approx B_c$, χ is practically a flat line with a very small negative slope, while the slope of the initial linear region changes sign when B crosses B_c. This behaviour can be qualitatively explained in terms of the classical Drude equations[2]:

$$\alpha \sim n\mu \frac{1 + \left(B_c^2 + B^2\right)\mu^2}{\left[1 - \left(B_c^2 - B^2\right)\mu^2\right]^2 + 4B_c^2\mu^2} \tag{1}$$

$$\chi \sim -n\mu^2 \frac{1 + \left(B_c^2 - B^2\right)\mu^2}{\left[1 - \left(B_c^2 - B^2\right)\mu^2\right]^2 + 4B_c{}^2\mu^2} \tag{2}$$

where μ is the electron mobility in $m^2/Vsec$ and B the applied field in T. According to eqn. 1, the initial slope of the absorption charging curve should always be positive and only slightly dependent on the applied field for $B \approx B_c$. Viceversa, eqn. 2 shows that the slope of χ at small electron densities is a very small negative number when $B = B_c$, negative for $B < B_c$ and positive for $B > B_c$, if $\mu B \gg 1$, a condition satisfied in our measurements where typically $\mu \approx 10\, m^2/Vsec$ and $B \approx 0.4\, T$, see below. As fig.1 shows, such predictions are in good agreement with our findings. This fact further corroborates the interpretation of the absorption lineshape introduced in Ref.[5].

We have also swept the B-field with a superconducting magnet up to $10\, T$. Figure 2 shows a typical cyclotron resonance of SE measured on a helium film of initial thickness $d_{He} \approx 300 \AA$, covering a coated Si platelet different from that used to take the data of fig.1. (At high B-field values, $1 < B < 10T$, both α and χ assume the same values as at $B = 0T$ without showing any particular structure). In contrast to the measurements on bulk helium[1,3,9], the peak is clearly asymmetric and its maximum occurs around $0.40\, T$, a value less than that expected on bulk helium equal to $0.42\, T$, which is represented by a vertical line in the two graphs. The dotted and dashed lines represent fits to the data using Drude formulas 1 and 2. Evidently, they cannot yield a good fit over the entire B range but only in the low or

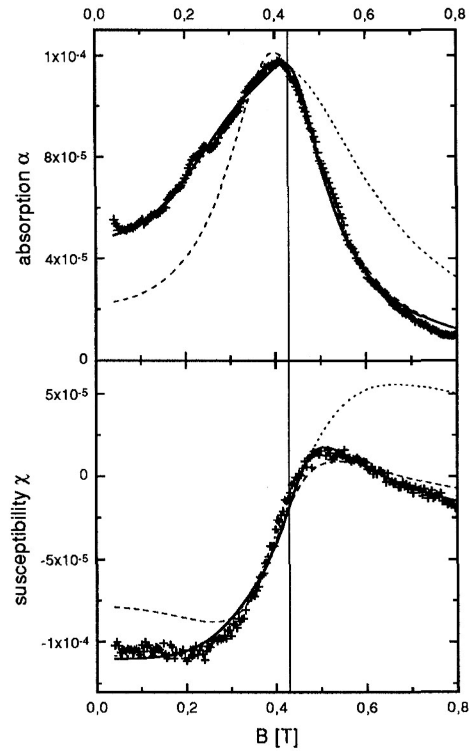

Fig. 2. CR of SE on an helium film of initial thickness $d_{He} = 300Å$, $T = 1.25K, n \approx 6 \times 10^9 cm^{-2}$. The vertical line indicates the cyclotron field of a free electron. The fit lines are explained in the text.

high B-field regions respectively, where their agreement with the data points is such that it becomes difficult to distinguish them. The best parameters of these nonlinear fits are $\mu = 7.7 \pm 0.15 m^2/Vsec$ and $B_c = 0.41 \pm 0.08\,T$ for the dashed line which reproduces rather well the high field shoulder and $\mu = 4.4 \pm 0.1 m^2/Vsec, B_c = 0.40 \pm 0.05\,T$ for the dotted line.

Given these results, we have tried to modify Drude formulas by introducing a phenomenological mobility which smoothly joins the results in these two regions and which depends on B according to the equation:

$$\mu = \mu_0 + (\mu_1 - \mu_0)\frac{[\tanh(k(B - B^*)) + 1]}{2} \tag{3}$$

where μ_0 and μ_1 are the SE mobilities in zero and in high magnetic field respectively, k is a numerical factor which sets the rapidity of the mobility change (typically, $k \approx 10$) and B^* is a free parameter which indicates where the mobility change occurs. The solid line in fig. 2 represents a fit to the data using the modified mobility 3. In the scale of the graphs it is very difficult to distinguish these curves from the experimental points. Similar asymmetric curves were also seen in different experiments[10,11] but no attempt to explain the measured lineshapes was offered. Currently we are fitting with the corrected Drude formulas the results we obtained by varying the film thickness, the electron density and the temperature in order to see whether this approach yields interesting and consistent results.

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