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Observation of liquid-to-crystal transition in a two dimensional electronic system

D. Marty, J. Poitrenaud and F. I. B. Williams

DPh-G/PSRM, CEN Saclay, B.P. N° 2, 91190 Gif sur Yvette, France

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Résumé. — En étudiant le signal d'absorption des électrons à deux dimensions déposés à la surface de l'hélium liquide et excités par un champ électrique de fréquence fixe 25 MHz, nous avons observé la transition liquide-cristal.

Abstract. — We have observed the liquid-to-crystal transition in a two dimensional system of electrons at the surface of liquid helium, by studying the absorption signal of the electrons excited by an electric field of a fixed frequency 25 MHz.

Electrons constrained to move on a flat surface constitute an excellent system on which to test ideas on two dimensional ordering transitions. The interaction is exactly known and is characterized by a single parameter, the charge e , for the ideal case of unrestricted geometry. In the classical limit one can then construct two characteristic energies $e^2 n^{1/2}$ for the Coulomb interaction and kT for the temperature (n is a real number density). Then the relevant variable is

$$\Gamma = \pi^{1/2} e^2 n^{1/2} / kT.$$

One expects order as $\Gamma \rightarrow \infty$, disorder as $\Gamma \rightarrow 0$. Infinitely long range spatial order in two dimensions only exists for $\Gamma = \infty$, but if one applies instead the criterion for a solid of Kosterlitz and Thouless [1] of long range topological order (closure of Burgers circuits), one finds a liquid-to-solid transition for $\Gamma_c \approx 80$ [2]. Recent computer estimates based on comparison of free energies of liquid and solid configurations give $\Gamma = 125 \pm 15$ [3].

The experiment described here is a measure of the melting temperature T_c of a system of electrons condensed onto a liquid helium surface which constitutes a good approach to such a two dimensional system. We observe the variation of signal due to longitudinal vibrations (or plasmons) with the temperature.

The liquid surface although very smooth is deformable and this facilitates the detection of the transition. Shikin [4] pointed out that an electron held

onto a liquid surface depresses the liquid beneath it. The binding energy of a single electron to its deformation is typically of the order of a few mK under our conditions. When N particles are rigidly correlated the binding energy of the ensemble ($N \times$ a few mK) is to be compared with the thermal energy T of its centre of mass motion. In the liquid state where correlation extends over only a few particles the substrate deformation is not bound to the particles for our temperatures (> 0.3 K) and the dynamics can be treated independently predicting a plasmon spectrum [5] :

$$\omega_p^2(k) = \frac{2 \pi n e^2}{m} k \frac{2}{\coth(ka) + \coth(kb)}, \quad (1)$$

where the last factor corrects for non infinite electrical geometry (k is the wave vector of the excitation in the plane of the electrons $z = 0$, itself parallel to two plane parallel conductors at $z = a$ and $z = -b$, see Fig. 1). These modes were first observed by Grimes and Adams [6].

In the solid state, however, the correlation quickly extends over hundreds of particles and the substrate deformation becomes bound to the electrons. As pointed out by Fisher *et al.* [7] the dynamics must then take into account the motion of the correlated surface deformation to which we can ascribe an in-plane displacement variable with an associated dynamical mass m^* per unit cell. The physical picture is one of an electron lattice riding on a waffled surface with the

Fig. 1. — Schematic view of the experiment cell. A : guard-ring. F. : tungsten filament. G : grid. L : coil. P : plate. S : liquid helium surface.

appearance of coupled motion of electron and waffle displacement. As $k \rightarrow 0$ one finds optical and acoustical modes whose longitudinal frequencies are given by :

$$\omega_{\text{opt}}^2 \sim \omega_L^2 + \omega_p^2(k) \quad (2)$$

$$\omega_{\text{ac}}^2 \sim \frac{m}{m^*} \omega_p^2(k) \quad (3)$$

where $\omega_L^2 \sim \frac{m^*}{m} \omega_R^2$ is the local mode frequency and $m^* = \frac{e^2 E_{\perp}^2 n^2}{2 \alpha^2 g^2} \frac{\rho}{n \alpha g}$.

In the particular simple case where $\frac{m^*}{m} \gg 1$, $\omega_{\text{ac}}^2 \ll \omega_R^2$ and taking into account only the first cell of the hexagonal reciprocal lattice. g is the reciprocal lattice vector, $\omega_R^2 = \frac{\alpha}{\rho} g^3$ is the ripplon frequency, α the surface tension and ρ the density of the liquid helium substrate. $E_{\perp}$ is the perpendicular holding field on the electrons and we note that under the saturation conditions where the asymptotic field above the electrons is zero $\epsilon E_{\perp} = 2 \pi n e$ and $\omega_L^2 \sim n^3$, unlike $\omega_p^2 \sim n$.

While for large k ($kR \gg 1$; R being the cell radius)

$$\omega_{\text{opt}}^2 \sim \omega_p^2(k) \quad \text{and} \quad \omega_{\text{ac}}^2 \sim \omega_R^2.$$

Figure 2 shows the variation of ω_p and ω_{opt} versus electron density.

The detection of the acoustic branch with a swept frequency spectrometer enabled Grimes and Adams [8] to affirm for the first time the existence of the electron solid and to measure the transition temperature.

The experiment described here is more sensitive to the behaviour of the optical mode. It consists in

Fig. 2. — Calculated frequency of 2D electronic system longitudinal excitations versus electronic density. Full line : plasmon frequency in the liquid for the three lower modes; wave vector k values are calculated from the limit condition $J_0(kR) = 0$, J_0 being zeroth order Bessel function, R the confinement radius of electrons. Dotted line : electron ripplon coupled modes optical frequency in the solid after [7]; see eq. (2). ν_e is the experimental work frequency (24.5 MHz).

monitoring the absorption of energy from in-plane longitudinal component of electric field of fixed wave vectors ($k \sim 2 \text{ cm}^{-1}$ and harmonics) and fixed frequency, as a function of temperature and electron density. A sketch of the frequency response of the electrons for fixed k illustrates the situation rather simply, on figure 3. One readily sees that, to the extent that there exists an absorption at ν_e in either phase, the shift of the optical plasmon mode can be detected.

Fig. 3. — Qualitative absorption curves in the 2D liquid (left curve) and in the 2D solid (right curve) for $n = 5 \times 10^8 \text{ cm}^{-2}$ and $k = 1.12 \text{ cm}^{-1}$. The damping is presumed the same.

The acoustic mode contributes little because weak and narrow.

Experimentally we measure the absorption with a fixed frequency (24.5 MHz) heterodyne spectrometer whose quality factor Q is about 1 000 at 1.2 K in the absence of charges.

The free surface of helium lies between the plates of the condenser which together with the coil L forms the resonant circuit. This high Q circuit was designed to produce principally a vertical component of electric field and to have sufficient sensitivity to detect the generation of ripplons of reciprocal lattice vector for wave vector. The fringe fields however are sufficient for detecting very easily radial electronic modes and in our present conditions these swamp any possible ripplon signal because of the very much lighter effective mass.

Electrons are generated by thermoelectronic emission from a tungsten filament F, heated by a 30 ms pulse. They cross the grid G (see Fig. 1) and settle at the surface S, until the electric field due to the surface charge balances the d.c. electric field due to the plate bias, i.e. $\epsilon V_p/a = 4\pi en$, where V_p is the voltage between plates, a the lower plate-surface distance, $\epsilon = 1.057$ is the liquid helium dielectric constant and n the electronic density. (One checks n by integrating the excess grid current while discharging the surface.)

Electronic density can be varied up to

$$0.8 \times 10^9 \text{ cm}^{-2}.$$

The temperature, which may be varied from 0.3 K to 1.2 K, is established by a helium 3 refrigerator and is measured with carbon resistors, calibrated against ^3He vapour pressure. A second ^3He refrigerator is used as a thermal anchor to reduce heat leaks, principally that due to a fountain pressure column in the ^4He fill capillary.

We have recorded absorption signals *versus* temperature for different values of voltage V_p , i.e. for different values of density n . Such a signal is plotted on figure 4. On cooling, the signal increases untill 0.8 K, becomes stationary then rather abruptly decreases from c point, at temperature T_c .

Fig. 4. — Experimental record of the absorption signal *versus* temperature. The temperature scale is not linear and corresponds to a linear time scanning, during a cooling sequence. Voltage is $V_p = 220$ V, density $n = 6.1 \times 10^8 \text{ cm}^{-2}$.

For a horizontal excitation field $E_k e^{i\omega t}$, the power absorbed by the electrons is :

$$A_k = \frac{1}{2} \frac{e^2 E_k^2 S}{m} \frac{n\tau}{1 + \omega^2 \tau^2 \left[\frac{\omega_k^2}{\omega^2} - 1 \right]^2} \quad (4)$$

S is the surface occupied by the electrons, τ the electronic relaxation time (related to mobility by $\mu = e\tau/m$), ω the experimental angular frequency ($2\pi \times 24.5$ MHz); (at our work frequency $\omega\tau$ varies from 0.9 at $T < 0.6$ K to 0.05 at 1.2 K); ω_k , the k mode eigenfrequency for plasmons — ω_p see eq. (1) — if in the liquid, and the coupled mode frequency ω_{opt} — see eq. (2) — if in the solid.

At temperature T above T_c , if we compare our experimental signals with eq. (4) — using mobility values measured by other authors [6, 9] — the variation of the signal with temperature qualitatively coincides with the variation of the relaxation time τ . But it is difficult to reach perfect agreement between experiment and theory without knowing the exact Fourier decomposition of the exciting field.

We have interpreted T_c as the liquid-to-crystal transition temperature. One may suppose indeed that, at fixed density, when the temperature is lowered, the signal due to plasmons in the liquid becomes a signal due to the optical mode (of angular frequency ω_{opt}) in the crystal.

Temperature T_c varies with plate voltage V_p (i.e. with density). We list in table I (n_c , T_c) coordinates of these points c. Plotting these points logarithmically, one finds they are rather well aligned on a straight line of slope 1.8, i.e. $n_c \sim T_c^{1.8}$ (1.8 is calculated by the least squares method from experimental points).

In order to compare these results with those of Grimes and Adams [8], we have compared both series on figure 5, in $(n^{1/2}, T)$ coordinates.

The liquid-to-crystal transition is expected for a constant value of $\Gamma = \pi^{1/2} n_c^{1/2} e^2 / kT_c$, i.e. n_c proportional to T_c^2 .

If we calculate Γ values from our experimental points (see Table I) we get $\Gamma = 118 \pm 10$ (to be

Table I. — c point coordinates and Γ values for these points.

$n_c (10^8 \text{ cm}^{-2})$	$T_c (\text{K})$	$\Gamma_c = \frac{\pi^{1/2} e^2 n_c^{1/2}}{kT_c}$
1.44	0.292	122
1.48	0.295	122
1.60	0.302	124
1.64	0.315	120
2.04	0.357	118
2.48	0.395	118
2.92	0.435	116
3.34	0.476	114
4.95	0.59	112

Fig. 5. — Liquid-to-crystal transition in the $(n^{1/2}, T)$ plane. Circles : measurements of Grimes and Adams [8]. Crosses : our measurements (coordinates of « c » points).

compared with the results of Grimes and Adams [8] : 137 ± 15). It should be borne in mind when contemplating the discrepancy between these two results that the two experiments do not measure quite the same phenomenon.

Systematic variation of Γ with temperature (which corresponds to the fact that we measure a slope 1.8 and not 2, for the straight line $\ln n_c$ versus $\ln T_c$) may be due to an imprecision in the determination of n_c (perhaps because of a residual field due to trapped charges).

The measurements we present here result from a slightly different manifestation of the same phenomenon observed by Grimes and Adams [8] and analysed by Fisher *et al.* [7]. If the method gives very much less and more indirect information on the excitations of the system, it allows one to detect the transition very easily with a very good signal to noise ratio. Our ultimate purpose is to see the ripplon signal with a rf field strictly perpendicular to the surface, but it seemed interesting to describe this result though the discrepancy with the first measurement of Γ seems real.

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