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STABILITY OF ELECTRONS ON SUPERFLUID ^{4}He FILMS

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The stability of 2-dimensional electron systems on saturated films of superfluid ^{4}He has been investigated. Electron densities up to 10^{11}cm^{-2} have been observed to be stable, nearly two orders of magnitude more than on bulk ^{4}He. The thickness of films charged to such high densities is found to be drastically reduced.

Electrons on liquid helium are an example of a particularly clean and nearly ideal 2-dimensional Coulomb system, which has revealed such interesting phenomena as the transition to a 2D electron solid (1). In the experiments performed to date these electrons behave like a classical Coulomb system, because the electron density accessible on bulk liquid helium is restricted to n 2×10^9cm^{-2}, a range where the Fermi energy is much smaller than the Coulomb energy.

The limit in the electron density on bulk helium is due to an electrohydrodynamic (ehd) instability which develops as a result of the coupling between excitations of the liquid surface and the electron system. A considerably higher density ought to be accessible when the electrons are supported by a thin helium film rather than bulk liquid (2,3). In the dispersion relation of the low frequency coupled plasmon-ripplon modes, given by (3)

$$\omega^2 = \left\{ \left(\frac{3\alpha}{\rho d^4} + g\right)k + \frac{\sigma}{\rho}k^3 - \frac{4\pi e^2 n^2}{\rho}k^2 F(k,\varepsilon) \right\} \tanh(kd) \qquad (1)$$

the term originating from the van der Waals-interaction, α/d^4, is then orders of magnitude larger than the acceleration due to gravity, g, giving rise to an enhanced stability of the film. (Here ρ and σ are the density and surface tension of He, d is the film thickness, and the factor F is approximately equal to the dielectric constant ε of the solid substrate.)

The stability limit where according to eq. (1) ω drops to zero is plotted in Fig. 1. For a thickness of 300 Å - a typical value for a saturated film 1 cm above the bath level - it is expected that a density $n_c \sim 3\times10^{10}$cm^{-2} can be reached, one order of magnitude more than on bulk He.

In our experiments on the high-density behavior of the 2D electron - He film system we have used saturated films whose thickness d_0 before charging, as measured by ellipsometry, could be varied between 200 and 500 Å by changing the level of the bulk liquid. A small glow discharge served as an electron source. The charge density was obtained from the applied voltage U and a measurement of the electric field above the electron layer by means of a vibrating capacitor plate. In order to decide whether at a certain density the electrons were located above the film, or whether part of them had penetrated the liquid, U was reduced to zero or slightly negative bias. The electrons on the film, which are only weakly bound and mobile, then leave the film surface, whereas those charges which have punched the film are localized on the solid substrate and cannot be removed by small negative fields.

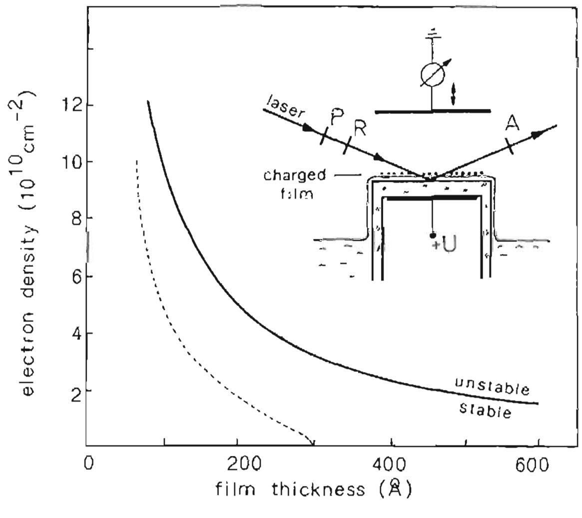

Fig. 1: Stability diagram of charged ^{4}He films. The solid line represents the locus of vanishing ripplon frequency (eq. 1) at the critical wave vector k_c, where the ehd instability sets in (after ref. (3)). The dotted line represents an example of a path for a saturated He film, given by eq. 2 as discussed below. The insert shows the principle of the experimental set-up. Ellipsometer components: P - polarizer, R - retardation plate, A - analyzer.

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So far we have mainly studied insulating substrates, such as a polymer foil (ε=3.8) and glass (ε=6.5), which was polished mechanically or by flame treatment. It was found that electron densities up to a critical value $n_c \sim 10^{11}\mathrm{cm}^{-2}$ are mobile* and can be completely removed again (6). For higher densities n the amount exceeding n_c is tightly bound to the substrate and can be neutralized only by a separate glow discharge cycle. The exact value of n_c varies slightly for different samples and is also affected by the quality of the sample surface as, e.g., minute traces of frozen air. The conclusion that the mobile part of the electrons is indeed stable above the He film is corborated by the observation that, once the film is boiled off, all electrons are localized and cannot be removed from the surface.

The high density of electrons attainable on saturated He films appears promising for further studies of 2D electron systems (7). Yet a comparison of our results with Fig. 1 is disturbing, at the first glance, because the experimental instability threshold is distinctly higher than anticipated for d $\gtrsim$200 Å on the basis of the ehd instability. What is more, a noticeable influence of the initial film thickness, which might by expected from Fig. 1, could not be observed. This apparent discrepancy is resolved when the curves plotted in Fig. 2 are considered: As a helium film is charged, its thickness is not constant, but decreases as a result of the electronic pressure according to

$$d = (1/d_0^{\,3} + 2\pi n^2 e^2/\alpha)^{-1/3} \qquad (2)$$

(d_0 is again the thickness of the uncharged film). The reduction in d in turn raises the instability threshold, calculated from eq. 1, the film thus stabilizes itself. As seen in Fig. 2 the data are in satisfactory agreement with the solid lines representing eq. 2. Since for high electron densities the curves converge, it is not surprising that the experimentally observed stability limit is not significantly influenced by the initial film thickness d_0.

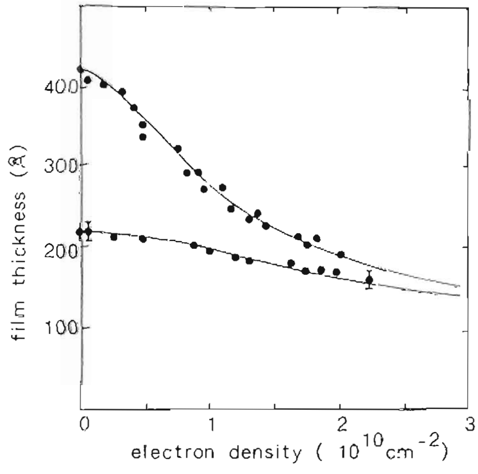

Fig. 2: Thickness d of charged saturated ^{4}He films as measured by ellipsometry. The temperature was 1.6 K, the initial thickness d_0 of the uncharged films 220 and 420 Å, respectively. (The relatively low electron density reached in this experiment was not limited by an instability of the charges on the film, but by dielectric breakdown in the leads.)

The question remains which process finally leads to the loss of the electrons from the film surface and thus limits n_c. It is conceivable that, apart from the collective ehd instability, tunneling of individual electrons through the film into surface states of the substrate becomes important(2). Although for a homogeneous film on a perfectly flat substrate the tunneling rate is probably negligible even at the highest densities investigated here, any presence of surface roughness will locally decrease the film thickness and hence act as a "weak spot" in the film. In a addition, the film thickness will be reduced locally by the dimple forming underneath each electron. Measurements on carefully prepared samples will have to show the relevance of the respective mechanisms.

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* The mobility is much smaller than on bulk He, however, probably due to the formation of polarons (4,5).