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IONS AT THE CRITICAL INTERFACE OF ^{3}He–^{4}He MIXTURES

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Trapping of ions at the interface of ^{3}He–^{4}He mixtures has been studied near the tricritical point. The "soft" critical interface leads to a strong dependence of the trapping times both on temperature and on the applied electric field.

Electrons at the free surface of liquid helium have been studied quite thoroughly in recent years, as an example for a particularly clean two-dimensional Coulomb system [1]. A number of predicted phenomena, however, has until now escaped experimental verification, like the transition to an ordered state (Wigner-crystal) [2], the dimples associated with the interaction of individual electrons with the helium surface [3], or the modification of the ripplon dispersion relation by the presence of surface charges [4]. Some of these phenomena should be much more easily detectable, if the perturbation of the surface due to its interaction with the Coulomb system could be increased, for instance by decreasing the surface tension σ of the helium substrate.

We have started to investigate similar Coulomb systems, where σ is orders of magnitude less than at the free helium surface, namely positive and negative ions at the interface of phase-separated ^{3}He–^{4}He mixtures. Near the tricritical point (temperature $T_t = 0.867$ K, ^{3}He concentration $x_t = 0.675$) this interface undergoes a critical softening, which manifests itself in a rapid decrease of the interfacial tension σ_i [5].

Far below T_t negative ions ("electron bubbles") are not able to penetrate the ^{3}He–^{4}He interface from the upper, ^{3}He-rich phase, because of a high energy barrier at the interface [6]. This barrier results from the differing properties of the coexisting phases and has been estimated to be 220 K below $T = 0.3$ K. Thus it must be possible to hold a layer of such electron bubbles immediately above the interface at a distance of about the bubble radius $R \sim 20$ Å.

Conversely, for positive ions ("snowballs") an energy barrier due to the image potential should prevent their passage in the reverse direction, from the lower to the upper phase. Therefore, at low temperatures a layer of snowballs should be formed just below the interface in the presence of an appropriate electric holding field.

Upon approaching the tricritical point the two phases become more and more similar, and the barrier for either type of ion decreases, until finally the ions can by thermal activation pass under the action of the applied electric field after a shorter and shorter trapping time τ. We have determined τ separately for both positive and negative ions as a function of temperature T and electric field E.

Trapping times were measured in the conventional way by observing the decay of the current across the interface after the ion-source was switched off [7]. This method was applicable for trapping times between 1 and 100 s. For longer τ's when the currents became too small we applied a different method, using the fact that due to the electric field the ions exert a force upon the interface. This force leads to a macroscopic, yet very shallow deformation of the interface ($<10^{-2}$ mm deep, proportional to the number of trapped ions), which was detected optically and allowed a sensitive determination also of very long τ's. Good agreement was found for electrically and optically determined τ's.

The resulting trapping times are plotted in fig. 1 versus the temperature difference $(T_t - T)$. Remarkable is the strong temperature dependence: τ varies by three

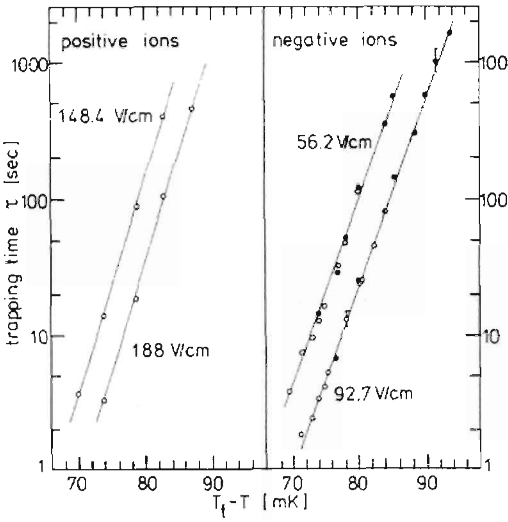

Fig. 1. Trapping time τ of negative and positive ions versus temperature. Electric holding fields are indicated; open and closed circles refer to electrical and optical data points, respectively. For clarity only a small fraction of the data is shown.

orders of magnitude within a temperature interval of only 20 mK, both for negative and positive ions. Besides, the absolute value of τ is quite comparable for the two kinds of ions.

The data suggest a dependence $\tau \propto e^{\Delta W/kT}$ – indicated by the straight lines – with an energy barrier ΔW at the interface varying roughly as $\Delta W \propto (T_t-T)$. From the slopes the absolute value of ΔW can be estimated. Note that the temperature dependence of ΔW is responsible for the strong variation of τ since kT changes by only 2.5% within the investigated temperature interval.

As can be seen from the nearly constant slopes in fig. 1 the electric field shows little effect upon the barrier height for either type of charge, but has a marked influence on the absolute value of τ. This becomes more obvious in fig. 2, where the variation of τ versus E is plotted for constant temperature. Qualitatively the decrease of τ with increasing E seems reasonable because at high fields the ions are drawn closer to the interface.

A more quantitative comparison of these results with the behavior expected from the simple snowball and bubble model [8], however, shows serious discrepancies:

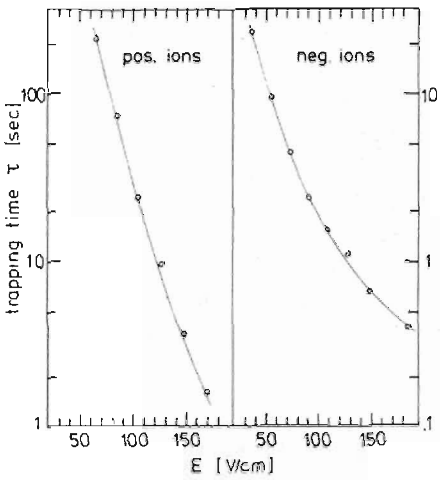

Fig. 2. Trapping time τ versus holding field E. T_t-T = 73 mK for negative and 70 mK for positive ions.

(i) For *positive ions* the energy barrier is mainly determined by the difference of the polarizabilities of the ^{3}He- and ^{4}He-rich phases. The experimental energy barrier ΔW^+ as deduced from fig. 1 is about a factor of 2 smaller than calculated from this model, e.g. $\Delta W^+ \sim 20$ K instead of 40 K at (T_t-T) = 80 mK. Such a reduction is not unexpected because of the accumulation of ^{4}He atoms in the vicinity of the positive ions, which has also been observed in recent measurements of the positive ion mobility [9,10]. The dependence of τ on the electric field is stronger than predicted from the image potential alone; it seems necessary to take the influence of the critical interface into account, like the reduction of the image force by the diffuse interfacial profile [5,6], or the local deformation of the soft interface by the individual ions.

(ii) For *negative ions,* the observed variation of τ with E is also much stronger than expected from the calculated potential near the phase boundary [6], suggesting again the influence of the critical interface. Besides, the temperature dependence of τ is only in poor agreement with the prediction of the bubble model. A quantitative analysis of the trapping times on the basis of the simple bubble model is very problematic, however, since the absolute value of the bubble energy W is about 10^3 K, whereas the difference $W_3 - W_4$ between the ^{3}He- and ^{4}He-rich phase is of the order of only 10 K for the temperatures considered here. The calculated interfacial barrier is therefore very sensitive to even minor uncertainties in the various contributions to the bubble energy, like the surface tension or the potential well of the bubble [8].

Thus the trapping time data can provide a very sensitive test for models of positive and negative ions at the critical interface of ^{3}He$-$^{4}He mixtures. In addition, our experiment has shown that both positive and negative ions can be trapped at the interface for times > 100 s, as long as $(T_t - T) > 80$ mK. It should be possible therefore to study in more detail such two-dimensional Coulomb systems interacting with a soft substrate.

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