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CRITICAL DRIFT VELOCITY OF IONS IN LIQUID HELIUM

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We have measured the drift velocity $\langle v_D \rangle$ of positive ions in liquid helium II in the temperature range 1.06 to 0.927°K as a function of the applied electric field. We have found that above a critical field strength E_c the drift velocity no longer increases linearly with the increasing field, but suffers a discontinuity. While the value of this critical field E_c depends on the temperature, the corresponding critical velocity $\langle v_c \rangle$ appears to be a temperature-independent quantity in the range so far investigated.

The apparatus used to measure the mobility is a time-of-flight method, which has been more fully described by one of us.[1] Essentially one measures the drift velocity from the time taken by the ions to go from a grid to an electrode, which is connected to a vibrating reed electrometer by a suitable filter. Two apparatus have been used, with different electrode distances and different ionization sources, and they gave identical results.

The reproducibility of our drift velocity data was within ±2 %, while the mobility $\mu = \langle v_D \rangle / E$ derived in this way is affected by a further common systematic error, due to the uncertainty in the absolute value of the square wave voltage which was estimated to rise up to ±2 %. In this range our absolute values of the zero-field mobility were reproducible on different days, and were also in agreement with those measured by Reif and Meyer[2] and by ourselves[3] by different techniques.

Some typical results of this investigation are reported in Fig. 1 in the customary way, as a plot of the mobility versus the applied field. A glance at this graph shows that below the critical

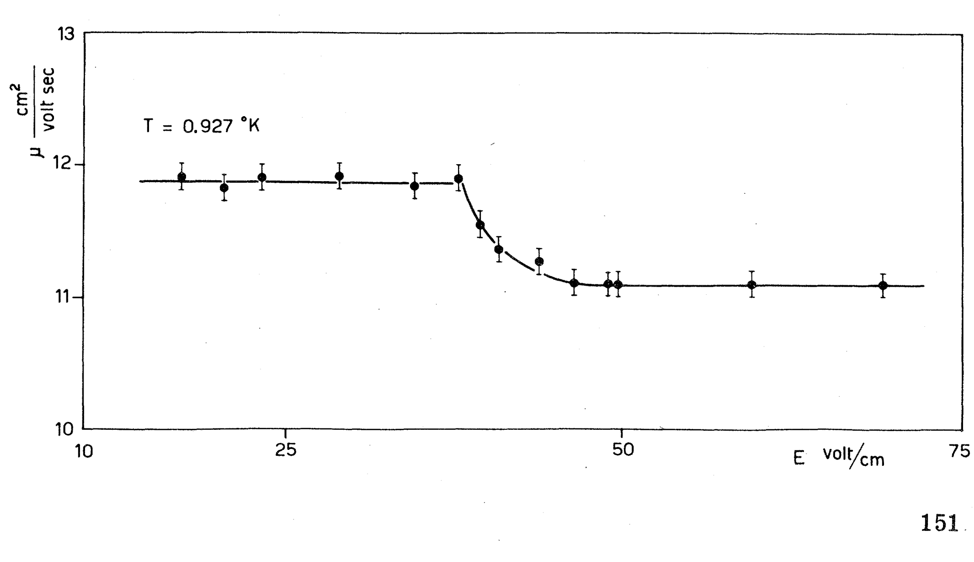

FIG. 1. Experimental values of the mobility at T=0.927°K as a function of the applied electric field E.

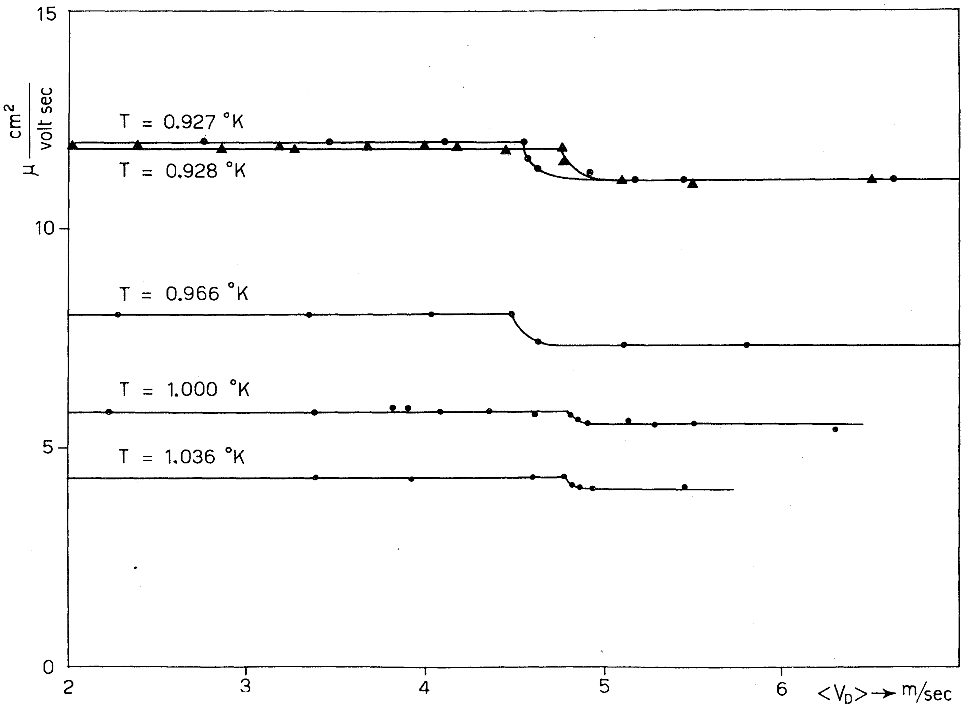

FIG. 2. Plot of the mobility versus drift velocity at different temperatures.

field of 37 v/cm the mobility is indeed field independent, but above it the mobility sharply decreases to a lower constant value. The sharp change in the mobility is well outside the experimental error, and also the discontinuity is clear from the shape of the curve around E_c.

In Fig. 2 we give the results of some runs made at different temperatures in a plot of mobility versus drift velocity, particularly convenient to show that the discontinuity always falls around the same value of the drift velocity, while the mobility changes by a factor of 3. For the sake of clarity the experimental errors in the mobility and drift velocity are not shown in this plot. In Table I we give the critical velocities so far detected under different experimental conditions. Each value of $\langle v_c \rangle$ is evaluated as the mean value of the two measured drift velocities where the break was found; the uncertainty in $\langle v_c \rangle$ indicated in the table is therefore one half of the value of this range. These values of $\langle v_c \rangle$ cluster in the range $\langle v_c \rangle = 4.70 \pm 0.15$ m/sec, indicating indeed the existence of a threshold independent of the temperature.

Table I. Observed critical velocities.

Run	T (°K)	$\langle v_c \rangle$ (m/sec)
3B	1.036	4.79 ± 0.10
3A	1.000	4.83 ± 0.10
5A	0.966	4.56 ± 0.15
4A	0.928	4.77 ± 0.10
8A	0.927	4.56 ± 0.10

In one run we were able to achieve still higher drift velocities, and a second discontinuity was observed as shown in Fig. 3. This second discontinuity appeared at a value $\langle v_c \rangle = 9.22 \pm 0.20$,

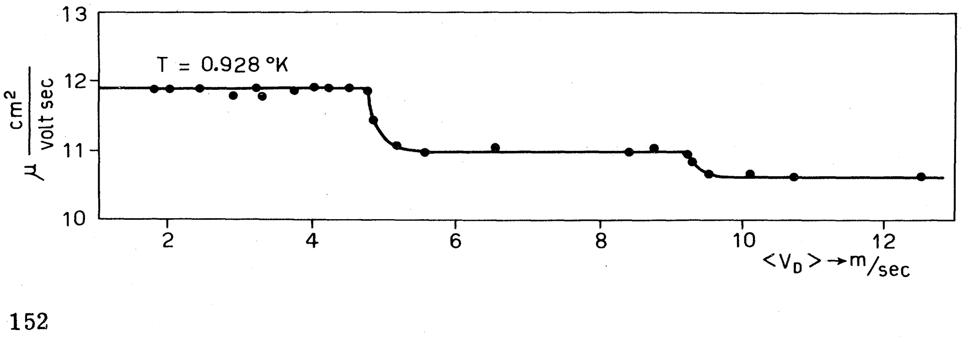

FIG. 3. A similar plot to Fig. 2 for one temperature and for an extended range of drift velocities.

which is larger than the first one by a factor of 1.96 ± 0.08, as if a repetition of this phenomenon can exist at a velocity twice as large.

The change in the mobility values at the discontinuity is never larger than 10% and therefore this phenomenon may easily escape observation in a plot of the mobility versus field when few experimental points are taken, and may then be confused with a slight and continuous field dependence. We believe this to be the reason why Reif and Meyer[2] did not notice this phenomenon at 0.98°K, where they were interested only in the zero-field mobility. It is also clear that at temperatures higher than the ones reported here it becomes progressively harder or downright impossible to detect this discontinuity. Some preliminary runs performed in this laboratory, at temperatures lower than 0.90°K, indicate that this discontinuity in the mobility is more difficult to detect there because of the superimposed continuous decrease. Reif and Meyer[2] have concentrated their work on the field dependence of the mobility essentially below this temperature, and have thoroughly investigated this continuous decrease in terms of mean-free-path phenomena. Therefore we believe our experimental work not to be in contrast with their data, but instead to provide a fine structure of the mobility versus field curve which is observable only in a narrow temperature range.

An interpretation of the meaning of the critical drift velocities detected in these experiments is not easily found in the current picture[4] of the ionic motion in liquid helium II. The sharpness of the transition and the stepwise shape of the curve rules out any approach in terms of hot ions, which is customary to explain the decrease of the mobility with the increasing field strength when the drift velocity is comparable to the thermal velocity of the ions. On the other hand, we know that these velocities are much too low to be possibly explained in terms of inelastic processes involving the creation of one roton or phonon.

As a further possibility one may suggest the same argument now used to explain the critical flow phenomena, which involves the creation of quantized vortex lines. The creation of one quantized vortex ring of atomic size behind every ion in motion would easily provide a critical velocity of the magnitude observed here, and would also give an account of the observed multiplicity in terms of different quantum numbers of circulation. However, if the Feynman[5] expression for the vortex ring energy and momentum are used, the effective mass of the ion turns out to be as large as 10^4 helium atom masses. Details of the calculation are not given here, but this figure follows simply from the energy and momentum conservation conditions.[2] Such a value of the effective mass is much larger than the estimated[6,7] static mass, and seems rather inconsistent.

One final remark should be made concerning the unexpectedly sharp onset of the drop in mobility. The only two possible explanations which suggest themselves are (1) a very sharply peaked velocity distribution due to a large effective mass of the ion, or (2) a kind of cooperative interaction with a large number of nearby ions through the long-range Coulomb forces.

The lack of a proper theoretical treatment of this problem does not allow us at the present time to come to a more definite conclusion.

Experiments are planned in this laboratory to extend these measurements over a wider range of field strengths and temperatures by an improved technique.

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[1] S. Cunsolo, Nuovo cimento (to be published).

[2] F. Reif and L. Meyer, Phys. Rev. 119, 1164 (1960).

[3] G. Careri, F. Scaramuzzi, and J. O. Thomson, Nuovo cimento 13, 186 (1959).

[4] For a discussion on the behavior of ions in liquid helium, see also G. Careri, Progress in Low-Temperature Physics (North-Holland Publishing Company, Amsterdam, 1961), Vol. 3, p. 58.

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[6] K. R. Atkins, Phys. Rev. 116, 1339 (1959).

[7] J. de Boer and A. 't Hooft, Proceedings of the Seventh International Conference on Low-Temperature Physics (University of Toronto Press, Toronto, 1960), p. 510.