Critical Velocities of Ions in Liquid Helium II Detected by Heat Flush*

G. CARERI, S. CUNSOLO, AND M. VICENTINI-MISSONI
Istituto di Fisica, Università di Roma, Roma, Italy
(Received 21 May 1964)

The discontinuity in the drift velocity of ions in liquid helium, previously detected by the time-of-flight method, is confirmed by the heat-flush method in a wide channel. The critical velocity is found to be $\langle v_c\rangle = 4.96\pm0.35$ m/sec independent of beam geometry and of ionic density. The detailed analysis of the beam displacement in the two-fluid counterflow process allows one to conclude that the new dissipation suffered by the beam at $\langle v_c\rangle$ is essentially due to its interaction with the normal fluid.

1. INTRODUCTION

A CAREFUL investigation[1,2] of the behavior of the drift velocity $\langle v\rangle$ of positive charges in liquid helium as a function of the electric field E, recently carried out in this laboratory, has shown some unexpected sharp discontinuities. More precisely, working at a fixed temperature around 1°K, it was found that at a critical field E_c, the mobility μ falls from one constant value to another lower one. While E_c was temperature-dependent, the corresponding drift velocity $\langle v_c\rangle = \mu E_c$ was not, and had the value 5.2 ± 0.2 m/sec. No simple explanation for this phenomenon was found in the framework of the Landau picture of liquid helium.

The experiment reported above was performed by the time-of-flight method,[3] and therefore made use of ac electronics operating at 10^{-2}–10^{-4} sec. We thought it desirable to check the above results by a dc technique, making use of the heat-flush effect which has been shown in our laboratory[4,5] to yield the ionic drift velocity under proper experimental conditions. Besides being an independent check on the existence of a discontinuity in the drift velocity and of its quantitative aspect, this counterflow process can offer further information on the nature of the process.

A preliminary account of this paper was submitted[6] at the Eight International Congress of Low Temperature Physics, London 1962.

2. MOTIVATION FOR THE EXPERIMENT

We wish to indicate briefly the information one can get from a proper analysis of the ionic-beam displacement due to a steady heat flow in a wide channel.

Consider an experimental arrangement in which the heat input induces a counterflow process, described in the two-fluid picture in terms of the normal-fluid velocity $\langle \mathbf{v}_n\rangle$ and the superfluid velocity $\langle \mathbf{v}_s\rangle$. Suppose for the moment that the ion experiences a dissipative force from both the normal fluid and the superfluid. The balance of forces applied to the ionic charge e in motion gives

$$\frac{e}{\mu_n}(\langle \mathbf{v}_d\rangle-\langle \mathbf{v}_n\rangle)+\frac{e}{\mu_s}(\langle \mathbf{v}_d\rangle-\langle \mathbf{v}_s\rangle)=e\mathbf{E}, \quad (1)$$

where μ_n and μ_s are the mobilities of the ions with respect to the normal fluid and the superfluid. Let us set the z axis in the direction of $\langle \mathbf{v}_n\rangle$ and apply the electric field which acts on the ionic beam in an orthogonal direction, say along the x axis. Then, due to the heat flow, there is a beam displacement α, which is given in terms of the drift velocity $\langle \mathbf{v}_d\rangle$ by

$$\tan\alpha = \langle v_{dz}\rangle/\langle v_{dx}\rangle. \quad (2)$$

From Ref. 4 and from the temperature dependence of the mobility[3] it was concluded that the ions interact only with the normal fluid. From the newly acquired knowledge of the existence of discontinuities in the mobility values[1,2] this statement must now be restricted to the low-field region. Therefore, Eqs. (1) and (2) yield for $E<E_c$

$$\tan\alpha = \langle v_n\rangle/\mu_{n0}E. \quad (3)$$

where μ_{n0} is the mobility with respect to the normal fluid in the low-field region. Then a plot of $\tan\alpha$ versus $1/E$ is a straight line through the origin.

For $E>E_c$, the following possibilities exist:

(a) The mobility change at E_c could be due to a change of interaction with the normal fluid. Then the relation between $\tan\alpha$ and $1/E$ is of the same type as for $E<E_c$ [Eq. (3)] but with a different value of μ_n, say μ_{n1}. If this is the case, then the complete plot of $\tan\alpha$ versus $1/E$ must be composed of two straight lines which meet at the origin, each one corresponding to a different value of mobility, and the transition from one line to the other should occur at E_c.

(b) On the contrary the mobility change at E_c could be due to the setting in of a new interaction with the superfluid only.

* Work supported jointly by Consiglio Nazionale delle Ricerche Istituto Nazionale di Fisica Nucleare, and the U. S. Army European Research Office.

[1] G. Careri, S. Cunsolo and P. Mazzoldi, Phys. Rev. Letters 7, 151 (1961) (later quoted as I).

[2] G. Careri, S. Cunsolo, and P. Mazzoldi, in *Eighth International Conference on Low-Temperature Physics, London, 1962* (Butterworths Scientific Publications, Ltd., London, 1963), p. 90.

[3] S. Cunsolo, Nuovo Cimento 21, 76 (1961).

[4] G. Careri, F. Scaramuzzi, and J. O. Thomson, Nuovo Cimento 13, 186 (1959) (later quoted as HF1).

[5] G. Careri, F. Scaramuzzi, and J. O. Thomson, Nuovo Cimento 18, 957 (1960) (later quoted as HF2).

[6] G. Careri, S. Cunsolo, and M. Vicentini-Missoni, in *Eighth International Conference on Low-Temperature Physics, London, 1962* (Butterworths Scientific Publications, Ltd., London, 1963), p. 86.

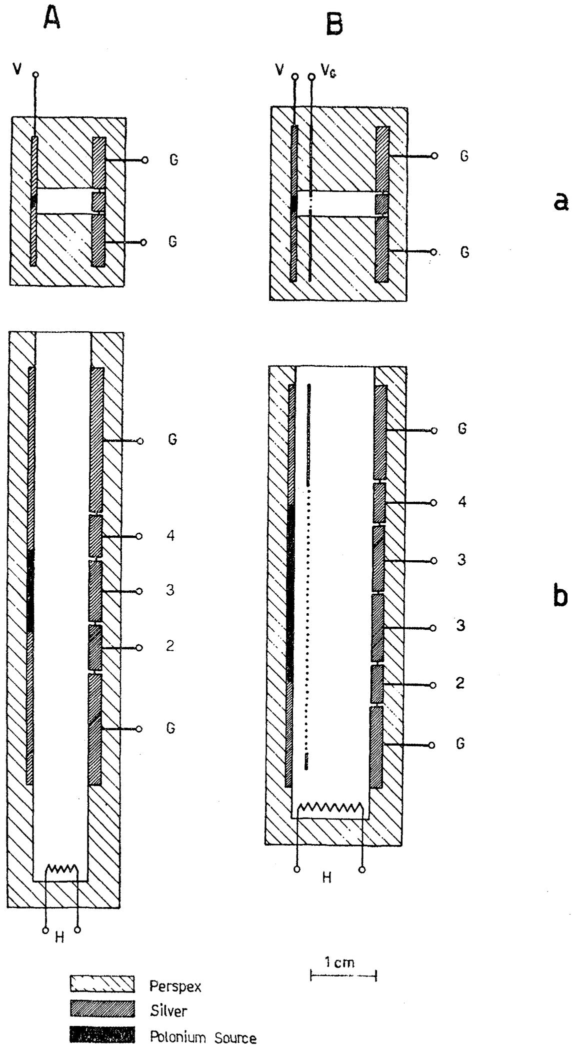

FIG. 1. Schematic view of the two experimental apparatuses: a: side view; b: top view.

Then, from (1) and (2),

$$\tan\alpha = \frac{\langle v_n \rangle}{\mu_n E}\left(1 - \frac{\mu_n \langle v_s \rangle}{\mu_s \langle v_n \rangle}\right). \qquad (4)$$

We can evaluate the term $\mu_n\langle v_s\rangle/\mu_s\langle v_n\rangle$ in this relation, since we work in a counterflow process around 1°K. μ_n/μ_s is related to the percentage change of mobility $\Delta\mu/\mu$ at the critical field, which we know from I is of the order of 6%. For this change of mobility $\mu_n\langle v_s\rangle/\mu_s\langle v_n\rangle < 1\times 10^{-4}$, and consequently in the plot of $\tan\alpha$ versus $1/E$ the transition at E_c would not be observable.

(c) Finally, the mobility change at E_c could be due to a change of interaction with the normal fluid which changes μ_{n0} to μ_{n2}, in addition to the setting in of a new interaction with the superfluid leading to the appearance of the term with μ_s. In this case one should observe the same kind of transition indicated above in (a), but the change of the slope of $\tan\alpha$ versus $1/E$ at E_c observed in the heat-flush experiment should be less than the change of mobility observed in I.

The conclusion of this analysis is then that a comparison of the mobility change observed by the time-of-flight method with the slope change observed by this method makes it possible to answer an important question concerning the nature of the new dissipation suffered by the ionic beam at the critical velocity, namely whether the new interaction is due to the normal fluid, to the superfluid, or to both.

3. APPARATUS AND EXPERIMENTAL PROCEDURE

(i) The apparatus and the technique are essentially the ones used in the previous work,[4] but in this paper the procedure of getting the drift velocity is different and the accuracy of the data much higher.

The apparatus is essentially an ionization chamber with several detecting electrodes, where an ionic beam can be produced by an α source and then deflected by the heat current. Several apparatuses have been used and their relevant features are shown in Fig. 1. While the frame was always made of Perspex, electrodes of polished silver were used in apparatus A and of gold-plated silver in apparatus B. Different sources were used, obtained by the usual self-deposition technique, and they provided ionic beams of variable ionic density, ranging from 1×10^5 to 8×10^5 ion/cm^3. Apparatus A is a multielectrode system, which allows one to observe the displacement of the beam at both ends by means of the current changes at electrodes 2 and 4. It is quite similar to the one described in HF1, and will not be described here any further. Apparatus B has been designed with a grid for the purpose of also obtaining time-of-flight measurements of the mobility in the channel during the heat flow.

The temperature was measured by means of a carbon resistor which was calibrated during each run against the He^4 vapor pressure in the range between the λ point and 1.3°K. A He^3 vapor-pressure thermometer was used to check that the extrapolation to low-temperature resistance value can give the actual value of the temperature with an accuracy of ± 0.005°K. The bath temperature was kept constant to 0.5 mdeg K by means of an electronic thermoregulator.

(ii) Using the above apparatus the beam displacement produced by the heat flow can be easily evaluated from the change ΔI_i in the current of the external electrode i. The beam displacement $\tan\alpha$, as shown in HF1, is given by

$$\tan\alpha = (\Delta I_i / I_3)(d_3/s), \qquad (5)$$

provided one assumes the ionic density of the beam is constant and the space-charge effects can be disregarded. I_3 is the current received by the central electrode, d_3 its length, and s the distance between the source (in apparatus A) or the grid (in apparatus B) and the collecting electrodes. In practice it was difficult to get good uniformity of the ion source, and therefore some corrections must be made as described in the following.

If the density on each electrode can be adequately described as constant, say ρ_i, then relation (5) can be written as

$$\tan\alpha=\frac{\Delta I_i}{I_3}\frac{d_3}{s}\frac{\rho_3}{\rho_i}. \qquad (6)$$

The ratio ρ_3/ρ_i is field-independent and can be obtained from the ratio I_3/I_i because

$$d_3(\rho_3/\rho_i)=d_i(I_3/I_i)\,,$$

where d_i are the lengths of the sections of the external electrodes facing the source. It is safer to evaluate I_3/I_i at high fields, labeled ∞, where the spreading due to diffusion and space-charge effects become negligible. Therefore, we write

$$\tan\alpha=\frac{\Delta I_i}{I_3}\frac{d_i}{s}\left(\frac{I_3}{I_i}\right)_\infty. \qquad (7)$$

It is better to measure the quantities d_i directly in the apparatus itself because the equipment can suffer unpredictible contractions in cooling from room temperature, in which the position of the ion source relative to the receiving electrodes may be shifted. d_i is measured as follows: Since $\Delta I_2/\Delta I_4=\rho_2/\rho_4$ and since at high fields $I_2/I_4=\rho_2 d_2/\rho_4 d_4$, it is easy to measure d_2/d_4. Furthermore the sum d_2+d_4 is known from the geometric arrangement, because the source length and d_3 remain constant in the cooling process.

(iii) The experimental procedure adopted to investigate a possible small change of the drift velocity around the critical field consisted mainly in observing the beam displacement at different values of the field near E_c, keeping the heat input $\dot{q}$ and the bath temperature T constant. This procedure is different from the one employed in HF1, where E and T were kept constant and $\dot{q}$ was changed.

The accuracy in measuring the beam displacement is affected by the sensitivity of the electrometers in reading the currents and by fluctuations in temperature. These errors have been evaluated and found to affect the value of a single determination of tanα by no more than ±3%.

TABLE I. Effect of the heat flow on the low-field mobility μ_0.

Run	T(°K)	E(V/cm)	$\dot{q}$(mW/cm^2)	μ_0(cm^2/V sec)
Co_a	0.980±0.005	50.0	0.0	7.40±0.22
	0.980±0.005	50.0	32.1	7.43±0.22
Co_b	0.955±0.005	37.5	0.0	9.28±0.30
	0.955±0.005	37.5	18.6	9.24±0.28
Co_c	0.943±0.005	37.5	0.0	10.22±0.31
	0.943±0.005	37.5	31.1	10.18±0.31

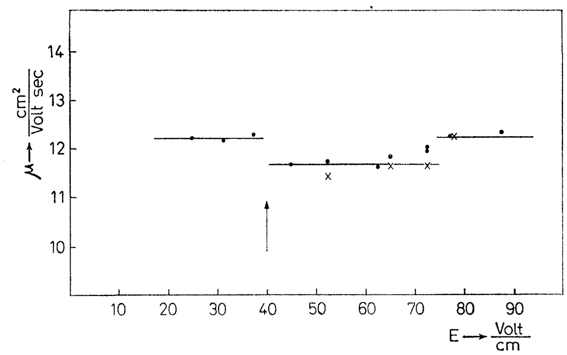

FIG. 2. The mobility μ as a function of the applied electric field in run $C14$. Black points are the mobility $\mu(S)$, the crosses the mobility $\mu(R)$.

4. EXPERIMENTAL RESULTS

The experimental results are presented in the following three sections. In Sec. (a) we report the preliminary runs which allow us to define the limits of accuracy of the method. In Sec. (b) one single run is shown in detail, and in Sec. (c) we report the main results of eight runs.

(a) The first group of runs was devoted to the study of a possible effect of the heat flow on the mobility around the expected discontinuity. The low-field mobility is expected not to suffer a change by the heat current, according to the work in HF1. However, to check this point further, in the run designated by C_0, measurements of mobility have been taken with the time-of-flight method in the apparatus B, while the heat was flowing. The ionic density of the beam was 2×10^5 ion/cm^3. Results are given on Table I, and it is clear that there is no effect on both electrodes up to 31 mW/cm^2. For larger heat inputs, the effect of the temperature gradient existing in the channel begins to be important, and its effect must definitely be taken into account if the heat input exceeds 50 mW/cm^2.

Next, the effect of the heat flow on the expected discontinuity in the drift velocity was studied again by the time-of-flight method at the temperature $T=0.920$ °K and the heat input $\dot{q}=43.6$ mW/cm^2. Denote by $\mu(R)$ a mobility measurement taken during the heat flow, and $\mu(S)$ a mobility measurement taken soon after the heat flow has been switched off. As can be seen from Fig. 2, where the results of this run are shown, there is evidence of the discontinuity at a field of 40 V/cm, corresponding to a critical velocity $\langle v_c\rangle=4.90\pm0.30$ m/sec. If the electric field is somewhat less than 70 V/cm the heat flow has no effect on the mobility, i.e., $\mu(S)=\mu(R)$. As the electric field increases further, both $\mu(R)$ and $\mu(S)$ rise to the low-field value.

It has been established in a number of runs at different temperatures that the heat affects the mobility when the electric field is such that the drift velocity of ions is larger than 7.5 m/sec. Therefore, in order to compare the results of the heat-flow method with the

TABLE II. Critical velocities detected in different runs.

Run	T(°K)	μ_0(cm^2/Vsec)	$\dot{q}$(mW/cm^2)	E_c(V/cm)	$\langle v_c \rangle$(m/sec)	$\Delta\gamma/\gamma$
C_6	0.903±0.013	15.6 ±2.2	27.8	30.1±0.6	4.70±0.76	7.2±3.6
C_7	0.918±0.005	13.23±0.78	25.6	33.7±0.7	4.46±0.36	6.5±3.2
C_5	0.926±0.006	12.15±0.75	17.9	43.9±0.9	5.33±0.43	5.6±2.8
C_1	0.953±0.005	9.12±0.27	21.5	54.1±1.5	4.94±0.28	8.7±4.3
C_3	0.953±0.005	9.31±0.45	28.8	57.8±1.5	5.38±0.40	10.8±5.4
C_9	0.963±0.005	8.48±0.40	31.4	56.2±1.3	4.76±0.33	7.4±3.7
C_2	0.971±0.005	7.37±0.38	43.3	60.2±1.3	4.74±0.33	8.0±4.0
C_4	0.973±0.005	7.74±0.38	51.3	70.7±1.2	5.47±0.36	6.5±3.2

ones of the time-of-flight[1,2] method, we must never exceed the drift velocity of 7.5 m/sec, i.e., we can check the first discontinuity only.

(b) Run C_1 was made with apparatus B so that we could at the same time measure the mobility by the time-of-flight method and by the beam displacement due to the heat flow. The ionic density of the beam was 8×10^5 ion/cm^3. The bath temperature was $T=0.953 \pm0.005$ °K and the heat input was $\dot{q}=21.5$ mW/cm^2; the plot of $\tan\alpha$ versus $1/E$ is given in Fig. 3. As one can see, the data fall on two straight lines which meet at the origin. The data give clear evidence of a discontinuity at a field of 54.1±1.5 V/cm, which is recognized as the critical field. The percentage change of the slope, $\Delta\gamma/\gamma$, is 8.7±4.0%. By the time-of-flight method the mobility in the subcritical region was found to be 9.12±0.27 cm^2/V sec and is in agreement with the value of 9.31±0.45 cm^2/V sec, derived from the best curve of mobility versus temperature now available,[3,4,7] in conjunction with the known bath temperature.

From the critical field and the mobility value we deduce the critical velocity $\langle v_c \rangle=\mu E_c=(4.94\pm0.28)$ m/sec, in agreement, within the experimental errors, with the previous results.[1,2]

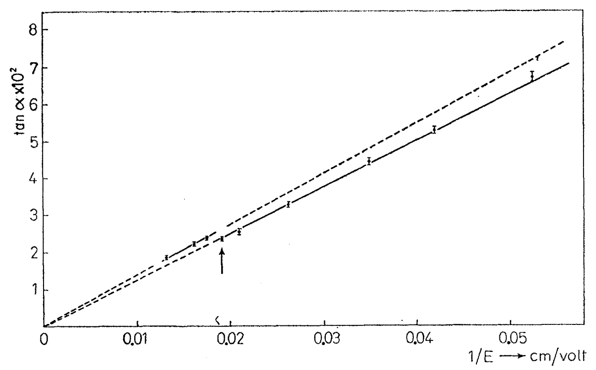

FIG. 3. Evidence for the discontinuity in the ionic beam displacement versus the reciprocal electric field $1/E$ in run C_1; the discontinuity is indicated by the arrow. Note that experimental data fall on two straight lines (dotted lines) which meet at the origin.

[7] Since the paper quoted in Ref. 3 was published, more measurements of mobility at various temperatures have been performed by ourselves and others [L. Meyer and F. Reif, Phys. Rev. **110**, 279 (1958); F. Reif and L. Meyer, *ibid.* **119**, 1164 (1960)] in the temperature range we are interested in here. All these new data are in good agreement with the previous ones (Ref. 3) and support the least-squared curve given previously. Therefore, the error in the mobility determination in this paper is mainly due to the temperature uncertainty.

We note that one could get the mobility value directly from the slope of $\tan\alpha$ versus $1/E$, assuming the validity of the hydrodynamical equation

$$\dot{q}=\rho ST\langle v_n \rangle, \tag{8}$$

where S is the entropy per gram and ρ the total density. In this way we found $\mu_0=10.20\pm0.20$ cm^2/V sec, which is not consistent with the measured value reported above. The normal-fluid velocity in the channel is lower than the value calculated from Eq. (8), implying that either a small quantity of the heat supply is lost from the wide channel through small leaks in the Perspex connections, or else Eq. (8) is not valid in turbulent flow.

From the analysis of this run we conclude that the heat-flush method as used above and the time-of-flight method give quite consistent results.

(c) Many different runs have been made with apparatus A, but while they are all consistent in themselves, we will quote here only the seven runs which had a higher accuracy. The ionic density of the beam was in the range $1\div2\times10^5$ ion/cm^3.

The experimental data are reported in Table II, starting from the lowest temperature. In the runs C_2, C_3, C_4 the deflection of the beam was measured only on electrode 2, while in the others it was measured both on electrodes 2 and 4, and the quoted results are the average of the two. As one can see from Table II, the values of the critical velocity and of the percentage change of the slope are independent of the ionic density of the beam and of the shape and geometry of the apparatus (see Fig. 1).

Figure 4 is a normalized plot of all results and gives clear evidence of the independence of the critical velocity and change of slope with temperature and rate of heat supply. The average value of the critical velocity is found to be

$$\langle v_c \rangle=4.96\pm0.35 \text{ m/sec}.$$

5. DISCUSSION

From the experimental data quoted in Table II and plotted in Fig. 4, one can derive the following conclusions:

(a) The displacement undergone by the ionic beam

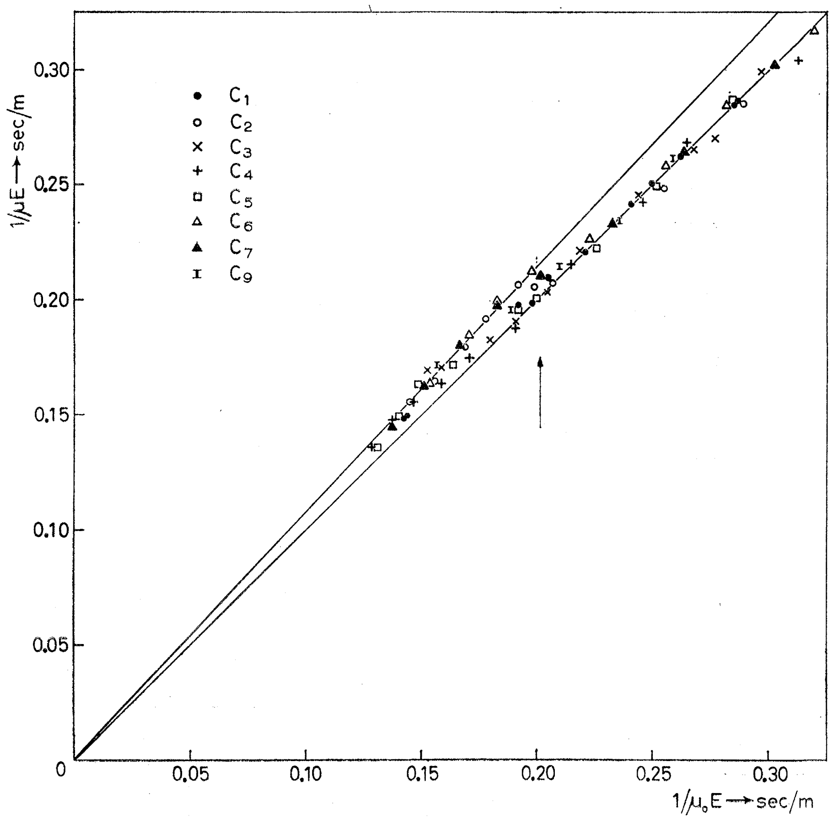

FIG. 4. Normalized plot ($1/\mu E \equiv \tan\alpha/\langle v_{dz}\rangle$ versus $1/\mu_0 E$) for all the runs. The straight lines represent the best fit of subcritical and supercritical regions. Different symbols refer to the different runs quoted in Table II. The discontinuity is indicated by the arrow.

in the channel during the heat flow suddenly increases at a critical field. The corresponding drift velocity along the direction of the electric field, $\langle v_c\rangle = \mu E_c$, does not depend upon the temperature. Its average value, $\langle v_c\rangle = 4.96\pm0.35$ m/sec, is in agreement, within the experimental errors, with the value obtained by the time-of-flight method in the absence of heat flow.

(b) The value of the critical velocity is not affected by large change in the ionic density (up to a factor of 8), or by changes in shape or geometry. This shows that the process which gives rise to the discontinuity does not involve collective effects in the ionic beam, but only single ions.

(c) The plot of Fig. 4, and the analysis of the counterflow process in the channel described in Sec. 2, give evidence that the new dissipation suffered by the beam at $\langle v_c\rangle$ is due mainly to an increase in its interaction with the normal fluid. The word "mainly" means that this interaction would be entirely due to the normal fluid if the change of slope $\Delta\gamma/\gamma$ at E_c observed in the heat-flush method had quantitatively corresponded to the change of mobility $\Delta\mu/\mu_0$ found with the time-of-flight method. Actually these small jumps are affected by large experimental errors and one cannot exclude the presence of a small interaction with the superfluid [case (c) of Sec. 2]. However, an increase in the interaction with the superfluid only is out of question.

(d) The effect of the heat input on the mobility at drift velocities larger than 7.5 m/sec, while undoubtedly proved from an experimental point of view, seems to require more work to allow a proper understanding of it.

From the above we conclude that a single ion increases its interaction with the normal fluid at a well-defined value of its velocity. This statement considerably reduces the many possible processes which could be involved, because dissipative effects inside the beam itself and other effects due to the superfluid component only can now be excluded. A tentative picture of this process has been outlined elsewhere,[8] and is more deeply analyzed in the companion paper.[9]

[8] G. Careri, S. Cunsolo, P. Mazzoldi and M. Vicentini-Missoni, *Proceedings of the NATO Theoretical Physics Spring School, Naples 1963* (W. A. Benjamin Company Inc., New York, to be published).
[9] G. Careri, S. Cunsolo, and P. Mazzoldi, preceding paper, Phys. Rev. **136**, A303 (1964).