Study of Superfluidity in Liquid He by Ion Motion

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Ions produced in liquid helium by ionization with α particles have been exploited as microscopic probe particles to study the properties of the superfluid. A time-of-flight method was used to measure directly the drift velocity u of the ions in the liquid for various values of the applied electric field $\mathcal{E}$ and at temperatures T down to 0.5°K. The field independent mobility $\mu^{(0)}=u/\mathcal{E}$ obtained in the limit of sufficiently small fields increases very rapidly below the λ-point. Its temperature dependence over most of the temperature range below 2°K is of the form $\mu^{(0)}=\alpha\exp(\Delta'/kT)$ and can be explained by the scattering of the ions from the collective excitations (rotons) present in the fluid. The nonlinear dependence of u on $\mathcal{E}$ at higher field strengths was also investigated and suggests the possibility of ions creating excitations in the quantum fluid as an important inelastic scattering process at sufficiently large fields. Some additional experiments are suggested.

THE motivation underlying the present experiments is an attempt to investigate the superfluidity of liquid helium from a relatively microscopic point of view by a study of the motion of atomic size probe particles in the fluid. As probe particles we have used ions since the electric charges on such particles make them readily observable even in small concentrations and allow their motion to be easily controlled by externally applied electromagnetic forces. By virtue of the superfluid property one would expect that a particle moving sufficiently slowly through the quantum fluid in its ground state at absolute zero would encounter no "resistance" to its motion.[1] On the other hand, at higher temperatures the particle will suffer scattering processes determined by the number and nature of the elementary excitations present in the fluid. Thus it should be possible, by studying the motion of microscopic probe particles, to make apparent the possible interactions between a particle and a quantum fluid exhibiting superfluidity and to check the collective description of the latter in terms of elementary excitations.

In the present work we have focused our attention on the measurement of the drift velocity u which an ion acquires when subject to a force provided by an applied electric field $\mathcal{E}$. The simplest situation to interpret is that where $\mathcal{E}$ is kept sufficiently small so that the ion never acquires an energy appreciably in excess of its equilibrium thermal energy in the fluid. The ion then resembles most closely an ideal probe which disturbs the medium minimally. Under these circumstances $u\propto\mathcal{E}$, and the mobility $\mu=u/\mathcal{E}$ of the ion is independent of $\mathcal{E}$. Here the behavior of the mobility as a function of temperature is of particular interest since a decrease in the possible scattering processes as one approaches the ground state of the superfluid at absolute zero should be directly measured by a correspondingly enhanced mobility. On the other hand, the case of larger electric fields is also worthy of investigation, particularly since there then exists the possibility of ions *creating* excitations in the background fluid.

Direct measurements of ion drift velocities in liquid helium above 1.2°K have been reported by us briefly in a previous note.[2] Ions in liquid helium have also been studied by Williams[3] who made mobility measurements above 1.4°K at very high electric fields, and by Careri et al.[4] who studied ion motion in heat flush experiments.

EXPERIMENTAL METHODS

To measure the ionic mobilities we adopted, with a few refinements, the method described in a previous note.[2] This method[5] permits a direct time-of-flight measurement of the drift velocity in a given electric field and has the virtue of allowing one to work with rather small electric fields and correspondingly small drift velocities. The "drift velocity spectrometer" is shown schematically in Fig. 1. The α particles emitted from the Po^{210} source S (about 10 microcuries) are stopped in the liquid helium within a very short distance (less than 0.3 mm) and there give rise by ionization to a copious supply of ions. Some of the latter can be drawn out by an electric field and finally arrive at the collecting electrode C. The resulting current I (of the order of 10^{-13} amp or less) is measured with a vibrating reed electrometer. The main drift space is defined by the grids A and B spaced about 1 cm apart. The pairs of grids AA' and BB' act, respectively, as two gates which are alternately opened and closed in synchronism ν times per second by the application of square wave electric fields between AA' and between BB'.[6] As a result, the

[1] From a quantum-mechanical point of view, the nature of the excited states of the fluid is such that creation of an elementary excitation by the particle is impossible under these circumstances. See, for example, the discussion of T. D. Lee and C. N. Yang in the Proceedings of the Midwest Conference on Theoretical Physics, Washington University, St. Louis, 1958 (unpublished), pp. 150–153.

[2] L. Meyer and F. Reif, Phys. Rev. **110**, 279 (1958). This paper will hereafter be referred to as I.

[3] R. L. Williams, Can. J. Phys. **35**, 134 (1957).

[4] G. Careri, F. Scaramuzi, and J. O. Thomson, Nuovo cimento **13**, 186 (1959).

[5] The method is an adaptation of one used for ion mobility studies in gases by A. M. Tyndall and C. F. Powell, Proc. Roy. Soc. (London) **A129**, 162 (1930).

[6] The spacing between AA' and between BB' is about 1 mm in our experiments.

number of ions reaching C will be a maximum essentially whenever the time T_0, required for the ions to drift the distance s_0 from A to B under the influence of the electric field $\mathcal{E}$ applied between these grids, is equal to an integral number of periods ν^{-1} of the gating fields. The current I_0 arriving at C is then a periodic function of ν, the separation $\bar{\nu}$ in frequency between any two adjacent maxima in I_0 being a direct measure of T_0^{-1}. A more detailed analysis of the action of the gates can be found in Appendix B. It may be instructive to point out that this method of measuring drift velocities is a close analog of the historically important method of Fizeau for measuring the velocity of light by a rotating toothed wheel.[7]

A He^3 refrigerator was used to carry our measurements into the temperature range below 1°K[8]. Good temperature stability is of importance in our experiments since the ionic mobilities are rapidly varying functions of temperature and since, when using rather small ion currents, an individual measurement of drift velocity is moderately time-consuming. Hence a device exploiting the temperature stability of a boiling liquid, like He^3, has a decided advantage over the ordinary adiabatic demagnetization setup. In our arrangement, shown in Fig. 2, the copper can (a) provides an isothermal enclosure containing the drift velocity spectrometer as well as some carbon resistance thermometers. The He^4 (about 80 cm^3 of liquid) necessary for the experiment is introduced into the can (a) through the capillary tube (c). The latter has a quite small bore diameter (0.005 in.) to minimize heat transport into the copper can by He^4 film flow. The brass can (b)

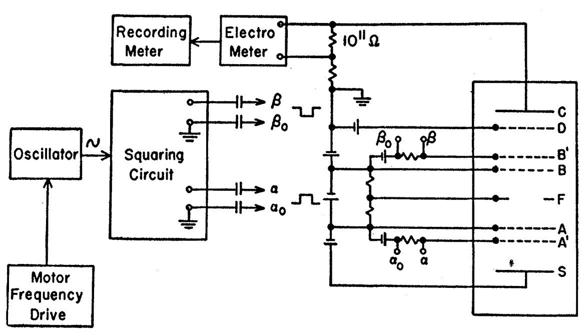

FIG. 1. Schematic diagram of the velocity spectrometer used for the measurement of ion drift velocities. The grid assembly shown on the right is immersed in liquid helium. S is the Po^{210} source and C the collecting electrode. The main drift space is between grids A and B, F being a guard ring which helps to maintain a uniform electric field in this region, while A' and B' are the pulsed grating grids. The batteries indicated in the diagram actually provide variable sources of dc potentials for the grids by the use of suitable potentiometers.

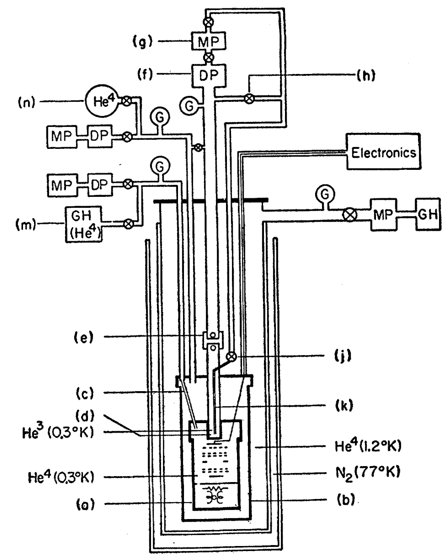

FIG. 2. Schematic diagram of the He^3 refrigerator. The main parts of this device are explained in the text. The symbols are: MP = mechanical pump, DP = diffusion pump, G = vacuum gauge. The bulb (n) provides He exchange gas for preliminary cooling down, while (m) denotes a small gas holder (GH) which stores the He^4 used to fill the experimental chamber (a). The radiation trap in the He^3 pumping line is designated by (e).

provides the vacuum jacket which insulates the can (a) thermally from the surrounding He^4 bath at 1.2°K. The amount of He^3 used as the working substance of the refrigerator is 300 cm^3 of NTP gas, corresponding to approximately $\frac{1}{2}$ cm^3 of liquid. The liquid He^3 is evaporated in the small chamber (d) in the top of the copper can (a). The temperature of the He^3, and hence of the experimental chamber (a), is lowered by pumping on it with the pumps (f) and (g), and can be controlled by the by-pass valve (h). The refrigerating action can be made continuous by recondensing the He^3 at 1.2°K in heat exchange with the main He^4 bath and then allowing it to trickle back down into the evaporating chamber (d) through the low-temperature throttle valve (j) and the capillary (k). Temperature measurements below about 1.2°K were made by calibrating during each run the carbon resistance thermometer against the vapor pressure of He^3[9] measured when the He^3 in (d) is used as a vapor pressure thermometer under static conditions, i.e., with the pumps (f) and (g) shut off. The refrigerator is capable of functioning down to temperatures of about 0.35°K. A long-term temperature stability with a drift rate of the order of 0.001°K per hour can be obtained without special precautions.

EXPERIMENTAL RESULTS AT LOW FIELDS

We first discuss the field-independent "zero-field" mobility $\mu^{(0)}$, i.e., the mobility measured in a range of

[7] See, for example, F. A. Jenkins and H. E. White, *Fundamentals of Optics* (McGraw-Hill Book Company, 1957), 3rd ed., p. 385.

[8] Similar He^3 refrigerators have been described by H. A. Reich and R. L. Garwin, Rev. Sci. Instr. **30**, 7 (1959), and by V. P. Peshkov, K. N. Zinov'eva, and A. I. Filimonov, J. Exptl. Theoret. Phys. U.S.S.R. **36**, 1034 (1959) [translation: Soviet Phys.-JETP **36**(9), 734 (1959)].

[9] The calibration made use of the measurements of the He^3 vapor pressure vs temperature of S. G. Sydoriak and T. R. Roberts, Phys. Rev. **106**, 175 (1957).

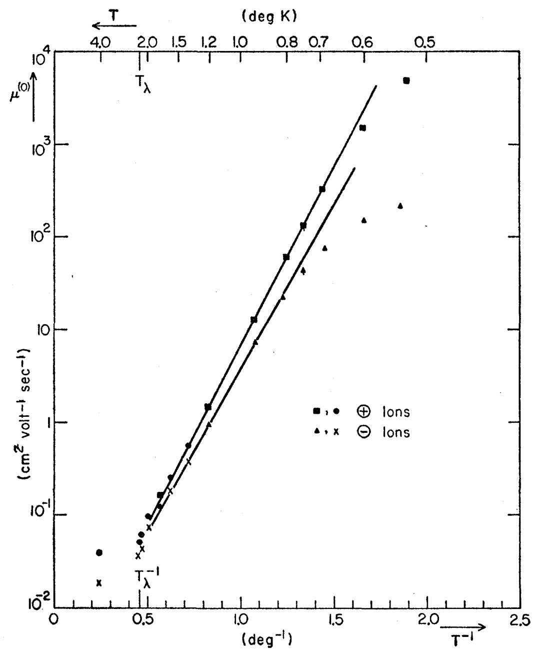

FIG. 3. The zero-field ionic mobility $\mu^{(0)}$ on a logarithmic scale as a function of the reciprocal absolute temperature T^{-1}. The squares and triangles denote experimental points obtained with the present apparatus, the two points with vertical tails indicating measurements made with the main drift space increased in length by 70%. The circles and crosses denote the old data of I multiplied by a correction factor 1.11 to bring their absolute values into agreement with the more recent data in the region of overlap.

electric field values $\mathcal{E}$ sufficiently small so that the drift velocity u is proportional to $\mathcal{E}$. Physically this region of small fields is characterized by the fact that $\mathcal{E}$ is kept small enough so that the energy imparted to an ion by the applied field $\mathcal{E}$ in a mean free path l is small compared to its thermal energy, i.e.,

$$\varphi\equiv e\mathcal{E}l/(\tfrac{3}{2}kT)\ll 1. \tag{1}$$

As will be apparent from our measurements, the mean free path increases very rapidly with decreasing temperature. Hence, especially at low temperatures, it becomes necessary to work with rather small electric fields if one wishes to maintain the condition (1). For example, the thermal energy of an ion corresponds approximately to a temperature of 1°K, i.e., to an energy of about 10^{-4} ev; thus, for a mean free path of 10^{-4} cm, a field $\mathcal{E}\ll 1$ volt/cm is required to satisfy the condition (1). Care must, therefore, be taken in the experimental measurements to check that one is indeed working with values of $\mathcal{E}$ sufficiently small so that the field-independent mobility has been reached.

The apparatus described in the previous section has been used to measure the ion drift velocities at various temperatures and for various values of the applied electric field. The temperature dependence of the zero-field mobility $\mu^{(0)}$ is shown in Fig. 3. This is a plot of $ln\ \mu^{(0)}$ as a function of T^{-1} of the same type as that shown in I, but extended into the temperature range below 1.2°K. The very rapid increase of the mobilities with decreasing temperature below the λ-point is certainly a very striking demonstration of the superfluid character of the liquid helium in which our probe particles are moving. For example, for positive ions, the mobility at 0.5°K is about 10^5 times larger than it is at the λ-point (2.18°K).

In Fig. 3 the experimental points in the temperature range from approximately 2°K down to about 0.65°K for positive ions and down to about 0.8°K for negative ions lie quite accurately on straight lines represented by equations of the form

$$\mu^{(0)}=\alpha\exp(\Delta'/kT), \tag{2}$$

where α is a constant. Here the values of the parameter Δ' are, respectively, for positive and negative ions:

$$\Delta'_+/k=8.8°\text{K},\quad \Delta_-'/k=8.1°\text{K}. \tag{3}$$

At temperatures below the temperature ranges just mentioned the measured zero-field mobilities are seen to fall increasingly below the straight lines (2). In the high-temperature range from approximately 1.5°K up to 2°K, the experimental points tend to lie slightly above the straight lines (2) by amounts just outside the limit of experimental error.

Except for a common scale factor, the values of the measured zero-field mobilities should be accurate to within 2%. The absolute values of the mobilities are less well known since electrical edge effects near the grids make the effective length of the drift space between grids A and B somewhat uncertain. To check this possible source of systematic error we used the present apparatus to measure ion drift velocities under identical conditions except that the drift space AB was changed in length by a factor 1.7. The two sets of measurements agreed with each other to within 5%. Hence we believe that the absolute values of our measured mobilities can be trusted to within comparable accuracy. Finally it should be mentioned that the present measurements overlap the temperature range of the earlier measurements of I taken with a quite different apparatus and with a more primitive experimental technique (involving sinusoidal instead of square wave gating fields between AA' and BB'). In the region of overlap the two sets of measurements agree with each other except for a common scale factor which indicates that the measurements of I were 11% too low in absolute value compared with the presumably more reliable values obtained with the present apparatus.

DISCUSSION

An interpretation of the ion mobility results involves the nature of the collective excitations of the quantum fluid and their interaction with the ionic probe particles. We base our discussion upon the familiar Landau spectrum of the elementary excitations of liquid helium.[10]

[10] See, for example, E. M. Lifshits, *A Supplement to "Helium"* (Consultants Bureau, New York, 1959).

These excitations can be treated, at temperatures sufficiently below the λ-point, as a dilute gas of quasi-particles.[11] The dispersion relation for the excitations, i.e., the relationship between their energy ϵ and momentum p, has recently been directly measured by neutron scattering.[12] According to this collective description, ions moving in the liquid suffer collisions with the excitations present in the fluid.[13] At temperatures greater than about 0.5°K, the collisions limiting the mean free path l of the ions are predominantly those with the excitations of large momentum, i.e., with rotons. An ion in liquid helium represents, in a collective description of the liquid, an excitation of a new kind of the fluid as a whole. Associated with the ion excitation there exists a dispersion relation connecting its energy E to its momentum P. We shall assume it to be of the form

$$E=\Gamma+(2M)^{-1}P^2, \tag{4}$$

where M is an effective mass parameter for the ion and Γ is a constant independent of P. In the presence of an electric field $\mathcal{E}$, simple kinetic theory then yields for the ion drift velocity u the relation $Mu=e\mathcal{E}\tau$, τ being the mean time between ion collisions. The ion mobility is then

$$\mu=(e/M)\tau=(e/M)l\langle v_{ir}\rangle^{-1} \tag{5}$$

where $\langle v_{ir}\rangle$ is the mean relative speed between ion and roton. Here

$$l=(n_r\sigma_{ir})^{-1}, \tag{6}$$

where σ_{ir} is the ion-roton scattering cross section and n_r is the number of rotons per cm^3. Writing the dispersion relation for the excitations in the roton region in the customary form

$$\epsilon=\Delta+(2\,\mu_0)^{-1}(p-p_0)^2, \tag{7}$$

one finds, using Bose statistics for the excitations:

$$n_r=2(2\pi)^{\frac{3}{2}}h^{-3}p_0^2(\mu_0 kT)^{\frac{1}{2}}\exp(-\Delta/kT). \tag{8}$$

In the region of small electric fields $\langle v_{ir}\rangle$ is simply the relative speed under thermal equilibrium conditions, i.e.,

$$\langle v_{ir}^2\rangle=\langle(\mathbf{v}_i-\mathbf{v}_r)^2\rangle=\langle\mathbf{v}_i^2\rangle+\langle\mathbf{v}_r^2\rangle,$$

where $\mathbf{v}_i$ and $\mathbf{v}_r=(\partial\epsilon/\partial\mathbf{p})$ are, respectively, the ion and roton velocities. For the ions, which are sufficiently dilute to obey classical Boltzmann statistics, the equipartition theorem yields $\langle\mathbf{v}_i^2\rangle=3kT/M$; for the rotons one computes $\langle\mathbf{v}_r^2\rangle=kT/\mu_0$. Hence, neglecting the small distinction between the rms and mean values,

$$\langle v_{ir}\rangle=(kT/\mu_0)^{\frac{1}{2}}(1+3\mu_0/M)^{\frac{1}{2}}. \tag{9}$$

One thus would predict the following temperature dependence of the ion mobility:

$$\mu^{(0)}\propto(\sigma_{ir}T)^{-1}\exp(\Delta/kT),\quad \Delta/k=8.65\text{°K}, \tag{10}$$

where the value of Δ is the one obtained from neutron scattering data.[12] If the ion-roton interaction is assumed to be like that between hard spheres, e.g., of the form $V_0\delta(\mathbf{r}_i-\mathbf{r}_r)$, then the cross section σ_{ir} is simply a constant.

The experimentally observed temperature dependence (2) and (3) of the mobilities is very similar in form to the simple theoretical prediction (10); the activation energy Δ is, for the positive ions, within the limits of error of our present measurements essentially the same as that derived from neutron scattering,[12] while being slightly less than this for the negative ions. The description of liquid helium in terms of its collective excitations appears, therefore, basically correct in accounting for the interaction of an ionic probe particle with the quantum fluid. The fact that the experimental temperature dependence is represented best by (2) without the pre-exponential factor T^{-1} of (10) is probably only of minor significance since the assumption of a hard sphere interaction between an ion and roton is unlikely to be realistic. With an interaction varying more smoothly with distance, the cross section would depend on the relative ion-roton velocity; e.g., $\sigma_{ir}\propto v_{ir}^{-\gamma}$, with $\gamma\geq 0$. By (9), σ_{ir} then effectively contributes to the temperature dependence (10) of $\mu^{(0)}$ a factor $T^{\frac{1}{2}\gamma}$. That is, for $\gamma=2$, there would be no pre-exponential temperature factor in (10). It would seem rather difficult to make any statements, based on first principles, about the actual ion-roton interaction. It is precisely one of the deficiencies of the theory of elementary excitations in its present stage of development that the interactions between the quasi-particles are not derived from the actual Hamiltonian of the liquid, but are instead customarily assumed on the basis of purely phenomenological arguments.[11]

It has already been pointed out that in the temperature range from approximately 1.5°K up to 2°K the experimental points tend to lie slightly above the straight lines (2) of Fig. 3. This deviation accounts for the fact that the parameters Δ'/k deduced in I from data obtained above 1.2°K were lower by 0.5°K than those given in Eq. (3). The deviation is consistent with the neutron scattering results[12] which show that the effective value of Δ decreases as the temperature is raised to the vicinity of the λ-point.[14,15] The physical significance of this shift in Δ is simply that the density

[11] A consistent elaboration of this point of view applied to many aspects of the liquid helium problem can be found in the review paper by I. M. Khalatnikov, Uspekhi Fiz. Nauk. **59**, 673 (1956), or, in German translation, Fortschr. Physik **5**, 211 (1957).

[12] J. L. Yarnell, G. P. Arnold, P. J. Bendt, and E. C. Kerr, Phys. Rev. **113**, 1379 (1959).

[13] The situation here is analogous to that of a few He^3 atoms dissolved in liquid He^4, a subject discussed theoretically on the basis of the theory of elementary excitations by I. M. Khalatnikov and V. N. Zharkov, J. Exptl. Theoret. Phys. U.S.S.R. **32**, 1108 (1957) [translation: Soviet Phys.-JETP **5**, 905 (1957)].

[14] The neutron scattering data[12] yield the empirical relation $\Delta/k=8.68-0.0048T^7$ °K. Thus Δ/k decreases by 0.5°K from 1.1°K to 1.8°K.

[15] The deviation might also be due, in part, to a violation of the condition (12) discussed below.

of excitations becomes great enough at these temperatures so that the effect of interactions between excitations is no longer negligible.

For positive ions at temperatures below about 0.6°K, the experimental points for $\mu^{(0)}$ lie increasingly below the straight line (2). Since at this temperature the roton concentration is already as low as 2×10^{16} cm^{-3}, both the atoms of the He^3 isotope occurring in their natural abundance (in well helium their abundance is 1.4×10^{-7},[16] i.e., there are about 3×10^{15} He^3 atoms per cm^3 of liquid helium) as well as phonons may begin to provide scattering centers for the ions of importance comparable to rotons. Experiments on liquid helium with the He^3 concentration reduced by methods based on heat flush or superfluidity should help to distinguish between these two additional scattering processes.[17] The reason why the deviation from the straight line (2) occurs already at higher temperatures for the negative ions is not clear.

It should be pointed out that the exact nature of the charge carriers whose mobility is measured in the present experiments is not known. This is, of course, equally true of ions in the ordinary liquid above the λ-point. For example, the possible ions may well be basically He_2^+ ions since the molecular He_2^+ ion is very stable and, in He gas at higher pressures, He_2^+ ions are more numerous than He^+ ions.[18] The situation in the case of the negative charge carriers is particularly uncertain. Since their mobility is *less* than that of the positive ions, it is exceedingly unlikely that they are simply electrons. Nor is there any evidence in our own experiments, nor in those of other workers,[3,4] for the existence in the liquid of any fast moving particles which might be identified with essentially free electrons.[19] On the other hand, the He^- ion is only metastable,[20] and whether a more complex ion like He_2^- is appreciably more stable is problematical. It is also conceivable that one may be dealing not with simple ions, but rather with an electron or hole which attaches itself temporarily to a He atom, or group of such atoms, before jumping over to an adjacent one. In the present experiments our interest has been focused on the striking temperature dependence of the ionic mobilities, irrespective of the detailed nature of the ion. We have, therefore, assumed the latter to be characterized by a dispersion relation of the form (4). A justification of this form or an evaluation of the parameters contained therein on the basis of first principles would be very difficult tasks. It is, however, likely that whatever the sign of the charge of an ion, the electric polarization of the liquid helium in its vicinity ought to result in an increase of its effective mass in the fluid appreciably above the value of this parameter if the ion were made electrically neutral.[4,21]

It is of interest to derive from our mobility measurements an estimate of the ion mean free path in the liquid. This estimate will depend on the assumed effective mass M of the ion. For the rotons, the parameters of Eq. (7) are known from the neutron scattering results,[12] i.e.,

$$\Delta/k=8.65°\text{K},\quad p_0/\hbar=1.92\ \text{A}^{-1},\quad \mu_0/M_{\text{He}}=0.16, \tag{11}$$

where M_{He} is the mass of the He atom. For $M=M_{\text{He}}$ and at a temperature of 1°K one finds by (9) that $\langle v_{ir}\rangle=1.4\times10^4$ cm/sec. Using the measured mobilities of Fig. 3, Eq. (5) yields for the positive ions $l=4.0\times10^{-7}$ cm. Since (8) and (11) give for the roton density at this temperature $n_r=9.3\times10^{18}$ cm^{-3}, Eq. (6) leads to an estimated ion-roton cross section $\sigma_{ir}=2.7\times10^{-13}$ cm^2. Now it is likely that $M>M_{\text{He}}$ (an effective mass as high as $M=40M_{\text{He}}$ has been suggested[21]); the estimated mean free path would then be considerably increased and the cross section correspondingly reduced. E.g., for $M=10M_{\text{He}}$, the foregoing estimates of l should be multiplied by a factor 8.4. Indeed, it is seen by (9) that $\langle v_{ir}\rangle$ depends only slightly on M for $M\gg\mu_0$ since the roton velocity is then much greater than that of the ion; hence, by (5), l is then approximately proportional to M for a given mobility. It is clear from this discussion that even at the relatively high temperature of 0.6°K the ion mean free path is already about 10^4 times greater than the interatomic spacing between He atoms in the liquid.

It should be noted that our kinetic theory arguments based on two-particle collisions are only valid if the collision diameter $(\sigma_{ir}/\pi)^{\frac{1}{2}}$ is appreciably smaller than the ion mean free path l, i.e., if

$$\zeta\equiv(\sigma_{ir}/\pi)^{\frac{1}{2}}/l\ll1. \tag{12}$$

For $M=M_{\text{He}}$ one computes $\zeta=0.75$ at $T=1°$K so that the condition (12) is not fulfilled above 1°K. Deviations of the temperature dependence of $\mu^{(0)}$ from the straight lines (2) might then be expected above this temperature. On the other hand, (6) leads to an estimate $\sigma_{ir}\propto l^{-1}$ so that $\zeta\propto l^{-\frac{3}{2}}$; hence, for $M\gg\mu_0$, one has approximately $\zeta\propto M^{-\frac{3}{2}}$. It follows that, if the effective mass M is large, the condition $\zeta\ll1$ may well remain fulfilled up to considerably higher temperatures. This fact may account for the validity of Eq. (2) in describing the behavior of $\mu^{(0)}$ up to about 2°K.

Our experiments invite comparison with measurements on dilute solutions of He^3 in liquid He^4 where the He^3 atoms act as electrically neutral probe particles in the fluid. At temperatures sufficiently high so that He^3–He^3 collisions are not yet predominant, the He^3-roton collisions should be responsible for limiting the

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[16] K. R. Atkins, *Liquid Helium* (Cambridge University Press, New York, 1959), p. 230.

[17] *Note added in proof.*—Recent measurements in liquid He enriched with He^3 show that scattering of ions by He^3 atoms in natural abundance is negligible above 0.5°K.

[18] A. V. Phelps and S. C. Brown, Phys. Rev. **86**, 102 (1952).

[19] This is unlike the situation found by Williams[3] in liquid argon where he did observe such electrons.

[20] E. Holøien and J. Midtal, Proc. Phys. Soc. (London) **A68**, 815 (1955).

[21] Some remarks on the nature of the ions and their effective mass can be found in a recent paper by K. R. Atkins, Phys. Rev. **116**, 1339 (1959).

He^3 mean free path and thus should determine the He^3 diffusion constant D_3. The theoretical temperature dependence of D_3 should then be of the form[22]

$$D_3 \propto \exp(\Delta/kT) \tag{13}$$

for reasons analogous to those leading to the mobility expression (10) for our ions. The connection here is a very close one since the diffusion coefficient D_i for ions in liquid helium is related to their mobility μ by the Einstein relation

$$D_i = (kT/e)\mu, \tag{14}$$

so that a direct comparison between the diffusion coefficients of He^3 atoms and of ions in the liquid is possible. Though the measurements of D_3 by Garwin and Reich[23] show the exponential behavior predicted by (13), the activation energy deduced from their results is $\Delta = 13.5$°K, i.e., about 50% higher than one would expect from the well-known roton parameter Δ or from the mobilities of the ions. The reason for the appearance of this anomalously high value is not clear.[24] It might be pointed out that the He^3 concentration used in their experiments is rather high, of the order of 1%; this is about 10^{17} times higher than the concentration of about 10^3 ions/cm^3 used in our experiments. At 1.5°K one computes by (14) for positive ions $D_1 = 4.8\times10^{-5}$ cm^2/sec, which is about 4 times smaller than the corresponding value of D_3.[23,25] The difference is not unreasonable since one would expect a larger scattering cross section and a larger effective mass for an ion as compared with a neutral He^3 atom.

FIELD DEPENDENCE OF DRIFT VELOCITY

We finally turn to a discussion of the ion drift velocity u as a function of electric field $\mathcal{E}$ at a given value of the temperature. Figure 4 shows a typical experimental curve of this kind obtained at a temperature of 0.75°K. The nonlinear dependence of u on $\mathcal{E}$ is quite apparent, the deviation from proportionality setting in at increasingly smaller values of $\mathcal{E}$ as the temperature is reduced. A characteristic parameter significant for the field dependence is the ratio φ defined in (1). One expects that, as long as $\varphi \ll 1$, $u \propto \mathcal{E}$. For larger values of $\mathcal{E}$ there should be a region where $u \propto \mathcal{E}^{\frac{1}{2}}$. Finally, if $\mathcal{E}$ is made sufficiently large, it should become possible for ions to *create* rotons in the background fluid. As shown in Appendix A, the creation process becomes possible only if the ion kinetic energy exceeds a critical value $\tilde{K}_r$

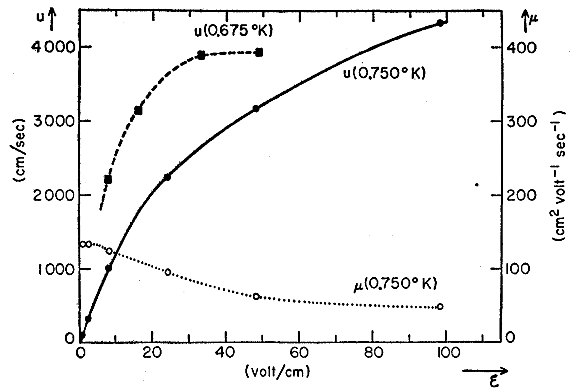

FIG. 4. Dependence of the positive ion drift velocity u and corresponding mobility $\mu = u/\mathcal{E}$ on the applied electric field $\mathcal{E}$ at 0.750°K. Part of a curve of u vs $\mathcal{E}$ at the lower temperature of 0.675°K is also shown for comparison.

which is necessarily greater than Δ, but which depends also on the effective mass M of the ion. Hence the creation process should come into play when $e\mathcal{E}l \gtrsim \tilde{K}_r$, and should become increasingly important as the main scattering process for the ion as the electric field is increased further. In the limit of quite large fields this should become the predominant scattering process and should lead to an ion drift velocity limited essentially by its critical velocity necessary for the creation of a roton. It should be clear that creation of an excitation by an ion corresponds to an inelastic scattering of the ion in which the latter loses energy in raising the liquid as a whole to a higher excited state separated by a well-defined quantized energy. The situation is analogous to the classical Franck-Hertz experiment in which an electron suffers an inelastic collision in raising an atom to a discrete excited state.

At 0.75°K the measured zero-field mobility yields by (5) the estimate $l \geq 6.5\times10^{-6}$ cm if one assumes that $M \geq M_{He}$. Thus, for $\mathcal{E} = 1$ v/cm, $e\mathcal{E}l/k \geq 0.075$°K. Hence for $\mathcal{E} = 3$ v/cm, $\varphi \geq 0.2$ and thus it is reasonable that in Fig. 3 the curve of u vs $\mathcal{E}$ should already begin to depart from proportionality at fields as low as this. It should be noted that in a detailed theory of the field dependence of the mobility[26] the effective mass M would be an important parameter. A study of curves of the type of Fig. 4 might then allow one to make estimates about the magnitude of M. Furthermore, since the energy $\tilde{K}_r$ necessary to create a roton is, by Fig. 6, of the order of 10°K for reasonable values of M, it follows that creation of rotons should become possible at fields of 130 v/cm or less; e.g., for $M = 10\ M_{He}$, for fields $\mathcal{E}$ greater than 20 v/cm. Thus it is clear that the process of creation of rotons by ions is one which becomes of importance at values of $\mathcal{E}$ well within the range of our experiments.

[22] The detailed theory for D_3 is given in reference 13.

[23] R. L. Garwin and H. A. Reich, Phys. Rev. **115**, 1478 (1959).

[24] It is possible that the effective mass of a He^3 atom is relatively small compared to that of an ion. It is then possible that the condition (12) may not be satisfied by a He^3 atom in the temperature range above 1.3°K from which the value of Δ was deduced in these experiments.

[25] The indirect determination of D_3 by J. J. M. Beenakker, K. W. Taconis, et al. [see *Progress in Low-Temperature Physics*, edited by J. C. Gorter (North Holland Publishing Company, Amsterdam, 1955), Vol. 1, p. 134] yields values of D_3 with an activation energy similar to that of reference 22, but an order of magnitude less in absolute value.

[26] Such a detailed theory is not available, though the related problem of ions in gases has been treated by G. H. Wannier [Bell System Tech. J. **32**, 170 (1953)]. and that of electrons in liquid helium by R. G. Arkhipov, J. Exptl. Theoret. Phys. U.S.S.R. **33**, 397 (1957) [translation: Soviet Phys.-JETP **6**(**33**), 307 (1958)].

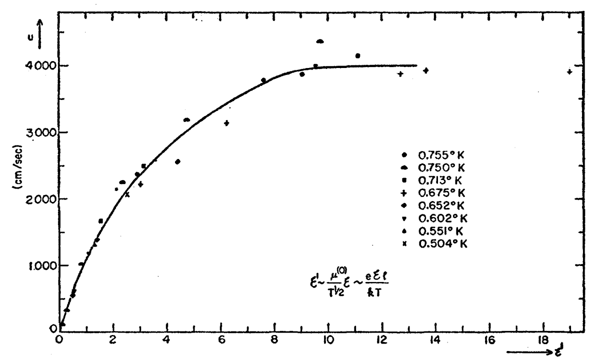

FIG. 5. Drift velocity u for positive ions as a function of the reduced field parameter $\mathcal{E}'$. The latter has been taken equal to $\mathcal{E}'=\frac{2}{3}\times10^{-3}(T^{-\frac{1}{2}}\mu^{(0)}\mathcal{E})$ cm sec^{-1} deg$^{-\frac{1}{2}}$, where $\mathcal{E}$ is the applied electric field and $\mu^{(0)}$ is the measured zero-field mobility at the given absolute temperature T. $\mathcal{E}'$ is proportional to the dimensionless parameter $e\mathcal{E}l(kT)$ where l is the ion free path. The experimental points were obtained from measurements at the temperatures listed on the drawing.

Unfortunately we have not yet been able to extend our measurements to significantly larger values of electric field. The reason is that at large values of the electric field the experimental curves of ion current vs gating frequency (which at lower fields or higher temperatures exhibit very well-defined periodically recurring peaks allowing accurate determinations of time of flight) tend to show appreciably reduced amplitudes of these peaks so that measurements of u become increasingly difficult. The reasons for this experimentally observed behavior are not yet clear to us and are under investigation.

Finally, one might expect, if φ is indeed the characteristic parameter determining the dependence of drift velocity u on $\mathcal{E}$, that the curves for the field dependence of u at various temperatures might all be combined into a single curve if one considers u as a function of the "reduced field" $\varphi=e\mathcal{E}l/(\frac{3}{2}kT)$. Since, by (5) and (9), l is related to the zero-field mobility $\mu^{(0)}$ by $l\propto T^{\frac{1}{2}}\mu^{(0)}$, this argument suggests that a universal curve should be obtained if u is plotted as a function of the reduced field parameter $(T^{-\frac{1}{2}}\mu^{(0)}\mathcal{E})$.[27] Figure 5 shows such a plot where the values of $\mu^{(0)}$ for the abscissa have been taken from the experimental data of Fig. 3. It is seen that the drift velocities measured at the various temperatures do indeed fall fairly well on a common curve for the temperature range investigated, i.e., from 0.75°K down to 0.50°K corresponding to a factor of over 50 in the magnitude of $\mu^{(0)}$.

CONCLUDING REMARKS

The work described in this paper suggests several other lines of investigation involving the study of liquid helium by means of ions. There are, first, some quite natural extensions of the present experiments. (a) The mobility measurements should be carried to lower temperatures (e.g., down to the temperature of 0.3°K available in the present apparatus) to study the situation where scattering of ions by phonons becomes predominant. One expects the mobility to vary like T^{-n} in this temperature region, where n can be quite large.[28] To make the phonon scattering observable it will, however, be necessary to reduce significantly the natural abundance of the He^3 impurities in the liquid helium by methods based on superfluid filters or heat flush. (b) It would be of interest to overcome present experimental difficulties to extend the drift velocity measurements to larger values of the electric field, a domain where the process of roton creation by ions ought to be of major significance. (c) Measurements of the ion mobilities as a function of pressure would also be worth while. In going from atmospheric pressure up to 25 atm, the melting pressure of helium at 0°K, the density of the liquid increases by 18%.[29] As a result, the parameters characterizing the excitation spectrum of the fluid ought to change significantly and a change in Δ, for example, ought to manifest itself quite clearly in a change of the slope (2) of the mobility curves. Arguments based on measurements of the coefficient of expansion of liquid helium[30] would lead one to expect a decrease of Δ by about 10%. (d) A much more difficult experiment would be a study of the vortex lines in a rotating container of liquid helium by their scattering of ions. The experiment would require rather low temperatures to make the scattering of ions by other excitations sufficiently small.

Another set of experiments involves the use of a magnetic field. (a) At sufficiently low temperatures, mobilities can be determined by ion deflection in a magnetic field H. For H perpendicular to the main electric field $\mathcal{E}$ there exists a mean magnetic force $F_m=eHu/c$ at right angles to the electric force $F_e=e\mathcal{E}$. As a result the ions will move in a direction making an angle θ with $\boldsymbol{\mathcal{E}}$, θ being given approximately by

$$\theta=F_m/F_e=\mu H/c. \tag{15a}$$

Alternatively, a small electric field $\mathcal{E}_1$ can be used at right angles to both $\mathcal{E}$ and H to reduce the magnetic deflection to zero and to make this into a null method. For $H=10^4$ gauss, $\theta>0.1$ radian for $\mu>10^3$ cm^2 v^{-1} sec^{-1} so that the method ought to be applicable at temperatures below about 0.6°K. Since the "Hall mobility" thus measured need not necessarily be equal to the "drift mobility" measured by the velocity spectrometer (this can happen, for example, if the charge is not perma-

[27] *Note added in proof.*—Professor Michael Sanders kindly pointed out to us that, to be consistent with a universal curve, one ought to plot as ordinate $T^{-\frac{1}{2}}\mu$ rather than μ itself. This modification makes only a minor difference in the appearance of the curve of Fig. 5.

[28] One would predict $n=9$ if one assumes that scattering of an ion by a phonon is similar to that of a hard sphere by a sound wave of wavelength large compared to its radius. [This follows from the Einstein relation (14) applied to Eq. (4.43) of reference 13 which gives the calculated diffusion coefficient of He^3 in liquid helium in the temperature range of phonon scattering].

[29] W. H. Keesom, Helium (Elsevier Publishing Company, Inc., Amsterdam, 1942), p. 240.

[30] Reference 16, p. 66.

nently attached to a given ion), these measurements might also help in elucidating the nature of the ions. (b) A determination of the effective masses of the ions would be of considerable interest. The most direct method that suggests itself is measurement of the ion cyclotron resonance frequency $\omega_c = eH/(Mc)$ in a given magnetic field H. A necessary condition for the feasibility of this experiment is that the time τ between collisions of the ion be sufficiently large compared to the cyclotron period of revolution, i.e., one needs $\tau \gtrsim 1/\omega_c$. By using the expression for ω_c and Eq. (5) this condition can be written in terms of the ion mobility as

$$\mu H/c \gtrsim 1. \qquad (15b)$$

For $H=10^4$ gauss one thus needs $\mu \gtrsim 10^4$ cm^2 v^{-1} sec^{-1}, so that the experiment ought to become feasible at or below about 0.5°K. In this field the resonance frequency would be $\omega_c/(2\pi)=3.8$ Mc/sec for $M=M_{\mathrm{He}}$. Because of the small frequency and the small number of ions involved, the detection of cyclotron resonance by absorption of power would be prohibitively difficult; a method based instead upon detection of the effect of cyclotron resonance upon the ion beam would seem indicated.[31]

Ions should also be useful in some hydrodynamic experiments. At temperatures which are not excessively low the ions have mean free paths small enough so that they suffer many collisions with the excitations of the fluid. Hence the ions will participate in any convective motion of the excitations, i.e., they will move with the "normal fluid." The experiments of Careri et al.[4] have verified this fact in heat flush experiments. Now, in conventional hydrodynamic experiments on ordinary fluids like water, ink is often injected to label the fluid motions in a visible way. In an analogous way ions introduced into liquid helium should act effectively as an "ink" that would selectively label only the normal component of the fluid; in addition, since a known drift velocity can be superimposed upon the ions by application of a known electric field, the magnitude of the convective velocity of the normal component can then also be measured. For example, the problem of the hydrodynamic instability of liquid helium is one which involves the interactions between normal and superfluid motions in an intricate way[32] and is one where the ion "ink" might be useful. We are currently exploring, with Dr. Donnelly, the possibility of using ions and suitable probe electrodes in an experiment on hydrodynamic stability of liquid helium contained between rotating cylinders.

Finally, measurements of ion mobilities in liquid He^3 at low temperatures (<0.5°K) would be of considerable interest since they would yield information about the low-lying excited states of a Fermi liquid and could be compared with recent measurement of the self-diffusion in liquid He^3.[33]

[31] A method similar in principle to that used by J. H. Gardner [Phys. Rev. **83**, 996 (1951)] for the determination of electron cyclotron resonance represents one possibility.

[32] R. J. Donnelly, Phys. Rev. Letters **3**, 507 (1959).

ACKNOWLEDGMENTS

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APPENDIX A. CREATION OF AN EXCITATION BY AN ION

Consider the process in which an ion of momentum $\mathbf{P}$ and energy E creates an elementary excitation of momentum $\mathbf{p}$ and corresponding energy ϵ in the background fluid, the ion thereafter being left with momentum $\mathbf{P}'$ and energy E'. The conservation theorems for momentum and energy impose the conditions

$$\mathbf{P}=\mathbf{P}'+\mathbf{p}, \qquad (16)$$

$$E=E'+\epsilon. \qquad (17)$$

For the ion we assume the dispersion relation of Eq. (4). Solving Eq. (16) for $\mathbf{P}'^2$, and combining with (17) and (4), then yields the relation

$$\mathbf{P}\cdot\mathbf{p}=Pp\cos\theta=M\epsilon+\tfrac{1}{2}\mathbf{p}^2, \qquad (18)$$

where θ is the angle between $\mathbf{p}$ and $\mathbf{P}$. Since $\cos\theta\leq 1$, it follows that the velocity of the ion $\mathbf{V}=\partial E/\partial\mathbf{P}=\mathbf{P}/M$ must satisfy the condition $V\geq W$, where

$$W=\epsilon p^{-1}+(2M)^{-1}p, \qquad (19)$$

and where $V=|\mathbf{V}|$ and $p=|\mathbf{p}|$. Creation of an excitation is then only possible if

$$V\geq \tilde{W}, \qquad (20)$$

$\tilde{W}$ being the minimum value of the function W.

Using the dispersion curve for the elementary excitations,[12] Eqs. (19) and (20) show that creation of phonons becomes first possible when $V\geq c$, c being the velocity of sound. In addition, for M not too small, the condition $dW/dp=0$ determines another minimum value $W=\tilde{W}_r$ corresponding to the minimum ion velocity needed for the creation of a roton. As long as $M>0.9\,M_{\mathrm{He}}$, $\tilde{W}_r<$c. For $M\to\infty$, $\tilde{W}_r\to 58$ m/sec, the familiar Landau result for the critical velocity of a macroscopic body.[34] The dependence of $\tilde{W}_r$ on the effective mass M of the ion is shown in Fig. 6.

In order to examine the creation process in somewhat greater detail, it is necessary to make some statements about the cross section σ_c for creation of an excitation. In the absence of detailed knowledge of the ion-roton

[33] H. R. Hart and J. C. Wheatley, Phys. Rev. Letters **4**, 3 (1960).

[34] See reference 10, p. 16.

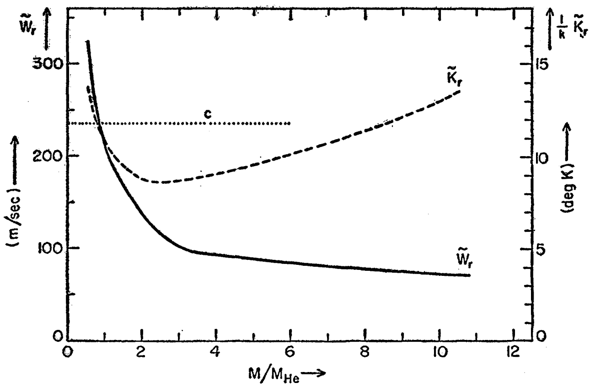

FIG. 6. Minimum velocity $\tilde{W}_r$ and corresponding ion kinetic energy $\tilde{K}_r=\frac{1}{2}M\tilde{W}_r^2$ necessary for an ion of effective mass M to create a roton. The effective mass M is expressed in units of the mass M_{He} of a He atom; the kinetic energy K is expressed in degrees by dividing by Boltzmann's constant k. The curves were computed by using Eqs. (17) and (18) and the excitation spectrum obtained from the neutron scattering data of Yarnell *et al.* (reference 12). The dotted line indicates the velocity of sound c which is the minimum ion velocity necessary to create a phonon; the corresponding ion kinetic energy is $(\frac{1}{2}Mc^2)k^{-1}=13.65(M/M_{\mathrm{He}})$ degrees.

interaction, one can give a simple argument based upon a δ-function type interaction, i.e., assuming that the matrix element F pertinent for the creation process is just a constant. This implies a purely statistical argument based only upon the volume of phase space available to the created excitation. Then one can write

$$d\sigma_c \propto \int V^{-1}F^2\delta(\epsilon+E'-E)\delta(\mathbf{p}+\mathbf{P}'-\mathbf{P})d^3\mathbf{p}d^3\mathbf{P}'$$

$$\propto V^{-1}F^2\int \delta(M\epsilon+\tfrac{1}{2}p^2-pP\cos\theta)p^2dpd(\cos\theta). \quad (21)$$

For a given initial ion velocity V, one then obtains a nonvanishing cross section σ_c of the form

$$d\sigma_c \propto F^2V^{-2}pdp \quad (22)$$

in the range of values of p such that

$$\cos\theta = W/V \leq 1. \quad (23)$$

To discuss the situation of roton creation close to threshold one need only know the behavior of W close to its minimum value $\tilde{W}_r$ occurring at $p=\tilde{p}$. There one can write

$$W=\tilde{W}_r+A(p-\tilde{p})^2, \quad (24)$$

with $A=\tilde{p}^{-3}[\Delta+(2\mu_0)^{-1}p_0^2]$. Integrating (22) over the possible values of p as determined by (23) yields near the threshold for roton creation the total cross section dependence on V

$$\sigma_c^{(\mathrm{tot})} \propto V^{-2}(V-\tilde{W})^{\frac{1}{2}}. \quad (25)$$

After creating a roton the ion will be left with a momentum component P_0' in the direction of its original momentum P. For a given value of P, the mean momentum loss

$$\langle P-P_0'\rangle = \langle p(W/V)\rangle \quad (26)$$

can be computed by averaging (26) over the possible values of p with the statistical weighting given by (22). The result near threshold for roton creation is

$$\langle P-P_0'\rangle = \tfrac{1}{3}\{[2(\tilde{W}/V)+1]\tilde{p} + [1-(\tilde{W}/V)]A^{-1}(\tilde{W}/\tilde{p})\}. \quad (27)$$

In the limiting case of sufficiently low temperatures or high electric fields the inelastic ion scattering involving roton creation should become the dominant process. A simple way of visualizing the resulting ion motion is to consider that the ion is accelerated by the electric field to some mean velocity $\bar{V}(\geq\tilde{W}_r)$ at which roton creation occurs with appreciable probability, after which the ion velocity falls back to a mean velocity V_0' and the acceleration process is repeated. This should lead to a limiting ion drift velocity $u=\frac{1}{2}\langle\bar{V}+V_0'\rangle$. For reasonable values of the effective mass M which are not too small, numerical estimates based on (27) show that $\langle P-P_0'\rangle$ can be expected to be appreciably smaller than P. Hence u will not be much smaller than the mean velocity $\bar{V}$ at which roton creation becomes appreciable. (If all roton creation occurred at threshold where $V=\tilde{W}_r$, then $u=\tilde{\epsilon}/\tilde{p}\approx 60$ m/sec.)

APPENDIX B. OPERATION OF THE DRIFT VELOCITY SPECTROMETER

We discuss briefly a simplified analysis of the action of the gating fields in the drift velocity spectrometers. The discussion should make clear the mode of operation of the instrument as used in the present experiments; in addition, by taking into account the nonideal behavior of the gates, it allows one to make estimates of the absolute values of the measured velocities.

The ions traverse the main drift space AB of length s_0 in a time T_0 under the influence of the electric field $\mathcal{E}_0$ applied between A and B. Denote the gate spacing between A and A' by s_1. The mode of operation is such that the gate is "opened" $\nu=1/\Theta$ times per second for a time $\tau=f\Theta$ by applying a field $\mathcal{E}_1=\mathcal{E}_0$ between A' and A which causes ions to traverse the space $A'A$ in a time T_1. We assume $f\leq\frac{1}{2}$; also, in the range of interest where ν is low, $\tau>T_1$. The ratio $g\equiv T_1/T_0=s_1/s_0$ measures the departure from the ideal case in which the time spent by an ion within the gate space would be negligible compared to T_0. During the remaining time $(\Theta-\tau)$ of each cycle the gate is "closed" by applying between A' and A a reverse field $\mathcal{E}_1'\leq-\mathcal{E}_1$ which drives any ions left inside the gate space back to the grid A' where they get collected. The gate space is thus assumed to be depleted of ions when the gate is again opened. The second gate consisting of B and B' is identical in dimensions and mode of operation.

If the first gate $A'A$ is thus opened for a time τ at the times $k\Theta(k=0,1,2,\ldots)$, the result is that ions will

arrive in front of grid B at times $(k\Theta+T_1+T_0)$ in bunches lasting a time $(\tau-T_1)$. The action of the second gate BB' is then to select for transmission past B' to the collector C only the part of each ion bunch arriving during a time θ, the magnitude of $\theta(0\leq\theta\leq\tau-T_1)$ depending only on the time difference between the arrival time of the bunch at B and the opening time $k\Theta$ of this second gate. The calculation of θ as a function of the delay time (T_1+T_0) is straightforward. Thus one can express the integrated ion current $A=\theta/\Theta$ (measured relative to that obtained if the gates are permanently open) arriving at the collector C as a function of the gating frequency ν. The result is a series of peaks, each peak of A vs ν being triangular in shape. For the m'th peak $(m=1,2,3, \ldots$; for $m=0$, there is only a half triangle) the apex of the triangle corresponds to a maximum intensity $A_m=f-g(1+g)^{-1}m$ and occurs at the frequency $\nu_m^{(0)}=m\bar{\nu}$ where

$$\bar{\nu}=(1+g)^{-1}T_0^{-1}. \tag{28}$$

The two frequencies at which the intensity A of the triangular peak falls to zero are, respectively, $\nu_m^{(-)}=(m-f)T_0^{-1}$ and $\nu_m^{(+)}=(m+f)\ (1+2g)^{-1}T_0^{-1}$. Since the gates are not ideal, i.e., $g>0$, each peak is somewhat asymmetrical in shape with $(\nu_m^{(0)}-\nu_m^{(-)})/(\nu_m^{(+)}-\nu_m^{(0)})=1+2g$. Experimentally one finds, at least in the range of electric fields sufficiently small so that the mobility is substantially field independent, that the observed peak shape and asymmetry agree quite well with these predictions though the peak amplitudes tend to decrease more rapidly with increasing order m than the foregoing simplified analysis would suggest. The important point is, of course, that the peak maxima occur at integral multiples of a fundamental frequency $\bar{\nu}$. This is experimentally very well satisfied, and at least three successive peaks have always been used in determining the fundamental frequency in any experimental measurement. Knowledge of $\bar{\nu}$ then leads to a determination of the time of flight T_0 through Eq. (28), the factor involving $g=s_1/s_0$ representing an approximate correction for the nonideality of the gates. The previously mentioned agreement within 5% of values of the drift velocity obtained when the main spacing s_0 was changed by 70% was obtained by taking this correction factor into account.

Finally it should be mentioned that we have also used an alternate mode of operation in which the gates are closed by putting the field $\mathcal{E}_1=0$ in the gate space. Ideally this should lead to a storing of the ions in the gate space until the next opening of the gate. One then gets symmetric peaks at integral multiples of the frequency $\bar{\nu}=T_0^{-1}$ and the amplitudes of successive peaks decrease very slowly. Despite the apparently greater simplicity of this mode of operation, the first mode of operation in which $\mathcal{E}_1$ is reversed in order to close a gate, involves a better defined gating action and has proved to be less subject to ambiguities, especially at larger values of the electric field when the nonlinear dependence of drift velocity on field becomes pronounced.