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Effective Mass of the Normal Negative-Charge Carrier in Bulk He II

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The first acceleration measurements are reported for negative ions in bulk superfluid ^{4}He. Data recorded at 70 mK, 25 bars for electric fields in the range $80 < E < 150$ V m^{-1} are consistent with an ionic dispersion relation identical to that of a free particle with mass $(87 \pm 5)m_4$, where m_4 is the ^{4}He atomic mass.

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Studies of the motion of positive and negative charge carriers have provided a particularly fruitful means of probing the properties of the (magnetically inert) superfluid ^{4}He. During the two decades following the pioneering experiments of Reif and Meyer[1] some hundreds of scientific papers have been published which describe work carried out on this basis[2] and which yield extensive and valuable information concerning, for example, the elementary excitations, critical velocities, surface properties, and macroscopic quantum states of the liquid. A quantity which is frequently of relevance to the analysis of experimental data is the effective mass m^* of the charge carrier (ion). It seems at first sight remarkable, therefore, that only one precise experimental determination[3] of m^* has so far been reported, and especially so considering that this measurement, being based on the resonance of ions trapped in a surface potential well, was entirely confined to the saturated vapor pressure. The latter restriction has given rise to what must be regarded as a serious lacuna in the experimentally determined properties of the negative ion. This is because of the expectation,[2] on sound theoretical grounds, that m^* for the negative ion should be strongly dependent on pressure: A decrease in m^* by a factor of circa 3 is to be anticipated between the saturated vapor pressure and the solidification pressure at 25 bars. It has not hitherto been possible to test this prediction experimentally. The purpose of the present Letter, however, is to report the development of a new technique which has enabled us to measure, for the first time, the effective mass of negative ions freely moving in bulk He II under elevated pressures.

The technique is a particularly straightforward and direct one, at least in principle, in that we simply measure the acceleration of the ion under a weak electric field E in the "mechanical vacuum" provided by isotopically pure He II at 70 mK, 25 bars. Under these conditions, drag due to residual excitation scattering is negligible and so, also, is the rate[4,5] at which quantized vortex rings are nucleated. In response to the steady force from the electric field, therefore, the ion undergoes an acceleration eE/m^* until it exceeds the Landau critical velocity, v_L. Thereafter, it proceeds at an average speed $\bar{v}$ which is limited only by the aperiodic creation of roton pairs.[6-8] For $E \simeq 10^2$ V m^{-1}, $\bar{v} = v_L$ to within 1%.[9] Provided that the instantaneous velocity v of the ion lies within the dissipationless range $-v_L < v < v_L$,[10] its dynamics are expected to be similar to those of a free particle.[11] The acceleration is readily determined from suitable time-of-flight measurements, using a modified version of the single pulse technique introduced by Schwarz[12]; knowing E, the required value of m^* follows immediately.

The experimental cell [Fig. 1(a)], a greatly enlarged version of that used earlier for velocity measurements,[6,8] has already been described briefly elsewhere in connection with the absolute determination of v_L,[9] and with the search for single roton emission.[13] In the present case the signals [Fig. 1(b)] were ungated and a forward bias was maintained continuously across G_1–G_2–G_3. Even for E as low as 100 V m^{-1} the ions are found to accelerate across their permitted velocity range of $\pm v_L$ within a few microseconds, which corresponds to movement through a fraction of a millimeter. One can be confident, therefore, that the ions are already traveling at v_L when they enter the measurement region between G_3 and G_4 and that they would continue at this speed all the way to C if E were maintained in the forward direction. In the present experiments, however, provision is made for transiently reversing E for an adjustable period Δt within $0.5 < \Delta t < 50$ μs.

The expected response of the ions to a field reversal pulse of duration Δt is sketched in Fig. 2 on the assumption of a (free-particle–like) uniform acceleration. Depending on whether $E\Delta t \gtrless 2v_L m^*/e$ the ion may (full curves), or may not (heavy dashed curves), decelerate to $-v_L$ prior to the reestablishment of the forward field. It is straightforward to show that in the former case the consequent delay τ_d in the ionic arrival time at C will be $2\,\Delta t$, and in the latter $(eE/m^* v_L)\Delta t^2$. In practice, to ensure an accurately measurable value of τ_d, some N field-reversal pulses are applied while the ions are in mid flight, well separated from G_3 and G_4, with N chosen in $1 < N < 100$ so as to increase the normal ionic transit time of circa 2 ms by 50–150 μs. We therefore expect to find that for $\Delta t \geq 2v_L m^*/eE = \Delta t_c$,

$$\tau_d = 2N\Delta t, \tag{1}$$

and for $\Delta t \leq \Delta t_c$,

$$\tau_d = (NeE/m^* v_L)\Delta t^2. \tag{2}$$

Values of τ_d were measured as a function of Δt for fixed E by using a computer (Nicolet 1180E; also employed for signal averaging during data

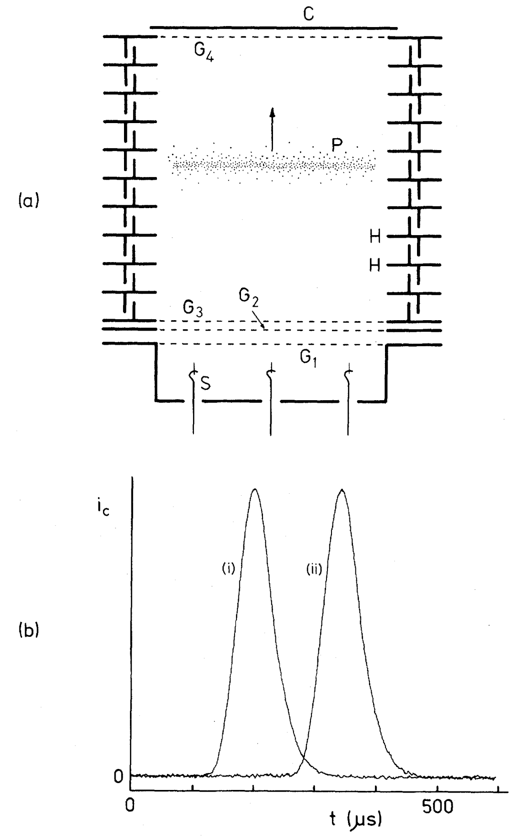

FIG. 1. (a) Electrode structure used for ionic time-of-flight measurements (diagrammatic). Ions are injected into the liquid by means of a short eht pulse (50 μs × 1100 V) applied to the field emission sources S. After passing through grids G_1, G_2, and G_3, they form a thin disk P propagating in the (101-mm-long) measuring space between G_3 and G_4 where uniformity of the electric field $\pm E$ is maintained by field-homogenizing electrodes H. (b) Examples of signals at the collector C (P = 25 bars, T = 70 mK, E = 132 V m^{-1}). The collector current i_c is shown as a function of time t: (i) reference signal with $N = 0$; (ii) delayed signal with N = 5, Δt = 14.0 μs. In each case, the abscissa origin has been fixed at a position 2.5 ms following the emitter pulse. Cross correlating the two signals gives τ_d = 140 μs, in agreement with (1).

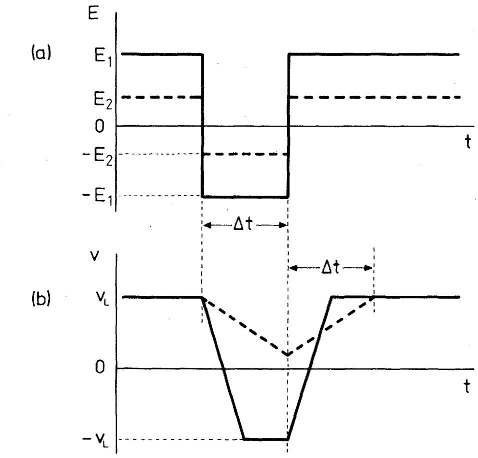

FIG. 2. Expected response of the ions to transient field reversal, assuming free particle dispersion. (a) The electric field E as a function of time t is reversed for a period Δt, for two values of E. (b) The ion may decelerate to a velocity $v = -v_L$ within Δt (full curve, corresponding to $|E| = E_1$), in which case the arrival time at C (Fig. 1) will be delayed by τ_d, for N such pulses, given by (1). Alternatively, the forward field may be reestablished before $-v_L$ has been reached (heavy dashed curve, corresponding to $|E| = E_2$), in which case τ_d is given by (2).

acquisition) to calculate the cross correlation function between each signal [e.g., Fig. 1(b) (ii)] and an undelayed reference signal [e.g., Fig. 1(b) (i)] previously recorded in the absence of the field reversal pulse train. From (1) and (2) we expect that a plot of $\tau_d/2N\Delta t$ against $E\,\Delta t$ will yield a straight line of gradient $e/2m^*v_L$ for $\Delta t \leqslant \Delta t_c$, and the constant value of unity for $\Delta t \geqslant \Delta t_c$; each case is independent of the chosen value of E.

Data obtained at 25 bars for several values of E are plotted in Fig. 3 and can be seen to define a universal curve which, gratifyingly, is very much of the expected form. The measurements could not be extended usefully above 150 V m^{-1} because the required values of Δt became too short to measure accurately, or below 80 V m^{-1} because of the poor signal-to-noise ratio necessary to prevent space-charge pulse spreading. Results were unaffected by changing either the signal magnitude, the ambient temperature (provided $T < 150$ mK), or the signal repetition rate of 8 Hz. A least-squares fit to the data for $E\,\Delta t > 4\times 10^{-4}$ V m^{-1} s gives a line of gradient zero and constant value 0.994 ± 0.003: The deviation from unity is only barely significant, statistically, could be accounted for if the reverse field was systematically very slightly smaller than the dc value of E, and lies well within the error limits of the individual measurements. A line fit to the data for $E\,\Delta t < 3\times 10^{-4}$ V m^{-1} s at each value of E and use of (2) yields the m^* values shown in the inset. The error bars refer only to statistical uncertainties in the fitting procedure. A grand average fit to the whole data set (sloping full line, Fig. 3) yields a value of $m^* = (87.4 \pm 1.3)m_4$. The intersection of this line with the line for $E\,\Delta T > 4\times 10^{-4}$ V m^{-1} s occurs at $E\,\Delta t_c = 3.40\times 10^{-4}$ V m^{-1} s, which corresponds to $m^* = 88.1 m_4$, and is consistent with the value obtained from the gradient. The net effect of systematic errors in the measurements is estimated to give an additional uncertainty of ± 3% in m^*, and we therefore conclude that $m^* = (87 \pm 5)m_4$ at 25 bars.

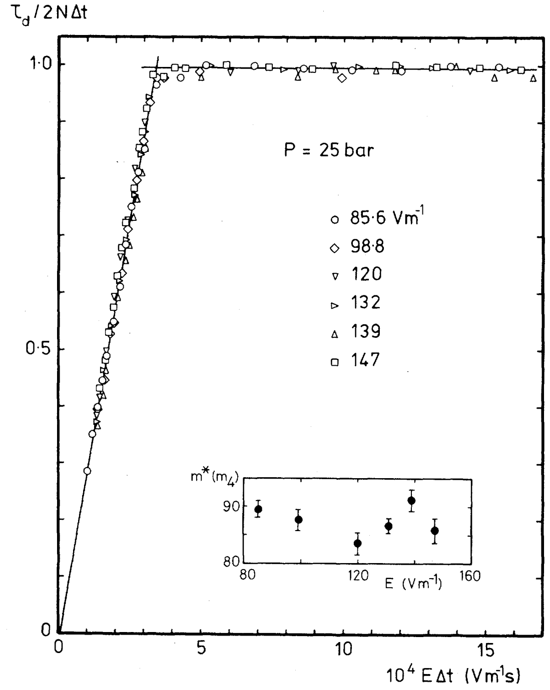

FIG. 3. Signal delay τ_d (μs) caused by N reversals of the electric field E (V m^{-1}) of duration Δt (μs), while the ions are between G_3 and G_4 (Fig. 1). The data recorded for different E all fall on a universal curve as predicted by (1) and (2). (For clarity, many points have had to be omitted.) The full lines represent linear least-squares fits to all data for $E\Delta t < 3\times 10^{-4}$ V m^{-1} s and $E\Delta t > 4\times 10^{-4}$ V m^{-1} s, respectively. Inset: values of the ionic effective mass m^*, in units of the ^{4}He atomic mass m_4, deduced by fitting (2) to data with $E\Delta t < 3\times 10^{-4}$ V m^{-1} s at each value of E.

As anticipated, this value is considerably smaller than the $m^* = (243 \pm 5)m_4$ measured by

Poitrenaud and Williams[3] at saturated vapor pressure. It is, however, in excellent agreement with the $m^* = (83 \pm 6)m_4$ which may be deduced from the hydrodynamic formula[14]

$$m^* = 2\pi R_i^3 \rho/3 \tag{3}$$

with the accepted value[15] of $\rho = 172.5$ kg m^{-3} at 25 bars and the ionic radius of $R_i = 1.15 \pm 0.03$ nm determined by Ostermeier[16] from mobility measurements at higher temperatures. Both of these high-pressure values are somewhat larger than the $m^* = (73 \pm 5)m_4$ deducible from the bubble model[17] on the (questionable) assumption of a sharp vacuum-liquid interface at the calculated[16] $R_i = 1.10 \pm 0.02$ nm. The discrepancy is small but will quite probably repay further investigation.

Finally, we note that the close agreement between experiment (Fig. 3) and Eqs. (1) and (2) demonstrates that any departures which may exist from free-particle dispersion ($\epsilon = p^2/2m^*$, where ϵ and p are energy and momentum, respectively) are insignificant: The dynamical behavior of negative ions in He II under our experimental conditions is indistinguishable from that of free particles of charge $-e$, constant mass $87m_4$, moving in a vacuum. The experiments have thus provided what is believed to be the first explicit and direct demonstration of the "mechanical vacuum" character of He II at very low temperatures (although this dramatic appellation has, of course, been in common use for a number of years).

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