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The Effect of Strong Electric Fields on Exotic Negative Ions in He II: Possible Evidence for the Nucleation of Charged Vortex Rings*

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Abstract: We present evidence suggesting that Ihas and Sanders' intermediate mobility exotic negative ions can nucleate quantised vortex rings in superfluid 4He when subjected to strong enough electric fields.

Several years ago, Doake and Gribbon discovered [1] that there can exist in He II a fast ion which, unlike the normal negative ion [2], may be accelerated to the Landau critical velocity v_L for roton creation without undergoing metamorphosis to a charged vortex ring, even under the saturated vapour pressure. Although Doake and Gribbon were unable to ascertain the physical conditions needed to generate this mysterious entity reproducibly, Ihas and Sanders showed [3,4] soon afterwards that the vital factor apparently lay in the provision of an electrical discharge in the vapour above the surface of the liquid. The latter authors also discovered that the glow discharge source produces not only the normal and fast negative ions, but also (astonishingly) a large number of other types of negative ion with low-field mobilities lying intermediate between those of the fast and normal ions.

The existence of this unexpected plethora of exotic negative charge carriers in He II constitutes an intriguing and still unsolved theoretical problem. Although the structure of the normal negative ion is understood in considerable detail [2] the nature(s) of the fast

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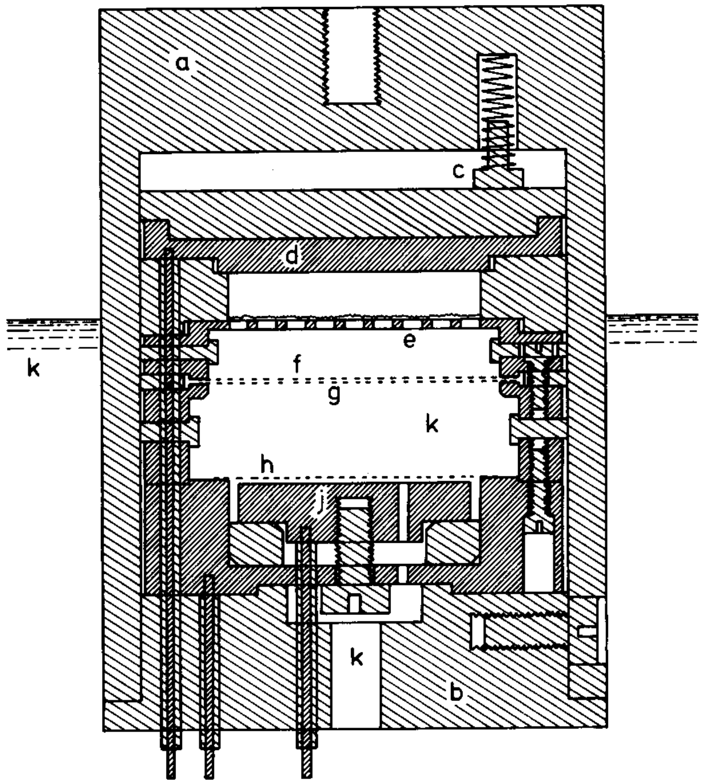

Figure 1: *Sketch (not a section) showing the principal component in the experimental cell: a - perspex body; b - perspex cap; c - spring-loaded plunger (total 3); d - brass cathode; e - perforated brass anode plate; f, g - gate grids; h - Frisch screening grid; j - collector; k - He II. The relatively dark-shaded components are of metal, and the lighter shading represents insulator.*

and intermediate ions remain(s) an entirely open question. One reason for our continuing ignorance is that the available experimental information [1,3,4] is rather sparse; and we have therefore embarked on a research programme aimed at remedying this unsatisfactory situation. In this Letter, we report the preliminary results of what is believed to be the first experimental study to be made of the behaviour of the intermediate mobility ions in strong electric fields.

Our ion cell is illustrated schematically in Fig. 1. It is similar in general design to that described by Ihas and Sanders except that, in order to achieve strong electric fields, we have made provision for the application of up to 3×10^3 V across a drift space of 10 mm. A glow discharge is struck between electrodes d and e, usually while keeping the liquid surface level with the upper surface of e. Ions then travel through the liquid to the first gate grid f, where they are stopped by the retarding potential normally maintained between f and g. Application of a transient negative voltage pulse to e and f opens the gate momentarily, and allows a thin disk of ions to enter the drift space between g and h. Finally, the ions pass through the screening grid h and are detected as they approach the collector j. To avoid electrical breakdown in the vapour outside the cell, all connections enter it from beneath. The level of the helium surface in the bath can be lowered by means of a fountain pump, which raises some of the He II via a needle valve to an upper reservoir; or it can be raised by switching off the fountain pump and opening the needle valve, so as to allow some of the He II to return to the bath again.

In Fig. 2 we show some typical ion signals at 1.03 K in electric fields E that are strong enough to have converted the normal ions to charged vortex rings. The large normal ion/vortex signal moves to the right with increasing E to reveal a number of small maxima corresponding (presumably) to the intermediate ions. Although signal/noise from our relatively short cell is (not surprisingly) rather poor, the drift velocity $\bar{v}$ the intermediate ions quite evidently decreases with increasing E. Behaviour of this type is, of course, highly reminiscent of that displayed by the charged vortex rings formed by normal ions, and it may therefore be regarded as an indication that intermediate ions, too, can form vortex rings. We have also made measurements for values of E well below that of the "giant fall" in v which occurs at E_{cn} for the normal ion. In agreement with the earlier work [3,4] we observe several quite distinct mobilities. As E is increased for $E < E_{cn}$ we find that $\bar{v}(E)$ for the principal intermediate ions bends over and approaches the horizontal. Further increase of E then causes each intermediate ion signal to vanish in turn, apparently because their $\bar{v}(E)$ characteristics undergo "giant falls", just as in the case of the normal ion, though occurring at a series of critical electric fields E_{ci} which lie at values of E considerably below E_{cn}. The corresponding critical drift velocities are found to be up to $10\mathrm{m\,s^{-1}}$ larger than for the normal ion. Unfortunately, it has not so far proved possible to associate individual species observed for $E < E_{ci}$ unambiguously with those for $E > E_{ci}$: this is because there is a range of E running from E_{ci} to beyond E_{cn} where the (relatively enormous) normal ion/vortex signal overlaps and entirely swamps the much weaker intermediate ion signals.

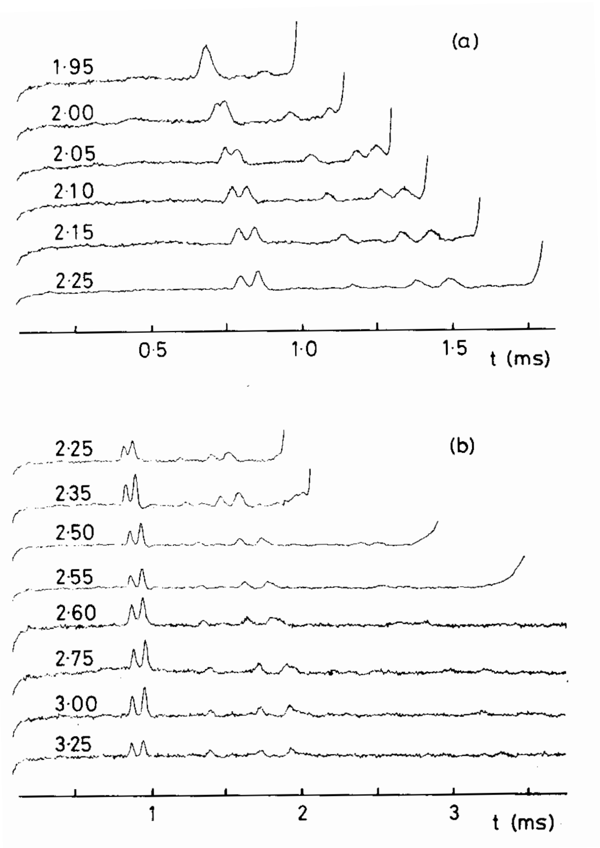

Figure 2: *The current at the collector of the velocity spectrometer (arbitrary units) as a function of the elapsed time t after application of a brief gate-opening pulse. Signals are shown for a range of (strong) electric fields, as indicated in units of 10^5 V/m by the number above each trace. The steep rise on the right-hand sides of the signals for* $E \leq 2.55 \times 10^5$ *V/m indicates the arrival of the (comparatively enormous) normal ion/vortex current. The change of timescale between sections (a) and (b) of the diagram should be noted.*

These experimental results are summarised by the $\bar{v}(E)$ plots of Fig. 3. In the interests of clarity, only three intermediate ion signals have been plotted for $E < E_c$ and only the fastest of them for $E > E_c$. We have also included, for comparison, our earlier measurements (with a slightly different electrode arrangement) of $\bar{v}(E)$ for the fast ion [5], which are clearly seen to flatten out close to v_L (60 m/s at SVP). The precision of the latter measurements is currently insufficient to establish whether or not the velocity is being limited by roton pair emission [6], as in the case of the normal ion: this will clearly be an interesting and important question for future investigations.

The behaviour of the intermediate ions for $E > E_c$ is, to say the least, rather puzzling.

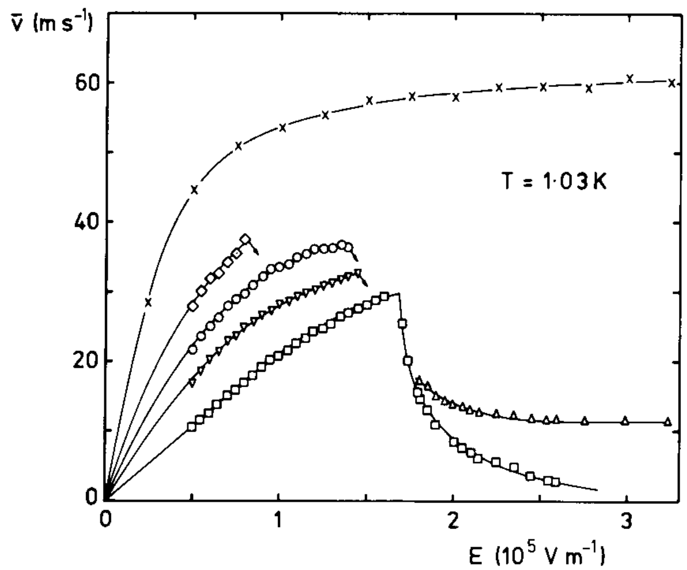

Figure 3: *Measured drift velocities $\bar{v}$ as a function of electric field E for several species of negative ion in He II at 1.03 K: the crosses represent the fast ion [5]; the diamonds, circles and triangles correspond to (selected) intermediate mobility ions; the squares indicate the (well-known) behaviour of the normal negative ion; and the full curves are guides to the eye. The arrows attached to the three low-field intermediate ion plots indicate the abrupt "disappearance" of the signals from those species, at critical values of E where they suddenly decrease in velocity and become engulfed by the very much larger normal ion signal.*

Drift velocities for the five most prominent species, determined from data such as those of Fig. 2 and plotted on an expanded scale in Fig. 4, each appear to tend towards a (different) field-independent limiting value of several m/s in very high electric fields. If the exotic carriers in this regime are indeed charged vortex rings, as we believe to be the case, then it seems extremely likely that their motion will involve a continuous sequence of escape-trapping-escape events [7] ; but it is far from clear why this should necessarily lead to drift velocities that are field-independent. We may note that, in view of their higher zero-field mobilities, the exotic ions are probably smaller than the normal one, so that the hydrodynamic potential [2] binding them to their rings will be weaker, and thermally activated escapes will be correspondingly more probable for any given temperature. We have found some indication that the plateau values of $\bar{v}(E)$ may *fall*

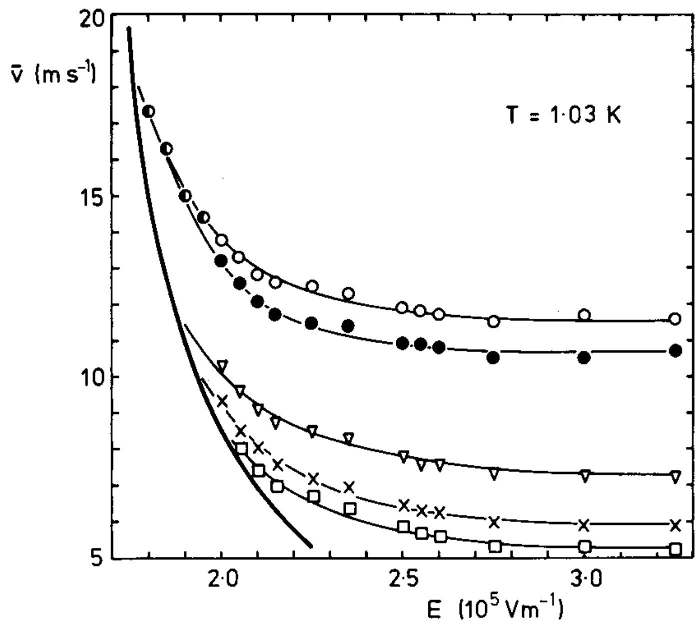

Figure 4: *Detailed plot, with expanded scales, of the high field region of Fig. 3, showing the drift velocity $\bar{v}$ as a function of electric field E for the five most prominent intermediate ions. The half-filled circles represent a case (as in the top signals of Fig. 2) where an ion peak was found to split into two separate peaks on further increase of E. The heavy full curve on the left corresponds to the peak of the normal ion/vortex signal, and the other full curves are guides to the eye.*

with increasing temperature. A possible explanation might be that the rate of vortex nucleation increases faster with temperature than that of thermally activated escapes; but the question cannot be investigated properly with our present apparatus because of the rapid increase with temperature of E_{cn} which quickly causes the normal ion signal to swamp the region of interest. Further studies, extending to lower temperatures and using a double-gated arrangement in order to separate the different ionic species before they reach the drift space of the velocity spectrometer, are currently being planned.

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