Quenching of the Ion/Vortex-Ring Transition in He II by Intense Electric Fields

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The rate ν at which negative ions nucleate charged vortex rings in isotopically pure superfluid helium-4 has been measured for electric fields of up to 2.5×10^6 V m^{-1} with pressures and temperatures within $17 < P < 25$ bars, $0.3 < T < 0.9$ K. It is found that the nucleation process is completely quenched ($\nu = 0$) for $E > 2\times10^6$ V m^{-1}. The implications of this result for theories of the nucleation mechanism are discussed.

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Superfluidity in helium-4 can break down in two (seemingly) quite separate ways when a small object travels at sufficiently high speed through the liquid. *Either* rotons are emitted[1-3] *or* a quantized vortex ring is created.[4-6] Where negative ions[6] are used as objects to probe the superfluid, the former process can be described in remarkable detail[7-9] on the basis of a "golden rule" calculation coupled with the postulate that the rotons are produced through a pair-emission process. Vortex-ring creation, however, is still poorly understood. Until recently, experimental data[10-12] have been relatively sparse and certainly insufficient to permit an unambiguous choice between rival theories[12,13] of the transition.

In the present work, we have been studying the ion/vortex-ring transition in isotopically pure He II under a wide range of physical conditions by means of an electric induction technique. The main purpose of this Letter is to present and discuss measurements made under intense electric fields E which appear to shed light on the microscopic processes through which rings are created. A full report of the research program, including extensive numerical data and a detailed exposition of experimental techniques, is to be presented elsewhere.[14]

The time dependence of the ion/vortex-ring transition under roton-emission–limited conditions can conveniently be measured by observation of the electric induction signal generated in a planar metal electrode by a group of approaching ions.[14,15] Given a suitable geometry and at least 100 V across the induction space of length L, the induced current i is closely proportional to the number of ions which have *not* metamorphosed to charged rings. At relatively low E it is found[16] that $i(t) \propto \exp(-\nu t)$ where ν is the rate of nucleation. In our present cell, $L = 2$ mm, thus enabling us to measure $i(t)$ for fields of up to $E = 2.5\times10^6$ V m^{-1}. Some typical induction signals are shown in Fig. 1 for a range of electric fields at 0.3 K, 17 bars. Although signal/noise is relatively poor from so short a cell, three observations may immediately be made. First, the top of the signal retains its exponential form, within experimental error, to the highest E. Secondly, ν clearly passes through a maximum as E is increased and then decreases to a negligible value at very large E. Thirdly, there is no indication at all of the pulse spreading, which would be expected if escape processes[17] were responsible for the decrease in ν at large E (such an effect being very evident in measurements near 0.9 K, where the signal distorts and the right-hand base line rises[14]). Values of $\nu(E)$ deduced from such signals are plotted in Fig. 2. It may be noted (a) that $\nu(E)$ falls to zero extremely rapidly above the (pressure-dependent) maximum in each case, with an effective cutoff field close to 2×10^6 V m^{-1} for all pres-

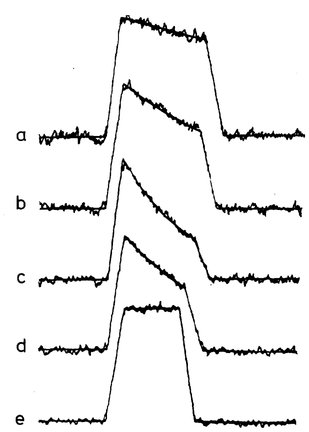

FIG. 1. Induction signals from negative ions in He II at 17 bars, 0.3 K, for electric fields (a) 1.3×10^5, (b) 2.6×10^5, (c) 5.8×10^5, (d) 1.2×10^6, and (e) 2.4×10^6 V m^{-1}. The computer-fitted theoretical signal shape (Bowley *et al.*, Ref. 14) has been superposed in each case. Signal narrowing at large E arises from the increased drift velocity of the ions.

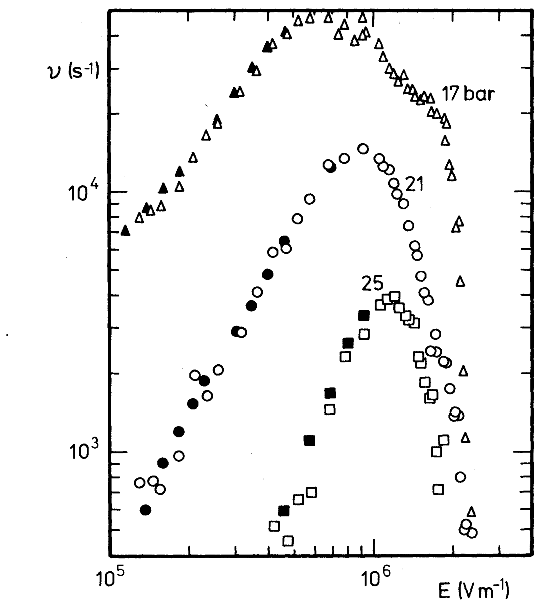

FIG. 2. The vortex nucleation rate ν for negative ions in He II at 0.3 K, as a function of electric field E, for three pressures. (Full symbols represent higher-precision data from the 5-mm cell).

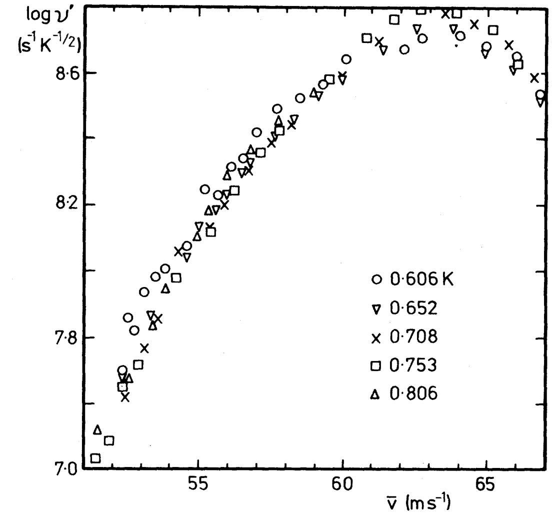

FIG. 3. Vortex nucleation by negative ions in He II at 23 bars for elevated temperatures. When the reduced nucleation rate ν' (see text) is plotted as a function of ionic drift velocity $\bar{v}$, the data recorded at different temperatures form a common curve.

sures; and (b) that some structure is evident on the high-E side of the maximum in the 17-bar curve [similarly shaped kinks also being found in $\nu(E)$ at 16 and 19 bars, not shown here].

At higher temperatures ν rises rapidly from the temperature-independent value ν_s measured below ca. 0.6 K. It seems[18] that a thermally activated nucleation process then comes into play and yields an additional contribution ν_r, so that the measured rate $\nu = \nu_s + \nu_r$. It is found (Fig. 3) that, for any given ionic drift velocity, $\nu_r \propto n_r$ where n_r is the thermal roton density: Plotting $\nu' = (\nu - \nu_s)/T^{1/2}\exp(-\Delta/kT)$, thus removing the temperature-dependent part of n_r, brings the data recorded at different temperatures onto a common curve. (Results shown are from the 5-mm cell because ν' data from the 2-mm cell are too scattered to be useful.) For all pressures, the maximum in $\nu'(\bar{v})$ [and so also in $\nu_r(\bar{v})$] occurs at a value of $\bar{v}$ about 5 m s^{-1} lower than in the case of $\nu_s(\bar{v})$. Apart from this, the variations of ν_s and ν_r with $\bar{v}$ are very similar, which strongly implies the existence of an underlying microscopic mechanism which is essentially the same for the two processes.

Other features which any satisfactory theory of vortex nucleation must be expected to encompass include (i) the presence of some structure in $\nu(E)$ below the maximum[19] as well as above it (Fig. 2); and (ii) the almost incredible sensitivity of ν to the presence of minute concentrations of ^{3}He (at, or below, the natural concentration of ca. 3 $\times 10^{-7}$).[16,20]

To what extent are existing theories able to account for these results? The theories can be divided into two main groups, as indicated symbolically in Fig. 4. The peeling model[12,21] envisages the nascent ring growing from a small initial loop of vortex line (a) nucleated from a "proto-ring" (perhaps a roton) localized near the equator of the ion. The application of a generalized Landau argument,[4] on the other hand, leads to the conclusion[13] that the initial ring would appear complete (b) as the result of a quantum tran-

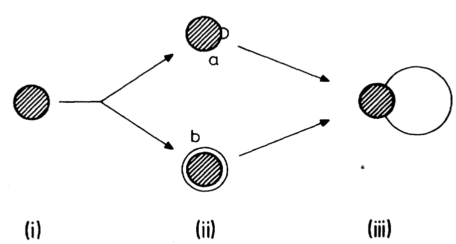

FIG. 4. Two possible ways in which an ion (i), moving perpendicular to the plane of the paper, might create a charged vortex ring (iii). The creation process (ii) may involve *either* (a) a small loop growing out continuously from the surface of the ion (Refs. 12 and 21) or (b) a quantum transition (Ref. 13) in which the nascent ring appears spontaneously, girdling the ion.

sition, with the critical ring taking a symmetrical position girdling the equator of the ion, which could then move sideways and become trapped on the vortex core. The latter model leads to critical velocities which are in reasonable agreement with values deduced from $\nu(E)$ measurements[16] at low E, and to a difference between the critical velocities for ν_s and ν_r which is consistent with the hypothesis[14] that the energy conservation requirement can sometimes be relaxed by the simultaneous absorption of a roton. Although our preference[14] is currently for (b), each of these very different models has a number of appealing features and it has not so far been possible to say with certainty which of them constitutes the better representation of reality.

We wish to point out, however, that the high-field $\nu(E)$ measurements reported in this Letter should, in principle, enable the matter to be resolved. It seems extremely probable that the decrease of $\nu(E)$ above the maximum stems from an instability of the initial ion/ring complex, and it appears likely *a priori* that the value of E necessary to quench nucleation process (a) will be quite different from that required to quench nucleation via the totally different initial configuration (b). [Intuition suggests that the shallow effective potential binding ion and ring in (b) is more readily overwhelmed by E than is the case for (a), where the ion is always situated on the vortex core.] Consequently, the shape of $\nu(E)$ above the maximum should be sensitively dependent on the microscopic nature of the transition.

Reliable calculations of $\nu(E)$ in this regime will be far from easy. For model (a), it will be necessary, first, to modify[13] and extend the existing theory[12] so as to take proper account of the distribution function of ionic velocities[8] and, secondly, to investigate in detail the stability and evolution in time of an ion with a small attached loop of vortex in the presence of an intense electric field. In studying the stability and evolution of the initial complex (b), it will be essential to take cognizance of the fact that, in general, the ion and ring start off with a relative velocity which is nonzero.[13] In either case, one may legitimately inquire whether continuum hydrodynamics is capable of providing an adequate description of events which occur on the scale of ca. 1 nm.

Notwithstanding these cautionary remarks, we would claim that the present data offer, for the first time, direct access to the microscopic processes involved in the turbulent breakdown of superfluidity in He II. Consequently, they are deserving of careful and detailed theoretical analysis.

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