Second, the temperature invariance of the conformation coefficients $C_{x,y}^{[n]}$ derived in this work, Eq. (18), *does not* imply an invariance of the average molecular conformation with temperature. What is proposed here is that in liquid crystals the average (observed) conformation of flexible molecules changes with temperature in a *constrained* way such that it preserves the invariance of the quantities given by Eq. (15). These remarks show that the theory allows for a synthesis of two conflicting interpretations given so far to the published data on DMR in liquid crystals.[1,4]

Let me finally point out that the theory developed in this paper should apply just as well in dealing with the anisotropic contribution to the chemical shift, which may be written in the form of Eq. (3) above.[6]

I wish to thank Professor P. G. de Gennes for his comments and Professor F. R. Dias Agudo and Professor A. Lopes Pinto for helpful conversations.

---

[1] P. J. Bos and J. W. Doane, Phys. Rev. Lett. 40, 1030 (1978).

[2] R. Y. Dong, J. Lewis, E. Tomchuk, and E. Bock, J. Chem. Phys. 69, 5314 (1978).

[3] P. J. Bos, J. W. Doane, and M. E. Neubert, unpublished.

[4] B. Deloche and J. Charvolin, J. Phys. (Paris) 37, 1497 (1976).

[5] A. Abragam, *The Principles of Nuclear Magnetism* (Oxford Univ., London, England, 1961).

[6] A. Saupe, Z. Naturforsch. 19A, 161 (1964).

[7] G. E. Shilov, *Linear Algebra* (Prentice-Hall, Englewood Cliffs, N.J., 1971).

[8] A. F. Martins, J. B. Bonfim, and A. C. Ribeiro, to be published.

Vortex Nucleation in Isotopically Pure Superfluid ^{4}He

R. M. Bowley
Department of Physics, University of Nottingham, Nottingham NG7 2RD, United Kingdom

and

P. V. E. McClintock, F. E. Moss,[(a)] and P. C. E. Stamp[(b)]
Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom

(Received 15 October 1979)

The first experimental measurements of the rate ν at which vortex rings are nucleated by negative ions in isotopically pure superfluid ^{4}He are presented. It is found that ν is considerably smaller than in the ordinary well helium employed in earlier work. By interpreting the data in terms of a generalized Landau argument values of the critical velocity v_ν for vortex nucleation and of a characteristic nucleation rate R_0 as functions of pressure P in $16 \leqslant P \leqslant 25$ bar are deduced.

Given the right conditions, an ion moving through He II can spontaneously undergo a transition to a charged vortex ring.[1] Although the properties[1-3] of such rings have been well understood for several years, the nature of the transition itself has remained something of an enigma despite considerable attention, both theoretical[4-6] and experimental.[7-10] It has, however, been demonstrated convincingly[7,8,10] that the transition is statistical in nature, rather analogous to radioactive decay, in that it can be characterized by a vortex ring nucleation rate ν. Unfortunately, inconsistencies and apparent anomalies in the experimental values of ν have prevented an unambiguous assessment of the models so far proposed to describe the nucleation mechanism.

In this Letter we report what are believed to be the first measurements of ν in isotopically pure superfluid ^{4}He and we show that the conflicting results of earlier experiments can be ascribed in large measure to the profound influence exerted on the nucleation process by the ^{3}He isotopic impurities naturally present (at ca. 2×10^{-7}) in ordinary well helium.

The experimental technique was the same as that described earlier[10] in connection with measurements of ν in ordinary (unpurified) liquid ^{4}He. The electrode structure is illustrated diagrammatically in Fig. 1(b). A thin disk of charge, gated by G_1G_2, passes through G_3 and proceeds towards C under the influence of a strong uniform electric field. Provided that the diameter of the electrode system is large compared both to the length of the measurement space and to the diam-

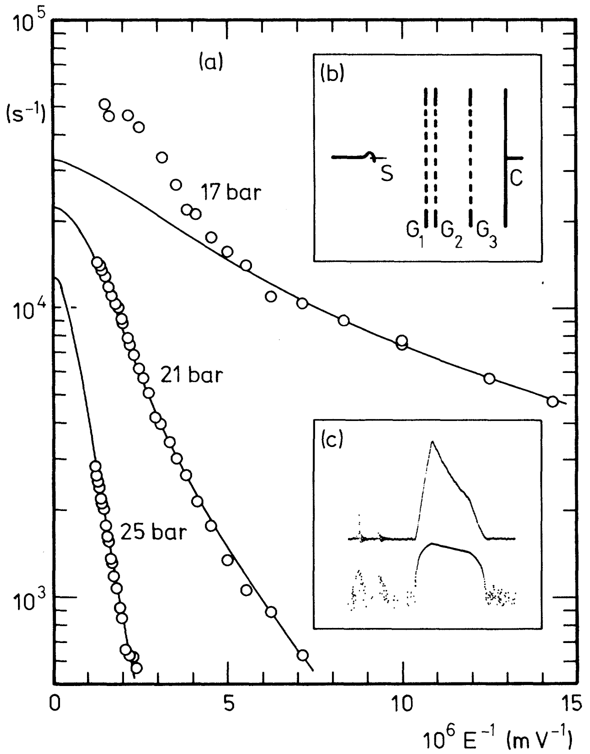

FIG. 1. (a) The vortex nucleation rate ν for negative ions in isotopically pure He II at 0.32 K, for three different pressures, plotted as a function of (electric field, $E)^{-1}$. The full curves represent fits of theory to the data. (b) The electrode arrangement used for measuring ν: S, field-emission ion source; G_1, G_2, and G_3 grids; C, collector. (c) Typical current pulse induced in the collector (upper trace) and its logarithm (lower trace), demonstrating exponential decay: $P = 20$ bars. $E = 7\times 10^5$ V m^{-1}, $T = 0.32$ K, and $\nu = 3770$ s^{-1}.

eter of the disk of charge, ν is given directly by the exponent of the decaying current [Fig. 1(c)] which is induced in C by the approaching charge. The sample of ^{4}He was prepared by use of a heat flush technique[11] which is believed capable of complete removal of ^{3}He isotopic impurities. In addition to a random error indicated by their scatter, our measurements of ν are subject to a possible systematic error of ± 150 s^{-1}, representing the combined effects of the finite rise time of the collector circuit and nonidealities of the electrode structure. We have found no evidence that our values of ν are affected either by the absolute magnitude of the signal or by the signal repetition rate (usually 6 Hz). We therefore conclude that possible complications arising from a buildup of vorticity in the measuring space can safely be ignored; and that no distinction need be drawn between an effective temperature within the disk of charge and the ambient temperature of the liquid.

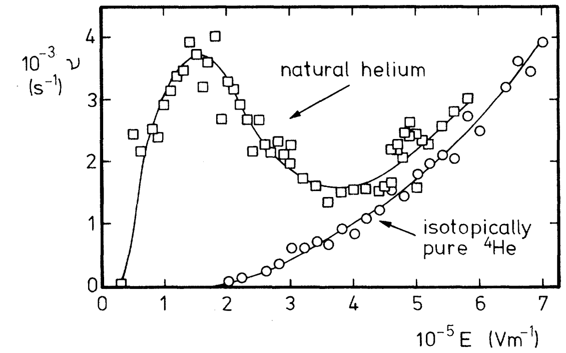

FIG. 2. The vortex nucleation rate ν for negative ions in He II of natural isotopic abundance (squares) compared with that in isotopically pure He II (circles), plotted as a function of electric field E, at a temperature of 0.52 K and a pressure of 24 bars. The full curves are guides to the eye.

In Fig. 2 we compare some of our present data with earlier measurements of ν in ordinary well helium using the same experimental cell. It is immediately apparent that, except in the case of very strong electric fields, ν becomes much smaller when the ^{4}He is isotopically purified. One may conclude that earlier work on vortex nucleation refers, in effect, to dilute ^{3}He-^{4}He solutions and not to ^{4}He as assumed hitherto. The data in Fig. 1 indicate how ν varies with electric field and pressure for the temperature-independent regime[10] found below 0.6 K. The temperature dependence of ν near 0.8 K turns out to be very similar to that found earlier[10] in the case of natural helium.

We have interpreted these results in terms of a model first suggested by Rayfield and Reif[1] and later developed in detail by Schwarz and Jang[5] and by Bowley.[6] This assumes that, in analogy to the Landau critical velocity v_L for roton creation, there exists a critical velocity v_ν which the bare ion must exceed in order that the transition to a charged vortex ring can occur without violating the requirements for conservation of energy and momentum. Under our experimental conditions, the drift velocity $\bar{v}$ of the ions is limited almost exclusively by roton creation,[12] and the ionic velocity distribution function $f(v,E)$ is usually such that the instantaneous velocity v of an ion seldom exceeds[5,13] v_ν. It can be seen immediately that the pure-^{4}He data are consistent with the main predictions[6] of this model. In particular, (i) ν increases monotonically with E such that the variation of $\ln\nu$ with E^{-1} is approximately linear for small E; (ii) ν increases rapidly as P is reduced, which was to be expected because $\bar{v}$ will increase[12] while v_v is believed[5] to decrease, thus increasing the area of $f(v, E)$ lying above v_v for any given value of E; (iii) for large values of E at the lower pressures, there are indications that the nucleation mechanism is starting to saturate, which might be expected to occur when the whole distribution function had moved above v_v if this resulted in vortex nucleation at an almost constant rate R_0, independent of E.

To make a quantitative comparison between theory and experiment we therefore make the minimum assumption that, as a function of the instantaneous ionic velocity v, the nucleation rate may be approximated by

$$\nu = R_0\theta(v - v_v),$$

where θ is the unit step function. We then compute[6] ν as a function of E using the known[13] shape of the distribution function, treating v_v and R_0 as constants to be determined by experiment. In doing so, we use Donnelly's roton parameters,[14] the ionic radii given by Ostermeier,[15] and values of the roton-emission matrix element deduced from ionic velocity measurements.[12] (For some pressures where no velocity measurements are available we have assumed that a plot of $\bar{v}$ against $E^{1/3}$ would still be linear with a gradient which was independent[12] of pressure.) The results of three such computations are shown as the full curves of Fig. 1(a). Values of v_v and R_0 derived by fitting the theory in this way to data recorded for a range of pressures between 16 and 25 bar are plotted in Fig. 3. We note (i) that for the higher P and lower E, the fit between experiment and theory is excellent; (ii) that, although the derived values of v_v are up to 10 m s^{-1} larger than expected, they may nonetheless be regarded as fully consistent with Schwarz and Jang's model[5] which was not expected to yield accurate quantitative predictions. The deviations found under conditions such that $\bar{v} \gtrsim v_v$ [e.g., Fig. 1(a), 17 bars, $E^{-1} < 5\times10^{-6}$ m V^{-1}] probably represent a rather unsurprising failure at high velocities of the assumptions inherent in (1). Ions for which $v \gg v_v$ are not restricted to nucleation of the critical ring[5] at the constant rate R_0, but are also free to create larger rings: A more sophisticated version of the theory is clearly required, making explicit allowance for the dependence of ν on $v > v_v$.

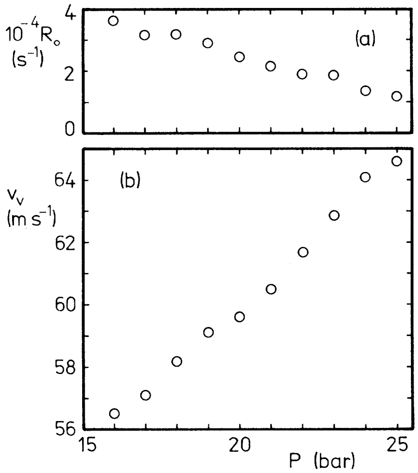

FIG. 3. Values of the parameters R_0 and v_v deduced by fitting the theory to experimental measurements of $\nu(E)$ at 0.32 K in isotopically pure He II, plotted as functions of pressure P.

The nucleation behavior at higher temperatures, where ν scales with the thermal roton density,[10] appears at first sight to be inconsistent with the generalized Landau argument discussed above, but we wish to point out that this is not necessarily the case. There may, for example, be a modified nucleation mechanism in which the conservation requirements are partially relaxed by the simultaneous absorption of a roton: The critical velocity v_{vr} for a roton-assited nucleation event of this nature can be estimated as being ca. $\Delta/m_i v_v \simeq 4.5$ m s^{-1} less than v_v, where Δ is the roton energy and m_i the ionic effective mass. Such processes would clearly occur at a rate which scaled with the thermal roton density, and they could well constitute the dominant nucleation mechanism at low electric fields, provided that the roton density was sufficiently large.

With ^{3}He also present in the liquid, the situation becomes a great deal more complicated, and further measurements of ν in a graded series of very dilute ^{3}He-^{4}He solutions are urgently required. We can, however, tentatively interpret the peak in the upper curve of Fig. 2 as follows. For low values of E, ν is increased by condensation of ^{3}He on the surface of the ion[16]: The values of v_v and R_0 are then those for a negative ion coated with ^{3}He. The average number n_3 of adsorbed ^{3}He atoms will be determined by a dynamic balance between adsorption and emission processes. The former occur at a rate which is expected to vary weakly with v, whereas the latter can only occur at all for $v \geq v_{c3}$ where v_{c3} is a critical velocity[9] for the process. Above a characteristic value of $\bar{v}$ (or, equivalently, of E), n_3 may therefore be expected to decrease rapidly, leading to a correspondingly rapid decrease in ν towards the value found in pure ^{4}He, as observed (Fig. 2).

We conclude that vortex nucleation in pure ^{4}He below 0.6 K can be well described in terms of a generalized Landau argument. Further work will be needed to establish whether or not the phenomenon can in fact be treated on the same basis in the cases of higher temperatures and of ^{3}He-^{4}He solutions. We hope that our present results will provide an impetus towards the development of a microscopic theory of the breakdown of superfluidity through vortex nucleation in liquid ^{4}He.

We acknowledge gratefully the assistance of Professor W. M. Fairbairn in developing the technique used in these experiments. This work was supported by the Science Research Council.

---

[a] Permanent address: Department of Physics, University of Missouri, St. Louis, Missouri 63121.

[b] Present address: School of Mathematical and Physical Sciences, University of Sussex, Falmer, Brighton BN1 9QH, Sussex, United Kingdom.

[1] G. W. Rayfield and F. Reif, Phys. Rev. 136, A1194 (1964).

[2] T. C. Padmore, Phys. Rev. A 5, 356 (1972).

[3] A. L. Fetter, in *The Physics of Liquid and Solid Helium,* edited by K. H. Bennemann and J. B. Ketterson (Wiley, New York, 1976), Pt. I, Chap. 3.

[4] R. J. Donnelly and P. H. Roberts, Philos. Trans. Roy. Soc. London, Ser. A 271, 41 (1971).

[5] K. W. Schwarz and P. S. Jang, Phys. Rev. A 8, 3199 (1973). See also E. I. Blount and C. M. Varma, Phys. Rev. B 14, 2888 (1976).

[6] R. M. Bowley, J. Phys. C 9, L367 (1976).

[7] J. A. Titus and J. S. Rosenshein, Phys. Rev. Lett. 31, 146 (1973).

[8] R. Zoll and K. W. Schwarz, Phys. Rev. Lett. 31, 1440 (1973).

[9] D. R. Allum and P. V. E. McClintock, J. Low Temp. Phys. 31, 321 (1978).

[10] P. C. E. Stamp, P. V. E. McClintock, and W. M. Fairbairn, J. Phys. C 12, L589 (1979).

[11] P. V. E. McClintock, Cryogenics 18, 201 (1978).

[12] D. R. Allum, P. V. E. McClintock, A. Phillips, and R. M. Bowley, Philos. Trans. Roy. Soc. London, Ser. A 284, 179 (1977).

[13] R. M. Bowley and F. W. Sheard, Phys. Rev. B 16, 244 (1977).

[14] R. J. Donnelly, Phys. Lett. 39A, 221 (1972).

[15] R. M. Ostermeier, Phys. Rev. A 8, 514 (1973).

[16] D. R. Allum and P. V. E. McClintock, J. Phys. C 9, L273 (1976).

Stabilization of Atomic Hydrogen at Low Temperature

Isaac F. Silvera and J. T. M. Walraven
Natuurkundig Laboratorium der Universiteit van Amsterdam, 1018 XE Amsterdam, The Netherlands

(Received 19 November 1979)

Atomic hydrogen has been stabilized at temperatures of 270 ± 20 mK and in magnetic fields up to 7 T. It is believed to be gaseous. A sample displayed no measurable decrease in density after 532 sec. Covering of exposed surfaces with a film of ^{4}He is essential.

Atomic hydrogen (H) with one proton and one electron is the simplest atomic system provided by nature. Just as helium and its isotopes display fascinating properties at low temperature and high density, atomic hydrogen and its isotopes are expected to exhibit spectacular phenomena. Until now it has not been possible to study condensed atomic hydrogen experimentally, as under normal circumstances it is highly unstable with respect to recombination to H_2 which has a binding energy $\epsilon_b/k_B = 52\,000$ K in the singlet spin state, $^1\Sigma_g{}^+$. However, in the spin-polarized state, $^3\Sigma_g{}^+$, a pair of atoms have no bound state. We refer to a dense gas of atoms with electron spins polarized, so that all pairs interact within the $^3\Sigma_u{}^+$ potential, as polarized hydrogen ($H\uparrow$). We have created a gas of H in a cell at $T = 270 \pm 20$ mK and in magnetic fields up to 7 T. Using specially developed detectors we have established that after loading the cell, the density did not change to within experimental error for periods up to 532 sec, the longest period investigated. Without our special conditions, we calculate that the sample would have a decay-time constant of ~ 80 μsec, due to surface recombination if kinetic effusion of the gas to the surface is rate limiting. The lifetime of this sample was increased by at least a factor 7×10^7 in this sense. We shall refer to samples with increased lifetimes of $> 10^6$ as stabilized. In most cases we observed stabilized