Journal of Low Temperature Physics, Vol. 43, Nos. 1/2, 1981

Superheating in He II and the Extension of the Lambda Line*

L. J. Rybarcyk and J. T. Tough

Department of Physics, Ohio State University, Columbus, Ohio

(Received October 14, 1980)

Experiments are described which show that liquid He II can persist in metastable thermodynamic states with a degree of superheating considerably larger than previously observed. A unique response is observed when the superheated He II undergoes the phase transition to He I. These results provide unique data for the extension of the λ line into the metastable region of the phase diagram.

When the temperature of a homogeneous liquid substance is increased above its boiling point, the liquid is said to be superheated if no vapor is present. The superheated liquid is a perfectly well-defined thermodynamic state of the substance,[1] but since its chemical potential is greater than that of the vapor, the liquid is metastable to vaporization. The first-order phase transition from superheated liquid to vapor is ordinarily nucleated by impurities in the liquid, by ionizing particles or radiation, or by large external disturbances. The details of these inhomogeneous processes are not very well understood. Beams[2] has pointed out that the unique properties of He II (superfluid ^{4}He) severely restrict the possible nucleation agents and make this substance particularly appealing for studies of superheating. Previous experimental results have been ambiguous. Linnet and Frederking[3] found no evidence for superheating at all. Krafft[4] found that He II could be weakly superheated, with an experimentally well-defined limit as shown in Fig. 1. Childers and Tough[5] observed superheating well beyond the Krafft limit, although no attempt was made to define a maximum degree of superheating. The extreme sensitivity of the superheated He II to mechanical vibrations probably accounts for the discrepancies between these various experiments.

This paper reports an attempt to establish an upper limit to the superheating of He II using a highly vibration-isolated cryostat. The

*Work supported by the National Science foundation grant DMR 7925089.

0022-2291/81/0400-0197$03.00/0

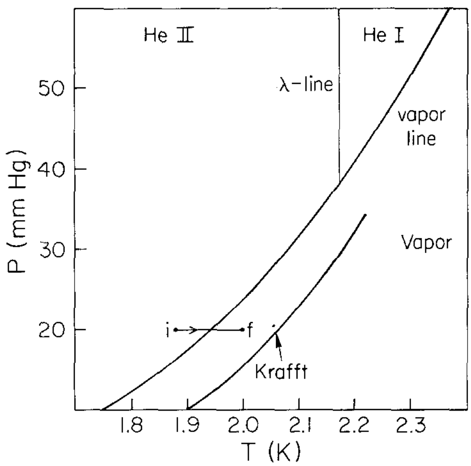

Fig. 1. The phase diagram of ^{4}He showing liquid He I, liquid He II, and vapor phases. In these experiments, a helium sample moves from stable to metastable superheated He II along a path such as $i \to f$. The experimental upper limit to superheating found by Krafft[4] is also indicated.

experimental technique employs the special properties of He II and becomes inoperative if the liquid He II sample crosses the λ line marking the second-order phase transition to He I (see Fig. 1). The results indicate He II can be superheated to the actual boundary of that phase, where superheated He II becomes superheated He I. Measurements of this transition give for the first time the extension of the λ line into the metastable superheated region of the phase diagram.

The apparatus is shown schematically in Fig. 2 and is similar in many respects to that used by Childers and Tough.[5] The liquid He II sample is contained in a small (0.72 cm^3) epoxy reservoir containing a heater and resistance thermometer. The sample is connected to a large bath of He II by a small glass capillary (approximately 10^{-2} cm diameter $\times$ 10 cm long), but is otherwise isolated from the bath by a massive nylon block. The bath is maintained at a temperature T by standard electronic regulation techniques and is as free from mechanical vibration as is practically possible.* The power dissipated by the heater in the reservoir can be maintained at a value $\dot{Q}$. In the steady state (at large $\dot{Q}$), the nonlinear thermohydrodynamic properties of the He II in the capillary are such that the temperature of the

*The cryostat was on a 800-pound table supported by air mounts. The single pumping line to the cryostat was passed through a large box of sand, virtually eliminating any pump vibrations from reaching the apparatus.

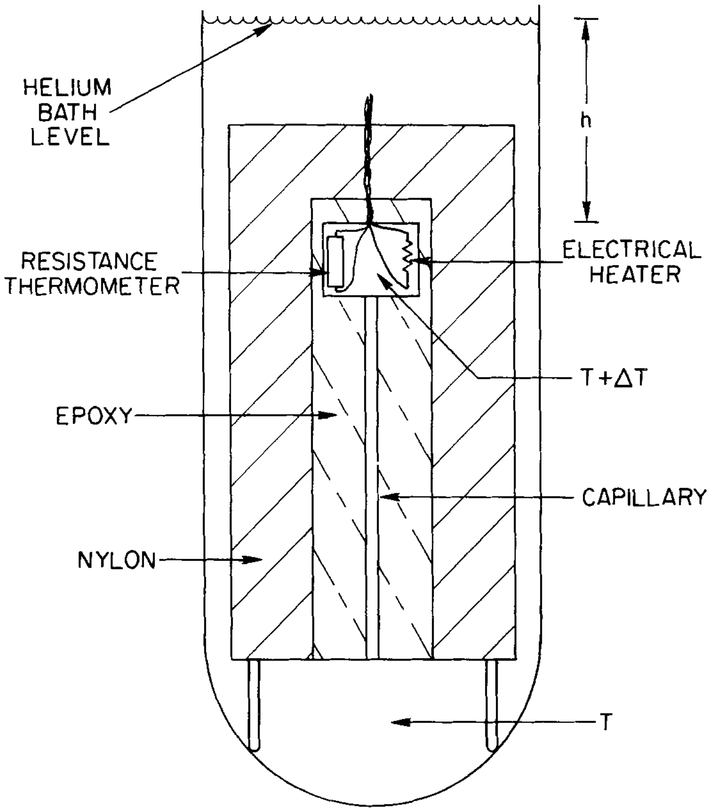

Fig. 2. Schematic diagram of the experimental apparatus. The helium sample contains a heater and thermometer and communicates with the bath by means of a glass capillary.

sample in the reservoir is $T+\Delta T$,[6] where

$$\Delta T = lb(\dot{Q}/A)^3 \tag{1}$$

and where l and A are the length and area of the capillary, and b is a quantity which depends on measured properties of the He II and is of the order 10^{-3} $(\mathrm{K/cm})/(\mathrm{W/cm}^2)^3$. The pressure of the sample in the reservoir is approximately

$$P = P_v(T) + \rho g h \tag{2}$$

where $P_v(T)$ is the vapor pressure of the bath at temperature T, and h is the distance the reservoir is below the bath level (approximately constant during a run) and ρ is the helium density. There is a small correction to the pressure given by eq. (2), but the effect is negligible in these experiments.[7] Thus Eqs. (1) and (2) indicate that as the power $\dot{Q}$ is increased, the temperature of the

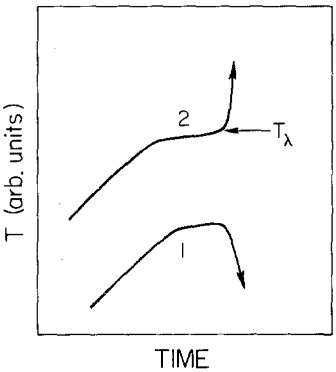

Fig. 3. The two distinctively different responses shown by He II samples as the extent of superheating is increased. Curve 1 indicates a formation of vapor and a subsequent cooling. Curve 2 indicates the transition to He I and a subsequent heating.

He II sample increases dramatically while the pressure remains virtually unchanged, as shown by the line form *i* to *f* in fig. 1. Superheated liquid He II states are produced when the trajectory of the sample on the phase diagram passes through the vaporization line.

In these experiments a large heating rate $\dot{Q}$ (order of 1 mW) is supplied to the sample, which then proceeds slowly through those steady states along

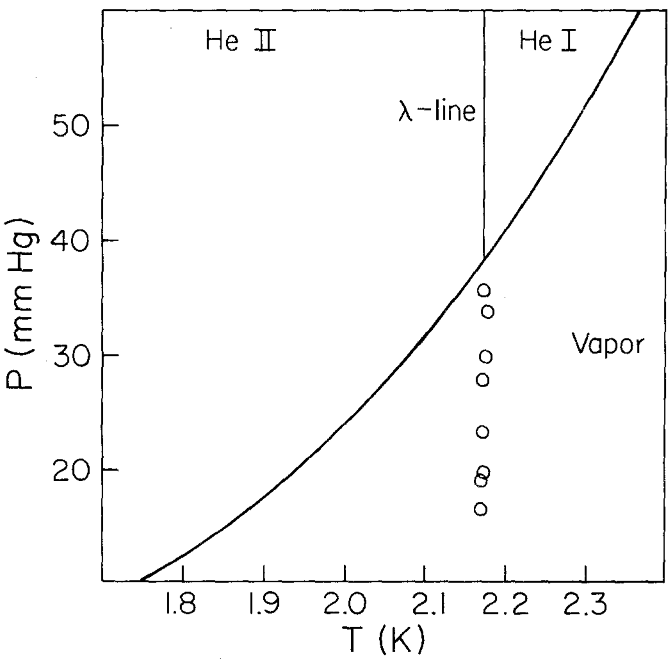

Fig. 4. The helium phase diagram including the present data for the extension of the λ line to metastable superheated region.

a path such as *i* to *f* in Fig. 1. (The thermal resistance provided by the He II in the capillary and the heat capacity of the sample are sufficiently large that the change in temperature of the sample occurs quite slowly.) Examples of data showing the temperature as a function of time are given in Fig. 3. Two distinctly different responses are shown by these results. In curve 1, the sample is in a superheated state and abruptly begins to cool. This response indicates the formation of vapor and cooling of the sample back to the vaporization line. In a number of experiments identical responses were produced by sharply rapping on the experimental apparatus. There can be no question but that a response such as shown in curve 1 is the signature of the first-order phase transition of superheated He II to vapor. In curve 2, the sample is seen to abruptly *increase* in temperature. This occurs because the helium at the hot end of the capillary has finally become He I. The enormous thermal resistance of He I effectively isolates the sample from the bath, and the sample begins to heat rapidly. This response is then the signature of the second-order phase transition from superheated He II to superheated He I. This same technique can of course be used to determine the location of the λ line on the *stable*, liquid portion of the phase diagram and is a variation of the original method of Keesom and Clusius.[8] The results of the present experiments can be used to map the extension of the λ line into the metastable superheated region of the phase diagram.

Figure 4 shows the data for temperatures of "type 2" transitions as a function of the sample pressure. The results indicate that the λ line continues into the metastable region with little or no change of slope.

No attempt was made in these experiments to study "type 1" transitions corresponding to the formation of vapor. These would often occur spontaneously during a run without any obvious cause. As noted above, a mechanical shock could also nucleate the vapor phase transition, but the apparatus appeared to be far less susceptible to this effect than that used by Childers and Tough.[5] Possibly the fact that the capillary connects to the bottom of the sample rather than to the top is important in this regard.

These experiments have shown the He II can persist in a metastable superheated state to the extent of the phase boundary with superheated He I. This natural limit is substantially larger than any previously reported. The results also show that the λ line marking the second-order phase transition from He II to the He I continues into the region of metastable states without obvious change of slope.

ACKNOWLEDGMENT

The advice and encouragement of Dr. Robert Ashton are gratefully acknowledged.

REFERENCES

1. L. D. Landau and E. M. Lifshitz, *Statistical Physics* (Pergamon Press, London, 1958), p. 260; D. L. Goodstein, *States of Matter* (Prentice-Hall, New Jersey, 1975), p. 446.
2. J. W. Beams, *Phys. Rev.* **104**, 880 (1956).
3. C. Linnet and T. H. K. Frederking, *J. Low Temp. Phys.* **21**, 447 (1975).
4. G. Krafft, *J. Low Temp. Phys.* **31**, 441 (1978).
5. R. K. Childers and J. T. Tough, in *Low Temperature Physics—LT* 13, K. D. Timmerhaus, W. J. Osullivan, and E. F. Hammel, eds. (Plenum, New York, 1974), p. 359.
6. P. E. Dimotakis and J. E. Broadwell, *Phys. Fluids* **16**, 1787 (1973).
7. R. K. Childers and J. T. Tough, *Phys. Rev. Lett.* **35**, 527 (1975).
8. W. H. Keesom and K. Clusius, *Proc. Sect. Sci. K. Acad. Wet. Amsterdam* **34**, 605 (1931); Leiden Comm. 2166.