Experimental study of the λ transition in helium in narrow gaps

V. I. Panov and A. A. Sobyanin
P. N. Lebedev Physical Institute, Academy of Sciences of the USSR

(Submitted 11 March 1982)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 8, 329–332 (20 April 1982)

Quantitative measurements of the temperature shift of the λ transition in liquid ^{4}He contained in thin plane parallel gaps with well controlled geometry and thickness $0.28 < d < 0.54$ μm were performed. The value of the critical index $n = 1.58 \pm 0.09$ characterizing the dependence of the temperature shift of the λ point on the gap thickness, $\Delta T_\lambda = Ad^{-n}$, is determined. The average value of the unknown parameter $M = 0.6 \pm 0.3$, contained in the phenomenological Ψ theory of superfluidity of helium II, is calculated near the λ point from the results obtained for the coefficient A.

PACS numbers: 67.40.Kh, 67.40.Bz

Studying size effects near the λ transition in helium yields information on the boundary conditions for the order parameter, the macroscopic wave function $\Psi = \eta e^{i\phi}$, and makes it possible to check the phenomenological theory of superfluidity of helium II near the λ point (see also Ref. 4 and the references cited in Ref. 3).[1–3] One of the most important conditions of this theory is a dependence of the λ-transition temperature in thin films, gaps, and capillaries on their smallest dimension. In the case of a plane parallel gap with width d, the predicted dependence has the form[3]

$$T_\lambda - T_\lambda(d) \equiv \Delta T_\lambda(d) = 2,53\cdot 10^{-11}\left(\frac{M+3}{3}\right)^{3/4} d^{-3/2}\ {}^\circ\mathrm{K}, \tag{1}$$

where d is measured in cm, $T_\lambda = 2.172$ K is the λ-transition temperature in the helium volume and M is a parameter in the theory[3] (for $M < 1$, the transition to the superfluid state in a gap is a second-order transition, while for $M > 1$, it is a first-order transition). Available experimental data on the shift of the λ point in porous materials[3,5] and films [3,6–8] qualitatively confirm the presence of a dependence $\Delta T_\lambda \propto d^{-3/2}$, but it is practically impossible to make a quantitative comparison with the theoretical relations due to the uncertainty in the size of the pores and the small thicknesses of the films investigated. For this reason, the numerical value of the parameter M, contained in the theory,[3] has up to now remained undetermined.

In this paper, we present the results of an experiment based on the use of the capacitance method to detect the λ transition,[9] which allowed checking relation (1) quantitatively.

The shift in the λ transition temperature was studied and the numerical value of the free parameter M was determined from observations of the breaks in the curve showing the temperature dependence of the difference between the density of liquid ^{4}He in the gap $\rho_d(T)$ and in the bulk $\rho_\infty(T)$, $\Delta\rho(T)$. We measured the temperature dependence of the difference in dielectric constant $\Delta\epsilon(T)$ of helium in wide ($d_0 \to \infty$) and narrow gaps, in the form of flat electrical capacitors with a reliably controlled thickness d_i. In the experiment, we used measuring capacitors with the following capacitance gaps between the plates: $d_1 \simeq 2.85 \times 10^{-5}$ cm, $d_2 \simeq 3.60 \times 10^{-5}$ cm, and $d_3 \simeq 5.60 \times 10^{-5}$ cm. As a reference capacitance, we used a capacitor with a gap $d_0 \simeq 5 \times 10^{-3}$ cm. In making the measuring capacitors, the magnitude of the gap and its parallelism were fixed to within 2% (the latter was realized using an optical method). Figure 1 shows the circuits used for the measurements, which allowed recording the magnitude of the difference between the capacitance of the measuring and reference capacitors, related to the change in the density of ^{4}He in one of the capacitance gaps relative to the other. The capacitors were placed on a horizontal surface on a massive sapphire block in a copper chamber, filled with pure liquid ^{4}He. Semiconductor resistance thermometers were located between the capacitors in the sapphire block in order to record the temperature difference $\Delta T_\lambda(d)$ between the λ transitions in the narrow and wide gaps. During the measurements, the quantity $\Delta T_\lambda(d)$ was determined to within 1×10^{-6} K. The liquid helium pressure was recorded with a membrane capacitive manometer, placed at the top of the chamber. Bellows, which made it possible to vary the helium pressure in the chamber from the saturated vapor pressure to $\sim 10^3$ Torr, were placed in the same location. The ^{4}He studied was introduced from an external volume at a temperature of $T \simeq 1.9$ K through an overgap and a closing valve. The chamber was connected with the help of thermal bridges to two isothermal platforms, on which inductance coils and feed lines were placed, in order to decrease the influx of heat to the chamber. A heater, which allowed varying the rate of change of temperature from $\sim 1 \times 10^{-4}$ K/min to $\sim 3 \times 10^{-3}$ K/min, was located on the surface of the chamber. An electronic circuit, consisting of an inductance bridge of the measuring ca-

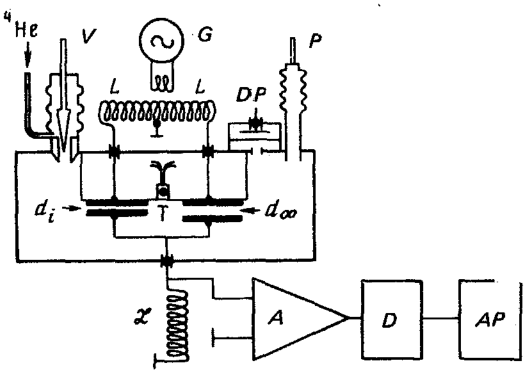

FIG. 1. Diagram of the arrangement used for the measurements: V is a valve; P is a pressure bellows; DP is a pressure sensor; T is a thermometer; L is an inductance; G is a generator; Z is a resonant circuit; A is an amplifier; D is a detector; AP is an automatic plotter.

pacitances and the recording system, was used to measure the relative change in the dielectric constant with accuracy $\Delta\epsilon \simeq 1 \times 10^{-9}$, which corresponds to a relative density variation $\Delta\rho/\rho \simeq 1.7 \times 10^{-8}$.

Figure 2 shows a typical signal trace, reflecting the temperature behavior of the difference in dielectric constants (or densities) of helium in narrow and wide gaps. The trace was obtained by cooling helium through the λ point at a constant rate equal to 5×10^{-4} K/min. The first break in the curve corresponds to the transition of helium in the wide gap, while the second (corresponding to the maximum on the curve) was identified with the λ transition in helium in the narrow gap. The values of $\Delta T_\lambda(d)$ averaged over several experimental curves for each gap are presented in the lower left-hand corner in Fig. 3a. Figure 3b illustrates the dependence $\Delta T_\lambda(d)$ on a double logarithmic scale. As is evident from the figure, all three experimental points fall on the same straight line, corresponding to a power-law dependence $\Delta T_\lambda(d) \propto d^{-n}$ with index $n = 1.58 \pm 0.09$, nearly coinciding with the theoretical value of $n = 1.5$. If it is assumed that $n = 1.5$, then for each of the three gaps, it is possible to calculate the parameter M with the help of Eq. (1). The results are shown in Fig. 3a. The fact that the magnitude of the parameter M increases slightly with decreasing d can be explained qualitatively by the effect of Van der Waals forces.[1 0,3] However, quantitatively, this effect is less than that observed and lies within the limits of error of the measurements. For this reason, we are inclined to identify the observed dependence $M(d)$ with the systematic error in the experiment that was not taken into account.

In addition to the magnitude of the shift in the λ-transition temperature, the temperature behavior of the difference between helium densities in the narrow and wide gaps is

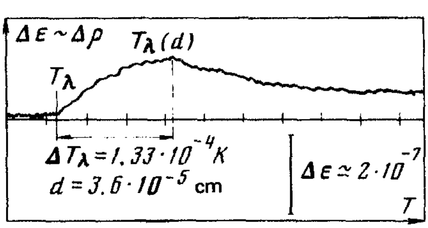

FIG. 2.

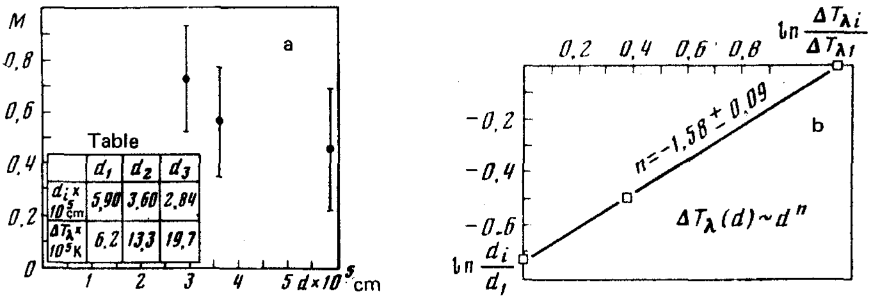

FIG. 3. a) Dependence of the parameter M on the gap thickness.

also of great interest (Fig. 2). Analysis of the corresponding experimental data will be presented in a more detailed paper.

In conclusion, we note that in a gap, in contrast to bulk helium, the temperature $T_\lambda(d)$, at which the thermodynamic quantities exhibit an anomaly, can generally differ from the temperature $T_0(d)$ for the appearance of superfluidity in the gap. It is natural to associate the temperature $T_\lambda(d)$ with the temperature at which a nonvanishing local average value of the square of the order parameter $|\bar{\Psi}|^2 \propto \rho_s$ first appears in the gap. On the other hand, the transition to a strictly superfluid state, which is stable relative to the creation of vortices,[12-14] must occur at a lower temperature, when the product $\rho_{s}d$ exceeds some constant value, independent of the gap width.[1)] In this connection, it would be of great interest to study in the same gaps such "purely superfluid" properties as superthermal conductivity or propagation of fourth sound.

We thank V. B. Braginskiĭ and V. L. Ginzburg for showing interest in this work and for valuable discussions. We are also grateful to G. V. Simonov for considerable help in building the electronic measuring system.

1)In applications to films and helium layers with arbitrary thickness, this assertion was first, as far as we know, made by Pitaevskiĭ[11] (see also Ref. 14 and 15).

1. V. L. Ginzburg and L. P. Pitaevskiĭ, Zh. Eksp. Teor. Fiz. **34**, 1240 (1958) [Sov. Phys. JETP **34**, 858 (1958)].
2. Yu. G. Mamaladze, Zh. Eksp. Teor. Fiz. **52**, 729 (1967) [Sov. Phys. JETP **25**, 479 (1967)].
3. V. L. Ginzburg and A. A. Sobyanin Usp. Fiz. Nauk **120**, 153 (1976) [Sov. Phys. Uspekhi **19**, 773 (1976)].
4. V. L. Ginzburg and A. A. Sobyanin, Phys. Lett. **69A**, 417 (1979).
5. G. A. Gamtsemlidze, M. I. Mirzoeva, Dzh. N. Tsaava, G. K. Shonia, and S. El'-Sabban, Zh. Éksp. Teor. Fiz. **79**, 2334 (1980) [Sov. Phys. JETP **52**, 1182 (1980)].
6. I. Rudnick, Phys. Rev. Lett. **40**, 1454 (1978).
7. J. Maps and R. B. Hallock, Phys. Rev. Lett. **47**, 1533 (1981).
8. B. Lambert, A. Levelut, R. Perzynski, and D. J. Salin, J. Low Temp. Phys. **23**, 623 (1976).
9. V. I. Panov and V. A. Khvostikov, Zh. Eksp. Teor. Fiz. **83**, No. 7 (1982) (to be published).
10. A. A. Sobyanin, Zh. Eksp. Teor. Fiz. **63**, 1780 (1972) [Sov. Phys. JETP **36**, 941 (1973)].
11. L. P. Pitaevskiĭ, Report at the XX All-Union Conference on Low Temperature Physics, Moscow (1979).

12. V. L. Berezinskiĭ, Zh. Eksp. Teor. Fiz. **61**, 1144 (1971) [Sov. Phys. JETP **34**, 610 (1972)].
13. J. M. Kosterlitz and D. J. Thouless, J. Phys. C **6**, 1181 (1973).
14. V. Ambegaoker, B. I. Halperin, D. R. Nelson, and E. D. Siggia, Phys. Rev. B **21**, 1806 (1980).
15. W. F. Saam, Phys. Rev. B **23**, 1485 (1981).

Translated by M. E. Alferieff
Edited by S. J. Amoretty