PHYSICAL REVIEW
LETTERS

VOLUME 16 | 16 MAY 1966 | NUMBER 20

TEMPERATURE DEPENDENCE OF THE SUPERFLUID DENSITY IN He II NEAR T_λ*

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(Received 1 April 1966)

The phase transition in liquid He^4 at the λ point is of interest for the general theory of phase transitions as well as for an understanding of the quantum properties of the superfluid. Liquid helium below the λ transition is characterized by the macroscopic occupation of a single quantum state. This state determines a superfluid velocity field, $\vec{v}_S$, throughout the liquid. There is a mass flow $\vec{j}_S$ associated with the superfluid velocity. The relation $\vec{j}_S = \rho_S \vec{v}_S$ defines a superfluid "density," ρ_S. The superfluid density becomes equal to the total density, ρ, at absolute zero and decreases rapidly to zero at T_λ.

In this Letter we wish to report a direct determination of the temperature dependence of ρ_S in the neighborhood of the transition. The apparatus and experimental method is similar to that reported earlier.[1] A persistent superfluid current is formed in an annular container of He II. The angular momentum of the persistent current is measured by a gyroscopic technique.

The previous experiment demonstrated that the quantum state of macroscopic occupation can remain fixed even when the temperature is cycled to within 10^{-5} °K of the λ transition. As a consequence of this stability the angular momentum of a persistent current is a reversible function of temperature, proportional to the superfluid density. Thus the measurement of persistent-current angular momentum provides a direct means for determining the temperature dependence of ρ_S. An increase in sensitivity and a reduction in vibrational noise were required in the earlier gyroscopic apparatus before useful measurements could be made closer than 10 mdeg to T_λ.

The experimental procedure was as follows. First, the λ point was identified by a discontinuity in the resistance of a doped-germanium thermometer. Then a persistent current was formed by rotating the container while cooling through T_λ. A sequence of values for the angular momentum was obtained, approaching but not exceeding T_λ. The angular-momentum measurement was then repeated at a lower temperature to check on any possible attenuation of the current. Finally the resistance of the thermometer was remeasured at T_λ. The values of angular momentum were normalized to give ρ_S/ρ, using the asymptotic value at lower temperatures where ρ_S approaches the total density, ρ.

The values ρ_S/ρ obtained are shown in Fig. 1. The data from near T_λ to about 100 mdeg below T_λ are consistent with a power law (solid line), $\rho_S/\rho = A(T_\lambda - T)^\alpha$ where A is a constant and $\alpha = 0.67 \pm 0.03$. The data of Dash and Taylor,[2] obtained by the classic method of Andronikashvilli, are shown (open triangles) for comparison. It is gratifying, considering the difference in experimental method, that the measurements agree within 2% in ρ_S/ρ. The data

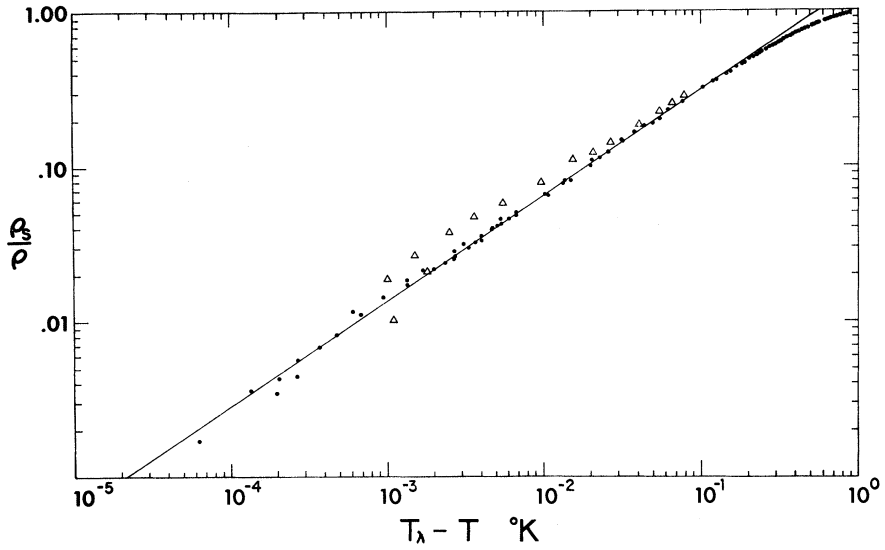

FIG. 1. Values of ρ_S/ρ obtained in the present experiment are plotted as solid circles as a function of $(T_\lambda - T)$. The data of Dash and Taylor[2] are plotted as open triangles.

near T_λ are shown in greater detail in the linear plots of Fig. 2.

In discussion of second-order phase transitions it is convenient to define an order parameter which goes to zero at the transition. In the case of liquid helium the order parameter ψ is taken to be complex,[3] $\psi = \eta e^{i\varphi}$ where $\eta^2 = \rho_S$. The superfluid velocity is reflected in the phase factor through the relation $\vec{v}_S = (\hbar/m)\nabla\varphi$. In terms of this definition, our data give a magnitude for the He II order parameter proportional to $(T_\lambda - T)^\beta$ where $\beta = 0.335 \pm 0.015$.

A similar dependence is observed in other systems with a λ singularity in the specific heat. For example, the sublattice magnetization in the antiferromagnetic material[4] MnF_2 is proportional to $(T_N - T)^\beta$ where $\beta = 0.335 \pm 0.010$ and T_N is the paramagnetic-antiferromagnetic critical temperature. Measurements on the liquid-gas density difference for a simple fluid such as xenon in the coexistence region[5] indicate a power-law dependence with $\beta = 0.345 \pm 0.015$. In addition, the series expansion calculations[6] for the three-dimensional lattice gas indicate a value for β of $\frac{5}{16} = 0.3125$. These similarities suggest that the square root of the superfluid density is the correct parameter to be used in making an identification between the λ transition in liquid helium and the λ transitions of other systems.

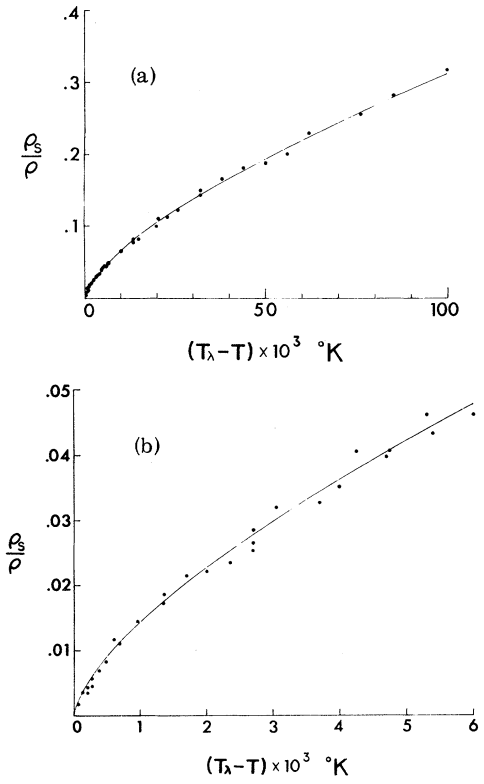

FIG. 2. (a) Values of ρ_S/ρ obtained for the first 100 mdeg below T_λ; (b) detail of the first 6 mdeg. The solid line is the function $\rho_S/\rho = 1.438(T_\lambda - T)^{2/3}$.

*Work assisted by grants from the National Science Foundation and the Army Research Office (Durham).

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VALENCE-BAND BENDING TO THE FERMI LEVEL AND RADIATIVE RECOMBINATION IN ZnS WITH LIQUID ELECTRODES*

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(Received 14 March 1966)

In groups IV and III-V semiconductors the band bending at interfaces is controlled by surface states, whereas in II-VI semiconductors such as ZnS the band bending is controlled by the electrodes.[1] The work function of the anode must equal or exceed the sum of the electron affinity and band gap of the II-VI semiconductor in order for the band bending to be sufficient to bring the valence-band edge into coincidence with the Fermi level at the surface, thereby facilitating hole injection. From the photoelectric threshold[2] of CdS and related measurements[3] on ZnS, we estimate that the threshold anode work function for hole injection into ZnS is 7 eV. This high value explains the previous failures to achieve positive hole injection into ZnS except by "formed" patches or by tunneling through insulating barriers.[4] The work function of oleum (fuming sulfuric acid) is believed on the basis of its strong oxidizing power to be approximately this value. This is supported by the observation of hole injection into anthracene which is concurrently dissolved by the oleum.[5]

We have observed blue electroluminescence at room temperature originating in copper-activated zinc sulfide crystals at the interface with an oleum (H_2SO_4 plus 30% excess SO_3) anode. The experimental setup consisted of a U tube containing the oleum with an opening near the bottom approximately 1 mm in diameter to which the crystal was cemented. The other electrode was a mercury-indium amalgam. There is negligible chemical reaction of the oleum with the ZnS crystal. With oleum as the anode, evolution of gas was observed and found to correspond to the order of magnitude of one molecule per charge carrier. This can be explained by the conductivity of the oleum being due to hydrogen ions which are neutralized on injection of positive holes into the crystal and then form H_2 molecules. Strong rectification was observed. Figure 1 gives the energy band diagram of the ZnS-oleum junction in thermal equilibrium, showing the p-type inversion layer at the ZnS-oleum interface. The injection of positive holes with forward bias and radiative recombination of electrons with trapped holes are also shown in Fig. 1. Measurements of the voltage drop in the anode region yield 3.4 V for the diffusion voltage. Figure 2 gives the electroluminescent brightness versus current. The superlinear range can be explained by saturation of nonradiative recombination states. The light originates at the anode with the shape of the opening in the U tube. The position of the metallic electrode had no effect on the brightness-current relation, although the voltage changed due to different series resistance of the crystal. From measurements compared to a standard lamp the efficiency is approximately 10^{-4} photons per electron with 12 V

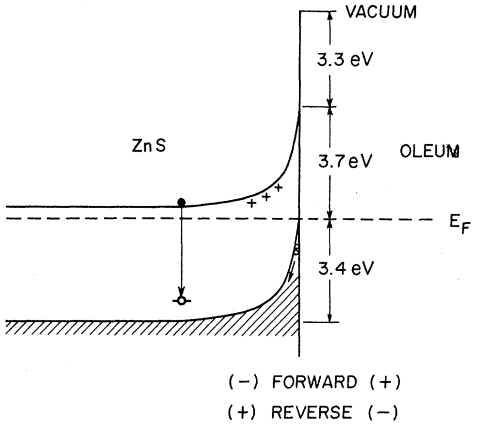

FIG. 1. The energy band diagram of ZnS near the anode in thermal equilibrium.