Electrokinetic phenomenon in helium II

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An electrokinetic phenomenon specific to helium II which arises due to transport of charges injected into the liquid by the normal component and which occurs in the absence of total mass transport, is observed. This phenomenon is analogous to the thermoelectric phenomenon in metals. The dependence of the thermo-emf on the intensity of heat liberation is investigated and the electrokinetic potential is estimated.

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As is well known, electrokinetic phenomena observed in dispersed media are related to the existence of free charges on the interface between the solid and the liquid, which are formed by the electrical double layer. If the liquid flows through a dispersed medium, then the charges in the diffusion part of the double layer are displaced and excess charge of one sign is carried away along the direction of the fluid flow. The motion of charges along the wall produces a surface current and establishes a potential difference at the ends of capillaries, which in turn gives rise to a "volume" conduction current flowing in the opposite direction. The potential difference increases until the surface current is equal to the volume current. This potential difference is called the flow potential U_{flow} (Ref. 1)

$$U_{\text{flow}} = \frac{\epsilon_0 \epsilon \zeta \Delta P}{\kappa \eta}, \tag{1}$$

where ΔP is the pressure drop at the ends of the capillaries; η, ϵ, and κ are the viscosity, dielectric constant of the liquid, and the electrical conductivity of the liquid,

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respectively; ζ is the electrokinetic potential; and ϵ_0 is the vacuum dielectric constant. To observe this phenomemon in helium II, external charge must be introduced into the helium.

Let us assume that a closed volume is placed into a bath with helium II. The volume is connected to the bath via capillaries. If a constant temperature difference is maintained at the ends of the capillaries, then oppositely flowing currents of s and n components are established in them. In the case of steady flow, this situation satisfies the condition for the absence of mass trasport:

$$\rho_s v_s + \rho_n v_n = 0. \tag{2}$$

Furthermore, the velocity of the n component v_n and the temperature difference ΔT at the ends of the capillaries are determined by the intensity of heat liberation $\dot{Q}$ in the closed volume:

$$v_n = \frac{\dot{Q}}{\rho \sigma T \Sigma S}, \tag{3}$$

$$\Delta T = \frac{8\pi \eta_n l}{(\rho \sigma)^2 T S \Sigma S},$$

where ρ, ρ_s, and ρ_n are the densities of the liquid helium and of its s and n components; v_s is the velocity of the s component; σ is the entropy per unit mass of helium; T is the temperature η_n is the viscosity of the normal components; l is the length of the capillary; S is the cross section of the capillary; and ΣS is the sum of cross sections of all channels. If a charge is introduced into hellium II, then this charge, as any extraneous particle, will be entrained in the motion of the n component (if the s component moves at subcritical, velocity), creating a potential difference at the ends of the capillaries. Thus the appearance of a flow potential in helium II, in contrast to classical liquids, can be observed in the absence of a mass transfer, and the magnitude of the potential difference arising in this case can be regulated by the temperature difference (intensity of heat liberation). This phenomenon is the analog of the thermoelectric phenomena observed in metals. Using (3) and the fact that the flow of the n component obeys the Poiseuille law, we obtain from (1) for the thermo-emf ϵ_T:

$$\epsilon_T = \frac{8\pi \epsilon_0 \epsilon \zeta l}{\kappa \rho \sigma T S \Sigma S} \cdot \dot{Q}. \tag{4}$$

To observe the phenomenon experimentally, we constructed a plexiglass cell and placed it in a bath with helium II (we regulated the temperature of the bath to within $\pm 10^{-3}$ K). The closed volume 1 (Fig. 1) was connected to the helium II bath with the help of the disk 2, into which strictly parallel cylindrical channels with a diameter of 10 μm were inserted; the disk was $l = 1$ cm thick and had a diameter of 5 mm; the channel-filling factor of the disk was 0.5. A heater 3 consisting of a constantan wire with a resistance of 160 Ω and a radioactive source 4, placed in a lead housing 5, open in a direction toward the disk, was placed in the volume 1. The distance from the source 4 to the disk 2 was $l_1 = 4$ cm. The surface of the active part of the 137 Cs source had a diameter of 5 mm and its activity at a distance of 4 cm was equal to 0.5 μCi. A

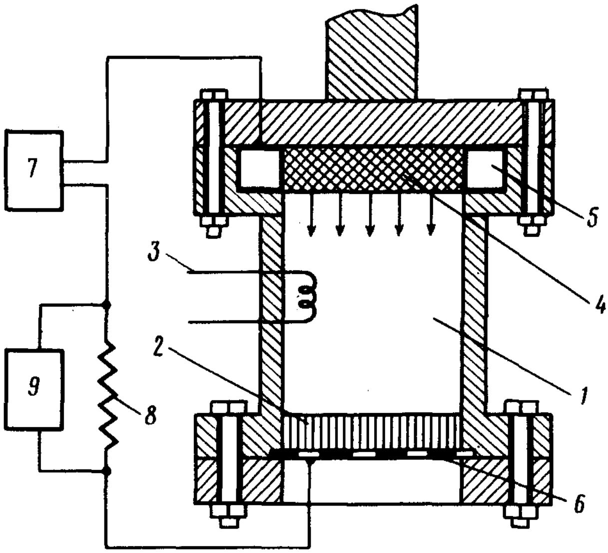

FIG. 1. Diagram of the experimental cell.

metallic grid 6 was pressed to the disk 2. All parts of the cell, which were closely fitted to each other, were attached in such a manner that when heat was liberated from the heater, the heat transfer to volume 1 occurred primarily due to the flow of the *n* component through the capillaries. The metallic housing of the source 5 and the grid 6 were connected to a voltage source 7, creating a potential difference $U_0 = 300$ V between them. As a result, a voltage drop U_1 was recorded across the resistance 8 $R_0 = 9.1 \times 10^5\ \Omega$ with the help of an FZO digital voltmeter 9. This measurement permits determining the electrical conductivity of the liquid κ. Viewing the volume 1

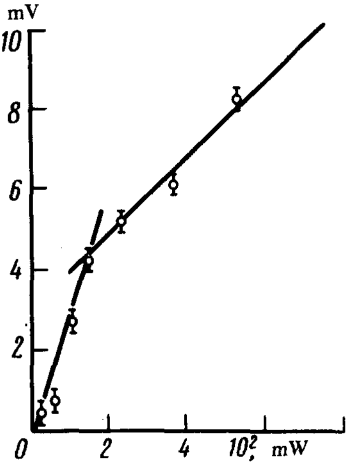

FIG. 2. Dependence of the thermo-emf ϵ_T on the intensity of heat liberation $\dot{Q}$.

as two resistances $R_1 = l_1/2\kappa\Sigma S$ connected in series—the resistance of the liquid to the capillaries and $R = l/\kappa\Sigma S$—the resistance of the liquid in the capillaries and taking into account the fact that $U_1 \ll U_0$, we can write.

$$U_0/\ (R + R_1) = U_1/R_0 \ ,$$

Hence

$$\kappa = \frac{U_1\ (l + (l_1/2))}{RU_0\ \Sigma S} = (4.4 \pm 0.4) \cdot 10^{-7}\ (\Omega.\mathrm{m})^{-1} \qquad (5)$$

We have then liberated some thermal power $\dot{Q}$ in the heater. At the same time, we measured the drop in the voltage across the resistance R_0 to a value U, indicating the appearance of a thermo-emf (flow potential) in the circuit: $\epsilon_T = U - U_1$. Figure 2 shows the dependence of the thermo-emf on the intensity of heat liberation $\dot{Q}$ with a bath temperature of 1.5 K obtained as a result of these measurements. We attribute the first section of the curve (up to the break) to the subcritical flow regime of the components and the section after the break to the supercritical regime. The decrease in the rate of increase of ϵ_T in the supercritical state is due to the interaction of charges with quantized vortices. Thus the measurements of the thermo-emf permit determining the critical rate of vortex formation. The electrokinetic potential ζ can be estimated from (4) using the estimate κ (5) and $\epsilon_T/\dot{Q} = 0.03$ V/W from Fig. 2:

$$\zeta = (20 \pm 4)\ \mu\mathrm{V}\ .$$

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