Density relaxation during a rapid transition of ^{4}He from the two-phase state to the single-phase state near the vaporization critical point

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The relaxation of density inhomogeneities upon a rapid transition of ^{4}He from the two-phase state to the single-phase state has been studied near the critical point for vaporization. The scaling of the relaxation time has been determined. The relaxation slows because of a decrease in the thermal diffusivity.

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We have studied the relaxation of density inhomogeneities in ^{4}He upon a transition from the two-phase region to the single-phase region near the critical point caused by a rapid heating. The measurements are carried out in a special copper cell (Fig. 1). The density is determined from the dielectric constant of the helium in the gap of a cylindrical capacitor (1). The length of this capacitor is 1.5 cm, its diameter is 2 cm, and the gap width is 6×10^{-3} cm. The volume of the cell above the capacitor has a height of 0.2 cm. The temperature of the copper wall of the cell is measured with a germanium resistance thermometer (4), calibrated within 0.001 K on the basis of the helium pressure on the critical isochore.[1] The capacitance of the capacitor is measured with a modified R589 bridge with a sensitivity of 0.0003 pF at a total capacitance of 350 pF of the capacitor. Helium enters the cell through a capillary (2) and a valve (5). The temperature gradients are reduced by placing all the electrical leads and the capillary in good thermal contact with the guard rings (3).

The experiment is begun by filling the cell with helium at a density near the critical value. The cell is held at a constant temperature ~0.1 K below the critical temperature. The meniscus lies below the capacitor. A heater (6) then raises the temperature of the copper wall of the cell rapidly to the experimental temperature, which is above the temperature of the transition to the single-phase state, T_t; the wall is held at this temperature within 0.0002 K. At this temperature the density gradients become smoothed out; this process is exponential toward its end. In calculating the relaxation time t_r we used the values of the density in the range in which it varies near the equilibrium value, $\delta\rho/\rho \leqslant 0.05$, which corresponds to $\delta T/T \leqslant 10^{-5}$. For densities near the critical value the dependence of t_r on $\tau_t = (T - T_t)/T_t$ is a power law, within the scatter in the data. We recorded several such curves over the density range $-0.14 < \Delta\rho < 0.14$, where $\Delta\rho = (\rho - \rho_k)/\rho_k$, and over the temperature range $10^{-3} < \tau < 3 \times 10^{-2}$, where $\tau = (T - T_k)/T_k$. The critical index for these curves lies between 0.50 and 0.75. The relaxation time varies from 0.5 to 12 min.

Changes in the length and width of the capacitor by a factor of 2 did not affect the relaxation time.

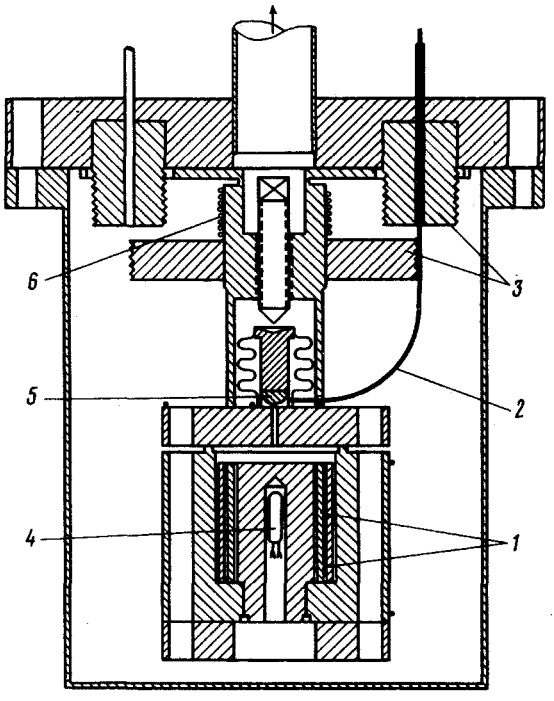

FIG. 1. The experimental apparatus.

If the scaling theory of critical phenomena[2] applies to this relaxation of inhomogeneities, then the dependence of the product $t_r \times \tau^{\nu}$ on the variable $\tau \times (\Delta\rho)^{-1/\beta}$ should be a universal function, where ν is the critical index of the relaxation time (the correlation radius), and β is the critical index of the boundary curve. This is in fact what we see in Fig. 2, which shows experimental curves of these values for various densities. The value $\beta = 0.375$ is taken from Ref. 1. The scatter of the experimental points is minimized by adopting the critical index $\nu = 0.7$.

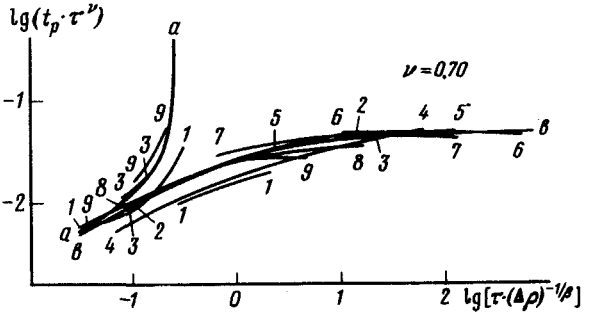

FIG. 2. Scaling function for the relaxation time for density inhomogeneities near the critical point for the vaporization of ^{4}He. The time is given in minutes. The curves correspond to the experimental temperature dependence of t_r for various densities $\Delta\rho$: 1-1– –0.137; 2-2– –0.100; 3-3– –0.087; 4-4– –0.067; 5-5– –0.050; 6-6– –0.028; 7-7– –0.046; 8-8– –0.073; 9-9– –0.109. a-a, b-b–Scaling function of the thermal diffusivity for $\tau < 0$ and $\tau > 0$, respectively.

What are the reasons for the observed relaxation? For an instantaneous establishment of a temperature equal to that of the cell wall along the helium, the relaxation of the density inhomogeneities might be retarded by the hydrodynamic drag of the medium. Estimates show that the greatest retardation in this case results from the increase in the second viscosity. The characteristic time for this relaxation can be found from $t_r = \rho_k^{-1}(\partial P/\partial\rho)^{-1} \times \zeta$. According to Ref. 1, we have $\partial P/\partial\rho = 1.81 \times 10^8 \times \tau^{1.116}$ cm^2/s^2 and $\zeta = \eta \times \tau^{-2}$ (Ref. 1). With $\eta = 20 \times 10^{-6}$ Ps it is found that even with $\tau = 10^{-4}$ we have $t_r \cong 5$ s. This time is far shorter than the relaxation time observed in the present experiments. The relaxation time for the temperature gradients in the copper cell itself is also negligibly short. We believe that the observed relaxation may be interpreted as a process resulting from the relaxation of temperature inhomogeneities in the layer of ^{4}He above the capacitor.

According to the fluctuation theory of critical phenomena, the scale time for temperature relaxation can be calculated from the scaling equation of state (for example, that of the linear model), from the equation relating the compressibility to the binary correlation function, and from the equation relating the thermal diffusivity to the correlation radius. Figure 2 shows the dependence of $t_r \times \tau^{\nu}$ on $\tau \times (\Delta\rho)^{-1/\beta}$ calculated in this manner, within a constant (curves a-a and b-b). The value of the constant is chosen to fit the experimental scaling function. We see from Fig. 2 that there is a correspondence between the experimental and theoretical results. Accordingly, the ratardation of the density relaxation observed in the present experiments is associated with a relaxation of temperature inhomogeneities near the critical point for helium.

Shripov *et al.*[3] have previously observed a retarded relaxation of the density and concentration of a liquid near a critical point, with a critical index for the relaxation time between 1 and 1.2. They attributed the retardation to a decrease in the diffusion coefficient at a constant mobility of the particles. In light of the experiments discussed in the present letter, the equalization of the temperature along the liquid must be taken into account in interpreting the results of Ref. 3.

In conclusion we wish to point out that the critical index for the correlation radius of helium is $\nu = 0.543$ according to measurements of the Rayleigh line,[4] while measurements of the scattered-light intensity[5] yield $\nu = 0.63$, in satisfactory agreement with the value found in the present work

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