

Relaxation processes in phonon–impuriton system and effective thermal conductivity of superfluid ^3He – ^4He solutions

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Abstract

By the method of stationary thermal flow, the measurements of effective thermal conductivity in the superfluid solution ^3He – ^4He with initial molar concentration 9.8% ^3He in the temperature range 0.1–0.5 K have been carried out. At temperatures below 0.23 K, where the phase separation of the mixture occurs, the measurements were carried out in the lower superfluid phase with changing concentration following the phase diagram with decreasing the temperature. Experimental data were compared with the prediction of the kinetic theory of the phonon–impuriton system of a solution. The analysis allows us to establish the relaxation time hierarchy in such a system and to provide the quantitative estimation of the times of impuriton–impuriton and phonon–impuriton relaxation. It is shown that a rather good agreement between experimental data and theory can be obtained by the use of one fit parameter.

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1. Introduction

The specific feature of the kinetic behaviour of superfluid helium is the variety of relaxation processes occurring in this quantum system. The situation is especially interesting in the superfluid systems ^3He – ^4He where kinetic properties are determined by three types of elementary excitations—phonons, rotons and quasiparticles ^3He (impuriton excitations).

The heat conductivity researches give an important information about kinetic processes in superfluid solutions ^3He – ^4He . Up to this time, experiments in this region were carried out for dilute solutions with molar concentration less than 5% ^3He in ^4He [1–5]. For the concentrated solutions, the heat conductivity measurements were done only at temperatures above 0.65 K [6]. Theoretical studies of thermal conductivity and other transport coefficients of superfluid solutions ^3He – ^4He

were carried out in Refs. [7–12]. Authors established a complicated hierarchy of relaxation times of the processes. The contribution of each process was found out in thermal conductivity, viscosity, diffusion and sound properties (first and second ones) (see, for example, Ref. [12] and references therein).

In superfluid solutions, an effective thermal conductivity coefficient is usually measured in the experiment. As shown by Khalatnikov and Zharkov [7], this coefficient has a contribution of three factors—diffusion, true thermal conductivity and thermal diffusivity. The reason is that under heating, an impuriton excitation arises in the liquid along with a thermal excitation flow. The present work is devoted to the experimental study of thermal conductivity processes in superfluid solutions ^3He in ^4He at large enough concentrations and low temperatures. In this case, kinetic properties are determined by impuritons ^3He and phonons only and roton contribution can be neglected. Besides, at low temperatures, the researched solution has first-order phase transition–phase separation. This work continues previous researches of effective thermal conductivity [13] to

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obtain a more complete and correct information on processes of phonon–impuriton and impuriton–impuriton relaxations.

2. Experimental technique and results

The method of the stationary heat flow, which was generated by a flat heater located in the bottom part of a cylindrical measuring cell, was used to measure the thermal conductivity coefficient. Detailed scheme of the experimental cell was described in Ref. [14]. The cell is 2.4 cm in diameter and 4.7 cm in height, the walls were made of stainless steel. The stationary distribution of temperature after the switch on of a thermal flow was registered by two identical resistance thermometers located at two fixed distances of 10 and 27 mm between them. The top part of the cell has permanent thermal contact to a cold source-plate of the dilution ^3He – ^4He refrigerator, whose temperature was measured by a thermometer based on the melting curve of ^3He .

The solution with initial concentration $x_0=9.8\%$ ^3He was investigated in the temperature range 100–500 mK. Below the temperature of about 235 mK, this solution separates into superfluid phase on the bottom and a top one—normal with concentration close to pure ^3He . In this case, both thermometers were located in the lower superfluid phase. The measurements were carried out at constant temperature of a plate of the ^3He – ^4He dilution refrigerator and the top flange of the cell and at various values of heat flow. Special attention was paid to the absence of convective phenomena and linear connection

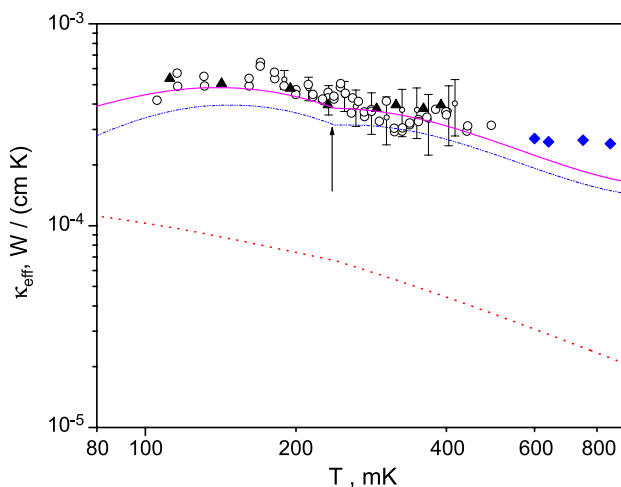


Fig. 1. Temperature dependence of the effective thermal conductivity coefficient of a superfluid solution with initial concentration 9.8% ^3He in ^4He . Arrow shows a separation temperature of mixture. (○ and ▲) Data of the present work for two distances between thermometer: 10 and 27 mm; (◆) data of Ref. [6]; solid line is calculated by Eq. (8). Dashed lines 1 and 2 are phonon and impuriton parts of thermal conductivity, respectively.

between the value of input heat flux \dot{Q} and the arising gradient temperature ∇T :

$$\dot{Q} = -\kappa_{\text{eff}} \nabla T \quad (1)$$

The coefficient of proportionality κ_{eff} in Eq. (1) is an effective thermal conductivity coefficient.

The effective thermal conductivity coefficient temperature dependences measured in the experiment are shown in Fig. 1. For completeness, the data of Ref. [6] are also shown in Fig. 1, which are in a good agreement with the actual data. Comparison of experimental data with calculation in the framework of modern kinetic theory requires detailed analysis of relaxation processes in this system.

3. Hierarchy of relaxation times in the phonon–impuriton system of solutions

The process of equilibrium establishment in the subsystem ^3He quasiparticles (impuriton system) is defined by the impuriton relaxation time τ_{ii} , which is determined by different ways for degenerated and non-degenerated systems. The investigated range of temperatures and concentration corresponds by conditions to the intermediate one. In this situation, the relaxation time τ_{ii} can be written as:

$$\tau_{\text{ii}} = \frac{\alpha}{xT}. \quad (2)$$

Here, we use the dependence of τ_{ii} on concentration and temperature equal to that for viscous relaxation [12]. Constant α was determined by the best fit to experimental data. The obtained values of τ_{ii} for the investigated solution are shown in Fig. 2 (curve 5) at $\alpha=1.2 \times 10^{-11}$. It can be seen in Fig. 2 that τ_{ii} is the smallest among all others. This provides a fast equilibrium establishment in impuriton subsystem.

In the phonon subsystem, the equilibrium is established in a more complicated way. It is known that the phonon spectrum is decayed and three-phonon processes are possible resulting in a fast establishment of equilibrium along some space direction (longitudinal relaxation). For thermal phonons with mean energy $\bar{\varepsilon}=3k_{\text{B}}T$ the longitudinal relaxation time is [12]:

$$\tau_{\parallel} = 2.6 \times 10^{-10} T^5 \text{ (s)} \quad (3)$$

Complete equilibrium in the system is determined by the process of interaction of phonons with impuritons. As was shown in Ref. [15], in these conditions, a two-step relaxation mechanism is realized: High-energy phonons due to Rayleigh scattering are arranged to impuritons, and all other phonons to these phonons with characteristic time τ_{\parallel} . As a result, phonon–impuriton relaxation time is:

$$\tau_{\text{phi}} = \frac{\int \tilde{t}(\tilde{t} + \tau_{\parallel})^{-1} n' y^4 dy}{\int (\tilde{t} + \tau_{\parallel})^{-1} n' y^4 dy}, \quad (4)$$

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