Torsion oscillator study of 3-dimensional superfluidity of ^{4}He thin films in 10 μm porous glass

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Abstract

The superfluid density of thin helium films (superfluid transition temperature 0.1 K $< T_C <$ 0.88 K) condensed on 10 μm porous glasses was studied. In spite of 2-dimensional linear behavior of T_C-film thickness relation, the 3-dimensional coherence length is found to be larger than the pore size over the whole superfluid temperature range. We discuss the 3-dimensional nature of the superfluidity of the system.

Key words: 3D superfluidity, coherence length, ^{4}He film, porous glass, torsional oscillator

1. Introduction

Thin films of ^4He in restricted geometries are an interest physical system. On the one hand, they are two-dimensional (2D), and the superfluid transition in such system is described by the Kosterlitz-Thouless (KT) theory[1], as it has been proved in a number of experiments[2–4]. On the another hand, helium films in porous media form a 3D-inter-connected system which reveals additional and different features in comparison with flat films[5–7].

From general reasoning, a 3D connected film can be considered as or 2D either 3D depending on some characteristic length scale in compared with the pore size[8]. The correlation length ξ attributed to vortex interaction in the KT theory is the length scale parameters which influences the helium film response in the 2D case under conditions of linear response.

Research with superfluid helium films in glass pores of relatively large size allows a clarification of the role of pore size in 3D superfluidity.

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2. Experiment

The torsional oscillator (TO) method allows one to get information about both change of He mass involved in oscillation because of superfluid density (ρ_s) changing and the energy loss because of vortexes's birth, through the measurement of frequency and amplitude of oscillation correspondingly[2–4].

We used a Be-Cu TO, which operates at frequency about 273 Hz with a quality factor $Q \simeq 10^6$ for the empty cell at $T = 0.25K$). The experimental cell contains 26 cylindrical plates of porous glass (porosity is about 50% with a narrow distribution of pore size) with diameter 2.5 cm and thickness 0.1 cm each. The geometrical surface area of the glass and the volume of the cell were estimated to be $S = 2.5m^2$ and V=8.8 cm^3 respectively.

Measurements were carried out with films of different thickness in the temperature range 0.1 - 1.5 K.

3. Results and Discussion

The films investigated demonstrate superfluid transition temperatures $T_{\rm C}$ from 0.175 K up to 0.539 K. Values of $T_{\rm C}$ obtained increases linearly with 2D density or film thickness in a good accordance with KT Universal Relation[9].

This fact confirms 2D character of superfluidity in films investigated.

In Fig 1 the results of temperature sweepings for films with different thickness are presented. The horizontal scale is chosen as $t = 1 - T/T_{\rm C}$ for the best clarity.

In the vicinity of $T_{\rm C}$, the frequency shift which is proportional to ρ_s superfluid density increases with cooling. One can see it increases as $\Delta f/f \sim t^{2/3}$ (solid lines in fig. 1 are results of fitting), as it should be for 3D

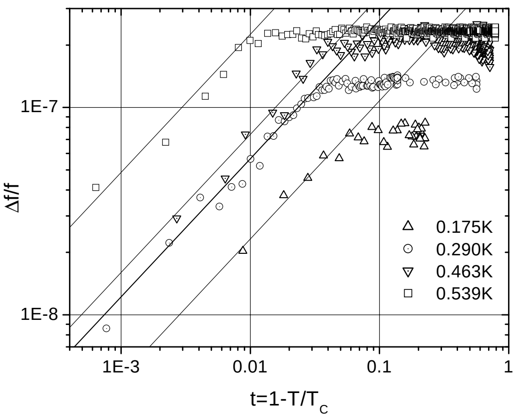

Fig. 1. The frequency shift $\Delta f/f$ dependence on temperature for films of different thickness (see $T_{\rm C}$ values in the insert). Straight lines show the slop 2/3.

At low temperature $\Delta f/f$ saturates at certain values which are proportional to $T_{\rm C}$.

From initial experimental data we know the coefficient of proportionality between Δf and changing of the mass oscillating ΔM. So one can calculate 3D coherent length ξ using well known Josephson relation :

$$\xi = \frac{m^2 k_{\rm B} T}{\hbar^2 \rho_s}, \qquad (1)$$

where $\hbar$ and $k_{\rm B}$ is Planck's and Boltzmann's constants. In our calculations of ξ we use $T_{\rm C}$ instead of T because main changes of ρ_s occur near $T_{\rm C}$. We take a course-grain average for $\rho_s = \Delta M/V$.

The results of the calculation are presented in Fig 2. In the $T_{\rm C}$ vicinities Josephson's correlation length exhibits 3D critical behavior $\xi \sim t^{-2/3}$, but the ξ dependence on the film thickness is not too obvious. At low enough temperatures decreasing of ξ is limited by the level of $\xi_{\min} \simeq 1.8 \cdot 10^{-3} cm$ which is common for all the films. Note that $\xi_{\min}$ and pore diameter are of the same order, it can be important for further interpretation of 3D mechanism of 2D films superfluidity.

It is interesting to study this new kind of 3D superfluidity where ρ_s is 4 orders of magnitude less than

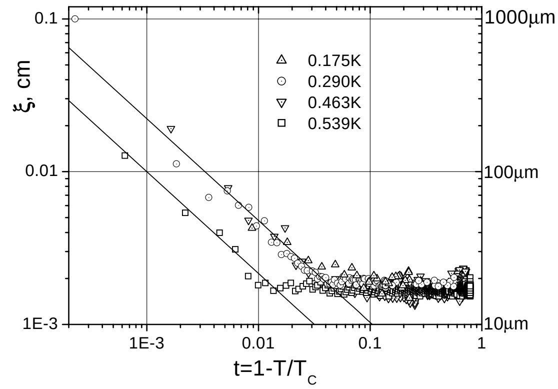

Fig. 2. Correlation length dependence on temperature for the same films. Straight lines show the slope of -2/3.

that of bulk ^4He. We continue to research this object in aspect of thermal excitations and critical velocity behavior in ISSP.

In conclusion the results obtained demonstrate both 2D and 3D superfluid features in the helium film placed in 10 μm porous glass. The former reflects in $T_{\rm C}$ behavior and the latter in the critical behavior of ρ_s as well as ξ.

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