Characteristics of the viscosity of liquid helium below 1 K

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The viscosity of pure He^4 and of weak He^3–He^4 solutions is measured in the temperature range 1.2–0.4 K. It was found that the viscosity of both He^4 and the solutions has a maximum corresponding to a temperature (0.63 K) that is independent of the He^3 concentration.

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Recently, Greywall,[1] on the basis of his data on the absorption of second sound in weak He^3-He^4 solutions, determined the temperature dependence of the viscosity η.[1)] For a solution of 0.1% He^3 Greywall observed a maximum on the $\eta(T)$ curve (T is the temperature). However, this property was not explained in Ref. 1.

It should be noted that there are at least two reasons for the occurrence of the maximum. One is related to the fact that for sufficiently weak He^3 concentrations in a certain temperature range the main contribution to the viscosity η_i with an impurity comes from the He^3-roton scattering processes in which η_i increases with decreasing temperature. However, at low temperatures when the rotons freeze, He^3-He^3 scattering becomes dominant (numerical calculations indicate that in this case the effect of the phonons can be neglected). Thus, for nondegenerate solutions η_i decreases with the temperature as $\sqrt{T}$. Consequently, a maximum for η_i occurs in the intermediate range.

The second reason for the appearance of a maximum is attributed to the transition in the temperature range for which the mean path length of the phonons approaches the characteristic dimension of the instrument.

For an unambiguous interpretation of this effect, we need data for the phonon-He^3 and He^3-roton scattering processes in the corresponding temperature and concentration ranges. Such data can be obtained through special experiments.

In this communication we give the results of direct investigations of the viscosity of the normal component of pure He^4 and weak solutions of helium isotopes with a He^3 content of 0.01, 0.06, 0.09, 0.18, and 0.47% in the temperature range 1.2–0.4 K. The measurements were performed by the oscillating sphere method.[2] In the instrument we used a hollow sphere with a radius of 25.30 mm, which was suspended on an elastic filament to obtain damping torsional oscillations. The entire oscillating system which was held at the same temperature, was placed at the center of the spherical chamber with a radius of 27.26 mm. The logarithmic damping decrement was measured as a function of the temperature, which allowed us to calculate the viscosity from the equations obtained by solving the corresponding hydrodynamic problem. The maximum error in determining η for all temperatures and concentrations c did not exceed 2 μpoise.

The results are given in Fig. 1. It can be clearly seen that η is maximum for all the indicated fluids with He^3 content below 0.47%. Moreover, the temperature corresponding to this maximum (0.63 K) [2] within the limits of experimental error is independent of He^3 concentration. An analysis leads to the conclusion that the maximum is not related to the presence of He^3 in the system, but is due to the fact that a transition occurs between the hydrodynamic and the Knudsen regimes in these experiments at a temperature below 0.7 K for the phonon gas. Thus, a certain effective viscosity, which differs from the hydrodynamic viscosity by the factor $\left(1+\frac{2\xi\lambda}{d}\right)^{-1}$, [3] where λ is the mean free path of the particles (in this case phonons), d is the distance between the surface of the sphere and the chamber walls (0.194 cm), and ξ is a coefficient characterizing the interaction between the phonons and the viscosimeter, corresponds to the value of η calculated from the hydrodynamic equations. Taking into account the above expression, we can describe the temperature dependence of the effective viscosity of He^4 with an accuracy of 5%, which is fully satisfactory for such a simple model. Taking into account the fact that the mean path of a phonon is $\sim T^{-9}$, [4] we easily see that the temperature corresponding to the maximum T_m should depend weakly on the instrument's size (inversely proportional to the ninth root, from which we can see that T_m in this work coincides with that of Greywall.

The numerical values determined from the analysis of the parameters of the scattering processes indicated above allowed us to establish that the maxima observed in our experiments and in Ref. 1 are not related to the peculiarities of the impurity part of the viscosity. Although the effect fundamentally related to this property does occur, in this case, however, it is small. As for the contribution of He^3 η_{phi} to the phonon part of the viscosity of the solution η_{ph}, it should be taken into account using the relation[5]:

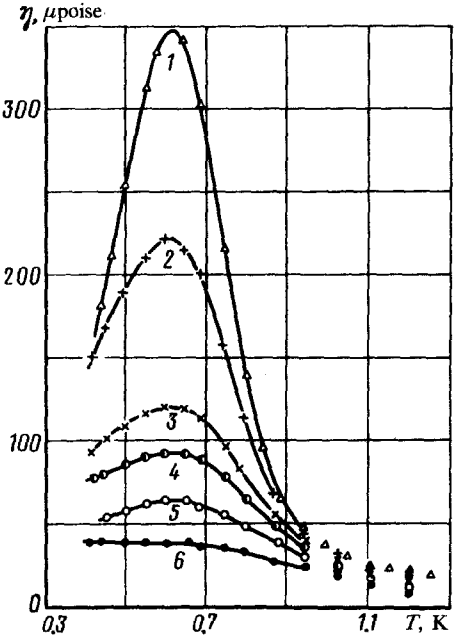

FIG. 1. Dependence of η on temperature. Curve 1 corresponds to pure He^4 and curves 2–6 correspond to solutions with a He^3 content of 0.01, 0.06, 0.09, 0.18, and 0.47%.

$$\eta_{ph}^{-1} = \eta_4^{-1} + \eta_{phi}^{-1},$$

where η_4 is the effective viscosity of pure He^4 measured by the given instrument, and

$$\eta_{phi}^{-1} \sim \frac{\sigma_{phi}\, n_3}{\rho_{nph}\, u},$$

where σ_{phi} is the cross section for scattering of a phonon by He^3, η_3 is the number of He^3 particles, ρ_{nph} is the phonon part of the normal density of the superfluid helium, and u is the the speed of sound.

The independence of the position of the η maximum on the He^3 concentration observed in these experiments indicates that η_{phi} is also independent of the temperature, and this means (since $\rho_{nph} \sim T^4$) that σ_{phi} is $\sim T^4$, i.e., Rayleigh scattering of phonons by He^3 quasiparticles occurs.

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[1)]We thank K.N. Zinov'eva for acquainting us with a preprint of Ref. 1.
[2)]The maximum observed in Ref. 1 also occurs at this temperature.

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