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Observation of an electromagnetic absorption peak in the millimeter wave range in liquid helium at the superfluid λ transition

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An observation of an electromagnetic absorption peak in the millimeter wave range in liquid helium at the λ transition is reported. The value of the helium-loss tangent at the temperature T_λ of the λ transition is about 10^{-5}. The peak shape is slightly asymmetric under temperature T. There is a sharper drop of absorption at $T<T_\lambda$, with a dependence close to t^{-1}, where $t=|T-T_\lambda|/T_\lambda$, and a flatter one at $T>T_\lambda$. The occurrence of this microwave absorption peak at the λ point indicates directly that the superfluid fraction affects kinetic electrical properties. The mechanism of dielectric losses at the λ transition is discussed.

The superfluid λ transition in liquid helium has attracted attention as a subject for investigation for a long time, because this liquid makes available the most favorable conditions for theoretical and experimental study of the critical phenomena resulting from the phase transition. Numerous works have been devoted to the critical phenomena in ^{4}He over recent decades (see, for example, Refs. 1 and 2 and the literature cited in these reviews). The temperature singularities of the heat capacity, heat conductivity, sound velocity and absorption, and other physical properties of liquid helium have been carefully studied in these investigations. At the same time, the electrical properties of liquid helium in the critical state, which are of significant interest, have been insufficiently studied until now.

Because helium is a monatomic liquid characterized by weakly interacting atoms, its polarizability α is connected with an elastic deformation of the electron shell only and has characteristic frequencies in the optical range. This circumstance makes it possible to use the Clausius-Mossotti equation $(\varepsilon-1)/(\varepsilon+1)=4\pi\alpha\rho/3M$, where ε, ρ, and M are the dielectric permeability, density, and molecular weight, respectively, for the description of the static electrical properties of liquid helium. In this case, α is assumed to be independent of temperature.[3] Under this assumption the temperature dependence of liquid-helium density was determined in the temperature interval 1.6–4.2 K by means of static dielectric permeability measurements.[4] The assumption of the temperature independence of α in this interval signifies really that the electric polarizability of helium is unaffected by the superfluid fraction.

In Ref. 5 an attempt to detect the temperature dependence of α was undertaken by means of careful independent ρ and ε measurements above and below the transition temperature T_λ. The change of α in the temperature interval 1.6–4.2 K was measured and a small degree of α temperature dependence was observed at the λ point. This temperature dependence may be the influence of the superfluid fraction on the electrical properties of liquid helium. Nevertheless, the accuracy of the α determination, which was mainly coupled with measurements of ρ with a relative accuracy of the order of 10^{-4}, was insufficient to draw reliable conclusions about the effect of the superfluid fraction on liquid-helium polarizability.

There is another possibility to detect the influence of the λ transition on the electrical properties of liquid helium. It consists in measuring the kinetic electric effects associated with absorption of electromagnetic energy. However, such measurements are a serious experimental problem because of extremely low dielectric losses in liquid helium even at microwave frequencies. Such a low level of dielectric losses is due to the fact that helium polarizability possesses characteristic frequencies in the optical range. On the evidence of Ref. 6 the loss tangent of liquid helium ($\tan\delta_{\mathrm{He}}$) is less than 5×10^{-6} at the frequency 9.1 GHz. This causes the following considerations. Owing to the increase of the superfluid-fraction relaxation time τ in the neighborhood of the λ point, a significant increase of dielectric losses can be expected at angular frequencies ω of the order of the inverse relaxation time. The increase of $\tan\delta_{\mathrm{He}}$ in this case must be directly coupled with the effect of the superfluid fraction on the electric properties of liquid helium.

From ultrasonic velocity and absorption measurements it follows that the times of both order-parameter relaxation at $T<T_\lambda$ and order-parameter fluctuations on both sides of T_λ agree well with $\tau=\tau_0 t^{-x}$, where $\tau_0=1.8\times10^{-12}$ s, $t=|T-T_\lambda|/T_\lambda$, and $x=1.062$.[7] Owing to the great increase of dielectric losses under increasing ω one can see from the above τ that suitable frequencies to detect the influence of the superfluid fraction on the electrical properties of liquid helium are in the millimeter wave range. However, the measurement of extremely low dielectric losses in the millimeter wave range has been extremely difficult because the usual methods using cavity resonators,[8] including superconducting ones, are not suitable for this purpose, owing to their insufficiently high quality in the millimeter wave range.

The present paper describes the observation of an electromagnetic absorption peak in the 8-mm wave range in liquid helium at the superfluid λ transition. A quasioptical method to measure the extremely low dielectric losses in condensed media recently created by[9] has been used for the measurements in liquid helium.

The essence of this method modified for liquid-helium measurements is the following. A dielectric sphere immersed into liquid helium is used as a microwave dielectric sphere resonator (DSR). The sphere is of a diameter $D \gg \lambda\varepsilon_0^{-1/2}$, where λ is the electromagnetic wavelength in vacuum and ε_0 is the dielectric permeability of the sphere material. Under these conditions oscillations of the "whispering gallery" type can be excited in the sphere. The electromagnetic field of these oscillations is located near the sphere surface and decreases exponentially with distance both outside and inside the sphere. Owing to this fact the oscillations possess extremely high quality Q_r. If the sum of the losses in the sphere material and radiation losses is much less than those in the liquid helium, it is the latter that determine the loaded DSR quality.

In order to get stable oscillations of the "whispering gallery" type and the highest Q_r a uniaxial crystal is used as the sphere material. As was shown in Ref. 9, the "whispering gallery" type of oscillations possessing caustics shaped as thin belts can be excited in such a DSR. These oscillations are unaffected by the dielectric inhomogeneities of the sphere material. In order to avoid decrease of the unloaded DSR quality through dielectric losses in the material of the sphere, the latter was prepared from a sapphire single crystal ($\varepsilon_0=10$) which possesses extremely low microwave dielectric losses at low temperatures. According to Ref. 10, in sapphire crystals $\tan\delta < 10^{-8}$ at the frequency 36.6 GHz at temperatures $T < 15$ K. The measuring DSR is a sapphire sphere of diameter 30 mm with a precise optically polished surface whose coarseness (roughness) does not exceed 0.1 μm. In order to eliminate the source of dielectric losses at the surface of the sphere, the latter was cleaned thoroughly by prolonged boiling in a chromium mixture followed by washing in ammonia solution and treatment in a gas discharge. Owing to the extremely low dielectric and radiation losses in the sapphire DSR, its unloaded quality in vacuum was about 10^8, which made it possible to use it for measuring the extremely low dielectric losses in liquid helium.

The measurement of dielectric losses in liquid helium by the DSR method was as follows (Fig. 1). By means of a short impulse of the electromagnetic field a set of "whispering gallery" type oscillations was excited in the DSR immersed into liquid helium. The decay of the oscillations possessing the longest lifetime τ_m was measured and used to determine the value of $\tan\delta_{\rm He}$. For this aim, an impulse with carrier frequency of about $\omega/2\pi=36.6$ GHz, duration 0.2 μ s, and repetition-rate frequency 250 Hz from a microwave oscillator was directed along the waveguide transmission line to an antenna having a wide directional pattern. The antenna was placed near the sphere and cooled by liquid helium. In order to minimize the losses caused in the DSR by the antenna, it was chosen in the form of a thin sapphire circular dielectric waveguide which radiated from the end on the surface of DSR. The dielectric waveguide of diameter 2.6 mm and length 15 mm was supplied by the standard rectangular metal waveguide. The same antenna was used for the detection of oscillations excited in the DSR. For the same purpose of loss minimization the sapphire sphere was placed in a copper sleeve of diameter 50 mm and supported in the sleeve with the help of three sapphire needles which eliminated the source of the losses in the DSR due to its support.

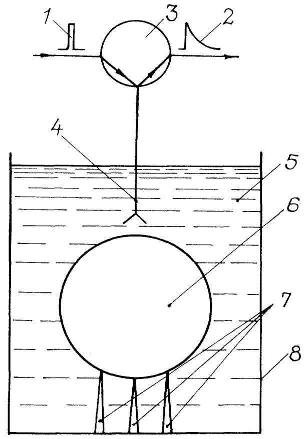

FIG. 1. Schematic of an excitation of the electromagnetic oscillations in a sapphire sphere immersed into liquid helium. (1) the input impulse; (2) the impulse response resulting from the damping of the electromagnetic oscillations in the sapphire sphere; (3) circulator; (4) antenna; (5) liquid helium; (6) sapphire sphere; (7) sapphire needles; (8) copper sleeve.

Taking into account the spherical symmetry of the DSR and that $\varepsilon_0 \gg \varepsilon_{\rm He}$ it is easy to relate the liquid-helium dielectric losses to τ_m, namely, $\tan\delta_{\rm He}=\varepsilon_0(\varepsilon_{\rm He}\omega\tau_m)^{-1}$, where $\varepsilon_{\rm He}$ is the dielectric permeability of liquid helium. Because the quality of the sapphire DSR placed in vacuum exceeded the quality of the DSR immersed into liquid helium by more than two orders of magnitude the error in determining $\tan\delta_{\rm He}$ did not exceed 5% near the λ transition.

The results of the $\tan\delta_{\rm He}$ measurements show a considerable increase of the microwave dielectric losses in a wide temperature region near the λ transition (Fig. 2).

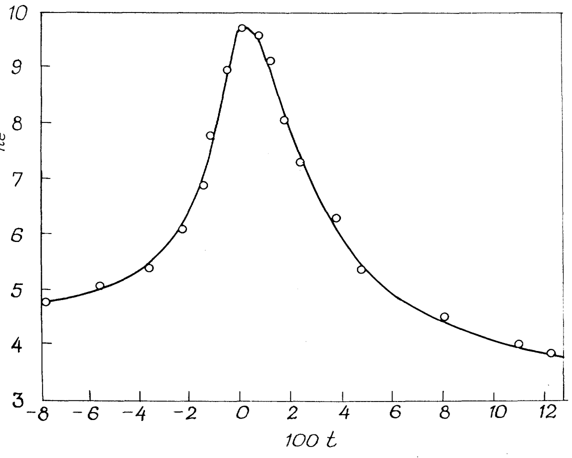

FIG. 2. Temperature dependence of the dielectric losses in liquid helium in the neighborhood of the λ transition.

The value of $\tan\delta_{\text{He}}$ increases from 3.4×10^{-6} at $T=4.2$ K up to 10^{-5} at $T_\lambda=2.17$ K. The measurement error of the temperature was less than 0.1% A wide dissipation peak occurs at T_λ. The peak shape is weakly asymmetric with respect to temperature: there is a sharper drop of the absorption at $T<T_\lambda$ with a temperature-dependence power law close to t^{-1}, and flatter dependence at $T>T_\lambda$. It is significant that the electromagnetic energy absorption away from the λ transition is temperature asymmetric too: $\tan\delta_{\text{He}}$ is 4.6×10^{-6} at 1.8 K and 3.4×10^{-6} at 4.2 K. Thus it has been estimated that the transition of liquid helium into the superfluid state is accompanied by a large microwave dielectric-loss increase, which is associated with the manifestation of the superfluid fraction in the kinetic electric properties of liquid helium.

For the explanation of this result the following considerations can be given. The key question is about the mechanism of the microwave-field interaction with a gas of elementary excitations in superfluid helium. A mechanism similar to that of microwave dielectric relaxation in nonpolar dielectric crystals at low temperatures through photon-phonon interaction[11] may be proposed. In our case the coupling between the microwave electromagnetic field and the superfluid fraction may be realized by means of the pressure resulting from electrostriction[12] caused by an electric component of the microwave field. Under the action of the microwave electric field the state of the elementary excitation gas deviates from its equilibrium one. Since the relaxation time of the superfluid fraction is of the order of ω^{-1}, this deviation does not have time to follow the quick change of the microwave electric-field strain. As a result an increase of gas entropy takes place, which is accompanied by microwave energy absorption. In different temperature regions in the neighborhood of the λ point the phonons, rotons, and vortex excitations can serve as such excitations (microwave photon-phonon, -roton, and -vortex interactions). Such a mechanism makes it possible to explain the microwave dielectric losses at temperatures $T<T_\lambda$.

The same mechanism may be realized at temperatures $T>T_\lambda$ where areas of the coherent state of liquid helium are produced as a result of fluctuations. The temperature interval where the λ transition is manifested in the increase of dielectric losses is comparatively great: $\Delta t\cong0.05$. This is in agreement with the theoretical conclusion[13] that the width of the λ transition for the kinetic properties of liquid helium increases under increasing electromagnetic-field frequency ω.

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[1] P. C. Hohenberg, Physica B+C **109B-110B**, 1436 (1982).

[2] V. Dohm and R. Folk, Physica B+C **109B-110B**, 1522 (1982).

[3] J. Wilks, *The Properties of Liquid and Solid Helium* (Clarendon, Oxford, 1967).

[4] B. N. Eselson, V. G. Ivantsov, P. S. Novikov, and R. I. Sherbatchenko, Ukr. Fiz. Zh. Ukr. Ed. **14**, 1837 (1969).

[5] V. Kempinsky *et al.*, Fiz. Nizk. Temp. (Kharkov) **14**, 451 (1988) [Sov. J. Low Temp. Phys. **14**, 247 (1988)].

[6] C. J. Grebenkamper and J. Hagen, Phys. Rev. **80**, 89 (1950).

[7] R. Carey, C. Buchal, and F. Pobell, Phys. Rev. B **16**, 3133 (1977); R. Williams and I. Rudnick, Phys. Rev. Lett. **25**, 276 1970).

[8] E. I. Ginzton, *Microwave Measurements* (McGraw-Hill, New York, 1957).

[9] E. M. Ganapolskii, A. V. Golik, and A. P. Korolyuk, Low Temp. Phys. **19**, 892 (1993).

[10] V. B. Braginsky, V. S. Ilchenko, and Kh. S. Bagdassarov, Phys. Lett. A **120**, 300 (1987).

[11] V. L. Gurevich, *Transfer of Phonon System* (Elsevier, Amsterdam, 1987).

[12] V. L. Ginzburg and A. L. Sobjanin, Usp. Fiz. Nauk **154**, 545 (1988) [Sov. Phys. Usp. **31**, 289 (1988)].

[13] C. A. Williams, J. Low Temp. Phys. **93**, 1079 (1993).