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Resonance absorption of microwaves in He II: Evidence for roton emission

A. Rybalko,[1,*] S. Rubets,[1] E. Rudavskii,[1] V. Tikhiy,[1] S. Tarapov,[2] R. Golovashchenko,[2] and V. Derkach[2]
[1]*B.I.Verkin Institute for Low Temperature Physics and Engineering, NAS of Ukraine, 47, Lenin Avenue, Kharkov, 61103, Ukraine*
[2]*Institute of Radiophysics and Electronics, NAS of Ukraine, 12 Proskury Strasse, 61085 Kharkov, Ukraine*

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Microwave (MW) absorption in liquid ^{4}He is investigated in the frequency range of 40–200 GHz at $T=1.4–2.5$ K. A "whispering gallery" of waves was generated by a dielectric disk resonator immersed into the liquid. Resonance absorption of MWs was detected at the frequency, which corresponds to the roton minimum of the liquid helium excitation spectrum. The creation of a single roton is possible because of the presence of the resonator wall which absorbs an extra momentum. The resonance frequency is shown to decrease with temperature in an excellent agreement with the temperature dependence of the roton gap obtained previously in the neutron scattering experiment.

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An observation of electric induction in superfluid ^{4}He induced by relative motion of its normal and superfluid components has been recently reported.[1,2] This new extraordinary effect was revealed in two different types of experiments: electric potential oscillations were generated by a second-sound wave where the velocities of normal v_n and superfluid v_s components relate as $v_n=-v_s\frac{\rho_s}{\rho_n}$ (here ρ_n and ρ_n are the densities of the superfluid and normal components, respectively), and by liquid helium motion in a torsion oscillator whose walls affect the normal component only. In both experiments, the amplitude of the electric potential induced was about $10^{-8}–10^{-7}$ V. For liquid helium consisting of electrically neutral and spherically symmetrical atoms, this observation was unexpectable. A reverse effect (second-sound wave generation by an ac electric field) was also observed.

The experimental finding of mechanoelectric effect in He II has stimulated a number of theoretical studies aiming to explain its mechanism.[3–8] On the basis of experiments,[1,2] it could be assumed that the relative motion of the normal and superfluid components is a result of internal electromagnetic forces related to the macroscopic quantum ordering. Anyway, these experiments indicate that there is a certain relationship between mechanical and electric phenomena in superfluid helium whose nature is not clearly understood.

In this Rapid Communication, we continue our study of the connection of the relationship between mechanical and electric phenomena in superfluid helium using microwaves. It is expected that the electric component of a microwave (MW) will generate superfluid and normal flows in He II which, in turn, will interact with the MW. In addition to previous studies of MW absorption in He II,[9–11] we use microwaves of substantially higher frequencies comparable with typical frequencies of rotons.

The setup for measuring the absorption of an electromagnetic wave by liquid helium in the frequency range of 40–198 GHz used a dielectric disk resonator operating in the "whispering gallery" mode.[12,13] The resonator with 19.00 mm in diameter and 1.0 mm in thickness was perfectly suitable for generating high-Q whispering gallery modes.[13] It was mounted horizontally in the cell filled with liquid helium and supported by spring-loaded metallic rods set at the disk center. The resonator was operated in the mode of the passing electromagnetic wave. Dielectric rectangular waveguides made of isotropic quartz served as exciting and receiving antennas. They had an absorbing element at one end. The other rectangular ends were pasted hermetically into hollow metallic pipes (waveguides) coming out from the cryostat. The vector of the electric component of the exciting electromagnetic field was perpendicular to the disk axis.

The oscillation spectrum of the system consisting of radial and azimuthal modes was registered on-line on a monitor. Only the azimuthal HE_{mn}-type (whispering gallery) modes with the radial $n=1$ and azimuthal $m=17–84$ indexes were used in these experiments. The frequency spacing between the adjacent modes was 2.3 GHz, and the frequency tuning was realized by a mating block. The tuning step was 1–10 MHz on rough tuning and 140 kHz on fine tuning. The scanning velocity in the precision regime was 100 Hz/s. During measurements, we added the triangularlike voltage of $\Delta U \simeq 10^{-5}–10^{-3}$ V to the basic voltage of the generator (1000–1500 V).

The resonator was excited with a set of generators covering the frequency range 40–200 GHz. Two regimes were used: frequency scanning (regime 1) and fixed-frequency measurement (regime 2). To increase the signal-to-noise ratio, the electromagnetic wave was modulated with a modulator and low-frequency generator. The signal that passed through the low temperature part of the unit was detected and fed to a low-bandpass amplifier.

The resonance field in the dielectric disk resonator was excited solely by traveling waves. Resonance was observed when the phase of the traveling wave coincided on each subsequent passage of the wave along the generating line of the resonator. The electromagnetic field of these oscillations was concentrated in a narrow spatial area adjacent to the cylindrical surface of the resonator.

The amplitude-frequency characteristic of the resonator was first measured in helium gas at $T=4.2$ K with a pressure of 3–5 Torr. These conditions ensured reliable cooling of the whole system and then the mode was selected at the required frequency. The highest value of the signal amplitude in vacuum was taken as 100%. When liquid helium was condensed to the cell, the resonance mode frequencies

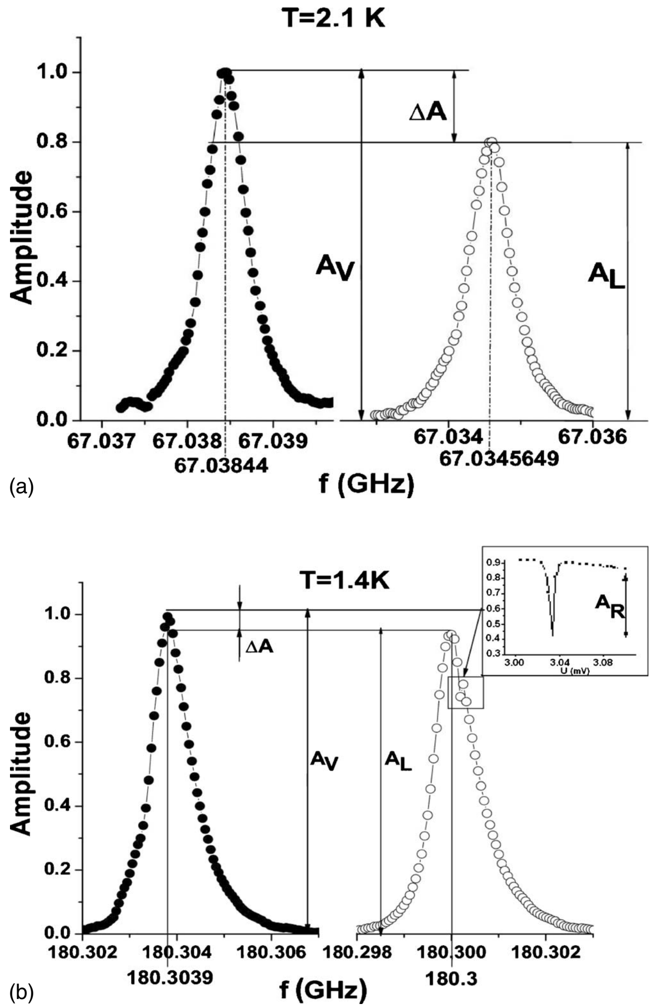

FIG. 1. Typical resonance curves of whispering gallery modes obtained with a dielectric disk resonator with $m=29$ (a) and $m=78$ (b). ●: vacuum at $T=4.2$ K and ○: liquid helium. Inset in (b): the portion of resonance absorption in the precision scanning regime (enlarged scale, averaging over 25 curves).

shifted in accordance with the change in the liquid dielectric constant. The signal amplitude decreased as the dielectric losses grew larger. We could thus compare the losses in liquid helium and in vacuum.

Figure 1 shows the resonance curves for two modes at $f \sim 67$ GHz ($m=29$) [Fig. 1(a)] and $f \sim 180$ GHz ($m=78$) [Fig. 1(b)]. The curves on the left correspond to measurements in vacuum and the curves on the right correspond to measurements in helium. The curves were processed by approximating them by Lorentz functions (see Ref. 14)

$$A(f) = \frac{A_0}{1 + 4Q^2\left(\dfrac{f}{f_0} - 1\right)^2}, \quad (1)$$

where $A(f)$ is the current value of the signal amplitude, and A_0 is the maximum amplitude. Two parameters—resonance frequency f_0 and Q factor—were determined. It is seen that the signal amplitude in liquid helium (A_L) is less against the signal amplitude in vacuum (A_V).

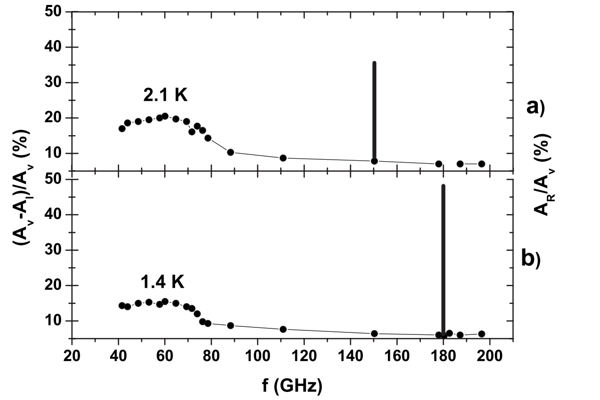

FIG. 2. Frequency dependence of the relative amplitude of an electromagnetic wave traveling in He II. (a) $T=2.1$ K and (b) $T=1.4$ K. The resonance absorption line is shown by a vertical solid line (the scale of its height is on the right).

In contrast to other modes, the $m=78$ mode at $T=1.4$ K had a specific resonance peak in the liquid appearing as a sharp dip in the smooth resonance curve at a certain fixed frequency depending on temperature [Fig. 1(b), inset]. As temperature is increased the resonance peak shifted to the lower frequencies and moved from one mode to another. We attribute the feature to the resonance absorption of the electromagnetic wave at this frequency (see below). It was found that a decrease in the signal amplitude $\Delta A/A_V = (A_V - A_L)/A_V$ was frequency-dependent. It can be taken as a quantitative characteristic of the relaxation (dielectric) losses in the liquid. The resonance absorption of the electromagnetic wave can be described by the ratio A_R/A_V. Since the modes had different amplitudes and Q factors in vacuum, the ΔA and A_R values were normalized to A_V of the corresponding mode.

The typical spectra of dielectric losses and resonance electromagnetic wave absorption in He II taken at two temperatures are shown in Fig. 2. It is seen that the spectrum of dielectric losses (axis on the left) has a broad maximum in the band of 40–80 GHz, which increases with increasing the temperature. The losses can be caused by resonantly induced generation of phonons in He II with energies about 2–4 K. The process intensity rises on approaching the λ point (see Ref. 10) presumably due to the fluctuations in the vicinity of the phase transition.

Figure 2 also illustrates an effect—resonance absorption of an electromagnetic wave at a certain frequency f_R which depends on temperature. The process has two specific features: (i) the Q factor of the mode decreases by 5%–20% when f_R coincides with the mode frequency, and (ii) a very narrow absorption line appears in the smooth spectrum of relaxation losses. The signal amplitude decreases by $A(R)$ at $f=f_R$ [Fig. 1(b), inset]. Due to the finite bandwidth of the generator, it was impossible to measure the absorption linewidth precisely. The highest power fed to the resonator was about 1 mW and the effect was power-independent. Namely, the resonance frequency f_R did not change when the power was decreased by ~40 dB.

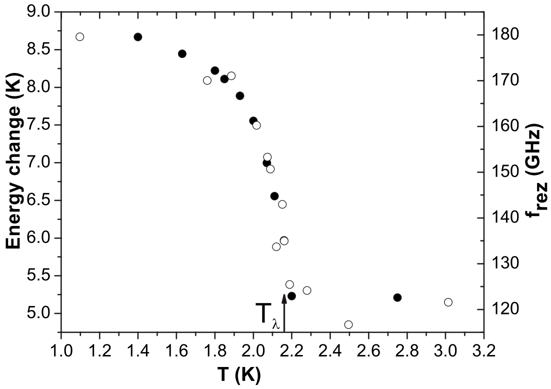

FIG. 3. Temperature dependence of the resonance absorption frequency (right-hand axis) and recalculated roton gap value (left-hand axis): •: this experiment and ◦: neutron experiment (Ref. 14).

At $T=1.4$ K [Fig. 1(b)] the resonance absorption frequency corresponds to the energy ~ 8.65 K, which coincides with the minimum roton energy Δ (roton gap). It is natural to relate the effect observed to the creation of roton excitations in He II, which absorbs the electromagnetic wave energy. To make sure that the scenario was correct, we performed measurements at different temperatures. The temperature dependences of the resonance frequency and the roton gap are shown in Fig. 3 along with neutron scattering data for Δ.[15,16] The results obtained by different methods are in very good agreement and thus support the idea of roton creation during the interaction between He II and the electromagnetic wave of a certain frequency.

We should emphasize that the shape of the resonance curve indicated an evolution as the temperature varied (Fig. 4). The resonance curve was measured using the precision regime of scanning (100 Hz/s) by changing the oscillator voltage ΔU. Figure 4 shows that the resonance absorption lines are resolutionably reliable and their width increases as the temperature rises.

The interaction of electromagnetic waves with elementary excitations in superfluid helium was previously investigated by the Raman method.[17] The Raman spectrum contained a sharp asymmetrical peak corresponding to the energy difference between the incident and reflected photons 18.5 ± 0.5 K, which is close to 2Δ. It was found later that the interaction of the electromagnetic wave with He II leads to the formation of a bound double-roton state with the binding energy 0.37 ± 0.10 K.[18] The rotons forming the bound state have almost equal but oppositely directed momentum.

The sharp peak of resonance absorption of the electromagnetic wave observed in our experiments corresponds to creation of a single roton. However, the momentum conservation law does not hold in this partial case because the momentum of the roton exceeds that of an incident photon by many orders of magnitude. Until now, no rotonlike quasiparticle with very small momentum has been detected in He II though its possibility has been a subject of discussions.[19–21] In particular, this possibility can be realized when an elementary excitation is produced by transferring the particle from the Bose-condensate to the above-condensate state because this requires finite energy. The

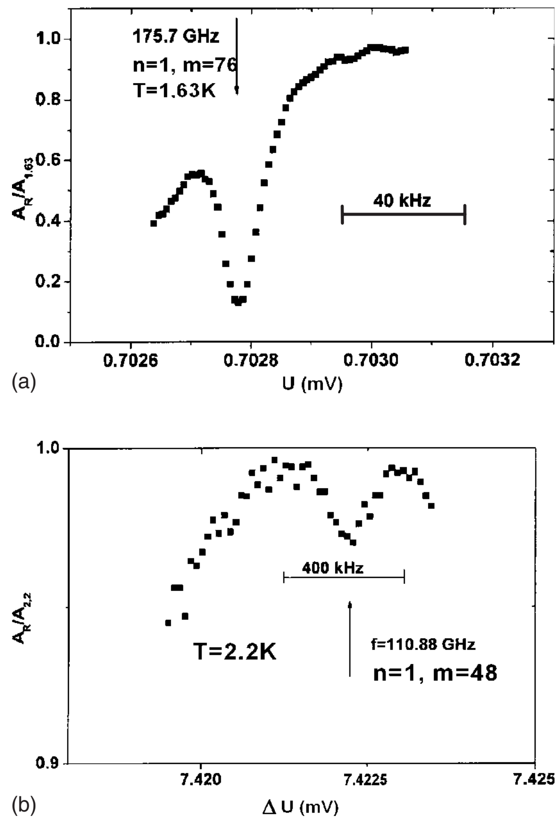

FIG. 4. Shape of the resonance curve at various temperatures: (a) $T=1.63$ K and (b) $T=2.2$ K.

spectrum of such excitations has a gap. Note that in its earlier version, the Landau theory of superfluidity admitted, along with phonons, the existence of particles whose spectrum has a gap at zero momentum.[20]

It is more reasonable to explain the resonance of the electromagnetic wave at some resonance frequency proceeding from the condition of this experiment in which the photon-superfluid helium interaction occurs near the resonator wall. In the spatially homogeneous case the creation of a single roton is impossible at this high frequency because of violation of conservation laws. In our experiment the boundary between the superfluid helium and the dielectric resonator creates inhomogeneity. We can thus assume that the boundary takes on the excessive momentum of the roton. To put it differently, the interaction of the electromagnetic wave with superfluid helium near the resonator wall leads to creation of a phonon in the solid wall[21] as well.

Note that in He II film the "layered" rotons can be excited, as it is shown in Refs. 22 and 23. To answer the question, is it possible to excite such rotons, in the present experiment we carried out the additional measurement for the resonator whose surface was covered by saturated helium film. We did not observe any resonance in such a condition, independently on resonance mode, within our accuracy. However, to conclude definitively one needs to increase the resonance Q factor at least two orders. One cannot also exclude that, in our experimental condition, the roton may be loosely bound to the resonator walls so that its energy is below but very close to that of bulk roton.

The effect of resonance absorption of an electromagnetic wave was also observed above the λ point. In this case $f_R \sim 120$ GHz, which corresponds to $\Delta \sim 5.2$ K and is in good agreement with neutron scattering data.

The intensity of inelastic Raman scattering of an electromagnetic wave in He II in a condition of excitation of roton was calculated theoretically in Ref. 22. We analyzed our absorption lines and compared them with the resonance scattering line of Eq. (12) of Ref. 22. We found the linewidth given by Eq. (12) is a few orders larger than that of our experiments. Note also that our lines can be fitted by Lorentzian functions whereas the line shape given by Eq. (12) is strongly asymmetric.

A very narrow resonance line means that there are coherent processes in the system. These processes might be associated with the interaction between atoms which has an electromagnetic origin. The problem will be studied in the future.

Another interesting finding is that the superfluid flow around the resonator registered by MW absorption is very sensitive to the cryostat orientation with respect to the Earth's rotational axis. When the cryostat is tilted at a certain angle, the superfluid flow either escapes from the resonator or becomes destroyed. Similar effects have been observed recently by Packard's group.[24] Of course, these results are beyond the scope of this Rapid Communication and require additional investigations.

To summarize, we have presented strong evidence that in superfluid helium there is the resonance absorption of microwaves whose frequency corresponds to the frequency of a single roton. This indicates that a MW creates rotons near the resonator wall. The resonance frequency is found to decrease as the temperature rises, which exactly corresponds to the temperature dependence of the roton gap obtained from neutron scattering data. It is important that these results are consistent with the existence of the relationship between mechanical and electric processes in superfluid helium observed previously. In particular, the electric component of the MW field induces the relative motion of the normal and superfluid components. Since the flow of the normal component is clamped near walls, this relative motion reveals itself as a circular superfluid flow around the resonator wall. We assume that the interaction of the MW with superfluid helium occurs owing to liquid polarization and the appearance of a macroscopic dipole moment whose origin is still to be found.

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*rybalko@ilt.kharkov.ua

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