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INVESTIGATION OF THE ANISOTROPY OF THE ENERGY GAP IN SUPERCONDUCTING TIN

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The methods and the results of measuring the temperature dependence of the attenuation coefficient of 70-Mcs ultrasound along various directions in a superconducting single crystal of tin are presented. From the difference in the temperature variation of the ratio α_s/α_n for sound propagating along the binary C_2 and tetragonal C_4 axes of the crystal it is concluded that the energy gap in tin is anisotropic. The width of the gap at the absolute zero along the C_2 direction is $(3.5 \pm 0.2)\,kT_c$, and along the C_4 direction it is $(3.1 \pm 0.1)\,kT_c$.

THE present microscopic theory of superconductivity[1] is in good agreement with a considerable amount of experimental data. It should, however, be noted that for a number of superconductors which have quite a pronounced lattice anisotropy the experimental results on the variation of the specific heat,[2] the thermal conductivity,[3] and the jump in the specific heat at the transition from the normal to the superconducting state, differ from the theoretical values.

This discrepancy can be explained by the fact that an isotropic model of the superconductor is considered in the theory of superconductivity, and the effect of the lattice anisotropy on the width of the energy gap is not taken into account. At the same time it is known that the transition temperature, and therefore also the width of the gap, is affected by the isotopic composition of the sample,[4,5] and by the homogeneous lattice deformation.[6] It is natural to expect that the anisotropy of the crystal lattice should manifest itself to an even larger extent in the width of the energy gap. Actually, as has been shown in the theoretical work of Khalatnikov,[7] account of superconductor anisotropy leads to values of the coefficient of thermal conductivity which vary with the crystallographic direction. It should, however, be noted that from the measurements of the thermal characteristics of the superconductor, the specific heat and the coefficient of thermal conductivity, one can only obtain indirect information on the anisotropy of the gap.

One of the simplest and most direct methods of observing the effect of the lattice anisotropy on the width of the energy gap is the attenuation coefficient of ultrasound propagating along various directions of the superconducting single crystal. Actually, one can determine from studies of the attenuation of a longitudinal ultrasound wave in superconductors[8] both the width of the energy gap at the absolute zero, and also its temperature dependence. For this purpose account must be taken of the following relation between the value of α_s/α_n (α_s and α_n are the coefficients of ultrasound attenuation in the superconducting and normal states respectively), and the width $2\epsilon_0$ of the energy gap:[8]

$$\alpha_s/\alpha_n = 2/(e^{\epsilon_0/kT} + 1). \qquad (1)$$

This formula, obtained for the isotropic case, means that α_s/α_n should be a function of the temperature only. In other words, for an arbitrary direction of propagation of the ultrasound wave in the crystal the temperature dependence of the ratio α_s/α_n should in the event of the validity of the isotropic model be identical.

With a view to clarifying the effect of the lattice anisotropy on the electron energy spectrum in a superconductor, we undertook to measure the temperature dependence of the attenuation coefficient of a longitudinal ultrasound wave along various directions of a single crystal of tin. A short communication of our results has previously been published.[9] In the present article we present a more complete account both of the methods of measurement and of the results obtained.

Figure 1 shows the block diagram of the measuring setup employed in the described experiments. Pulses $(1 \text{ to } 1.5) \times 10^{-6}$ sec long were fed at a repetition rate of 2500 to 3000 $\sec^{-1}$ to the radiating quartz crystals from the high-frequency generator, 2, operating at 70 Mcs. The pulsed operation of the generator was realized by connecting to the anode circuit of the generator a modulator fed by a 26-I rectangular-pulse generator. The quartz

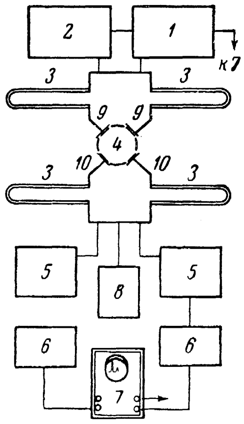

FIG. 1

crystals were connected to the high-frequency generator by ordinary flexible coaxial cables outside the Dewar and by an argentan coaxial line inside it. Between these lines was placed a coaxial cable 3 of variable length with the aid of which the generator was matched to the load. Similar components were used in the coaxial line connecting the receiving quartz crystals 10 to the calibrated attenuators 5.

Sample 4 was a spherically shaped single crystal of tin with a diameter of 13 to 15 mm on which planes perpendicular to the crystallographic axis with a diameter of 5 to 6 mm were etched by the electroerosion method. The radiating and receiving quartz crystals were glued to these planes with vacuum putty. The same putty was used to glue to the quartz crystals brass disks with a diameter of 5 to 6 mm and a thickness of 0.2 to 0.3 mm, to which the central conductors of the coaxial lines were connected. The sample was attached to a special holder, and the external conductors of the coaxial lines were grounded.

The tin samples used in the described experiments were very pure* with R(4.2°K)/R(300°K) = (1.8 to 2.5) × 10^{-5}. For such samples at helium temperatures and at 70 Mcs, the condition $l \gg \lambda$ is fulfilled (l is the mean free path of the electrons and λ is the wavelength of the longitudinal sound wave); the estimated value of $2\pi l/\lambda$ is in excess of 70.

The temperature dependence of the attenuation coefficient of the longitudinal sound wave was simultaneously recorded for two directions in the crystal. For this purpose, high-frequency pulses, giving rise to the propagation of ultrasound waves in two mutually perpendicular directions, were fed to one pair of mutually perpendicular radiating quartz crystals 9. The other pair of receiving crystals 10, placed opposite the radiating crystals, transformed the pulses transmitted by the crystal into electromagnetic signals which after passing the attenuators 5 were amplified by the amplifiers 6, and were then recorded with the aid of an oscillograph 7. The synchronization of the oscillograph beam was carried out with the aid of the same rectangular pulse generator 1 which controlled the operation of the high-frequency generator 2 through the modulator.

Having at our disposal attenuators which were calibrated with the standard signal generator 8, we could find the attenuation due to the conduction electrons for every temperature of the sample. For this purpose the curve of the temperature dependence of the attenuation coefficient was extrapolated to absolute zero, for which the ultrasound attenuation due to the electrons is zero.[8]

We used the device shown on Fig. 2 to record the temperature dependence of the ratio α_s/α_n down to 1°K. In an ordinary helium Dewar 3 we placed another small glass Dewar 2, inside which we placed the sample 1 attached to a special holder. The small Dewar was welded to a section of a kovar cylinder 5 whose upper portion was soldered to the external ground sleeve section 6. The ground sleeve was placed on vacuum putty which made the inner Dewar air tight both at room and at low temperatures.

High-frequency pulses from a high-frequency generator were fed to the crystal, and then from the crystal to the recording portion of the setup in the Dewar by means of coaxial argentan lines 4

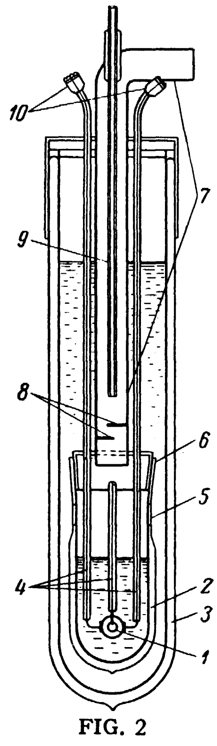

FIG. 2

*We take the opportunity to thank B. N. Aleksandrov for supplying the pure tin for the samples.

terminated at the external portion of the instrument by vacuum-sealed inserts 10. Coaxial cables of variable length were connected to these inserts (cf. Fig. 1).

In performing the experiments, liquid helium was first poured into the outer Dewar, and then through tube 9 into the inner small Dewar; during the measurements the crystal was in direct contact with the liquid helium.

The temperature was reduced by pumping out the helium vapor, initially by a common pump simultaneously from the inner and outer Dewar, and then, after a temperature of about 2°K had been reached, from each vessel independently. To screen the liquid helium in the inner small Dewar from infrared radiation coming from the sealed end of the device, small blackened copper-foil screens 8 were placed in the lower portion of the argentan tube 7, through which the helium vapor from the small Dewar 2 was being pumped out.

The temperature of the sample was determined from the pressure of the saturated helium vapor using the T_L55 scale.[10]

To check out the procedure and to establish the possibility of reaching conclusions on the anisotropy of the energy gap from the nature of the temperature dependence of α_s/α_n for various crystallographic directions, we measured the temperature variation of the coefficient of attenuation of longitudinal ultrasound under conditions in which the ultrasound was propagated along two mutually perpendicular binary C_2 axes (the black and white points on Fig. 3). It can be seen from Fig. 3 that in this case the experimental points fit the same curve excellently, thus proving that the physical properties of the superconductor are identical along two different C_2 axes.

Figure 4 illustrates the temperature variation of α_s/α_n when the ultrasound is propagated along the tetragonal C_4 and the binary C_2 axis. Unlike the preceding case, the temperature dependence of α_s/α_n is different in the C_4 direction than in the C_2 direction, which indicates a pronounced anisotropy of the energy gap in tin. The cited results were obtained from measurements on two samples; the experimental points obtained from each sample for the propagation of ultrasound along the same directions in the crystal fit the same curve well.

The following are typical absolute values of the electron part of the attenuation coefficient in a metal in the normal state near T_c:

$\alpha_n = (47.6 \pm 0.2)$ db/cm for the C_2 direction,

$\alpha = (21.4 \pm 0.2)$ db/cm for the C_4 direction.

It is of interest to estimate the width of the energy gap in superconducting tin along the C_2 and C_4 axes at absolute zero. Such an estimate is most simply obtained from the graphs of the dependence of $\log(\alpha_s/\alpha_n)$ on T_c/T. Actually, for $T \ll T_c$, as is easily seen from Eq. (1), the above dependence is expressed by a straight line whose slope yields the value of the width of the gap at 0°K.

The dependence of α_s/α_n on T_c/T for the C_2 and C_4 directions is shown in Fig. 5 on a logarithmic scale. The difference of the gap widths at the absolute zero follows directly from the various slopes of the linear portions of these graphs: $(3.5 \pm 0.2)kT_c$ along the C_2 axis, and $(3.1 \pm 0.1)kT_c$ along the C_4 axis.

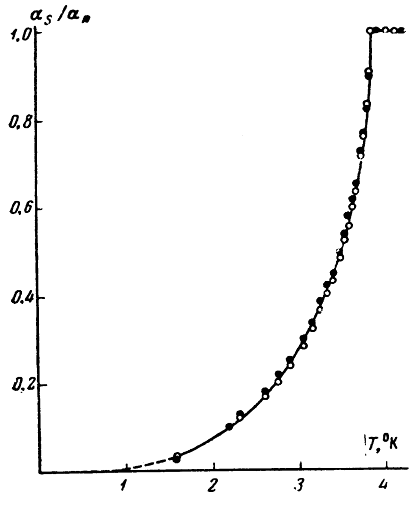

FIG. 3

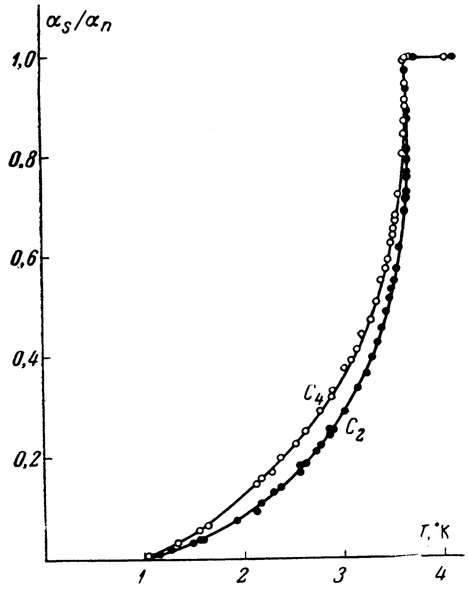

FIG. 4

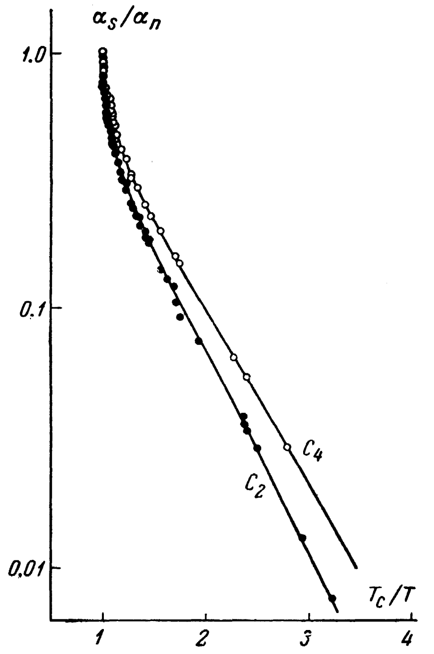

FIG. 5

The width of the gap at 0°K found for the C_4 axis agrees with the value obtained for this direction in analogous experiments of Morse et al.[11] whose results were published slightly later than our preliminary note.[9] The results of our experiments and the data of the above authors are in complete agreement, now that Morse et al. published a correction[12] in which they concede the error in their previous value of the gap width along the C_2 axis, and in which they cite the new value $(3.5 \pm 0.1)\,kT_c$.

The energy-gap anisotropy established in these experiments is due to the shape of the Fermi surface. Therefore, for those directions of the crystal for which anomalous behavior is observed in investigating the oscillations of the attenuation coefficient of the longitudinal ultrasound wave in a magnetic field,[13] one should apparently also expect a particularly strong deviation of the gap width from the values given by the present microscopic superconductivity theory.

It must be noted that along with the anisotropy of the temperature dependence of the attenuation coefficient, an anisotropy in the transition temperature T_c was also observed in our experiments. The temperature of the transition of the sample from the normal to the superconducting state for the C_2 direction exceeded the transition temperature for the C_4 direction in all the measurements by 0.004°K.

It is still impossible to say with all certainty that this is not caused by some side effects. However, it is clear that this phenomenon cannot be explained by unequal heat elimination from the sample by the helium bath during the propagation of the sound along different directions in the crystal. Actually, the simultaneous recording of the temperature variation of the attenuation coefficient in one and the same experiment excludes an effect of the above on the transition temperature. On the other hand, the difference of T_c for the C_2 and C_4 axes cannot be explained by the influence of the terrestrial magnetic field, since compensating for it did not lead to a disappearance of the difference in the transition temperatures.

In conclusion, we express our gratitude to A. I. Berdovskiĭ and É. I. Ponomarenko for help in the measurements, and also to V. L. Korpachevskiĭ for the exceptionally careful electroerosion cutting of the samples.

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