the values of D have been extrapolated roughly to the saturation vapor pressure.

Figure 3 shows the dependence of the thermal conductivity κ on T. For comparison, the thermal conductivity of He^4, obtained by Zinov'eva[8] from measurements of the attenuation of second sound, are shown. The dashed curves are theoretical, calculated from the results of Khalatnikov and Zharkov.[2] In this calculation the energy gap between the ground state of helium II and the lowest roton level was taken as $\Delta = 8.5°$ K. It can be seen from Fig. 3 that the thermal conductivity of weak solutions is little dependent on concentration in the temperature region between the λ point and 1.1° K. The curves for pure He^4 and for a mixture with C = 0.1% He^3 in He^4 diverge below 1.1° K. In this temperature region impurities influence the conductivity mechanism appreciably, reducing the mean free paths of rotons and phonons.

A more detailed discussion of the results and of the method, and the results of extending the measurements to lower concentrations will be published in the near future.

[1] A. N. Vetchinkin, Приборы и техника эксперимента (Instrum. and Exp. Techniques), in press.

[2] I. M. Khalatnikov and V. N. Zharkov, JETP 32, 1108 (1957), Soviet Phys. JETP 5, 905 (1957).

[3] Beenakker, Taconis, Lynton, Dokoupil, and van Soest, Physica 18, 433 (1952).

[4] Careri, Reuss, Scaramuzzi, and Thomson, Proc. Int. Conference Low Temperature Physics and Chemistry, Univ. of Wisconsin Press (1958), p. 155.

[5] Careri, Reuss, and Beenakker, Nuovo cimento 13, 148 (1959).

[6] Kramers, Wasscher, and Gorter, Physica 18, 329 (1952).

[7] R. L. Garvin and H. A. Reich, Phys. Rev. 115, 1478 (1959).

[8] K. N. Zinov'eva, JETP 31, 31 (1956), Soviet Phys. JETP 4, 36 (1957).

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PARAMAGNETIC RESONANCE IN SINGLE-CRYSTAL TIN

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THE paramagnetic resonance of conduction electrons in metals has been investigated by Feher and Kip[1] on small particles and thin films of lithium, sodium, and beryllium, and was noted also in potassium. The theory of the effect was worked out by Dyson,[2] Azbel', Gerasimenko, and Lifshitz.[3,4] Experiments on paramagnetic resonance of large single crystals of metal have not yet been described in the literature.

In the present work, electron paramagnetic resonance was observed on a single crystal of very pure tin with $< 6 \times 10^{-5}\%$ of impurities.[5] The single crystal had dimensions of $11 \times 6 \times 1$ mm and served as the inner conductor of a strip-type resonator tuned to 9.35×10^9 cps. The measurements were carried out at a specimen temperature of 2.3° K by the frequency-modulation method.[6,7]

The results of the experiment are plotted in Fig. 1, in which are seen three paramagnetic-resonance signals. The copper parts of the resonator, prepared from copper of technical purity, give the wide line 1. The narrow symmetrical line 2 is the signal from $\sim 10^{-10}$ mole of crystalline diphenyl picryl hydrazyl, placed in the resonator for calibration. Line 3 is the paramagnetic resonance of the tin sample.

Rotation of the constant magnetic field in the plane perpendicular to the high-frequency magnetic field permits the observation of an apparent small anisotropy of the effect: the peak of the resonance moves by an amount which is of the order of its width. The significant change of the amplitude of the peak, which occurs during rotation of the field, is possibly explained[4] by a change of the angle of inclination of the field with respect to the sample surface. However, these aspects of the phenomenon are still not sufficiently clear from the experimental point of view.

In Fig. 2 is shown, on a larger scale, a record of the paramagnetic resonance of the electrons of tin (right-side peak) and of the calibration signal. The values of the constant magnetic field were recorded by a proton magnetometer (as in Fig. 1). From this graph it is possible to find the difference between the factor g_{Sn} for conduction electrons in tin and the factor $g_d = 2.0036$ for diphenyl
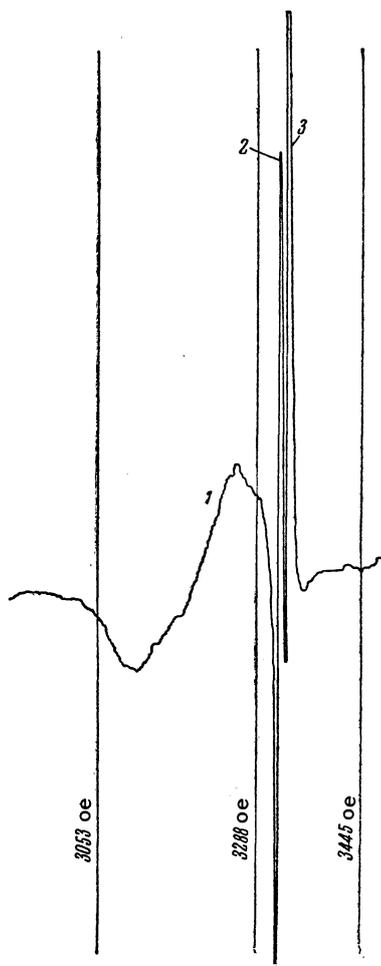
FIG. 1. Record of the experimental observation of paramagnetic resonance. Signals from three sources are seen: 1 – from the copper parts of the resonator, 2 – from diphenyl picryl hydrazyl, 3 – from single-crystal tin. The scale of the ordinate axis is proportional to the logarithmic derivative of the impedance of the sample with respect to the magnetic field, plotted along the abscissa.

FIG. 2. Paramagnetic resonance of the conduction electrons of single-crystal tin (on the right), recorded simultaneously with the calibration signal of the paramagnetic resonance of diphenyl picryl hydrazyl. The variables along the coordinate axes are the same as in Fig. 1.

picryl hydrazyl

$$(g_{Sn} - g_d) / g_d = (H_d - H_{Sn}) / H_{Sn} = - (4.55 \pm 0.15) \cdot 10^{-3},$$

from which $g_{Sn} = 1.9945 \pm 0.0003$ (here H_d and H_{Sn} are the resonance values of the magnetic field).

The experiments described yield interesting data on the electron-spin relaxation times in single-crystal tin. Estimating the relaxation time T_2 after Dyson[2] as the reciprocal of width ΔH of the paramagnetic resonance line, which is ~ 4.5 oe (Fig. 2), we obtain $T_2 \sim 1.2 \times 10^{-8}$ sec. The more precise expression found by Kittel and derived in reference 1 gives

$$T_2 = 1.35 / \gamma \Delta H \approx 1.7 \cdot 10^{-8} \text{ sec}$$

(γ is the gyromagnetic ratio). This value of T_2 is, however, underestimated by $20-30\%$ as a result of the line broadening due to the fact that the peak amplitude of modulation of the magnetic field was 1.7 oe. (For this reason the resonance line of diphenyl picryl hydrazyl in Fig. 2 is also broadened to ~ 2 oe.)

Considering the interaction of the spins with the lattice vibrations by means of orbital momen-

tum, Elliot[8] found, that the corresponding relaxation time T_1 must be proportional to $\tau_R / (\Delta g)^2$ where τ_R is the electron mean-free-path time, estimated from the conductivity of the metal, and Δg is the deviation of the g factor of the electrons of the material from its value for a free electron. (A relaxation of this character was obtained by taking account of the scattering of electrons on impurities in the case of semiconductors.)

A more exact calculation of this effect was carried out by Andreev and Gerasimenko.[9] However, it is impossible to use their formulae to calculate T_1, for they took into account only the interaction of the electrons with the lattice vibrations, whereas under the conditions of the experiment the principal scattering was by the impurities. It can be noted only that T_1 must be large because of the large value of $\tau_R \approx 10^{-9}$ sec in the sample investigated, which indicates weak interaction between the electrons and the lattice. The value of τ_R in the experiments of Feher and Kip[1] was on the order of 10^{-14} sec.

The relaxation time $T_2 \approx 1.7 \times 10^{-8}$ sec means that the free path of the electron without changing spin orientation reaches 1 or 2 cm, whereas the electron free path determined by the conductivity of the metal is $l \approx 0.1$ cm. For a sample thickness of 0.1 cm this means that the electron can traverse the samples repeatedly, retaining its spin direction both as it collides within the metal and as it is scattered on its surface. This conclu-

sion can also be drawn from the results of Feher and Kip.[1]

However, for metal particles that are smaller than the depth of penetration of the electromagnetic field, these circumstances are not of such importance, whereas in the case of bulk metal they may be of decisive importance in polarizing the nuclei of the metal by Overhauser's method,[10] as discussed by Azbel' et al.[3] From their results it follows that in paramagnetic resonance of the metal electrons significant polarization of the nuclei in the bulk metal should take place to a depth

$$\delta \sim l \, (T_2 / \tau_R)^{1/2} \approx 0.3 \text{ cm}.$$

Consequently, in a specimen 0.1 cm thick, with a high-frequency field applied at both sides, the polarization of the nuclei must be practically uniform throughout the volume. Since the sample thickness is less than the depth of spin diffusion δ, saturation of the resonance must be achieved in high-frequency fields which are significantly smaller than in the case of samples with thickness large compared to δ. This consideration clearly permits a significant reduction in the power rating of the generator and the expected Joule heating of the sample, which is of considerable experimental importance.

[1] G. Feher and A. F. Kip, Phys. Rev. **98**, 337 (1958).

[2] F. J. Dyson, Phys. Rev. **98**, 349 (1955).

[3] Azbel', Gerasimenko, and Lifshitz, JETP **32**, 1212 (1957), Soviet Phys. JETP **5**, 986 (1957).

[4] Azbel', Gerasimenko, and Lifshitz, JETP **35**, 691 (1958), Soviet Phys. JETP **8**, 480 (1959).

[5] V. B. Zernov and Yu. V. Sharvin, JETP **36**, 1038 (1959), Soviet Phys. JETP **9**, 737 (1959).

[6] M. S. Khaĭkin, JETP **37**, 1473 (1959), Soviet Phys. JETP **10**, 1044 (1960).

[7] M. S. Khaĭkin, Приборы и техника эксперимента (Instrum. and Exp. Techniques), in press.

[8] R. J. Elliott, Phys. Rev. **96**, 266 (1954).

[9] V. V. Andreev and V. I. Gerasimenko, JETP **35**, 1209 (1958), Soviet Phys. JETP **8**, 846 (1959).

[10] A. W. Overhauser, Phys. Rev. **92**, 411 (1953), G. R. Khutsishvili, Usp. Fiz. Nauk **71**, 9 (1960), Soviet Phys.-Uspekhi **3**, 285 (1960).