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1961

SovietRxiv

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PARAMAGNETIC RESONANCE OF CONDUCTION ELECTRONS IN COPPER*

(Presented by Academician I. K. Kikoin on 24 IX 1960)

Over the past 15 years numerous works have appeared devoted to the study of electron paramagnetic resonance (e.p.r.) in condensed media; however, this phenomenon has been poorly studied for the metallic state. To date, several papers have been published in which the results of studies of e.p.r. in alkali metals and their alloys are presented ([1−9]). Attempts to detect resonance in other metals were unsuccessful, since the spin relaxation time of the conduction electrons is substantially shorter than the relaxation time of the conduction electrons in alkali metals ([6]).

The theory of electron resonance absorption, developed by Dyson ([10]), describes well Kipp' s experimental results for the group of alkali metals. In particular, Dyson' s theory predicts a dependence of the absorption-line shape on the ratio of the spin relaxation time T_{sp} and the diffusion time of electrons T_{d} from the skin layer into the depth of the metal. If these times differ substantially and $T_{\text{sp}} \gg T_{\text{d}}$ (this condition is satisfied for alkali metals), the absorption line is a superposition of two curves: a narrow line with half-width of order $\Delta\nu_1 \sim T_{\text{sp}}^{-1}$ and a broad one with $\Delta\nu_2 \sim T_{\text{d}}^{-1}$.

The shape of the narrow line proves to be asymmetric with respect to the resonant value of the field, and the asymmetry increases as $T_{\text{d}}/T_{\text{sp}} \to 0$. The conclusion of the theory concerning the asymmetry of the absorption line was confirmed experimentally ([6]).

In the present communication we describe experiments on the study of the dependence of the surface resistance of copper in a magnetic field H for a frequency $\nu = 3.6 \cdot 10^{10}$ Hz, carried out with the aim of observing e.p.r. The sample for the study was a copper resonator of waveguide type, made of pure electrolytic copper** with a value $R_{4.2^\circ\text{K}}/R_{300^\circ\text{K}} < 10^{-3}$, which, however, because of deformation of the copper in the process of fabricating the resonator, changed to the value $R_{4.2^\circ\text{K}}/R_{300^\circ\text{K}} = 10^{-2}$. Before the study, the surface of the resonator was carefully etched and electrolytically polished.

The quality factor of the resonator as a function of magnetic field was measured at three temperatures: room, nitrogen, and helium.

Fig. 1

Figure 1: Fig. 1

Figure 1 shows the change in the ratio of the surface resistance in a field and without a field, $R(H)/R(0)$, as a function of the magnetic-field strength H for a copper resonator at temperatures 77 and 4.2° K. As is seen from these curves, the surface resistance of the resonator has a maximum in a magnetic field. From the magnetic-field strength at the maximum, the g-factor was determined; it has the value ~ 2.1.

* The work was reported at the XIII All-Union Conference on Spectroscopy in June 1960.

** We express our gratitude to Prof. D. P. Zosimovich for providing very pure copper foil, prepared in the laboratory of the Institute of Inorganic Chemistry of the Academy of Sciences of the Ukrainian SSR.

It should be noted that the shape of the absorption line depended substantially on temperature; the intensity of the line with g-factor 2.1 increased somewhat as the temperature was lowered, whereas the more broadened line became wider and at helium temperature practically disappeared.

Since, generally speaking, two mechanisms of resonance absorption are conceivable—paramagnetic resonance on impurities and resonance on conduction electrons—it was of interest to clarify the nature of the observed lines. For this purpose the temperature dependence was studied for the intensity of the line produced by the copper resonator and of the absorption line of the radical.

Fig. 1

As is known, for paramagnets the line intensity increases strongly as the temperature is lowered, whereas conduction electrons, because of the degeneracy of the electron gas, give absorption that is independent of temperature.

As a result of the experiment it turned out that the intensity of the radical line, when the temperature is changed from 77 to 300° K, decreases by 4 times, while the intensity of the absorption line produced by the resonator remains practically constant. Thus, within Dyson' s theory, the experimental results obtained may be interpreted as meaning that the line with $g = 2.1$ is due also to the mechanism of spin relaxation of conduction electrons. The narrowing of this line with decreasing temperature is apparently connected with an increase in the spin-relaxation time to the values $T_{\text{sp}} = 1.7 \cdot 10^{-10}$ sec at 300°K; $2.1 \cdot 10^{-10}$ sec at 77°K and $4.2 \cdot 10^{-10}$ sec at 4.2°K, while the broadening of the second absorption line is caused by a decrease in the diffusion time of electrons from the skin layer into the metal.

It should be said that the shape of the absorption line is unclear, since according to Dyson the line should be highly asymmetric. The experiment (especially at $T = 4.2°K$) gives a symmetric absorption line. However, the theory is constructed under assumptions that are not realized experimentally. Indeed, in the theory it is assumed that the spin-relaxation time T_{sp} is 4–5 orders of magnitude larger than the time between collisions of electrons with phonons τ, whereas in the experiment $T_{sp}/\tau \sim 10^2$. In addition, the theory is constructed under the assumption $\mu H \ll kT$, while at helium temperatures $\mu H \sim kT$. The theory also assumes independence of the diffusion mechanism from the magnetic field H, whereas in fields of 10^4 oersted and $T \sim 4°K$ this influence should manifest itself. It is possible that taking all these circumstances into account may lead to a line shape different from that which follows from Dyson' s theory.

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Received
23 IX 1960

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Note: Figure translations are in progress. See original paper for figures.