ROLE OF INTERELECTRON COLLISIONS IN THE ELECTRIC RESISTANCE OF TRANSITION METALS

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We measured the temperature dependence of the electric resistance of yttrium, zirconium, niobium, molybdenum, lanthanum, lutetium, hafnium, tantalum, tungsten, rhenium, and iridium in the temperature range 0.38–70°K (for superconductors, the lower measurement-temperature limit was governed by T_c). We separated the contribution made to the electric resistance of these metals by the interelectron collisions. The magnitude of this contribution correlates qualitatively with the magnitude of the electronic specific heat.

1. FORMULATION OF PROBLEM

CONDUCTION electrons in a metal experience electrostatic interaction with one another, which can be described by a screened Coulomb potential. The electron-electron interaction is sufficiently large and comparable with other types of interactions in the metal. This circumstance leads to the appearance of singularities in a number of properties of metals, primarily in the kinetic properties. These singularities cannot be explained without taking into account the interaction between the electrons, which leads to the occurrence of an additional mechanism of electron-electron scattering.

The influence of the electron-electron interaction on the electric resistance of non-transition metals, the conduction electrons of which are characterized by a quadratic isotropic dispersion law (for example, sodium), was theoretically considered in [1-4]. It follows from these investigations that the electron-electron resistance ρ_{ee} should be proportional to the square of the temperature, but this mechanism of conduction-electron scattering can make a noticeable contribution only if electron-electron Umklapp processes take place during the scattering, as a result of which the summary wave vector of the interacting electrons is replaced by the reciprocal-lattice vector. If there are no Umklapp processes and only normal electron-electron processes are significant, then ρ_{ee} is negligibly small. Estimates made in [2-4] show that for sodium at $T = 4°K$ the electric resistance due to the interelectron collisions without account of the Umklapp processes amounts to 3×10^{-5} of the electron-phonon resistance. No T^2 dependence was ever observed in univalent non-transition metals (Na, K, Cu, Au, Ag).

A different situation arises in transition metals, whose electronic subsystem is characterized by several groups of carriers with different effective masses. If it is assumed that the electronic subsystem is not closed (for example, the "heavy" carriers rapidly transfer the acquired momentum to the lattice), then the collisions of the "light" carriers with the low-mobility "heavy" carriers should strongly influence the conductivity of the metal (at low temperatures). It was shown theoretically in [4,5] that the electric resistance due to the electron-electron collisions is proportional to T^2 and increases with increasing effective mass of the "heavy" carriers. At low temperatures, ρ_{ee} may turn out to predominate in the total temperature-dependent part of the transition-metal resistance.

According to calculations,[5] an appreciable contribution of electron-electron scattering should become particularly strongly manifest in the electric resistance of transition metals whose electronic subsystem contain groups of carriers with large effective masses. Consequently, proceeding along the period from one transition metal to the adjacent one, it is quite probable that a correlation will be observed between the values of ρ_{ee} and the electronic specific heat. It should be mentioned that one can expect a purely qualitative correlation, since ρ_{ee} is determined not only by the values of the effective masses of the carriers, but depends also on the screening constant and on the Fermi energy, as well as on the probability of the electron-electron Umklapp processes.

Experimental information on the influence of electron-electron collisions on the electric resistance of transition metals is quite limited. Until now, the only transition (nonferromagnetic) metals in which a $\sim T^2$ dependence of the electric resistance could be observed were Mo,[6,7] W,[6] Nb, Pd,[8] Pt,[8,9] Re,[10] and Os.[11] As to the series of experimental investigations by White and Woods (see their review article, [8], they did not separate the contribution to the electric resistance by electron-electron scattering, with the exception of Nb, Pd, and Pt.

In view of the patent lack of experimental data, it is of interest to measure $\rho(T)$ in a number of 4d and 5d transition metals for the purpose, first, of separating the contribution made to the electric resistance by the electron-electron collisions and, second, to attempt to establish a correlation between the coefficient of T^2, which determines the magnitude of this contribution, and the coefficient γ in the electronic specific heat.

For a correct solution of this problem, in our opinion, it is necessary to satisfy the following experimental requirements.

1. The measurements must be carried out at temperatures where ρ_{ee} is larger than or at least of the

Metal	Orientation of sample axis, deg ⟨100⟩	⟨110⟩	⟨111⟩	Chemical purity (at.%)	$\frac{\rho\,(300°\,K)}{\rho\,(4.2°\,K)}$
Y	Polycrystal			99.9	10
Zr	Polycrystal			99.9	34
Nb	39	12	28	99.9	21 *
Mo-7 **	34	16	27	~99.9999	5050
La	Polycrystal			99.9	24 *
Lu	Polycrystal			99.9	15
Hf	Polycrystal			99.9	32
Ta	38	7	33	99.99	190 *
W-1 **	16	31	40	>99.9999	20800
	⟨0001⟩	⟨$\bar{1}$010⟩	⟨1$\bar{2}$10⟩		
Re	82	15	19	99.999	2200
Ir	40	18	20	99.99	151

*For Nb, La, and Ta, which become superconducting at $T > 4.2°K$ (the T_c of these metals are respectively 9.2, 5.8 and 4.3°K), the table gives the ratio $\rho(300°K)/\rho(T_c)$.

**The temperature dependence of the electric resistance of Mo was measured in 13 samples with $\rho(300°K)/\rho(4.2°K)$ ratios from 85 to 5050, and that of W in seven samples with ratios $\rho(300°K)/\rho(4.2°K)$ from 66 to 20 800.

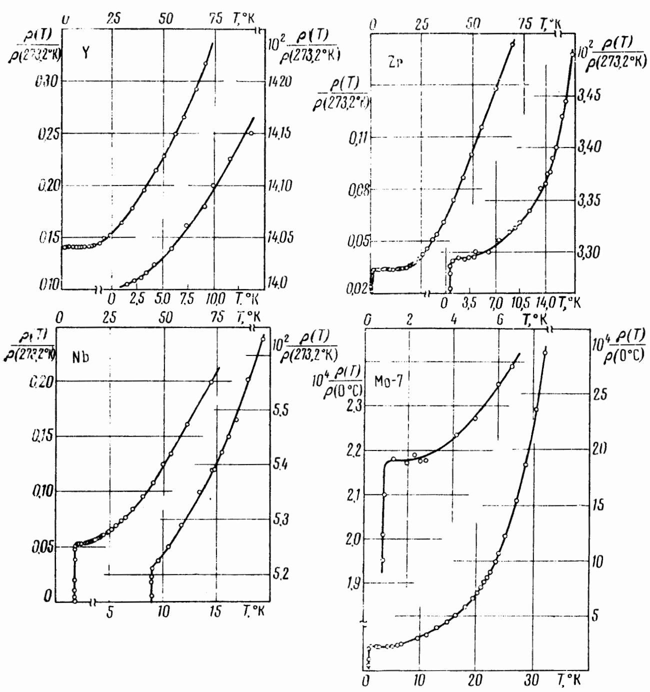

FIG. 1. Temperature dependence of the electric resistance of 4d transition metals.

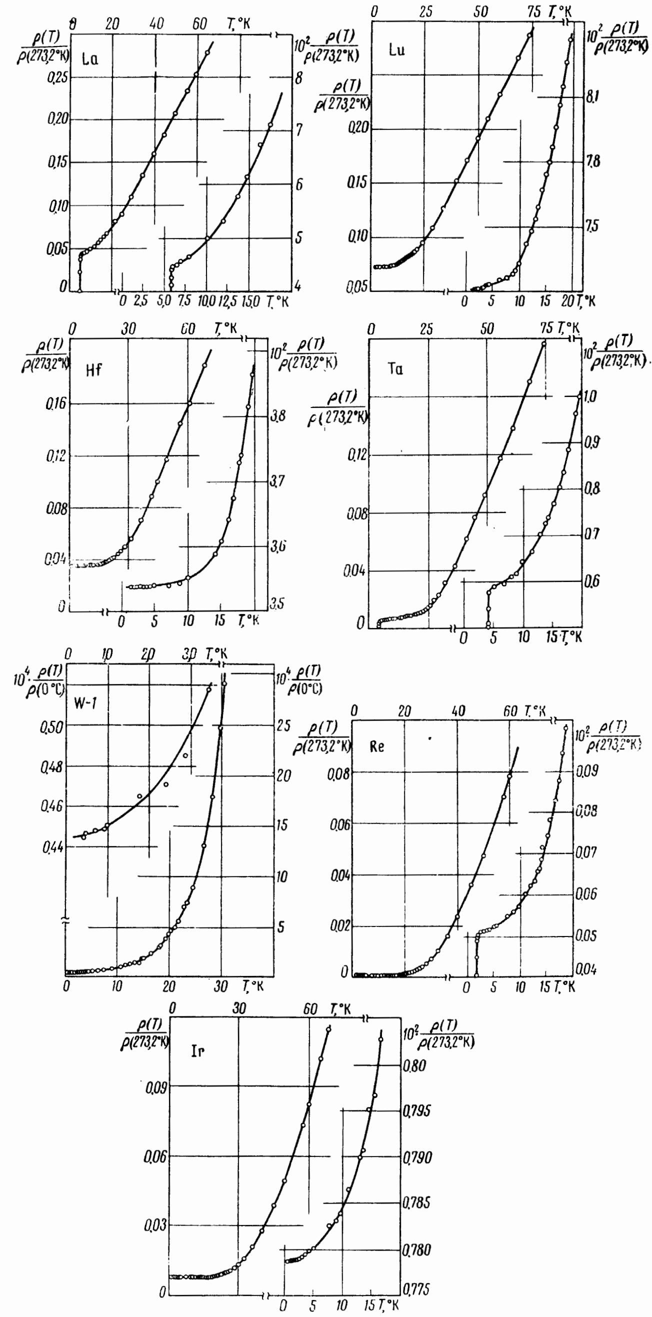

FIG. 2. Temperature dependence of the electric resistance of 5d transition metals.

same order as the contribution made to the resistance by the electron-phonon interaction (ρ_{eph}). This condition is perfectly attainable. For example, it follows from our measurements that $\rho_{ee} \approx \rho_{eph}$ for Ta at $T \approx 22°K$, for W at 19°K, and for Re at 13°K.

2. The transverse dimensions of the samples should greatly exceed the mean free path of the conduction electrons, so that the scattering of the latter by the boundaries of the sample (the size effect) will make no appreciable contribution to the electric resistance.

3. The measuring current should be low enough for its magnetic field not to produce the galvanomagnetic effect.

The foregoing requirements were satisfied.

2. MEASUREMENT RESULTS

We measured the temperature dependence of the electric resistance of 4d and 5d transition metals (yttrium, zirconium, niobium, molybdenum, lanthanum, lutetium, hafnium, tantalum, tungsten, rhenium, and iridium) at temperatures 0.38–70°K. For comparison, we measured the temperature dependence of the electric resistance of copper.

Y, Zr, La, Lu, Hf, and Re have a hexagonal lattice and consequently have a strong anisotropy of the electric resistance. To obtain values of $\rho(T)$ averaged over different crystallographic directions, we used polycrystalline samples of these metals. Nb, Mo, Ta, W, Ir, and

Cu have a cubic lattice and the electric resistance of these metals is isotropic in the absence of a magnetic field. The samples of these metals were single crystals grown by the crucibleless zone melting method with heating of the zone by electron bombardment. The characteristics of the samples are listed in the table, and the results of the measurements of the electric resistance are given in Figs. 1 and 2.

Typical dependences of the "ideal" electric resistance on the temperature in a logarithmic scale are shown in Fig. 3. This figures shows the transition from the T^5 dependence, which characterizes the "lattice" resistance, to the T^2 dependence, which obtains at sufficiently low temperatures ($\sim 10°$K).

An analysis of the results has shown that the temperature dependence of the electric resistance of the investigated metals cannot be described by the expression $\rho(T) = \rho_0 + bT^5$, but at $T < \Theta/10$ it follows very well an expression that includes, in addition to the two indicated mechanisms, also the scattering of the conduction electrons as a result of electron-electron collisions:

$$\rho(T) = \rho_0 + aT^2 + bT^5.$$

A criterion of the fit of the measured $\rho(T)$ dependence at $T < \Theta/10$ to the formula given above may be found in the following method of reducing the experimental data. If we use $[\rho(T) - \rho_0]/T^2$ as the ordinates and T^3 as the abscissas, then the result should be a straight line intercepting the ordinate axis at a; the slope of this line is equal to the coefficient b. The experimental data reduced by this method do indeed fit a straight line. A typical plot is shown in Fig. 4. For greater reliability, the measured $\rho(T)$ dependences were reduced in accordance with the foregoing formula with an electronic

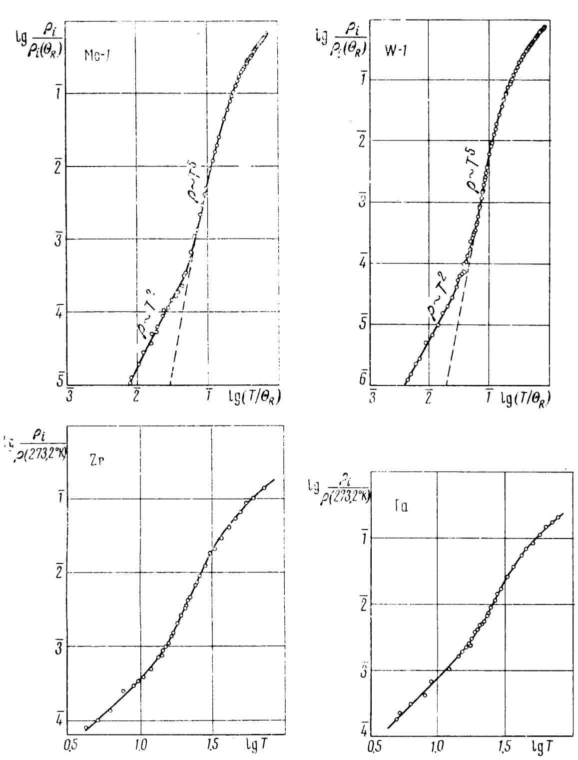

FIG. 3. Dependence of log ρ_i(T) on log T for Mo, W, Zr, and Ta.

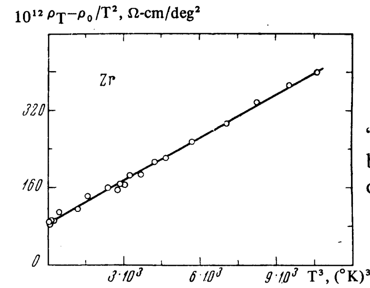

FIG. 4. Dependence of the "ideal" electric resistance, divided by the square of the temperature, on T^3 for Zr.

computer by least squares. Both reduction methods gave identical results.

For Cu in the region of helium temperatures we observed no deviations of the temperature dependence of the electric resistance from the T^5 law, a fact that would indicate the existence in this metal of a conduction–electron scattering mechanism connected with the electron–electron collisions.

The data obtained on the electric resistance of 4d and 5d metals show that in the temperature-dependent part of the electric resistance of all the investigated metals, at temperatures below $\sim 10°$K, the predominant role is played by scattering of conduction electrons resulting from electron–electron collisions.

Figure 5 shows a comparison of the values obtained for the coefficients a and the coefficients γ in the electronic specific heat. As expected, a correlation between these quantities is observed, especially at the beginning of the periods.

Unfortunately, not all the samples had as high a purity as the Ta, Re, and the purest Mo and W crystals, whose ratios $\rho(273°K)/\rho(4.2°K)$ were of the order of thousands or even tens of thousands. The presence of even small amounts of impurities can, generally speaking, influence the values of the coefficients a and b since, according to [12], the scattering of the conduction electrons by a vibrating impurity ion leads at low temperatures to an additional contribution to the electric resistance of the metal, proportional to T^2 and to the concentration of the impurities. In order to estimate this effect, we measured $\rho(T)$ of Mo and W using samples of different purity, with ratios $\rho(273.2°K)/\rho(4.2°K)$ from 66 to 20 800. It turned out that the values of a differ by not more than 30%, and those of b by 7%. However, even with such a variation in the values of the coefficient a, the obtained correlation between a and γ remains in force.

In addition, we determined the coefficients a and b for Mo and W from the "ideal" $\rho_i(T)$ dependence obtained by extrapolating the values of the electric resistance, measured in samples of different purity, to an "infinitely" pure sample, and showed that an important fraction of the contribution to the electric resistance, proportional to T^2, is not connected with the presence of impurities in these samples, but is determined by the electron-electron collisions.

Thus, the temperature-dependent part of the electric resistance of transition metals at sufficiently low temperatures is determined practically completely by the scattering of the conduction electrons as a result of electron-electron collisions, and the value of the coef-

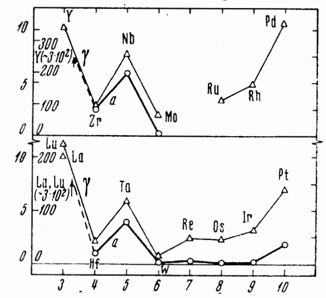

FIG. 5. Values of the coefficients a(O) and (Δ) for 4d and 5d transition metals (the values of a for Os and Pt were taken from [11] and [9]).

ficient a characterizing this scattering mechanism correlates with the value of the coefficient γ in the electronic specific heat.

In conclusion, we note that the existing theoretical calculations of ρ_{ee} for transition metals, which describe this scattering mechanism qualitatively correctly, were performed with considerable model-connected simplifications. A rigorous description of the electric resistance due to electron-electron collisions is possible only on the basis of a theory that takes into account the electronic structure and the topological features of the Fermi surface of the particular metal.

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