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NORMAL STATE RESISTANCE BEHAVIOR AND SUPERCONDUCTIVITY*

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It is found experimentally that s–d superconductors have anomalous curvatures in the temperature dependence of the normal state resistivity.

IN THE investigation of superconducting materials it is of interest to isolate those normal state physical characteristics which may be closely related to the material's superconductivity, but no normal state property has ever been successfully correlated with the occurrence of superconductivity. We suggest here that the temperature dependence of the normal state electrical resistivity (ρ) can be used to categorize many compounds and elements with respect to their superconductivity.

At temperatures much less than the Debye temperature, the Bloch–Grüneisen theory predicts $\rho_i \equiv (\rho - \rho_0) \propto T^5$, where ρ_0 is the residual term. When s–d scattering dominates, Wilson's theory[1] predicts $\rho_i \propto T^3$. A combination of these two extremes presumably applies when both s–s and s–d scattering are important. In both cases, however, when well above the Debye temperature, ρ_i should become proportional to T, i.e. to the number of phonons present. Such considerations do not apply if magnetic phenomena (ordering, level repopulation) occur.

While numerous arguments suggest that the Bloch and Wilson theories are crude approximations within their respective domains, the resistance behavior of many metals (elements and, in our experience, intermetallic compounds) can be well fitted with a resistive 'Debye temperature,' θ_R, which varies little with temperature.

There is, however, a large class of superconductors containing transition or f-metals which show gross deviations from these simple theories. This sort of resistance behavior is typified by the data (Fig. 1) for Zr_2Rh ($T_c = 11.3$°K), U_6Fe ($T_c = 3.9$°K) and La_3Co ($T_c = 4.3$°K). Near T_c, $\rho_i \propto T^3$. This region is followed by one of strong negative curvature ($d^2 \rho_i \propto T^3 < 0$). At room temperature, the curve is less than linear in T and does not at all conform to the Wilson (or Bloch)

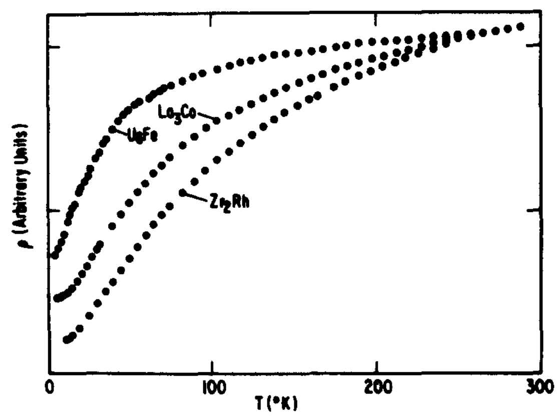

FIG. 1. ρ vs T for the superconductors Zr_2Rh, U_6Fe and La_3Co.

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form which requires smooth joining of the low temperature region, via a region of slight negative curvature, into the high temperature region in which $\rho_i \propto T$.

The morphology of these curves is strikingly similar to that of the resistance of V_3Si, Nb_3Sn and other high T_c β-*W*'s. Cohen *et al.*[2] have nicely fitted the resistance data for these superconductors using a modified *s–d* model in which there is considerable temperature-dependent Fermi-level motion due to the presence of a nearly empty or full high density of states *d*-band overlying a low density of states *s*-band Such a model fits the Zr_2Rh resistance data equally well.

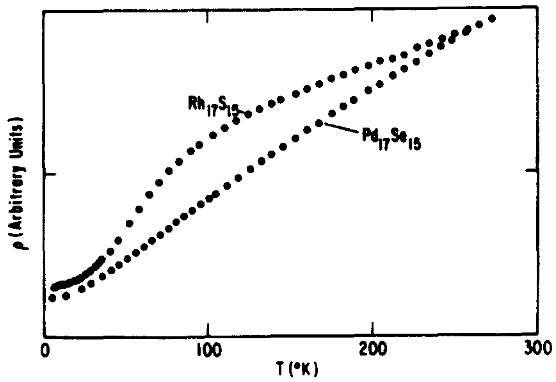

FIG. 2. ρ vs T for isostructural $Rh_{17}S_{15}$ ($T_c = 5.8$°K) and $Pd_{17}Se_{15}$ (no T_c to 1.00°K).

We illustrate the generality of this sort of behavior with further examples. Resistance data for $Rh_{17}S_{15}$ ($T_c = 5.8$°K) and isostructural $Pd_{17}Se_{15}$ (no T_c to 1.00°K) are shown in Fig. 2. For both compounds, $\rho_i \propto T^3$ at low temperatures, but the non-superconducting $Pd_{17}Se_{15}$ data follow the Wilson theory closely: $\theta_R = 126 \pm 6$°K over the range 20°K $< T <$ 295°K; the strongly curved resistance of $Rh_{17}S_{15}$ does not.

Figure 3 presents our data for isostructural La_3In ($T_c = 10.4$°K) and $LaIn_3$ ($T_c = 0.7$°K). In this case, $\rho_i \propto T^3$ for La_3In, but $\propto T^5$ for $LaIn_3$. The situation is similar (Fig. 4) for the isostructural and isoelectronic pair, YB_6 ($T_c = 6.8$°K) and LaB_6 (no T_c to 1.5°K). Here ρ_i varies as T^5 for LaB_6, and as T^3 for YB_6. The large ρ_0 of YB_6 obscures the curvature to some extent, but the difference between the two curves is evident.

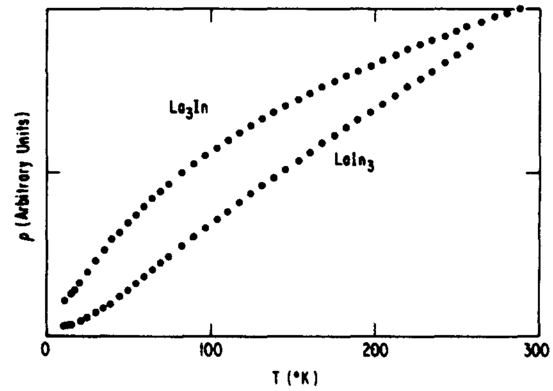

FIG. 3. ρ vs T for isostructural La_3In ($T_c = 10.4$°K) and $LaIn_3$ ($T_c = 0.7$°K). At low temperature, $\rho_i \propto T^3$ for La_3In, $\propto T^5$ for $LaIn_3$.

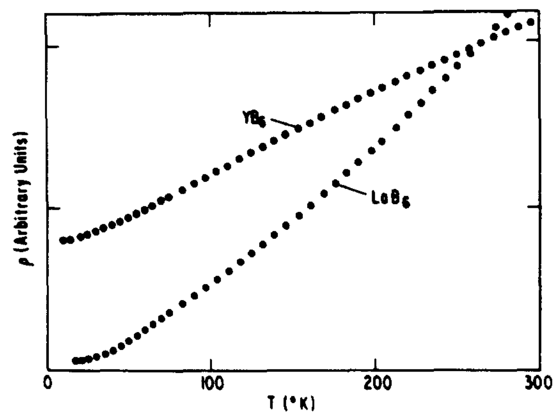

FIG. 4. ρ vs T for isostructural LaB_6 (no T_c to 1.5°K) and YB_6 ($T_c = 6.8$°K).

Thus far in our investigations, all superconductors with a resistance ratio > 2 which we have measured show this curvature provided $\rho_i \propto T^3$ at low temperatures. Exceptions occur when the scattering is dominated by impurities or vacancies; in these cases the phonon term is obscured, and Cohen's model predicts $d\rho/dT < 0$. $NbN_{0.9}$ exemplifies this behavior (Fig. 5). Other possible examples are <u>Mo</u>U,[3] <u>Ti</u>Mo,[4] TiO,[5] and Re χ-phases.[6] Examples of superconductors which show no curvature and have $\rho_i \propto T^5$ are $CoSi_2$ and $LaIn_3$ (mentioned above). This last group we wish to class separately as *s–p* superconductors. We also notice that elements which superconduct only under pressure (Y, Ba and Ce, for example) show equally marked changes in $\rho(T)$ as pressure is applied.[7] Finally, we mention here the resistance measurements of Clinard

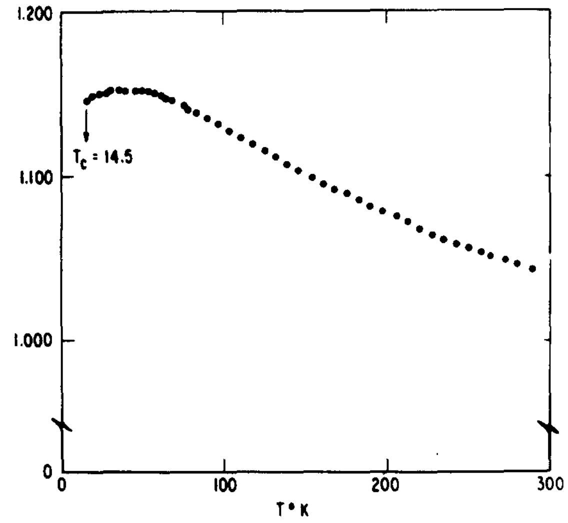

FIG. 5. ρ vs T for $NbN_{0.9}$ (T_c = 14.5°K).

and Kempter[8] on carbides which show again the difference between superconducting and non-superconducting materials.

We wish to emphasize that we have measured the electrical resistivities of many more superconductors than indicated here or elesewhere,[9,10] and our measurements show that the correlation between curvature of resistivity and superconductivity is a rule with very few exceptions. No doubt more exceptions will be discovered, but we are confident that they will not disprove the rule.

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Es wurde experimentell gefunden dass *s–d* Supraleiter abnormale Krümmung in der Temperaturabhangigkeit des Widerstandes im normalen Zustand haben.