CONDUCTIVITY OF QUASI-ONE-DIMENSIONAL CRYSTALS IN THE METALLIC PHASE

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Features of the conductivity of quasi-one-dimensional crystals in the metallic phase are considered.

Detailed experimental reports on organic complexes based on TCNQ have recently been published [1 - 3]. The most important result is the observation of so-called "phase transitions" into an antiferromagnetic state [1, 2] or of a Peierls transition [3]. The latter is of particular interest in view of the connection previously noted [4, 5] between the structural instability and the possible appearance of phenomena of the superconductivity type. There is still no theory of fluctuations in a quasi-one-dimensional metal (see [4, 5]). We confine ourselves here only to sufficiently high temperatures, when the fluctuations do not play an essential role, but nevertheless the behavior of all physical quantities exhibits certain singularities inherent in one-dimensional systems (see also [5, 6]).

We consider the conductivity of such systems in the temperature region where the kinetic equation is still valid, i.e., at $\hbar \ll \tau T$. In our case this condition means weakness of the interaction of the electrons with the phonons and of the electrons with one another, or else smallness of the defect concentration.

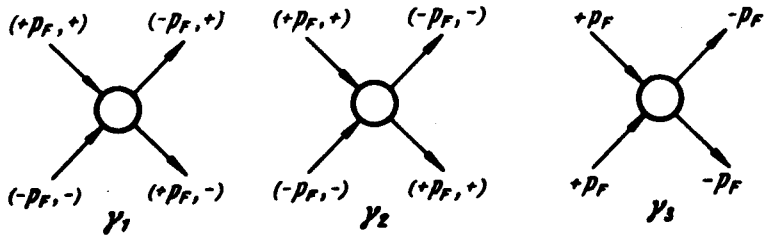

Fig. 1

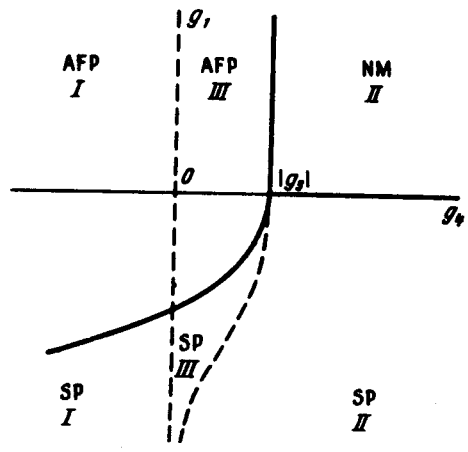

Fig. 2

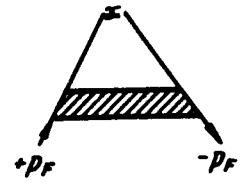

Fig. 3

The conductivity is determined, as always, by three mechanisms — impurity, electron-phonon, and electron-electron. An important distinguishing feature of the last two mechanisms is that the Fermi surface reduces to two points in the reciprocal lattice $\{-p_F, +p_F\}$. There is therefore no diffusion relaxation of the momentum, and the resistance is always determined by a direct transition of the electron from the point $-p_F$ to $+p_F$. The electron-phonon time at low temperatures is exponentially large

$$\tau_{eph}^{-1} \sim \exp|-\omega_0(2p_F)/T|,$$

where $\omega_0(k)$ is the phonon spectrum. For the same reason, an exponential factor appears also in τ_{ee}^{-1}, provided that the number of electrons per cell is not exactly equal to unity, when $2p_F = \pi/a$ (a is the lattice period) and the transition from p_F to $-p_F$ is made possible by Umklapp processes without a change of energy.

The non-exponential behavior of the relaxation time takes place in the considered simple model at temperatures higher than the Debye temperature ($T \gg \omega_D$), and in the case of exactly one electron per cell it occurs also at $T \ll \omega_D$. The latter takes place apparently in the experimentally investigated NMP - TCNQ [2] and TTF - TCNQ [3]. Let $T \ll \omega_D$, and let the effective mechanism be electron-electron scattering or scattering by defects. To avoid misunderstanding, we emphasize that in a one-dimensional system the repulsion integral for the first of these mechanisms, without allowance for the interaction effects described below, yields precisely $\tau_{ee}^{-1} \propto T$, and not $\tau_{ee}^{-1} \propto T^2$, as in the two- and three-dimensional cases. However, neither τ_{imp} nor $\tau_{ee}T$ remains constant at $T \ll \varepsilon_F$. The reason is that in the one-dimensional case all the scattering amplitudes γ are slowly-varying functions of the logarithm of the temperature (or energy) $\xi \equiv \ln(\varepsilon_F/T)$.

As shown in [5], the properties of the state are determined by three amplitudes, $\gamma_1(\xi)$, $\gamma_2(\xi)$, and the Umklapp amplitude $\gamma_3(\xi)$, which are shown in Fig. 1 (the $\pm$ signs designate the spin projections). Depending on the relation between the initial constants g_1, g_2, and g_3, the system can remain a normal metal (NM), or some type of instability can develop in it, such as a combination of superconducting and Peierls (SP) instability or a combination of antiferromagnetic and Peierls (AFP) instability. The thick solid lines of Fig. 2 show schematically the boundaries between the regions on the plane $g_4 = g_1 - 2g_2$, g_1.

The electron-electron time is

$$\tau_{ee}^{-1} \sim T|\gamma_3(\xi)|^2. \qquad (1)$$

Formulas for γ_3 are given in [5]. An investigation of these formulas shows that $\tau_{ee}T$ can behave in three ways with increasing $\ln T$: monotonic growth (I), decrease (II), and a curve with a maximum (III). The boundaries between regions I, II, and III are shown in Fig. 2 by dashed lines. In the Hubbard model, when $g_1 = g_2 = g_3 = g_4 = g$, we have (see [5])

$$T\tau_{ee} \sim (1 - g\xi)^2 \qquad (1')$$

For impurity relaxation, similar calculations [5, 6] yield

$$\tau_{imp}^{-1} \sim \exp\left\{ -\int_0^{\xi} \left[\frac{3}{2}\gamma_1(\eta) + \frac{1}{2}\gamma_4(\eta) + \gamma_3(\eta) \right] d\eta \right\} . \qquad (2)$$

The nature of the resultant renormalization factors is clear from Fig. 3, which shows the inserts corresponding to the electron interactions in impurity scattering with momentum transfer $2p_F$. At different ratios of g_1, g_2, and g_3, the time τ_{imp} as well as $\tau_{ee}T$ can exhibit all three types of dependences on lnT. In Hubbard's model we have

$$\tau_{imp} \sim (1+g\xi)^{3/2}(1-g\xi)^{-1/2}, \qquad (3)$$

i.e., τ_{imp} decreases when the superconducting instability region is approached (this behavior is typical of the Kondo effect), and increases in the case of the antiferromagnetic instability.

The amplitude of the electron-phonon interaction, which turns out to be significant at $T \gg \omega_D$, is likewise renormalized in accordance with Fig. 3. Therefore $1/T\tau_{eph}$ is determined in this region by formula (2).

The conductivity data used in the experiments [1 - 3] is insufficient to determine the parameters in the logarithmic formulas (1) and (3). The metallic behavior of the conductivity in TTF - TCNQ [3] above the transition is in qualitative agreement with (1).

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