Power law field dependence of the 2D magnetoresistance in $(TMTSF)_2PF_6$

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Abstract. The magnetoresistance of the quasi-one-dimensional organic conductor $(TMTSF)_2PF_6$ is studied for currents flowing parallel to the best conducting a and second best conducting b directions in magnetic fields perpendicular to the a-b plane under a hydrostatic pressure of 0.8 GPa. As a function of the magnetic field, the magnetoresistance follows a power law $\Delta R/R = (B/B_0)^{3/2}$ both in the a and b directions. The a-b plane conductivity anisotropy is field independent. The scaling field B_0, characterizing the strength of the magnetoresistance, follows an exponential temperature dependence $B_0 \propto \exp(T/T_0)$ with a field-independent characteristic temperature $T_0 = 10$ K.

The problem of the magnetoresistance in the quasi-one-dimensional organic conductor $(TMTSF)_2PF_6$ continues to receive considerable attention because there are indications that Fermi liquid (FL) theory is inappropriate to describe the peculiar behavior of this strongly correlated metal in a magnetic field [1,2]. The anisotropy of the electronic properties is well characterized by the room-temperature conductivities along the well conducting chains (a direction) and perpendicular to the chains (b and c directions): $\sigma_{aa} : \sigma_{bb} : \sigma_{cc} = 90 : 1 : (1/700)$ with $\sigma_{aa} \approx 1000\ \Omega^{-1}\mathrm{cm}^{-1}$ [3]. Without a magnetic field and at low enough temperatures, the transport properties are consistent with a three-dimensional (3d) FL state [4]: The anisotropies are temperature independent below about 80 K down to the temperature of the transition to a spin-density wave (SDW) insulator state at $T_{SDW} = 12$ K, and the temperature dependence of the resistivities is well described by a power law T^{α} with the exponent α close to 2. The transport in a magnetic field, on the other hand, is very difficult to understand in the framework of FL theory [1,2].

The magnetoresistance is best studied if the SDW transition is suppressed by applying a hydrostatic pressure. In our experiments, we apply a pressure of $p \approx 0.8$ GPa, for which $T_{SDW} \approx 5$ K. The temperature dependence of the resistance with current parallel to the chains, R_a, is shown in Fig. 1 without magnetic field as well as in a field perpendicular to the well conducting a-b plane. A very large magnetoresistance develops below about 40 K, in sharp contrast with the expectation for a metal with an open Fermi surface. As a result, the metallic temperature dependence of the resistance gradually turns to an "insulating behavior" ($dR/dT < 0$) with a resistance minimum occurring at a field dependent temperature T_{min} (see Fig. 1). At low temperature, the resistance saturates at a field-independent temperature $T_{sat} \approx 8$ K and varies little until the SDW transition.

This picture has been further enriched by studies of the magnetoresistance as a function of the orientation of the magnetic field. Chashechkina and Chaikin [5] find a "2d" behavior above about 5 K: here the magnetoresistance depends only on the c component of the field. At low temperature, however, the a-b component of the field also plays a role: If the field is parallel to a lattice vector of the crystal, then the resistance decreases with decreasing temperature, while dR/dT remains negative for incommensurate field directions [6]. In a detailed analysis of the angular dependence, Strong, Clarke, and Anderson [7] find evidence for non-FL behavior. They describe the system with the field in a commensurate direction as a collection of coherent 2d conducting planes. They argue that a field in an incommensurate direction, however, destroys interplane coherence leaving a set of incoherently coupled 2d non-FL's. Along a similar line of arguments, Behnia *et al.* [8] explain the resistance minimum in the 2d region by the "one-dimensionalizing" effect (confinement of coherence to the conducting chains) of the magnetic field [9].

In this article we investigate the magnetoresistance in the temperature range 5 K < T < 35 K, i.e., the region of strong "2d" magnetoresistance. The magnetic field is perpendicular to the conducting a-b planes and the current flows along the a or b direction. Our original aim—with the "one-

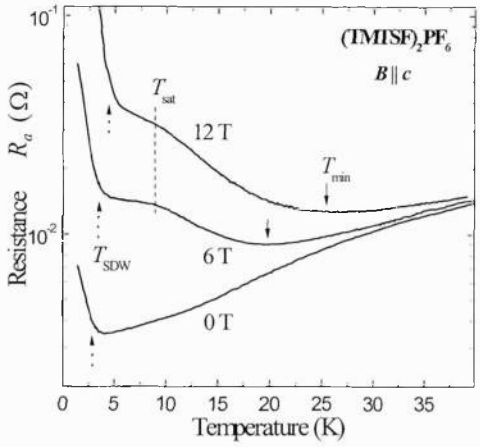

Figure 1

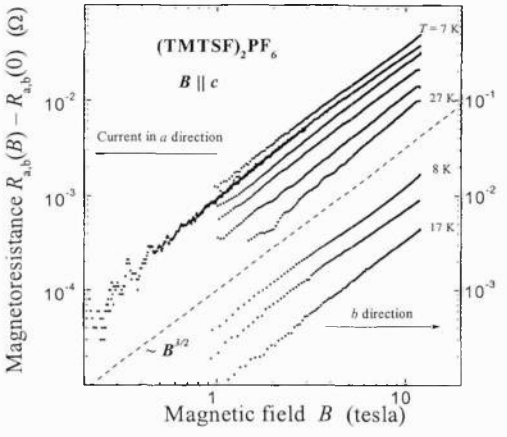

Figure 2

Figure 1: Temperature dependence of the resistance in the *a* direction in zero magnetic field as well as in magnetic fields of 6 T and 12 T applied perpendicular to the conducting planes. The hydrostatic pressure is 0.81 GPa.

Figure 2: Magnetoresistance *vs.* magnetic field at temperatures (from top to bottom) 7 K,10 K, 13 K, 22 K, 27 K in the *a* direction and 8 K, 12 K, 17 K in the *b* direction. The dashed line represents the power law $\Delta R \propto B^{3/2}$.

dimensionalization" picture in mind—was to infer a characteristic magnetic field separating the high-field "one-dimensional" state from the low-field state. We find no such characteristic field as the magnetoresistance both along *a* and *b* follows a power law:

$$\rho_{aa(bb)} = \rho^{0}_{aa(bb)} \left\{1 + [B / B_0(T)]^{\beta}\right\}. \tag{1}$$

The *a*-*b* anisotropy is field independent, i.e., the parameters B_0 and β are the same for the *a* and *b* directions. For the exponent we find a temperature-independent value $\beta = 1.49 \pm 0.1$. The temperature dependence of the scaling field B_0 is well described by an exponential form

$$B_0(T) = B_{00} \exp(T / T_0) \tag{2}$$

with $T_0 = 10$ K, $B_{00} = 1.8$ T.

We have measured the magnetoresistance of two $(TMTSF)_2PF_6$ single crystals. The arrangement of the electrode contacts allowed measurement with current flowing either along the *a* or *b* directions on the first sample, and only along the *a* direction on the second sample. A hydrostatic pressure of about 0.8 GPa (8 kbar) was applied to the samples in a Cu-Be cell with kerosene as pressure transmitting fluid. The samples were visually aligned so that the magnetic field was always perpendicular to the *a*-*b* plane.

The magnetoresistance as a function of magnetic field both in the *a* and *b* directions is shown in Fig. 2 for several temperatures. The power law Eq. (1) is obvious above 1 T, a limit set by the experimental error, up to the highest field 12 T. In case of the 17-K field scan, the magnetic field has been changed very slowly for an accurate resistance measurement, and the limit of validity of Eq. (1) can be extended down to about 0.3 T. The 17-K scan is a good example that no change in the field dependence occurs at the field B^* for which the temperature of the resistance minimum, T_{min}, is equal to the temperature of the field scan. In this case $B^* = 3.5$ T, i.e., the temperature dependence of the resistance is "metallic" ($dR/dT > 0$), if $B < 3.5$ T, and "insulating" ($dR/dT < 0$), if $B > 3.5$ T, still the power law Eq. (1) is equally valid in the entire field range of 0.3 T to 12 T.

The temperature dependence of the exponent β—obtained from 3-parameter fits of Eq. (1) to the results of field scans—is shown in Fig. 3. Below 20 K, there is no systematic temperature dependence, and the mean and standard deviation of all data points are 1.49 and 0.10, respectively. Above 20 K, a weak increase of the exponent is observed what may be due to the admixture of a regular B^2

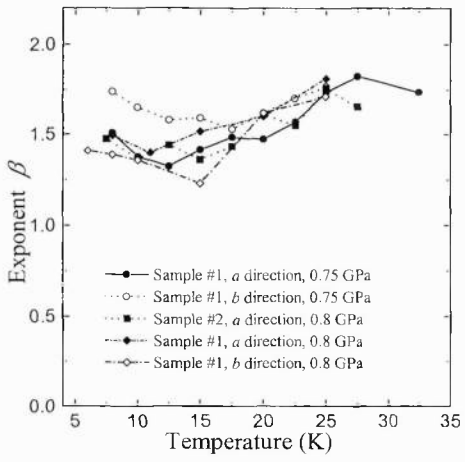

Figure 3

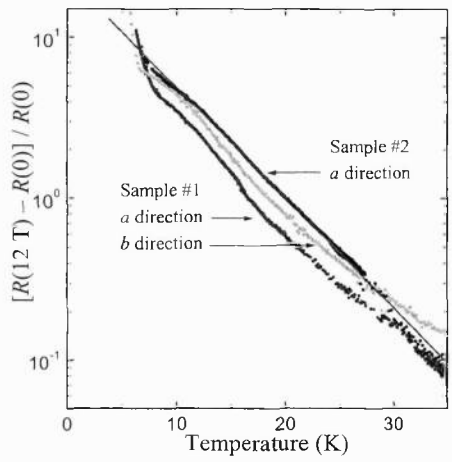

Figure 4

Figure 3: Temperature dependence of the power law exponent β in Eq (1) for two samples and two crystalline directions.

Figure 4: Normalized magnetoresistance *vs.* temperature in a constant magnetic field B = 12 T. The straight line represents Eq. (2).

magnetoresistance, but the simple fraction β = 3/2 provides a good description over the entire temperature range investigated.

Using a temperature independent exponent β = 3/2, the temperature dependence of the scaling field B_0 in Eq. (1) is conveniently determined from a comparison of B = 0 and B = 12 T temperature scans, as shown in Fig. 4. The linear temperature dependence in this semi-logarithmic plot corresponds to $\Delta R/R \propto \exp[(3/2)T/T_0]$, in agreement with Eq. (2). The results for the characteristic temperature T_0 are the following: Sample #1, *a* direction: 10.4 K, *b* direction: 10.4 K; Sample #2, *a* direction: 9.5 K. Therefore on both samples and in both crystalline directions the results are consistent with T_0 = 10 K.

A description of the magnetoresistance in a kinetic theory of FL quasiparticles leads to Kohler's law $\Delta R/R_0 = f(B/R_0)$ [10]. This relation, however, is incompatible with the observed power-law temperature dependence of the zero-field resistance *and* the exponential temperature dependence of the magnetoresistance. An easy way to see this is to combine Kohler's law with Eqs. (1) and (2) which yields an exponential temperature dependence for the *zero-field* resistance R_0 as well, in obvious contradiction with the experimental results for R_0. Moreover, the power-law exponent 3/2 for the magnetoresistance and especially the exponential temperature dependence are highly unusual in FL theory. Therefore an explanation of the magnetoresistance in the framework of a kinetic theory of FL quasiparticles is unlikely.

If the high-field resistance reflects precursor fluctuations of a phase transition to an SDW [11], one expects a divergent power-law behavior as the transition is approached from above. The exponential temperature dependence and the saturation of the magnetoresistance at about $T_{sat} \approx 8$ K, well above the transition temperature (typically 3 to 5 K in 12 T and close to p_c), are difficult to reconcile with this theory.

Our results are incompatible with the "one-dimensionalization" scenario at two points. First, at the heart of the "one-dimensionalization" argument is the observation of a field-dependent characteristic energy $T_{min}(B)$. Roughly speaking, the domain above this line in the B-T space would be the "one-dimensionalized" region. We find, however, no change in the behavior of the magnetoresistance when the $T_{min}(B)$ line is crossed in constant-temperature field scans. In other words, we find that the relevant energy scale of the magnetoresistance, T_0 = 10 K in Eq. (2), is independent of the magnetic field. Our second argument is that the *a*-*b* plane anisotropy is also field (and temperature) independent, pointing towards a coherent *a*-*b* plane transport in the entire field and temperature range investigated. We note here that the qualitatively very similar magnetoresistance along the *c* direction reported in Ref. [12] makes it likely that the transport is coherent along all spatial directions even in a magnetic field. If this is

so, the coherent 3d state should be a FL state. A speculative escape from this contradiction is that the Landau parameters of the FL are tuned by the c component of the magnetic field.

We conclude that none of the existing theories seem to account for the behavior of the magnetoresistance. To provide some clue for the interpretation of the phenomenon, we make some simple phenomenological considerations. It is important to emphasize that the two-parameter (T_0, B_{00}) fit described by Eqs. (1) and (2) works equally well above and below the resistance minimum T_{min} as well as around T_{sat} where the magnetoresistance saturates. This finding suggests, that the same mechanism is responsible for the magnetoresistance in the whole temperature range investigated, 5 K < T < 30 K. In particular, we find no difference in the behavior below and above the temperature of the resistance minimum, T_{min}.

Together with the new characteristic temperature T_0 = 10 K, we have now three nearly equal field-independent energy scales, the other two being the temperature of the saturation of the resistance in a magnetic field, T_{sat} = 8 K, and the interplane electron hopping integral t_c = 7 K. Previously, T_{sat} has been identified with t_c [2,5] based on the observation, that Lebed's anomalies [6] at commensurate field angles, a 3d effect, are only seen below T_{sat}. It is clear, however, from Fig. 2 of Ref. [5], that the saturation is equally observable at and away from the commensurate angles. The saturation, on the other hand, arises naturally from Eq. (2) because B_0 varies little if $T < T_0$. Since T_0 has been inferred from a "2d" temperature range, it is possible that $T_{sat} \approx t_c$ is merely a coincidence.

Finally we note that the exponential temperature dependence of the magnetoresistance with the exponent proportional to the temperature is highly unusual. By a purely formal analogy, this temperature dependence may point to the thermal excitations of a bosonic degree of freedom.

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