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Dissimilarity between metallic-like transport in the dielectric spin density wave and field induced spin density wave states in $(TMTSF)_2PF_6$

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We report similarities and differences of the transport features in the spin density wave (SDW) and in the field induced SDW (FISDW) phases of the quasi one-dimensional compound $(TMTSF)_2PF_6$. As temperature decreases below ≈ 2 K, the resistance in both phases exhibits a maximum and a subsequent strong drop. However, the characteristic temperature of the $R(T)$ maximum and its scaling behavior in different magnetic fields B evidence that the non-monotonic $R(T)$ dependences have different origin in SDW and FISDW regions of the phase diagram. We also found that the borderline $T_0(B,P)$ which divides the FISDW region of the $P-B-T$-phase diagram into the hysteresis and non-hysteresis domains, terminates in the $N=1$ sub-phase; the borderline has thus no extension to the SDW $N=0$ phase.

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The quasi-one-dimensional organic compound $(TMTSF)_2PF_6$ undergoes a phase transition from metallic to spin density wave (SDW) state as temperature decreases below $T_{\rm SDW} \approx 12$ K (at ambient pressure) [1, 2]. As pressure increases, $T_{\rm SDW}$ decreases and vanishes at $P = 6$ kbar [1, 2]. Application of the magnetic field B along the least conducting direction z (crystal axis c^*), restores the dielectric state; this takes place via a cascade of the field induced spin density wave states (FISDW) accompanied with a sequence of the quantum Hall effect (QHE) states with various numbers N of filled Landau bands[3 – 5]. A typical phase diagram of the FISDW states for $P = 7$ kbar is illustrated in the inset to Fig.1.

Earlier [6], we found that there is another boundary, $T_0(B)$ which subdivides the field of existence of the FISDW states (at $N \neq 0$) into the low temperature- and the high-temperature domains (see the inset to Fig.1). In the low-T domain, transitions between different FISDW states ($N \Longleftrightarrow N-1$) take place as the first order phase transitions, as magnetic field drives the system through the FISDW phases. In the high-T domain, the transitions between different phases have a crossover character. The above picture is consistent with a theoretical model recently suggested by Lebed [7] in

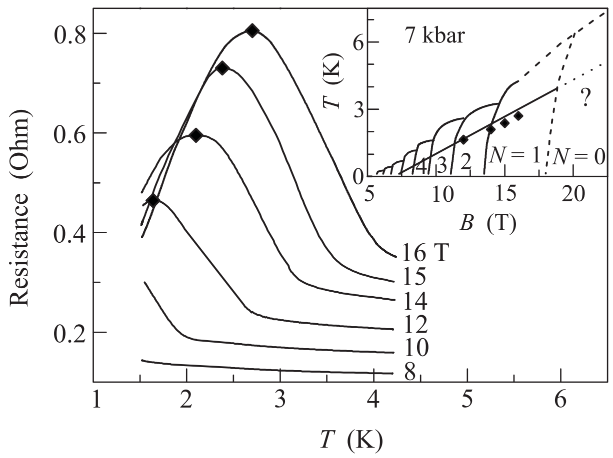

Fig.1. Typical temperature dependence of the resistance at $P = 7$ kbar in the FISDW regime, for six different values of B. Inset shows the $B-T$-phase diagram: solid curves represent the results from Ref. [6], dashed lines show the phase boundaries anticipated at higher fields according to Refs. [4, 5]. N values denote the sub-phase number. The thick straight line $T_0(B)$ separates the hysteresis and non-hysteresis regimes; dotted line is its would-be-extrapolation to the $N=0$ phase. Diamonds on the main panel and in the inset depict the coordinates of the $R(T)$ maxima at various fields

which the low-T and the high-T domains have a meaning of the quantum and semiclassical regions, respectively.

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The nesting vector is predicted to be partially quantized in the quantum domain and is not quantized in the semiclassical domain.

We also reported [6] that a qualitative difference between the two domains exists through the overall area of the FISDW phase. Specifically, the temperature dependence of the resistance $R(T)$ measured along the most conducting direction x (i.e. the crystal axis a) has a maximum in the vicinity of the same $T_0(B)$- line (see Fig.1); this coincidence was observed for different pressure values from 7 to 14 kbar.

The maxima in $R_{\max}(T)$ were observed earlier [8] in the $N \neq 0$ phases and have been associated with the onset of the quantum Hall effect [8 – 10]. Indeed, as T decreases, the Hall component of the conductivity σ_{xy} grows to the quantized value, $\sigma_{xy} \to Ne^2/h$. As a result of the interplay between the diagonal and off-diagonal components of conductivity, R_{xx} exhibits a maximum, as follows from the equation:

$$R_{xx} = \frac{\sigma_{yy}}{\sigma_{xx}\sigma_{yy} + \sigma_{xy}^2}. \qquad (1)$$

Within such an explanation (see e.g. Refs. [8, 9] and references therein), the $R(T)$-maxima are associated with the QHE and do exists in all phases with $N \geq 1$; obviously, such maxima should be missing in the dielectric SDW phase with $N = 0$. On the other hand, these maxima in $R(T)$ follow a borderline $T_0(B)$ which has a fundamental meaning [7].

The aim of the current studies is (i) to test whether the above explanation holds and $R(T)$ becomes monotonic in the dielectric $N = 0$ phase and (ii) to verify whether or not the quantum/semiclassical borderline $T_0(B)$ extends to the dielectric $N = 0$ phase as illustrated by the question mark in the inset to Fig.1.

We found an unexpected behavior of the resistance in the $N = 0$ phase: as temperature decreases, the resistance does not increase monotonically as anticipated for the insulating SDW state but exhibits a maximum and further falls down by a factor of ≥ 2. The scaling analysis of $R(T)$ for $N = 0$ and for the FISDW regime at $N \neq 0$ showed that the two effects of maxima in $R(T)$ have different critical exponents and thus the features of the resistance in the $N = 0$ and $N \neq 0$ phases have different origin. Our results demonstrate that the $T_0(B)$ boundary plotted through the high order FISDW phases has no extension in the lowest order $N = 0$ phase; this is consistent with the current theoretical interpretation [9]. On the other hand, the unexpected $R(T)$ maximum in the purely insulating $N = 0$ phase has no explanation in the frameworks of the existing theories.

Measurements were carried out on two samples (of a typical size $2 \times 0.8 \times 0.3\,\mathrm{mm}^3$) grown from a solution by a conventional electrochemical technique. We used either four Ohmic contacts formed at the $a - b$ plane or eight contacts at two $a - c^*$ planes; in all cases 25μm Pt-wires were attached by a graphite paint to the sample along the most conducting direction a. The sample and a manganin pressure gauge were inserted into a Teflon cylinder placed inside a nonmagnetic 18 mm o.d. pressure cell [11] filled with Si-organic pressure transmitting liquid. The cell was mounted inside the liquid He^4, or $\mathrm{He}^3/\mathrm{He}^4$ mixing chamber, in a bore of a superconducting magnet. For all measurements, the magnetic field was applied along z. Sample resistance was measured by four probe ac technique at 132 Hz, with a typical current $1.5\,\mu$A. The out-of phase component of the measured voltage was negligibly small, indicating Ohmic contacts to the sample. The temperature was varied slowly, at a rate ≤ 0.1 K/min in order to avoid deterioration in sample quality. The changes in the sample resistance were fully reproducible during the measurements including temperature sweeps; this indicated that the sample quality did not change. Measurements were done in magnetic fields up to 17.5 T and for temperatures down to 0.12 K.

According to the existing theory [12 – 15] and the known $P - B - T$ phase diagram [16, 2], the insulating $N = 0$ phase can be realized in 2 ways: either at high pressures/high fields $P > 6$ kbar, $B > 18$ T (as shown in the inset to Fig.1), or at low pressures/low fields $P < 6$ kbar. In the latter case, the required magnetic field B_z can be much lower; it should only exceed 0.2 T in order to quench the superconducting state. In the current studies we focused on the low pressure/low field regime.

Figure 2 shows the temperature dependence of the resistance in different fields, measured at pressure 5.4 kbar. Starting from high temperatures, $R(T)$ shows a typical metallic behavior. At temperature T_{SDW}, the sample resistance starts growing indicating the onset of the SDW state (with $N = 0$). Unexpectedly, in this purely insulating state, R exhibits a maximum at a certain temperature $T_{\max} \approx 1$ K and falls down by a factor of 2. Similar behavior of $R(T)$ was observed also at $P = 2.5$ and 5.5 kbar (the results for $P = 2.5$ kbar are shown in the inset to Fig.2). The maximum in $R(T)$ is seen for any magnetic fields; the temperature of the maximum increases with field. By taking $I - V$ curves in the vicinity of the $T_{\max}$, we verified that the $R(T)$ maxima are not related to depinning or Joule heating.

The $R(T)$ maxima seem similar to the ones typical for the FISDW regime at $N \neq 0$ (shown in Fig.1). However, the temperatures of the $R(T)$-maximum, $T_{\max}$, in

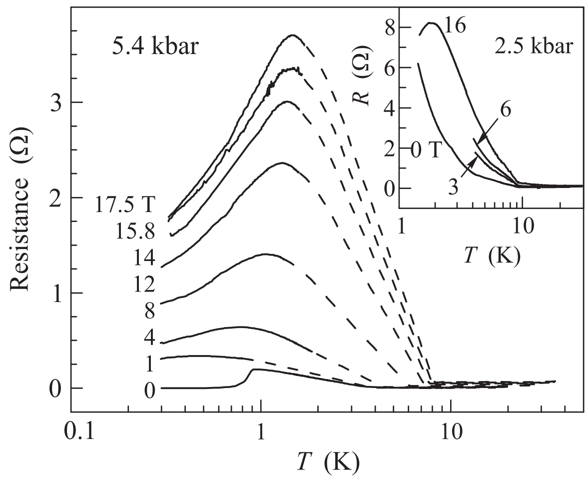

Fig.2. Resistance R vs temperature at pressure $P = 5.4$ kbar in the SDW regime, for different fields. Data for $B = 0$ and 15.8 T were measured overall range of T (solid lines), for other fields data were taken only at $T < 1.7$ K (solid lines). Dashed lines depict the anticipated behavior of $R(T)$. Inset shows similar results for $P = 2.5$ kbar

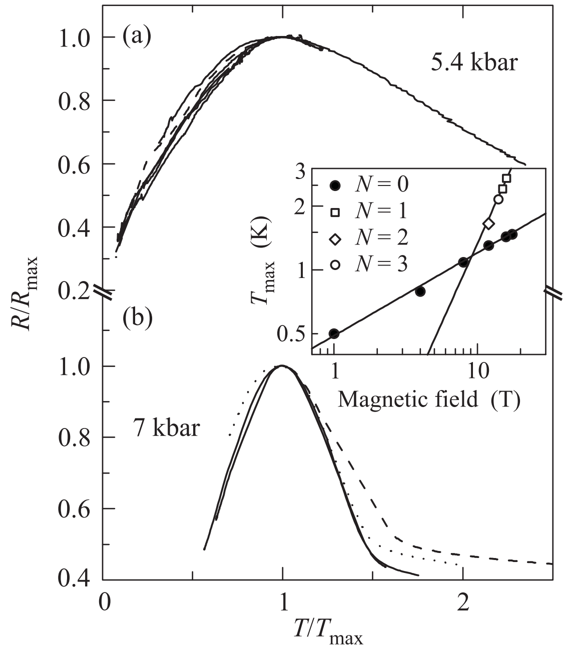

Fig.3. Normalized resistance $R(T)$ versus normalized temperature for different fields: (a) for $P = 5.4$ kbar ($N = 0$), and (b) for $P = 7$ kbar and various $N \neq 0$ (data are calculated from Fig.2 and Fig.1, correspondingly). Inset shows $T_{\max}$ vs magnetic field

the insulating $N = 0$ phase is less than that in the neighboring $N = 1$ phase by a factor of $\gtrsim 2$. This substantial difference can not be due to the minor difference in pressure (7 kbar vs 5.4 kbar) because $T_{\max}$ is only weakly pressure dependent [17]. It follows therefore that the measured $T_{\max}$ values in the $N = 0$ phase do not belong to the borderline $T_0(B)$ linearly extrapolated to the $N = 0$ phase (dashed line in the inset to Fig.1). Since we did not observe other $R(T)$-maxima (i.e., at $T > T_{\max}$) in the $N = 0$ phase, we conclude that the semiclassical/quantum borderline, $T_0(B)$, existing throughout the $N > 0$ FISDW-phases does not extend to the insulating $N = 0$ phase.

The fundamentally different origin of the $R(T)$-maxima in the FISDW and SDW phases is demonstrated by the following scaling analysis of the corresponding $R(T)$ data. In this procedure, we normalized the resistance $R(T)$ (for all curves taken at different magnetic fields) by its maximum value $R_{\max} = R(T_{\max})$ and replaced the temperature T for each curve by the reduced temperature $T/T_{\max}$. Figures 3a and b show the result of such simple scaling for $N = 0$ and $N \neq 0$ (i.e. for the SDW and FISDW regimes, correspondingly).

All the data (taken for different magnetic fields) collapse onto two different universal dependences $R(T/T_{\max})/R(T_{\max})$. For $N = 0$, all $R(T)$ curves, measured at magnetic fields from 1 to 17.5 T scale excellently thus demonstrating a similar origin. For $N > 0$ (Fig. 3b), the scaling is also good though there is a minor systematic departure of the individual curves from the scaling curve, which increases with N. We emphasize that the two universal scaling curves in Figs.3a and b are clearly different; the two scaling exponents $T_{\max} \propto B^{\gamma}$ are also different, $\gamma = 1.5$ and 0.4, correspondingly (see the inset to Fig.3). This difference demonstrates that the $R(T)$-maxima in the SDW phase and in the FISDW regime have different underlying mechanisms.

The borderline $T_0(B)$ determined empirically in Ref. [6], separates the regions of the existence and the absence of the first order phase transitions. It was also found that $R(T)$, for different fields and pressures exhibits a maximum at nearly the same border. On the other hand, according to the theory [8, 9] the maxima of $R(T)$ in the FISDW regime are caused by the developing QHE. Our finding that the $T_0(B)$ borderline has no extension to the $N = 0$ phase is therefore in a good agreement with the above interpretation, because there is no QHE in the $N = 0$ phase. Our data thus indicates that the QHE develops only in the "quantum" (low-T) domain. This conclusion suggests the absence of the QHE in the high-N phases where $T_0(B)$ vanishes to zero, e.g., for $N > 6$ at $P = 7$ kbar (see the inset to Fig.1).

In the purely insulating $N = 0$ phase, the QHE is missing and the appearance of the $R(T)$-maxima can not be explained by the growth of the off-diagonal conductivity. Therefore, the origin of the $R(T)$ maxima and of the strong drop in resistance towards low temperatures is puzzling. We wish to note an interesting coincidence. The temperature of the $R(T)$ maxima in the $N = 0$ phase is ≈ 1.5 K in strong magnetic fields ($B = 15 - 17$ T). On the other hand, the magnetoresistance in the $N = 0$ phase exhibits "rapid oscillations" [18] whose amplitude vanishes as T decreases below approximately the same temperature, 1.5 K. A symmetry-group analysis [19] shows that in $(TMTSF)_2X$ compounds there exist two incommensurate spin density waves. Although the second SDW has a smaller magnitude, it causes "rapid oscillations" and may preserve semimetallic properties as $T \to 0$. It is noteworthy, that the low-temperature region of the SDW phase diagram of $(TMTSF)_2PF_6$ was shown to have a non-trivial origin [20, 21] and was suggested to have an inner structure. We can not exclude therefore that the described above metallic-like behaviour of resistivity in the $N = 0$ phase is somewhat related to the inner subphases of the $N = 0$ SDW phase.

To summarize, we studied temperature and magnetic field dependence of the resistance of the quasi-one dimensional compound $(TMTSF)_2PF_6$ both in the FISDW ($N \neq 0$) and SDW ($N = 0$) phases. We found that the borderline $T_0(B, P)$ that divides the FISDW region of the $P - B - T$ phase diagram into the hysteresis and non-hysteresis domains terminates in the $N = 1$ sub-phase; the border has no extension to the SDW $N = 0$ phase. The maxima of $R(T)$ in the FISDW region develop only in the $N \neq 0$ phase; their existence thus correlates with the existence of the QHE. This co-occurrence agrees with the current theoretical explanation of the $R(T)$-maxima in the $N \neq 0$ phases. We found that in the SDW $N = 0$ phase which is considered to be insulating, the resistance does not grow infinitely as temperature decreases but exhibits a maximum at $T_{\max} \approx 1 - 2$ K and falls to lower temperatures. We found that the temperature of the $R(T)$-maxima, $T_{\max}(B)$, in the SDW phase is not a continuation of the border line $T_0(B)$ which separates the hysteretic and non-hysteretic domains in the $N \neq 0$ regime. A scaling analysis of the resistance has shown that the $R(T)$ maxima in the $N = 0$ and $N \neq 0$ phases have different origin. The unexpected strong drop of the resistance in the SDW $N = 0$ phase at $T < 1.5$ K has no explanation within the frameworks of the existing theories.

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