Unexpected Metallic-like Behavior of the Resistance in the Dielectric Spin Density Wave State in (TMTSF)$_2$PF$_6$

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We report unexpected features of the transport in the dielectric spin density wave (SDW) phase of the quasi one-dimensional compound (TMTSF)$_2$PF$_6$: the resistance exhibits a maximum and a subsequent strong drop as temperature decreases below $T_{SDW}\approx 12$ K (at ambient pressure) $\square \square$. As pressure increases, $T_{SDW}$ decreases and vanishes at $P = 6$ kbar $\square \square$. 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 by the sequence of the quantum Hall effect (QHE) states with various numbers $N$ of filled Landau bands $\square \square$. A typical phase diagram of the FISDW states for $P = 7$ kbar is illustrated in the inset to Fig. 1.

Earlier $\square \square$, we found that there is another boundary, $T_0(B)$ which subdivides the area of the 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 former domain, the transitions between different FISDW states ($N \leftrightarrow N - 1$) take place as the first order phase transitions which manifest experimentally in hysteretic variations of observable physical parameters as magnetic field drives the system through the transitions. In the latter domain, the transitions between different phases are not accompanied with a hysteresis and are not therefore of the first order. The above picture is consistent with a novel theoretical model suggested by Lebed $\square$ in which the low-temperature and the high-temperature domains have a meaning of the quantum and semiclassical regions, correspondingly. In this novel model, the nesting vector is predicted to be partially quantized in the quantum domain and is not quantized in the semiclassical domain.

We also reported in Ref. $\square$ that a qualitative difference between the two domains exists not only at the boundaries between the FISDW states, but through the overall area of the FISDW phase. We found that 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 $R_{\text{max}}(T)$ were observed earlier $\square \square$ in the $N \neq 0$ phases and have been associated with the onset of the quantum Hall effect $\square \square$. Indeed, as $T$ decreases, the Hall component of the conductivity $\sigma_{xy}$ grows to the quantized value, $\sigma_{xy} \rightarrow Ne^2/h$. 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:

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

Within such an explanation (see e.g. Refs. $\square \square$ and references therein), the $R(T)$-maxima are associated with the QHE and do exist 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 extrapolated $\square \square$ which has a fundamental meaning $\square$. 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 $\geq 2$. We found that the coordinates $T_m(B)$ of the $R(T)$ maximum in the $N = 0$ phase do not fall onto the $T_0(B)$ borderline extrapolated from the QHE region ($N \geq 1$) to the $N = 0$ phase. For
example, extrapolated to the same \( P \) and \( B \) values, \( T_{\text{on}} \) is typically a factor of 2 lower than \( T_{\text{on}}(B) \). We compared the temperature dependences of the resistance \( R(T) \) for \( N = 0 \) and for the QHE regime at \( N \neq 0 \) in the vicinity of the \( R(T) \)-maxima. The scaling analysis of the two quantities 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 thus demonstrate that the \( T_{\text{on}}(B) \) 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 \[11\]. On the other hand, the unexpected \( R(T) \) maximum in the purely insulating \( N = 0 \) phase has no explanation in the frameworks of the current theories.

Measurements were carried out on two samples (of a typical size \( 2 \times 0.8 \times 0.3 \text{mm}^3 \)) grown from a solution 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 \( 18 \text{ mm o.d. pressure cell} \quad [13] \) filled with Si-organic pressure transmitting liquid. The cell was mounted inside the liquid \( \text{He}^3 \), or \( \text{He}^3/\text{He}^4 \) 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 \( 132 \text{ Hz} \), 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 determined by \( \text{RuO}_2 \) resistance thermometer. The temperature was varied slowly, at a rate \( \leq 0.1 \text{K/min} \) 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 \( 17.5 \text{T} \) and for temperatures down to \( 0.12 \text{K} \).

According to the existing theory \[14\] and the known \( P - B - T \)-phase diagram \[15\], the insulating \( N = 0 \) phase can be realized in 2 ways: either at high pressures/high fields \( P > 6 \text{kbar}, B > 18 \text{T} \) (as shown in the inset to Fig. 1), or at low pressures/low fields \( P < 6 \text{kbar} \) (as shown in the inset to Fig. 2). In the latter case, the magnetic field \( B_z \) can be much lower; it should only be bigger than \( 0.2 \text{T} \) to quench the superconducting state. In the current studies we focused on the low pressure/low field region in order to avoid possible influence of the magnetic breakdown in strong fields on the \( R(T) \) behavior. Figure 2 demonstrates that the sample resistance varies in accordance with the phase diagram: as temperature decreases, \( R \) first decreases through the metallic phase, then \( dR/dT \) changes sign at the transition point to the insulating SDW phase and \( R \) grows by a factor of 40, and, eventually, \( R \) falls to zero as superconducting state sets in. The two squares at the \( R(T) \) curve in Fig. 2 mark the two corresponding transitions.

**FIG. 1.** Typical temperature dependence of the resistance at \( P = 7\text{kbar} \), in the FISDW regime for six different values of \( B \). Inset shows the \( B - T \)-phase diagram: solid curves represent the results from Ref. \[3\]; dashed lines show the phase boundaries anticipated at higher fields according to Refs. \[18,4\]. \( N \) values denote the sub-phase number. The thick straight line \( T_{\text{on}}(B) \) separates the hysteresis and non-hysteresis regimes; dotted line is its would-be-extrapolation to the \( N = 0 \) phase. The four diamonds on the main panel and in the inset depict the coordinates of the \( R(T) \) maxima at various fields.

**FIG. 2.** Resistance \( R \) vs temperature measured at pressure \( P = 5.4 \text{kbar} \) and at \( B = 0 \). Squares mark the onset of the insulating state at \( T = 4.8 \text{K} \) and of the superconducting state at \( T = 0.9 \text{K} \). The inset shows \( P - T \)-phase diagram at \( B = 0 \); dots are the experimental data, lines are the guide to the eye.

Figure 3 shows the temperature dependence of the resistance in different fields, measured at pressure \( 5.4 \text{kbar} \). Starting from high temperatures, \( R(T) \) shows a typical metallic behavior. At temperature \( T_{\text{SDW}} \), the SDW state (with \( N = 0 \)) sets in and the sample resistance starts growing. Unexpectedly, in this purely insulating state, \( R \) exhibits a maximum at a certain temperature \( T_{\text{max}} \approx 1 \text{K} \) and falls down by a factor of 2. Similar behavior of \( R(T) \) was observed also at \( P = 2.5 \text{ and } 5.5 \text{kbar} \) (the results for \( P = 2.5 \text{kbar} \) are shown in the inset to Fig. 3).
The maximum in $R(T)$ is seen for any magnetic field; the temperature of the maximum increases with field. In order to verify that the $R(T)$ maxima are not related to depinning or Joule heating, we measured the $I-V$ curves in the vicinity of the $T_{\text{max}}$. Figure 4 shows that the differential resistance, $R = dV/dI$, on both sides of the maximum, is independent of current up to nearly $4 \mu A$; this result demonstrates that the $R(T)$ maxima measured at $I = 1.5 \mu A$ are not related to the non-ohmic behavior. As current increases further, $R$ increases both, at $T > T_{\text{max}}$ and $T < T_{\text{max}}$. This high-current nonlinearity is therefore likely to be caused by depinning rather than overheating. The former mechanism should increase the resistance [13], whereas the latter one should cause $dV/dI$ to decrease with current for $T = 1.7 K$, and to increase for $T = 0.7 K$ (see Fig. 3).

The $R(T)$ maxima seem at first sight similar to the ones which are typical in the FISDW regime at $N \neq 0$ (shown in Fig. 1). However, the temperatures of the $R(T)$-maximum, $T_{\text{max}}$, in 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 ($7 \text{ kbar}$ vs $5.4 \text{ kbar}$) because $T_{\text{max}}$ is only weakly pressure dependent [13]. It follows therefore that the measured $T_{\text{max}}$ 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 $T > T_{\text{max}}$) 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 $R_{\text{max}} = R(T_{\text{max}})$ and replaced the temperature $T$ for each curve by the reduced temperature $T/T_{\text{max}}$. Figures 5a 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 $R(T/T_{\text{max}})/R(T_{\text{max}})$. 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. 5b), 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. 5 a and b are clearly different; the two scaling exponents \( T_{\text{max}} \propto B^\gamma \) are also different, \( \gamma = 1.5 \) and 0.4, correspondingly (see the inset to Fig. 5). 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. 8, 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 \cite{10, 11}, 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’ (hysteretic) 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, as shown in 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 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 co-occurrence that the field dependence of the resistance in the SDW phase and in the FISDW regime has smaller magnitude, it causes ‘rapid oscillations’ \cite{24} whose amplitude vanishes as \( T \) decreases below approximately the same temperature, 1.5 K. A symmetry-group analysis \cite{21} shows that in (TMTSF)\(_2\)X compounds there exist two incommensurate spin density waves. Although the second SDW has smaller magnitude, it causes ‘rapid oscillations’ and may preserve semimetallic properties as \( T \to 0 \). It is noteworthy, that a low-temperature region of the SDW phase diagram of (TMTSF)\(_2\)PF\(_6\) was shown to have a non-trivial origin \cite{24, 30} and was suggested to have an inner structure. We can not exclude therefore that the observed by us metallic-like behaviour of resistance in the \( N = 0 \) phase is somewhat related to 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)\(_2\)PF\(_6\) both in the QHE \((N \neq 0)\) and SDW \((N = 0)\) phases. We 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 \( N = 1 \) subphase; the border has no extension to the SDW \( N = 0 \) phase. The maxima of \( R(T) \) in the FISDW region (which have been shown to occur approximately at the same borderline) 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 \( T_{\text{max}} \approx 1 - 2 \) K and falls to lower temperatures. The \( R(T) \)-maxima in the ‘insulating phase’ take place in the linear conductance regime and are not caused by depinning or Joule heating. We found that the temperature of the \( R(T) \)-maxima, \( T_{\text{max}}(B) \), 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 frameworks of the existing theories.

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