QUASI-ONE-DIMENSIONAL CONDUCTORS IN MAGNETIC FIELD: PHYSICAL CONSEQUENCES OF "NON-STANDARD" THEORETICAL APPROACH

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Abstract. Qualitative comparison between "standard" and "non-standard" theories of Q-1-D conductors in magnetic field is given. It is shown that "non-standard" theory, unlike the "standard" one, explains such phenomena as reentrance and partial reentrance to metallic phase, correlation between appearance of cascade of SDW transitions and existence of superconductivity at zero magnetic field, the value of Hall conductivity in the high-field SDW state preceding reentrance in $(TMTSF)_2ClO_4$.

In this paper the behaviour of Q-1-D conductors $(TMTSF)_2X$, X=ClO_4, PF_6, ReO_4 in magnetic field is considered from the theoretical point of view. Introduction in the subject can be found in the papers of theorists [1], [2] and experimentalists [3], [4]. In my contribution I shall summarize observable physical consequences of "non-standard" theory [5], different from the consequences of "standard" theories, and compare them with recent experimental data. Discussion will be purely qualitative, rigorous mathematical statements and proofs can be found in [5].

By "standard" theories I mean the theories which follow and develop the approach of pioneering paper [6]. References are numerous and can be found in [1] and [2]. There are two basic points which differ "standard" and "non-standard" approaches. The first difference is physical and lies in the choice of the model for description of real materials. Before explanation how magnetic field H induces cascade of SDW transitons it is necessary to answer why there is no SDW at $H = 0$. The standard answer is: "Because there is no perfect nesting". It is assumed that the interaction constant has the sign favorable for SDW. Magnetic field improves nesting and thus induces SDW.

In the "non-standard" model the answer on the above question is: "Because the interaction constant has negative sign which is favorable for superconductivity and non-favorable for SDW". Really, all considered substances are superconductors at $H = 0$. When magnetic field is applied the effective amplitude of interaction between electrons changes sign due to renormalization and SDW appears. In this approach the question about the nesting at $H = 0$ is not essential.

To be precise we have to consider the whole set of g_1, g_2 and g_3 amplitudes. As was argued in [7], [8] probably g_1 is positive and thus small. g_3 is absent for X=ClO_4, ReO_4 because anion superstructures alternate Fermi momenta of the chains making them incommensurable with underlying potential. For X=PF_6 g_3 may be sufficiently small at the pressures when superconductivity appears. Thus to the first approximation g_1 and g_3 may be neglected. The discussed above question is the question about the sign of g_2.

The second point, which differs "standard" and "non-standard" approaches, is mathematical and concerns the methods used to treat the chosen models. In the "standard" approach only electron-hole loop diagrams, responsible for SDW, are taken into account in the ladder or mean-field approximation. In the "non-standard" approach so-called

(received November 15, 1989)

"parquet" approximmation is used. In addition to the electron-hole loops the electron-electron loops, responsible for superconductivity, are taken into account simultaneously. Thus generally speaking parquet approximation is more correct then the ladder one. Unfortunately to obtain explicit results in this method it is necessary to make some crude approximations so the method is applicable only for the high enough fields and its numerical accuracy is limited. By the same reason it is not used to describe thermodynamics at $T < T_c$.

Concluding the introduction I emphasize that the discussed two points of difference are independent because both models can be studied by both methods. In what follows by definition "standard" theory = "standard" model + "standard" method.

Now let me describe how the picture looks like in the "non-standard" approach. The starting point is to consider the wave functions of non-interacting electrons. A wave function of a quasi-one-dimensional electron in magnetic field is delocalized along the chains and localized in the perpendicular direction quite analogously to the Landau wave function for the isotropic dispersion law. Each wave function is centered around some chain. Let us consider what happens in very high magnetic field. When $H \to \infty$ every wave function shrinks to one chain. As the wave functions become purely one-dimensional in the case $H = \infty$ so any transition temperature T_c vanishes in the system of interacting electrons. When H is large but finite $H \gg H_0 = tc/ebv_F$ there is a small overlap of the wave functions belonging the nearest chains. Here t is the hopping integral in the direction perpendicular to the magnetic field, v_F is the Fermi velocity, b is the distance between the chains. Transition temperature is proportional to some power of the overlap and decreases when H increases. So increasing H at constant T we have to encounter a reentrant transition to metallic phase. It can be shown that $T_c \propto (H_0/H)^\alpha$, $\alpha \propto const/|g_2|$. So if $|g_2|$ is small (weak coupling limit), then T_c decreases as function of H very rapidly, practically vertically. Such behaviour is observed in experimentally [9].

It is necessary to underline here that the results about reentrance in high magnetic field are valid for any model. They are consequences only of the utilization of the "non-standard" parquet method.

Another important question concerning the high field region is what type of SDW appears here. As the overlape between the wave functions belonging only the nearest chains is nonvanishing, then it is quite natural that only two types of SDW are possible in this region. These are SDW with electron-hole pairing on the same chain or on the neighbouring chains. The first state appears when $g_2 > 0$, while the second appears when $g_2 < 0$. This corresponds to "standard" and "non-standard" models respectively. Appearence of the SDW pairing on the neighbouring chains at negative g_2 is a consequence of utilization of parquet method. It was also predicted by another method in [10], somewhat similar phenomenon was discussed in [11]. According to [12] the quantum Hall effect takes place in the SDW phases in magnetic field. Hall conductivity is equal to $\sigma_{xy} = 2Le^2/h$. In this formula the factor 2 comes from spins while the integer L in the picture [5] has physical meaning of distance between electron and hole in the condensate. So in the discussed above first SDW state $\sigma_{xy} = 0$, while in the second state $\sigma_{xy} = 2e^2/h$.

Now let us consider experimental situation. In $(TMTSF)_2ClO_4$ before the reentrant transition there is a long plateau of σ_{xy}. It was claimed in [13] that it corresponds to the 1/3 fractional quantum Hall effect. But at Fig. 1b of [9], where the value

$h/2e^2$ is indicated, it can be seen that the experimental value of ρ_{xy} is quite close to this value. For 1/3 fractional quantum Hall effect ρ_{xy} must be three times greater than $h/2e^2$ in complete contradiction with the experimental picture. Experimental data on absolute values of σ_{xy}, obtained in [14] and compared with [13] and [9], also support the statement that $\sigma_{xy} = 2e^2/h$ in the high-field SDW state. Thus from the above theoretical considerations we conclude that in $(TMTSF)_2ClO_4$ the electron-hole pairing on the neighbouring chains takes place in the high field SDW state. So for $(TMTSF)_2ClO_4$ the "non-standard" model with $g_2 < 0$ is relevant. The "standard" model predicts zero Hall conductivity before reentrant transition in contradiction with experiment in $(TMTSF)_2ClO_4$.

The situation in $(TMTSF)_2PF_6$ will be discussed below, for $(TMTSF)_2ReO_4$ there are no experimental data on σ_{xy}.

Now let us consider the moderate magnetic fields $H < H_0$. In this region the overlap between the wave functions belonging distant chains must be taken into account. Simultaneous treatment of the superconducting and the SDW divergencies in this situation can be performed within parquet approximation only numerically. The results of calculations [5] are given in the table:

$8H_0/H$	0.5	2	4	7	10	13	16
ξ	2.6	1.8	2.8	3.8	3.4	3.3	3.6
L	1	1	0	1	2	0	3

For several values of magnetic field, which are given in the first row, transition temperature T_c and the electron-hole distance in the condensate L were determined. The second row of the table gives the variable ξ related to T_c: $\xi \propto -\log T_c$, $T_c \propto \exp(-\xi/|g_2|)$. The third row of the table gives the value L related to the Hall conductivity by the formula given above. All shown results are for "non-standard" model ($g_2 < 0$).

Let us consider first of all the dependence $T_c(H)$. Let us decrease H from $H = \infty$. Firstly T_c increases that corresponds to the discussed above reentrant transition. But then in the region of moderate fields $H < 2H_0$ the dependence $T_c(H)$ is non-monotonious: T_c decreases, increases and decreases. Such behaviour, called the partial metallic reentrance, was observed experimentally [15]. This phenomenon does not appear in the "standard" theory. Appearance of this phenomenon in the theory is the consequence of utilization of parquet approximation. Although it was found [5] only for "non-standard" model probably it can be also found in the "standard" model if parquet method will be applied.

Let us now discuss the dependence $\sigma_{xy}(H)$ which is determined by the function $L(H)$. First of all the results for $L(H)$, shown in the table, should not be applied literaly to $(TMTSF)_2ClO_4$. Due to the anion superstructure the values may be different. But they should be applicable to $(TMTSF)_2PF_6$ where there is no superstructure. If the value $\sigma_{xy} = 0$ at $8H_0/H = 13$ is eliminated by some reason, then we receive the following sequence of values of L with the increase of H: 3,2,1,0. This is exactly the same sequence as in "standard"" theory. This sequence is observed experimentally in $(TMTSF)_2PF_6$ [4]. In "standard" model with the further increase of H there must be reentrant transition to a metal. On the contrary in "non-standard" theory, as shown in the table, there must be a transition to the SDW phase with $L = 1$ and then reentrant transition. So "standard" and "non-standard" theories differ by the value of σ_{xy} in the SDW phase immediately preceding reentrant transition. As reentrant transition has not been oserved in $(TMTSF)_2PF_6$ in available fields so the question of choice of the model for this substance remains open.

In conclusion, I summarize experimental features explained by "non-standard" theory:

1) Reentrance and

2) partial reentrance to the metallic state.

To explain features 1) and 2) it is necessary to apply "non-standard" parquet method to any model [16].

3) Correlation between superconductivity at $H = 0$ and the cascade of SDW.

4) The value $\sigma_{xy} = 2e^2/h$ in the SDW state before reentrance in $(TMTSF)_2ClO_4$.

To explain features 3) and 4) it is necessary to use "non-standard" model ($g_2 < 0$) and parquet method.

Applicability of "non-standard" model seems to be reasonable for $(TMTSF)_2ClO_4$ but for $(TMTSF)_2PF_6$ the question remains open. It would be very desirable to obtain more information about $(TMTSF)_2ReO_4$

References

[1] G.Montambaux, these Proceedings.

[2] M.Héritier, these Proceedings.

[3] F.Pesty and P.Garoche, these Proceedings.

[4] J.R.Cooper et al., these Proceedings.

[5] V.M.Yakovenko *Zh. Exp. Teor. Fiz.* **93**, 627 (1987), *Europhys. Lett.* **3**, 1041 (1987), *Phys. Rev. Lett.* **61**, 2276 (1988).

[6] L.P.Gor'kov, A.G.Lebed' *J. de Phys. Lett.* **45**, L433 (1984).

[7] S.A.Brazovskii and V.M.Yakovenko *Zh. Exp. Teor. Fiz.* **89**, 2318 (1985).

[8] Chr.Seidel and V.N.Prigodin *J. de Phys. Lett.* **44**, L403 (1983).

[9] M.J.Naughton, R.V.Chamberlin, X.Yan, S.-Y.Hsu, L.Y.Chiang, M.Ya.Azbel and P.M.Chaikin *Phys. Rev. Lett.* **61**, 621 (1988).

[10] S.A.Brazovskii and V.M.Yakovenko *Pis'ma v Zh. Exp. Teor. Fiz.* **43**, 102 (1986).

[11] C.Bourbonnais and L.G.Caron *Europhys. Lett.* **5**, 209 (1988).

[12] D.Poilblanc, G.Montambaux, M.Héritier and P.Lederer *Phys. Rev. Lett.* **58**, 270 (1987).

[13] R.V.Chamberlin, M.J.Naughton, X.Yan, L.Y.Chiang, S.-Y.Hsu and P.M.Chaikin *Phys. Rev. Lett.* **60**, 1189 (1988).

[14] M.Ribault *Low-dimensional conductors and superconductors*, NATO ASI series B **155**, 199 (1987).

[15] P.Garoche and F.Pesty *JMMM* **54-57**, 1418 (1986).

[16] Very recently an explanation of reentrance was given within the "standard" model by A.G.Lebed' and P.Bak, submitted to *Phys. Rev.*, 1989.