COMMENT ON "THEORY OF TWO-BAND SUPERCONDUCTORS"

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The main development stages of the superconducting theory of the systems with overlapping energy bands are formulated.

The main references on the classical papers of the author of this theory Moskalenko V.A. and his coworkers are listed. This list includes also the papers which are related to high-temperature superconductivity. Some peculiarities of the two-band model, which give qualitatively new results in comparison with usual one-band model are enumerated.

We are listing also our proper publications on the thermodynamic and collective oscillations of the two-band systems which are realized on the generalized Moskalenko model of systems with overlapping energy bands for the case when the charge carrier density is lower.

The application of two-band model for the description of the thermodynamical properties of the compound MgB$_2$ is also discussed.

The model of superconductor with the overlapping energy bands on the Fermi surface was proposed by Prof. V. Moskalenko more than 40 years ago [1] and some time later by H. Suhl, B. Matthias and L. Walker [2]. On the basis of this model Prof. Moskalenko with coworkers (Institute of Applied Physics, Moldavian Academy of Sciences) carried out investigations of thermodynamical and electromagnetic properties of multi-band superconductors. A few books and a lot of articles on this problem had been published, for instance, [3] - [12].

After discovery of high temperature superconductivity we attempted to apply our theory for explanation of the properties of these materials. For example, the review of our results has been published in 1991 [13].

Later we adapted the generalized Moskalenko model for the investigations of thermodynamical properties and collective oscillations in multi-band systems with the lowering density of charge carriers (see, for instance, [14]-[21]).

Last time there are many experimental results on the superconductivity in MgB$_2$ system where the theoretical conceptions of the two-band superconductivity are confirmed.

The consideration of the overlapping of the energy bands leads not only to the quantitative difference of results from the case of one-band superconductor, but in some cases to the qualitatively new results. For example:

1. In the two-band systems high temperature superconductivity is possible not only in the case of attractive interaction between the electrons, but even if the interaction between the electrons has repulsive character ($\lambda_{nm} < 0$, $n; m = 1 - 2$), but relation $\lambda_{11} \lambda_{22} - \lambda_{12} \lambda_{21} < 0$ is fulfilled [14].

2. In the impurity two-band superconductors, for example, Anderson theorem is violated, and the dependence of thermodynamical quantities on concentrations of non-magnetic impurity due to the interband scattering of electrons on impurity atoms appears [4].

3. In the two-band superconductors near of $T_c$ the upper critical field Hc$_2$ as a function of temperature has positive curvature, due to the relation $v_{F1} \neq v_{F2}$ ($v_{Fn}$ - the velocity of
electron on the \( n \)-th cavity of Fermi-surface). In the one-band case we have negative curvature [13].

4. In the two-band superconductors collective oscillations of exciton-type Leggett mode appear, caused by the fluctuations of phase of order parameters for different bands. In the three-band systems, and also in the two-band with lower density of charge carrier, which reduces to the three-band model, such oscillatory modes can be two [19], [20].

5. On the basis of the theory of superconductivity with overlapping energy bands one can explain a great number of experimental results in high-\( T_c \) materials [13].

6. The interest to the two-band model for superconductivity was recently renovated after the discovery the superconductivity in \( MgB_2 \) (\( T_c \sim 40K \)). A lot of properties of the two band superconductors was rediscovered in the very recent investigations on diborides and borocarbides. Our review article, published in *Usp. Fiz. Nauk.* [13], gives a complete list of the classical achievements on the problem.

The theory, presented in papers [1] - [13] contains the main physical concepts, the basic equations of the model and analytical expressions for the thermodynamical and electromagnetic characteristics of the superconductor with overlapping energy bands on the Fermi surface. Obtained results are correct for arbitrary relations between parameters of the theory of the adiabatical two-band model (for pure and doped systems).

Therefore, this theory is useable for the description of the thermodynamical and electromagnetic properties of the two-band superconductors, which have some peculiarities, allowing to put some confines on the parameters of the theory. In our opinion, this corresponds, in particular, to the superconducting compound \( MgB_2 \).

As follows from the overview of experimental and theoretical investigations of thermodynamical properties of \( MgB_2 \) [22], [23] this compound is many-band superconductor and anomalies of its properties are described by the two-band theory for pure [24] and doped superconductors [25], [26]. This theory contains, as a matter of fact, the same peculiarities as the theory proposed by Moskalenko and his coworkers many years ago (see [13] and its references). In particular, for the relations of the order parameters for different bands \( \Delta_1 \) and \( \Delta_2 \) to the temperature of the superconducting transition \( T_c \) we have \( \frac{2\Delta}{T_c} > 3.5 ; \frac{2\Delta_2}{T_c} > 3.5 \), but the relative jump of heat capacity \( \frac{C_s - C_n}{C_n} < 1.43 \) for the arbitrary choice of the theory parameters.

We also note results which we obtained long time ago [13] for the two-band model: the possibility of positive curvature of a function \( H_{c2}(T) \) near values \( T \sim T_c \) due to the relation \( v_{F1} \neq v_{F2} \) (\( v_{Fn} \) is the electron velocity on the cavity \( n \) of the Fermi surface).

Another important result, which is used in [23], [25], [26] for the elucidation of properties of \( MgB_2 \) - is the violation of Anderson theorem and appearance of the \( T_c \) dependence on the concentration of the non magnetic impurity due to the interband electrons scattering on impurity, the absence of the critical impurity concentration. This result was obtained by our group in 1965 [4].

In our opinion, the essentially new result in the development of the superconducting theory in systems with overlapping energy bands is the consideration of the angular dependence of the energy gap. Such anisotropic gap is in \( MgB_2 \).

In connection with this we mention papers [27]-[29], in which the method of calculating of the heat capacity in the two-band model with the consideration of the energy gap anisotropy is developed. The results obtained by these authors in the good way describe
experimental data on heat capacity in MgB$_2$ in ordered and non-ordered samples of this compound.

In our opinion, for the description of physical properties of many-band superconductors (including MgB$_2$) it is necessary to use already known results in this field, mentioned above.

Further development of the theory of the two-band model and its applying to the concrete materials must be done with the consideration of already obtained achievement.

It should be noted the important role of Prof. T. Mishonov and his colleagues, Who objectively estimated the importance of papers published in 1959 - 1991 years by Prof. V. Moskalenko and his coworkers.

References