# ON SOME ACHIEVEMENTS OF MOLDOVAN PHYSICS AND PRIORITIES IN THE FORMATION OF MODERN DIRECTIONS OF THE CONDENSED MATTER THEORY

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**Abstract**

The work is dedicated to the activities of academician V.A. Moskalenko, a prominent Moldovan scientist. The main directions and some important results of his scientific activities are considered. The priority of V.A. Moskalenko in the construction of the two-band superconductivity model and in the development of a multiband theory of superconductivity, as well as his significant contribution to the solution of modern problems of condensed matter physics, is shown.

## 1. Introduction

Moldavan physical science has suffered a heavy loss: an outstanding world-class scientist, professor, academician Vsevolod Anatolyevich Moskalenko passed away in his ninetieth year. Today it is difficult to imagine the life of the scientists of the physical community of Moldova without ever bright and profound scientific works and speeches of this incredibly hardworking and purposeful scientist. We, the physicists of the Republic of Moldova, are deeply grieved and proud of our compatriot who managed to overcome incredible difficulties and prove a priority over world science in the development of a number of scientific directions of theoretical physics in Moldova, thereby upholding the importance of the Moldovan state and people.

In our opinion, it is of interest to briefly describe the formation of the personality of V.A. Moskalenko and the manifestation of the great efforts to achieve the set goals. We will tell about the difficulties of life in his youth, about the incredible courage and purposefulness at the beginning of his scientific activity and the achievements of this period, which still influence the development of research in certain areas of physics.

Of interest is the choice of the scientific direction after the discovery of the mechanism of superconductivity, which had remained a mystery for almost 50 years. The desire for cognition of the unknown and interesting, which was inherent in V.A. Moskalenko, here has played a role and moreover, leads researchers to the disclosure of the picture of the real world. The correctness of V.A. Moskalenko's approach in science led to the need for a detailed study of the presence of overlapping energy bands in superconducting systems and other features of the energy spectrum. As a result, a new and significant direction in the development of theoretical physics has sprung up and covered many countries of the world.

Let us show the role of ideas of V.A. Moskalenko and his disciples in the construction of the theory of high-temperature superconductivity, the essence of which cannot be understood without taking into account the features of the energy spectrum, among which the idea of the existence of several overlapping electron and hole bands on the Fermi surface is on the first place. The theory developed by V. A. Moskalenko and his coworkers has become classical; to date, the priority of this theory in condensed matter physics has been proved. The priorities of the theory developed by Moldovan physicists in other fields of condensed matter physics are demonstrated, in particular, in the development of diagrammatic methods in the investigation of the role of electronic correlations in determining the properties of condensed matter. The universality of the activities of V.A. Moskalenko is briefly described in other current areas of development of theoretical physics as well.

## 2. Development of the Theory of Superconductivity on the Basis of a Two-Band Model

The first of the authors of this paper, almost all her working life from the student years, took part in numerous scientific researches and studies, being a coauthor of a number of research works written by V.A. Moskalenko, as well as the continuer of the development of the multiband theory of superconductivity. We will begin our description from those distant times when Moldova took the path of enlightenment and scientific research in a number of areas. These were difficult postwar years

In 1946, the Kishinev State University (now Moldova State University) was founded; it included several faculties for the study of natural sciences, particularly the Faculty of Physics and Mathematics, which did not have numerous students enrolled. However, among the students, there were quite capable and motivated young people, determined to learn and achieve high results. Several high-qualified specialists were invited, who established the educational process and, to some extent, the scientific research. In the process of studying, much attention was paid to self-reliant studies by studying the existing scientific problems using scientific literature. We will talk about theoretical physics. Along with the young employees, highly skilled specialists who arrived from other cities—Kiev, Leningrad, Odessa, etc.—also joined the work team. Thus, a base for the development of scientific research in theoretical physics was created.

Over time, V.A. Moskalenko became one of the leaders in the development of the theoretical physics in Moldova and headed the Department of Theoretical Physics of the Institute of Applied Physics of the Academy of Sciences of Moldova. At the beginning of his scientific career, his interests were related to the development of the theory of polarons and the optical properties of semiconductors. Despite the remoteness from the scientific centers, his works were relevant and significant.

Once, in one of the prestigious physics journals V.A. Moskalenko opened the work of academician N.N. Bogolyubov, studied it, and decided to go to Moscow to personally get to know Bogolyubov and his disciples. At that time, it was not easy. A determined character and purposefulness allowed V.A. Moskalenko to be in Moscow on an internship in a team of employees of world-famous academician (physicist and mathematician) N.N. Bogolyubov.

Scientific ties with outstanding physicists and professors, namely, S.V. Tyablikov, D.N. Zubarev, and other disciples of the school of academician N.N. Bogolyubov were quite close and maintained particularly with the disciples of V.A. Moskalenko.

Note that, in the late 1950s, the physical science was developed very rapidly. It is a question of a phenomenon of superconductivity. This phenomenon was discovered by Camerlene Ones in 1911 quite randomly when studying the properties of mercury at low temperatures. It was found that, as the temperature is lowered to the critical point ($T = T_c$), the resistance disappears and the motion of electrons in the crystal does not experience any obstacles. For almost 50 years, scientists have been looking for a way to determine the mechanism of the origin of this phenomenon. There have been a lot of different studies, both theoretical and experimental. Finally, in 1957, the result was obtained; it was presented in the works of Bardeen, Cooper, and Schrieffer [1]. It was found that the mechanism of superconductivity is attributed to the formation of bound pairs of electrons with opposite impulses and spins due to the indirect attraction of electrons through the crystal lattice. This was a huge discovery, which generated many additional problems. It was impossible to stay away from this discovery and the problems associated with it. Vsevolod Anatol'evich Moskalenko, along with his previous domain of research (candidate's dissertation was almost ready), decided to go headlong into research of superconductivity.

Note that the theory of superconductivity constructed in 1957 was based on an ideal, isotropic model. The first works, which took into account the real properties of metals, belong to V.A. Moskalenko [2] and Suhl H., Matitias B.T. and Walker L.R. [3]. As follows from the references in these papers, the articles of Moskalenko came to the editorial office of the Fizika metallov i metallovedenie (Physics of Metals and Metallography) journal a year earlier than the works of the authors of [3] and were published several months earlier. In addition, paper [3] contains a model and a study of the behavior of the superconducting transition temperature, while papers [2] contain, along with the results of [3], a study of the behavior and other thermodynamic characteristics, in particular, heat capacity jump at the point $T = T_c$. These circumstances make it possible to consider that the priority in the creation of a two-band model and the application of the model belongs to V.A. Moskalenko.

Vsevolod Anatol'evich Moskalenko, on his return from Moscow to Chisinau, organized intensive research in the Department of Statistical Physics on the basis of proposed model for superconductors with overlapping energy bands. At first, the studies were carried out in the diagonal approximation in the indices of the bands. The model is as follows: the formation of Cooper pairs of electrons within one energy band and the transition of the pair as a whole to another band, which provides the appearance of intraband $V_{nn}$ and the interband $V_{mn}$ electron interactions, which lead to an additional attraction of electrons, which favors an increase in the superconducting transition temperature. There are two order parameters $\Delta_1$ and $\Delta_2$ in the two-band model.

The studies of the properties of two-band (multiband superconductors) carried out in Moldova attracted the attention of scientists from different countries, and a new tendency has formed in low-temperature physics: study of the properties of superconductors with an anisotropic energy spectrum. Along with the development of the theory, studies of materials exhibiting the properties inherent in multiband systems were conducted. The leading theoretical research in this new direction was the work carried out in Moldova under the leadership of V.A. Moskalenko.

It is of interest to note that the properties of superconductors with overlapping energy bands were found to be significantly different from the properties of single-band ones not only in terms of quantity, but also in terms of quality. For example, in two-band superconductors, high superconducting transition temperatures are possible not only in the attractive interaction between electrons, but also in the case of repulsion, depending on the relationship between the interaction constants of the electrons. In an impurity two-band superconductor, the Anderson theorem is not satisfied for $\Delta_1 \neq \Delta_2$ and the thermodynamic properties depend on the impurity concentration.

Using the two-band model and acceptable values of the coupling constants, one can obtain a high $T_c$, two energy gaps of $2\Delta_1 / T_c > 3.5$ and $2\Delta_1 / T_c < 3.5$, a positive curvature of the upper critical field near the superconducting transition temperature, etc. In the two-band model, it is possible to decrease $T_c$ with increasing the disorder. Later, we considered more complicated two-band and multiband models for the case of the phonon and nonphonon mechanism of superconductivity. Numerous new results and the history of the development of the theory of superconductivity of multiband superconductors are given, in particular, in [4, 5].

In 1986, another grand event occurred—the discovery of high-temperature superconductivity (HTSC) in oxide ceramics ($T_c$ ~ 100 K). These compounds have a layered structure and have a rich set of physical properties. The following phase transitions are observed: magnetic, superconducting, and mixed states. The discovery of high-temperature superconductivity favorably affected the further development of the theory of multiband superconductors. A large number of results leading to qualitatively new relations between physical quantities and quite a good agreement between theory and experiment have been obtained. Analysis of the obtained results made it possible to publish a review article in the Journal of Advances in Physical Sciences (1991) [6]. According to a number of researchers, this paper contains the classical results of the theory of two-band superconductivity.

The great interest of researchers was caused by the discovery of the high-temperature intermetallic compound $MgB_2$ ($T_c \approx 40$ K). It seemed that all physicists involved in superconductivity switched to the studying the properties of this compound. It was found that, using the two-band model, one can describe all the observed anomalies of the physical characteristics of this substance. Physics journals were filled with papers in which the two-band theory of superconductivity was developed. We were amazed by the fact that our works of ten to twenty years ago were published as new and apparently as belonging to the new authors. Very often, no references to our research were cited. This attitude was the result of the collapse of the Soviet Union following a noticeable neglect for Soviet journals of physics and our scientific achievements. Within several years, we have achieved justice. It should be noted that a number of scientists from different countries of the world assisted V.A. Moskalenko in solving the problem of recognition of priority in the two-zone model (models in the theory of superconductivity) [7].

Finally, let us dwell on the last stage of the discovery of new superconductors. Since 2008, many papers presenting a new class of high-temperature superconducting compounds based on FeAs with the temperature of the superconducting transition of $T_c \approx 55$ K have been published. The Fermi surface intersects five bands arising from the *d*-states of Fe. An important role in these systems is played by the possibility of the emergence of a spin density wave state and a commensurate–incommensurate phase transition and the appearance of superconductivity.

In accordance with the statements of a number of scientists and the availability of published theoretical works, the properties of these high-temperature compounds should be described using the multiband theory of superconductivity. Research should be based on the theory of multiband superconductors described in our work [6], which represents the classical theory (M.V. Sadovsky, Usp. Fiz. Nauk 178, 1243 (2008)).

We can conclude that, in the Department of Statistical Physics of the Institute of Applied Physics of the Academy of Sciences of Moldova, as a result of research, a theory of the thermodynamic and electromagnetic properties of multiband superconductors has been developed; it’s used to describe a large number of modern anisotropic systems.

The priority of the V. A. Moskalenko's multiband superconductivity model on a global scale, as well as the relevance of the theory as applied to modern multiband (real) superconductors, has been proved.

The two-band superconductor model was proposed long before the discovery of high-temperature superconductivity; research based on it was carried out by V. A. Moskalenko with employees and many scientists from other countries. After the experimental confirmation of the significant effect of the features of the densities of electronic states on the properties of superconducting systems, the studies were substantially strengthened in view of the periodic discovery of new high-temperature compounds.

### 3. Study of Strongly Correlated Systems: Diagram Approach

An attempt to solve the problems that have arisen in the physics of superconductivity has broadened the scope of V.A. Moskalenko's scientific interests to the important domain of modern condensed matter physics, namely, the so-called physics of strongly correlated systems (SCS).

The fact is that transition metals, in compounds of which HTSC takes place (for example, copper oxide ceramics), comprise unfilled internal *d*- or *f*-shells. Coulomb repulsion of the electrons of these shells is strong (comparable to or exceeds the bandwidth). It was assumed that the strong Coulomb interaction of electrons can cause superconducting pairing. In addition, it could be assumed that, in HTSC, an important role is played by the interaction of electrons with lattice vibrations. Therefore, to study the HTSC phenomenon, it was necessary (a) to construct a theory that would take into account the energy of the strong Coulomb interaction and (b) to study the combined effect of strong electron interaction with one another and with phonons to elucidate the role of electron–phonon interactions.

By the time of discovery of HTSC, models taking into account strong correlations and features of the behavior of electrons in these systems had already been formulated. However, there was a need to reveal whether a superconducting phase exists in the systems described by these models. To this end, it was necessary to develop an alternative approach of quantum-statistical analysis of these systems, which would be self-consistent. This was due, in particular, to the fact that sometimes the use of various approximations and mathematical concepts that existed at that time led to some contradictory results obtained by different authors (for discussion, see, for example, [10]).

Therefore, V. A. Moskalenko considered that one of the primary tasks is the construction and development of methods for analyzing and calculating these systems. As noted by V.A. Moskalenko, the basis of these methods is the diagram technique and the Wick's theorem for statistical averages of T-products of operators [11].

Vsevolod Anatol'evich Moskalenko proposed the generalized Wick's theorem for strongly correlated electrons using the example of the one-band Hubbard model [11, 12]. According to this theorem, the averages of the T-product of electron operators in the interaction representation with the Hamiltonian $H_0$ can be represented as a sum that contains, in addition to the pair normal one-site products of operators corresponding to the usual Wick's theorem, irreducible one-site many-particle structures (Kubo cumulants).

On the basis of the generalized Wick’s theorem for strongly correlated electrons along with other mathematical concepts, V. A. Moskalenko and co-workers constructed diagram techniques for the main models of strongly correlated systems, namely, the Hubbard and Anderson models (and their generalized versions). The developed diagram technique for strongly correlated electrons was also generalized for strongly correlated electron systems with strong interaction with phonons.

Let us list some of the results that this approach allowed us to obtain when studying the role of strong correlations in high-temperature superconductivity, the Mott metal–insulator transition, and other important issues of modern condensed matter physics.

First of all, this technique allowed us to investigate the possibility of the superconducting state in the systems described by the main SCS models. With it, systems of equations that determine the superconducting state of the systems within these models were obtained, and the role of the strong Coulomb interaction in superconducting pairing was revealed. For some special cases in these models, equations that determine the temperature of the superconducting transition were obtained. Diagrammatic analysis of the Hubbard–Holstein, which takes into account, in addition to the strong interaction of electrons with each other, also the strongly electron-phonon interaction, allowed us to propose a new mechanism of superconductivity, which is based on the assumption of pairing of polarons by exchanging of phonon clouds [13]. On the basis of the developed diagram technique, V. A. Moskalenko also studied the thermodynamic properties of the systems described by the Anderson and Hubbard models [14–17]. For both models, the property of stationarity of the thermodynamic potential with respect to variations of the correlation function of the system was established. Interesting results were also obtained when considering the competing phases, such as the states of the spin-density wave of antiferromagnetism and superconductivity (due to correlations) [18] and many others.

The developed diagram technique for strongly correlated electron systems is an important result, first, from a technical point of view, since it allows us to construct a thermodynamic perturbation theory for the Green functions and correlation functions that contain important information about the macroscopic properties of the system. Second, being developed in order to clarify the properties of SCS, it has allowed V. A. Moskalenko and his colleagues to obtain important and interesting physical results in the study of SCS.

We note, in particular, as an example, the directions of theoretical research in the Academy of Sciences of Moldova.

(1) The theory of the thermodynamic and kinetic properties of two-band superconductors with variable density of charge carriers.

(2) Development of the theory of the thermodynamic properties of superconducting systems based on the Moskalenko's two-band model by means of generalizations, in particular, allowing to take into account all types of electron–phonon interactions, both intraband and inter-band, particularly between electrons of different zones, which also make it possible to describe the properties of two-layer systems with different layers and more complex modern structures.

(3) Development of the theory of superconductivity of liquefied systems (with small values of charge carrier density) in the Schafroth–Bose condensate scenario of local pairs.

(4) Development of diagram techniques for the study of strongly correlated systems using the model Hamiltonians of these systems

(5) Study of the role of strong correlation in high-temperature superconductivity and Mott metal–insulator transition, the thermodynamic and kinetic properties of the systems described by these models in the normal and superconducting phases.

## 4. Conclusions

In conclusion, we would like to note the constant striving of V.A. Moskalenko to increase the level of knowledge both of his own and of his disciples. To accomplish this goal, he made a lot of effort, which could not but affect the results in the issue of training of his scientific staff. In the Department of Statistical physics, about 30 candidatus scientiarum and habilitat theses were defended; in the Moskalenko’s School, 5 doctor habilitat theses were defended.

It is necessary to mention the long-term activities of V.A. Moskalenko and his colleges aimed at the organization of the Department of Field Theory and Nuclear Matter at the Institute of Applied Physics. We believed that it was necessary to have the most advanced scientific directions in the development of theoretical physics at the Institute of Applied Physics. Vsevolod Anatol'evich Moskalenko had to make a lot of effort and overcome many difficulties to solve this problem. Thanks to the persistence of V.A. and his assistants, this department was organized. This event promoted the Academy of Sciences to become a member of the large family of the countries belonging to JINR. The opportunity to be on the first line of research on various topics was opened.

Vsevolod Anatol'evich Moskalenko will remain forever in the memory of people who knew him, respected and loved him deeply. His research and the obtained results will be regarded as the foundations of the development of a stronghold of new ideas necessary for understanding the state of matter and practical applications.

Vsevolod Anatol'evich Moskalenko was not only a high-level scientist, but also a remarkable person. He will always be remembered as a very decent and delicate person with a gentle nature with people and, at the same time, firm in his convictions. We will always remember his kind laugh and smile. Being a talented and enthusiastic person, all his life he was doing what he loved, while remaining devoted to science. We lost a rare person, one of the titans of science, with whom the development of Moldavian theoretical physics began. He left behind a rich scientific heritage and a bright memory.

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