International Journal of Engineering, Science and Mathematics
Vol. 6Issue 7, November 2017,
ISSN: 2320-0294 Impact Factor: 6.765
Journal Homepage: http://www.ijesm.co.in, Email: ijesmj@gmail.com Double-Blind Peer Reviewed Refereed Open Access International Journal - Included in the International Serial Directories Indexed & Listed at: Ulrich's Periodicals Directory ©, U.S.A., Open J-Gage as well as in Cabell's Directories of Publishing Opportunities, U.S.A

A QUALITATIVE OVERVIEW OF THE MECHANISMS OF SUPERCONDUCTIVITY

SHAILAJ KUMAR SHRIVASTAVA
Principal, M.M. College, Bikram, Patna, Bihar, India
Email: shailajshri68@yahoo.com

Abstract: The mechanism of superconductivity continues to be one of the most fascinating and challenging topics in condense matter physics. The discovery of high-T_c cuprate superconductors and iron based superconductors has challenged the classical theories of condensed matter physics and opened a new chapter of strongly correlated electron systems. The key question of superconductivity is the nature of mechanism of pairing of carriers. The electron phonon interaction or spin fluctuations are considered to be central to the mechanism of superconductivity. In this article attempt has been made to highlights the brief outcome of various models and theories on the mechanism of superconductivity.

Keywords: High-T_c superconductors, electron- phonon interaction, spin fluctuation, pairing mechanism

I.Introduction

Dutch scientist Heike Kammerlingh Onnes [1] discovered that electrical resistance of various metals e.g mercury, lead, tin and many others disappeared when the temperature was lowered below some critical value T_c. Meissner and Oschenfeld [2] observed that when a material is cooled in the presence of a magnetic field, on reaching its superconducting transition temperature (T_c) the magnetic flux is suddenly completely expelled from its interior. It means it exhibits perfect diamagnetism. Gorter [3, 4] put forward the idea of a two fluid model, in which the electron gas within the superconductor has two components. One component has no entropy and carries the supercurrent while the other component has all the entropy and behaves like a normal electron gas. Below the super conducting transition temperature, the superconducting electrons short out the normal electrons so that the electrical resistance is zero. These two features were captured in the equation proposed by London brothers [5], who first realized the quantum character of the phenomenon. Ginzburg and Landau [6] created a theory describing the transition between the superconducting and normal phases. Although the Ginzburg and Landau theory explained the macroscopic properties of superconductors, the microscopic properties remain unsolved. Bardeen, Cooper and Schrieffer created microscopic theory (BCS theory) [7] which describe conventional superconductors in the low temperature and low magnetic field regime. According to BCS theory, the superconductors at below T_c have an energy gap equal to binding energy of the Cooper pair, which dominates the transition temperature. The binding energy of the Cooper pair depends on the density of electron states at the Fermi surface, and on the strength of electron phonon interaction.

High temperature superconductors are characterized by a layered two dimensional superconducting condensate and unique features that are very different from conventional superconducting materials. Recent studies [8, 9] reveal that the theoretical explanation for copper and iron superconductors could be the same and could even apply to other materials. The spin fluctuation mechanism of high-T_c superconductivity in copper oxide compound is determined by the high intensity of the antiferromagnetic exchange interaction. According to spin fluctuation mechanism [10], the pairing wave function of cuprate high-T_c superconductor should have d- wave symmetry. But unfortunately, some reports supported the d- symmetry for the high-T_c superconductors whereas others supported the s-symmetry. The survey of the mechanism of superconductivity [11] emphasized that all models used the conception of pairing with the subsequent formation of Bose- Condensate at T_c irrespective of the nature of the resulting attraction.

To explain the unique phenomenon of superconductors, a lot of models and mechanisms were proposed, among which some models like two fluid model, Ginzberg-Landau model, BCS model, exciton model, plasmon model, bipolaron model, magnon model, spin fluctuation model, carrier induced dynamic strain effect model etc are briefly discussed.

II.Two fluid models

In 1934, Physicist Gorter and Casimir [3, 4] developed the two fluid model of superconductivity in order to explain the thermodynamic properties of superconductors. The model suggests that in a superconducting material, a finite fraction of the electrons are condensed into a sort of superfluid that extends over the entire volume of the system. At zero temperature there is complete condensation and all electrons participate in forming the superfluid, only the electrons near the fermi surface have their motion significantly affected by the condensation [12].The normal electrons behaves as usual, as particles flowing in a viscous medium whereas the electrons in the superfluid, experience no scattering, have zero entropy and long coherence length, which give superconductors their unique properties [13]. As the temperature increases to T_c the fraction of electrons contained in the superfluid goes to zero and the system experiences a second order phase transition from the superconducting to normal state. Gorter and Casimir developed a formula relating the number of electrons in the superfluid to the temperature that would agree with their experiments.

$$n_s = n\left[1-\left(\frac{T}{T_c}\right)^4\right]$$

where n_s is the fraction of electrons in the superfluid. Other experiment at low temperatures have shown that there is a peaking of the specific heat just below T_c, indicating an increase in entropy as the system transitions to the normal state, thus implying that superconducting state has a greater degree of order than the normal state.The exponential decrease of the specific heat of the electron is given by

$$C_v = ae^{-b\left(\frac{T}{T_c}\right)}$$

The exponential behavior suggests the presence of an energy gap in the energy spectrum of the electrons. The gap, lying just at the Fermi level is extremely small, ~10^{-4} eV, but prevents electrons from being readily excitable and leads to a small specific heat.

III.London's theory

In order to explain the expulsion of magnetic field from the superconductor, the London brothers proposed a phenomenonological theory in 1935 [5] taking into account the two fluid model. All the free electrons in a superconductor are divided into two: superconducting electron of density n_s and normal electron of density n_n , with free electrons $n=n_s+n_n$. As the temperature increases from 0 to T_c, the density n_s decrease from n to 0. Further, assumptions are that the magnetic flux penetrates to a certain penetration depth λ that is independent on the strength of the magnetic field as well as the dimensions of the sample. But their results consistently overestimated the experimentally found values, and so their assumptions were discarded.

IV.Ginzburg-Landau model

Ginzburg-Landau [6] developed a phenomenological theory taking into account the quantum effects to explain the electrodynamical phenomena near the superconductor-normal metal phase boundary and the effect of magnetic field and current on superconductivity. It is based on the idea that the superconducting transition is a second order phase transition. They introduced a complex pseudo wavefunction as an order parameter $\Psi = |\Psi| e^{i\theta}$ which describe the superconducting electrons. The local density of superconducting electron was assumed to be

$$n_s(r) = |\psi(r)|^2$$

The amplitude $|\Psi|$ is zero in the normal phase above the superconducting transition T_c and is finite in the superconducting phase below T_c. In the presence of an external magnetic field the order parameter has a spatial variation. When the spatial variation of the order parameter is taken into account, the free energy of the system can be expressed in terms of the order parameter Ψ and its spatial derivative. This is valid in the vicinity of T_c. Below T_c the amplitude $|\Psi|$ is small and the length scale for spatial variation is long. Two temperature dependent parameters were introduced by G-L in the theory. The coherence length ξ gives the characteristic scale for the spatial variation of the order parameter Ψ and penetration depth λ is the range of the penetration of magnetic field. These two lengths diverge as $T \rightarrow T_c$. Another parameter,κ known as Ginzburg-Landau parameter and defined as

$$\kappa = \lambda(T) / \xi(T)$$

plays an important role in the theory. It may be mentioned that κ has a finite value at $T=T_c$. The macroscopic behavior of superconductors can be explained well by G.L. theory. This theory also provides the qualitative framework for understanding the dramatic supercurrent behavior as a consequence of quantum properties on a macroscopic scale. Their results were able to accurately match the experimental result of the time and were later shown to be a specific form the BCS theory.

V.Phonon mechanism of superconductivity

Bardeen, Cooper and Schrieffer (BCS) [7] were the first to propose a fundamental theory that explains the microscopic origin of superconductivity. According to them, superconductivity was associated with the existence of a bound pair of electrons, each electron in pair having equal but opposite spin and angular momentum, traveling through the lattice. The pairs, known as Cooper pairs, are bound by an electron-phonon interaction. The electron pair wave function is symmetrical s-wave type. The electrons in these pair states are no longer required to obey the Fermi-Dirac Statistics. The paired charge carriers interact over substantial distances to produce a coherent state [14]. Each Cooper pair requires a certain minimum energy to be displaced, and if the thermal fluctuations in the crystal lattice are smaller than this energy the pair can flow without dissipating energy. When an electron moves through the system, it creates a depression in the atomic lattice through lattice vibration known as phonon. If the depression of the lattice is strong enough, another electron can fall into the depression created by first electron –the so called water-bed effect become strong enough, Cooper pairs win over the creation of holes behind the electrons and the normal conductor through an unlimited supply of electrons by creation of Cooper pairs. The BCS theory accounted for many of the experimental observations such as the existence of an energy gap $2\Delta(0)$ between the superconducting and normal electrons with a predicted value close to 3.5 $k_B T_c$ at absolute zero. The value of gap coefficient $2\Delta(0)/k_B T_c$ decides the strength of electron phonon coupling in superconductors. When the coupling is strong, this ratio increases monotonically. To get high-T_c from electron-phonon coupling, one needs strong coupling, but if the coupling is strong enough to give very high T_c. then it is also strong enough to cause lattice stability. The BCS theory has been found to satisfactorily describe all superconducting phenomena in weakly coupled superconductors like Zn, Ga, Cd etc, which have $2\Delta << E_F$. The high-T_c cuprates follow BCS theory in some aspects such as persistent current, Josephson tunneling and vortex lattice phenomenon. This theory explains the magnetic flux through a superconducting ring is quantized because the superconducting ground state involves pairs of electrons. Superconductivity is well explained by BCS theory in alkali doped C_{60} and MgB_2 [15, 16]. However, this theory also implies that the forces binding the cooper pairs were very feeble, so they would be ripped apart by thermal vibrations at anything other than extremely low temperatures and therefore superconductivity might not occur above 30K. Many of the properties of high-T_c superconductors like small or no isotopic shift, short coherence length, unprecedently high transition temperature, electric and magnetic anisotropies etc. were markedly different from conventional superconductors. Hence BCS theory appears to be inadequate for high-T_c superconductors.

VI.Exciton Mechanism of superconductivity

The first exciton model, in which pairing is realized due to electron excitations was proposed by W.A. Little [17] for organic superconductors and by Ginzburg and Kirzhnitz [18] for layered systems. In this model, it was necessary to assume the existence of two groups of electrons: one of them is related to conduction band, where the superconducting pairing occurs due to the exchange by excitons which are excitations in the second group of almost localized electrons. The searches for superconducting in organic material were stimulated to a significant degree by the idea of Little about the possibility of high- T_c superconductivity is due to the excitonic mechanism of the Cooper pairing of electron in long conducting polymeric chains containing lateral molecular branches-polarizer's. In this mechanism, the effective attraction between electrons at the Fermi surface is induced by the exchange of excitons, rather than phonons. The exciton mechanism is in principle not restricted to one dimensional structure. Ginzburg has discussed the possibility of excitonic superconductivity in two dimensional systems. One of the main attractions of the proposed exciton mechanism is the apparent possibility of higher transition temperatures. In this model, the metal electrons at the Fermi surface tunnel into the semiconductor gap where they interact with virtual excitons, producing a net attractive interaction among the electrons in direct analogy with the phonon mechanism of superconductivity [19].The Exciton mechanism of superconductivity in a metal-semiconductor system is studied from the point of view of the complete electron-electron interaction. There is no experimental evidence for the existence of the excitonic mechanism of superconductivity because high energy intramolecular excitonic excitations cannot ensure the binding of electrons in pairs.

VII.Plasmon Mechanism of superconductivity

The charge fluctuation (Plasmon) mechanism of the d-wave Cooper pairing is due to the interaction between the charge carriers and the collective low frequency excitations of electron density. When an individual particle excites a Plasmon virtually, it produces an oscillating internal electric field and can attract another individual particle, which results in the negative interaction between the two particles. The Plasmon mechanism is determined by the dynamic rescreening of Coulomb interaction due to low frequency collective excitations in a system of light and heavy fermions. The low dimensionality along with the presence of several overlapping energy bands and a small value of the carrier concentration or Fermi energy makes the Plasmon mechanism favorable. The pairing is a result of the exchange of quanta of longitudinal plasma waves-Plasmons. The Plasmon mechanism leads to cooper pairing in both the d-wave and s-wave Cooper channels, but the superconductivity in the s-wave channel is suppressed by exchange-correlation effects [20].Compared with a three dimensional system, a two dimensional one is more favorable for the Plasmon mechanism of superconductivity[21].

VIII.Bipolaron Mechanism of superconductivity

An alternative mechanism for superconductivity was put forwarded by Mott [22, 23] known as bipolaron model. The concept was that " if an electron and a surrounding lattice distortion with high effective mass can travel through the lattice as a whole , and a strong electron-phonon coupling exists, the perovskite insulator could be turned into a high- T_c superconductor"[24]. A polaron describes the lattice distortion, which accompanies the motion of an electron through a solid. Bipolarons are bound pairs of polarons, which are mutually attracted by the lattice distortion. The bipolaron obey Bose-Einstein statistics. The superconductivity charge carriers are 'bipolaron'. The superconductivity is caused by superfluidity of the Bose-condensate of bipolarons. The idea of a polaron is based on the assumption about the auto localization of an electron in the ion crystal due to its interaction with longitudinal optical vibrations under the local polarization which is caused by the electron itself. The electron is confined in the local polarization induced potential well and conserves it by the own field [25,26]. Using a bipolaron model, Mott and his colleagues have been able to explain many experimental observations, notable among them being the small or absence of transport properties along the c-direction that is perpendicular to the CuO_2 planes. Bipolarons had been proposed earlier by a number of theoretician but only the intersite John-Teller (JT) bipolaron is the true elementary quasi particle occurring in the copper oxides [24, 27]. Kochelaev, Mihailovic and Kabanov used a three spin model for an analytical description of this J-T bipolaron concept [28-29]. This model consists of two Cu^{+2} ions with each has spin S=1/2 anti parallel to each other and the rest of the lattice, plus a hole mainly located on the neighboring oxygen, also with spins=1/2.Mahailovic and Kabanov add a second hole in oxygen orbital's with the anti parallel spin to the first. Therefore, the total spin is S=0, thus overcoming the difficulty to move in the AFM lattice which a single polaron with spin. A large number of properties of cuprates can be understood with this concept.

IX.Magnetic Mechanism of superconductivity

In this mechanism, the pairing is realized due to exchange by spin excitations-magnons. Magnon is a quasi particle which is the quantum synonyms of a spin wave of excitation in a magnetically ordered system. It involves the interaction between the conduction electrons caused by both the exchange by acoustic phonons and an additional interaction related to the exchange by spin waves (magnons) [30]. It starts with a superconducting material in the antiferromagnetc state, in which neighboring electrons have spins of opposite orientation. When the material is doped by the addition of another element, holes are created that also carry a spin. Each hole wants to spin antiparallel to the electron, but it also want to delocalized-spread its wavefunction to other sites. But it sees antiferromagnetic electrons whose spins are aligned parallel with it at these other sites. Its spin is tilted, so that the electron can have a favorable alignment of its spin with the antiferromagnetic electrons. This causes a spin polarization cloud to form, attracting a second electron and forming a pair. The interaction is mediated by polarizing spin degrees of freedom. It was shown that the superconductivity and ferromagnetism can co-exist in the same spatial regions. High-T_c superconductors reveal strong magnetic fluctuations in the region of doping which can be responsible for the pairing. In magnon pairing mechanism of superconductivity in cuprates, a conduction electron (oxygen pπ like) tends to repolarise the nearby copper d spins into local ferromagnetic order. As this oxygen pπ electron moves along, it tends to leave behind a wake with ferromagnetically paired copper spins. As a second conduction electron is scattered into the wake of first electron since there is already ferromagnetic polarization of the copper spins. The net result is the attractive interaction responsible for superconductivity [31].

Anderson [32] made an attempt to explain the Cooper pairing in high temperature superconductor by the participation of magnetic excitations. The Anderson model is based on the conception of magnetic ordering. This mechanism ensures the joining of carriers in pairs with compensated spin, the so called spinons. At the doping of high-T_c superconductors compounds, there arise holes which can form the complexes with spinons–holons. Superconductivity is explained by the pairing of holons i.e., by the creation of spinless bosons with double charge. That is, the pairing of carriers in the Resonance Valence Bond (RVB) model is realized due to the exchange of magnons. At low temperature, the paired holons form a superconducting condensate. Anderson proposed a resonating valence bond description of conduction in which the strongly coupled singlet pairs move about as bosons rather than as a normal simple hole conduction of an antiferromagnetic system. He suggested that this strong pairing model would explain the superconductivity of the cuprates and predicted a gapless superconductor [32]. This Anderson model is quite different from the magnon pairing model, where there is a hole in the oxygen pπ orbital, a large gap, and attractive pairing involving triplet coupling. He gave a 2-D model, so called “Luttinger liquid” model. In the Luttinger liquid, the spins and charges are carried separately by particles called ‘spinons’ and ‘holons’ respectively. The spinons are fermions with spin 1/2 and zero charge while holons are bosons having zero spin and a charge of e. Scattering of holons and spinons is proportional to spinon density of states which is linear in T. The study of antiferromagnetism in high-T_c superconductors through spinons and holons has not been experimentally identified.

X.Spin fluctuation mechanism

Pines [33, 34] proposed spin fluctuation mechanism for high-T_c superconductors, in which two spin flips are involved to create attraction between two electron through antiferromagnetic exchange coupling. Anderson was the first to point out a special role of strong electronic correlations in cuprates and the anti ferromagnetic exchange interaction associated with these correlations. He also proposed the exchange pairing mechanism in the frame work of t-J model [32]. In a high-T_c superconductor, the mechanism is extremely similar to a conventional superconductor. In this case, phonons virtually play no role and their role is replaced by spin density waves. As all conventional superconductors are strong phonon systems, all high-T_c superconductors are strong spin density wave systems. When an electron moves in a high-T_c superconductor, its spin creates a spin density wave around it. The spin density wave in turn causes a nearly electron to fall into the spin depression created by the first electron (called water-bed effect) a Cooper pair is formed. When the system temperature is lowered, more spin density waves and Cooper pairs are created leading to superconductivity. The indirect interaction of electrons through spin waves in a ferromagnetic metal has the character of attraction in the triplet state and, hence, can lead to the triplet pairing [35]. As these systems are magnetic in nature, due to the Coulomb interaction, there is strong Coulomb repulsion between electrons. The Coulomb repulsion prevents pairing of the Cooper pairs on the same lattice site. The pairing of the electrons occurs at near-neighbor lattice sites. This is the so called d-wave pairing, where the pairing state has a node (zero) at the origin [36, 37]. Spin fluctuation plays an important role in superconductors with heavy fermions [38]. Dahm et al [39] demonstrated that spin fluctuations have sufficient strength to mediate high-T_c superconducting generating d-wave superconducting state with transition temperature exceeding 150K. NMR measurements by Hattori et al. [40] have provided strong evidence that ferromagnetic fluctuations provide the pairing force that leads to superconductivity in UCoGe in which ferromagnetism and superconductivity seems to coexist. The antiferromagnetic spin fluctuations could possibly be the major mediating glue in the iron based superconductors [41, 42]. In Fe (Se,Te), the iron based superconductor, the Cooper pairs adopted a characteristics “S± wave” structure that is unique to a material with two types of electrons. The discovery of S± wave structure break new ground by supporting a mechanism for electron pairing based not on lattice vibrations, but on magnetism. The superconducting state in oxypnictides has been found to be consistent with the fully gapped S± pairing symmetry [43]. In iron arsenides, the vibrational mechanism is not strong enough to make them superconducting. Some iron arsenides are antiferromagnetic, rather than superconducting, so magnetism rather than atomic vibrations might provide electron glue.

XI.Carrier induced dynamic strain effect model

In this model, the superconducting state consists of the dynamic bound state of superconducting electrons, which is formed by the high energy non-bonding electrons through dynamic interaction with their surrounding lattice to trap themselves into the three dimensional potential wells lying in energy at above the Fermi level of the material[44-46]. The binding energy of superconducting electrons dominates the superconducting transition temperature of the material. Under an electric field, the superconducting electrons move coherently with lattice distortion wave and periodically exchange their excitation energy with chain lattice, and so the superconducting electrons transfer periodically between their dynamic bound state and conducting state. So the superconducting electrons cannot be scattered by the chain lattice and supercurrent persists without losing energy. The key point to achieve superconductivity is that the superconducting electron must periodically exchange its excitation energy with chain lattice. That is, the excitation energy of the superconducting electrons must be reversibly transferred between superconducting electrons and chain lattice. A superconducting material must simultaneously satisfy the following three necessary conditions required by superconductivity. First, the material must possess the high energy non bonding electrons with certain concentrations required by coherence lengths. Second, the material must have the three dimensional potential wells lying in energy at above the Fermi level of the material and the dynamic bound state of superconducting electrons in potential well of a given superconducting chain must have the same binding energy and symmetry. Finally, the band structure of the superconducting material should have a widely dispersive antibonding band, which crosses the Fermi level and run over the height of the potential wells to ensure the normal state of the material being metallic. According to the type of potential wells, the superconductors as a whole can be divided into two groups: the conventional and high temperature superconductors. The complex phase diagram, the linear temperature dependence of resistivity with temperature in normal state, the pseudogap, the T_c increasing with the number of CuO_2 planes, the lattice instabilities and hardening of superconducting state and the symmetries of superconducting waves etc. all can be uniquely understood under this new model. In addition the effect of strain and pressure, hole and electron doping, the replacement of trivalent rare earth elements and the oxygen concentration on the superconducting properties of cuprates can be consistently explained by this mechanism. Josephson effect, the origin of superconducting tunneling phenomenon, the tunneling mechanism in the multijunction systems as well as the unit of magnetic flux quantization are all physically reconsidered in this model.

XII.Conclusion

Superconductivity involves the macroscopic quantum condensation of paired electrons. Such pairing can originate from a variety of quantum interactions. There are various kinds of interactions electron-phonon interaction, spin–spin interaction, charge density waves, spin density waves, and so on. All models applied the conception of pairing with the subsequent formation of Bose-condensate at T_c regardless of the reason for attraction. At the present time, there exists no theoretical approach which would explain the totality of thermodynamical, magnetic and superconducting properties of high temperature superconductors from the single view point. One reason for this is that the superconducting materials are generally very complex and multilayered which makes theoretically modeling extremely different.

References

[1] H. K. Onnes, Leiden Commun., **122b, 124C,**1911
[2] W. Meissner and R. Oschenfeld, Naturwiss, **21,** 787, 1933
[3] Gorter, C.J. and H.G.B. Casimir, Phys. Z. 35,963, 1934a
[4] Gorter, C.J. and H.G.B. Casimir, Z.Tech. Phys., **15**, 5393, 1934b
[5] F. London and H. London, Proc. Roy. Soc. A, 149, 71, 1935; Physica C, 2, 341, 1935
[6] V. L. Gingberg and L. D. Landau. Sov. Phys.JETP. **20,** 1064, 1950
[7] J. Bardeen, L. Cooper and J. R. Schrieffer., Phys Rev., **106** 162; **108**, 1175, 1957
[8] T. Tohyama, J.Jap. Appl. Phys. 51, 010004, 2012
[9] L.de. Medici, G. Giovannetti, m. Capone, Phys. Rev. Lett. **112**,17,2014
[10] P. Monthoux, A.V. Balatsky and D. Pines 919920 Phys. Rev. B, 46(22) 14803-14817
[11] S.P. Kruchinin, Reviews in Theoretical Science, **2**, 1-22, 2014
[12] Schrieffer.J.R, Theory of Superconductivity, (Parsens Book), 1-4, 9-12, 1964
[13] Omar, Ali M, Elementary Solid State Physics (Pearson Education, 496, 1999
[14] J. Bardeen, Nobel Lecture, Science**, 181,** 1209, 1973
[15] J.H. Schon, Ch Kloc, B. Batlogg, Nature, 408,509
[16] J.Nagamatsu et al., Nature, 410, 63, 2001
[17] W.A. Little, Phys. Rev. A, **134**, 1416, 1964
[18] V.L. Ginzburg and D.A. Kirzhnitz (eds) High Temperature Superconductivity, Consultant Bureau, NewYork, 1982
[19] David Allender, James Bray, and John Bardeen, Phys. Rev. B, 7, **1020,** Feb.1973
[20] E.A. Pashiotskii and V.I. Penteger, Low Temp. Phys. **34,** 113, 2008
[21] Yasutami Takada, Journal of the Physical Society of Japan, **45**, 3, 786, 1978
[22] N. F. Mott, Contemp. Phys. **30,** 373, 1990
[23] N. F. Mott., Phys World, **9,** 16, 1996
[24] J.G. Bednorz and K.A. Muller, Z. Phys. B, **64**, 189, 1986
[25] A.S. Alexandrov and J. Ranninger, Phys. Rev. **23**, 1796, 1981
[26] S.I. Pekar, Gostekhizdat Moscow, **168,** 1951
[27] V.V. Kabanov and D. Mihailovic. J. Supercond. **13**, 959, 2000
[28] D. Mihailovic and V.V. KabanovPhys. Rev. B, **63**, 054505, 2001
[29] B.J. Kochelaev, J. Sichelschmidt , et al., Phys. Rev. Lett. **79**, 4274, 1997
[30] A.I. Akhiezer and I.Ya. Pomeranchuk, Zh.Eksp. Teor.Fiz, **36**, 819, 1959
[31] Guanhua Chen, William A. Goddard, Science, New Series, 239, 4842,899, 1988
[32] P.W. Anderson, Science, **235**, 1196, 1987; P.W. Anderson et al., Phys. Rev. Lett. **58**, 2790, 1987
[33] P. Monthoux and D. Pines, Phys. Rev. B, **49** 4261, 1994; P. Monthoux, A. Baletsky and D. Pines, Phys. Rev. B. **46,** 961,1992
[34] D. Pines, Physica C, **185-189,** 120, 1991
[35] S.P. Kuchinin, Physica C, **282-285**, 1397, 1997
[36] F. Onufrieva and P. Pfenty, Phys Rev Lett. **102**, 207003, 2009
[37] G. Bednorz and K.A. Muller, Z Phys. B, **64**, 189, 1986
[38] T. Morya and K.Ueda, Advances in Physics, **49**, 556, 2000
[39] T. Dahm et al., Nature, Physics **5**,217, 2009
[40] T. Hattori, et al., Phys. Rev. Lett. **108**, 066403, 2012

[41] K. Kuroki et al., Phys. Rev. Lett. **101**,087004, 2008
[42] A.V. Chubukov et al., Phys. Rev. B, **78**,134512, 2008
[43] D.C. Johnston, Adv. Phys. **59**, 803, 2010
[44] X.S. Zhao, Y.R. Ge, J. Schroeder, and P.D. Persans, Appl. Phys. Lett. **65**, 2033, 1994
[45] Xue-Shu Zhao, Yu-Ru-Ge and Xin Zhao, Journal of Material Science, **33**, 4267, 1998
[46] D.C. VanderLaan and J.W. Ekin, Appl. Phys. Lett., **90**, 052506, 2006