Description of the Oxygen Order evolution and its relation to the Superconducting Transition in \( \text{La}_2\text{CuO}_{4+y} \)

E. V. L de Mello  
*Instituto de Física, Universidade Federal Fluminense, Niterói, RJ 24210-340, Brazil*

(Dated: February 21, 2012)

The segregation of oxygen in the high critical temperature cuprate superconductor \( \text{La}_2\text{CuO}_{4+y} \) has been systematically studied along the years. In a recent set of experiments, Poccia et al related, for the first time, time ordering \( (t) \) of oxygen interstitials with the corresponding superconducting transition temperature \( T_c(t) \). We develop a phenomenological description of the time ordering forming pattern domains and show how it may affect the superconducting interaction. The superconducting self-consistent calculations in a system with electronic granular structure of varying hole doping yields also different local d-wave amplitudes. These amplitudes are of the order of magnitude of scanning tunneling microscopy measurements and they vanish at \( T^*(t) > T_c(t) \). Then, calculations with Josephson coupling among the isolated charge domains reveal that the superconducting interaction is likely to be scaled by the local free energy and capture the details of \( T_c(t) \). The accurately reproduction of these apparently disconnected phenomena establishes routes to the important physical mechanisms involved in the connection between sample production and on the origin of the superconductivity of cuprates.

PACS numbers: 74.20.Mn, 74.25.Dw, 74.62.En, 74.81.-g

I. INTRODUCTION

There are considerable evidences that the tendency toward phase separation is an universal feature of some oxides like cuprate superconductors and manganites. The presence of hole-rich and hole poor phases were detected in oxygenated \( \text{La}_2\text{CuO}_{4+y} \) almost immediately after the discovery of the superconductivity in these compounds and by subsequent works. Further experiments have observed evidences of complexity and electronic disorder in many other materials.

To describe this phenomenon in the context of cuprates some theories producing phase separation have been suggested, mainly based on doped Mott-Hubbard insulators. To cite just a few, some relies on Fermi-surface nesting which leads to a reduced density of states, or a free energy barrier between the two phases varies with the time what connects the time of oxygen ordering with the raise of \( T_c \) in \( \text{La}_2\text{CuO}_{4+y} \) with the subsequent measurement of the superconducting transition temperature \( T_c(t) \). Other new possibilities that require new approaches.

In this paper we describe the two parts of the Poccia et al experiment and try to provide an explanation to the raise of \( T_c \) with the oxygen ordering. We rely on a description of the phase separation in cuprates based on the time-dependent Ginzburg-Landau (TDGL) or Cahn-Hilliard (CH) equation introduced earlier. It is well known that these equations display solutions with two type of domains where the free energy assumes some minimum value, for high and low density. These valleys are surrounded by steep boundaries where the charges can get trapped, loosing part of their kinetic energy what enhances the mechanism of pair formation. The free energy barrier between the two phases varies with the time what connects the time of oxygen ordering with the variations on \( T_c(t) \). Scaling the superconducting interaction with the local changes of the free energy is one of our most interesting finding. Another new point is that in this granular-like system the resistivity transition temperature \( T_c \) occurs when the Josephson energy \( E_J \) among the grains is equal to \( K_B T_c \). These new ideas are endorsed by the close agreement with the data.

It has been determined experimentally that the superconducting state occurs only at some values of \( y \) in \( \text{La}_2\text{CuO}_{4+y} \) and that it is enhanced when the excess oxygen dopants form a three-dimensional ordered superlattice within the interstitials regions of the crystal. Systems with poor i-O ordering may have two types of
superconducting states with lower $T_e$'s than the one with more i-O ordering. On the other hand, since the superconductivity occurs mainly in the CuO$_2$ planes, it is clear that there is a connection between the i-O oxygen order and the charges in the planes. This connection has also been observed in other cuprates where the charges tend to agglomerate near the dopants. Consequently, it is an open question whether the electronic disorder is driven by the lower free energy of undoped antiferromagnetic (AF) regions (intrinsic) or by the out of plane dopants (extrinsic origin). Notice that the i-O disorder temperature (330K) is quite similar to Neel temperature and perhaps there is a connection between the two phenomena. In either case, being intrinsic or extrinsic, it is possible to assume that there is an one to one correspondence between the two phenomena. This one to one correspondence is a crucial ingredient of our work and will be explored in detail here. Consequently the i-O ordering time evolution is assumed to be described together with the planar electronic phase separation (EPS) by the CH equation.

**II. THE PHASE SEPARATION DESCRIPTION**

Normally the i-O order starts below the phase separation transition temperature $T_{ps} \approx 330$K. In the Poccia et al. experiment the system is heated to a disordered phase above 370K and quenched to 200-300K where the i-O have low mobility and the sample exhibits no i-O ordering and a poor superconducting state. However, by illuminating such a system at this range (200-300K) of temperature, they observed nucleation and growth of the ordered i-O domains with the time of irradiation $t$. Here we assume that this process is accompanied also by the nucleation of charge domains in the planes. A similar process where the holes in the planes follow the dopant atoms and segregate in inhomogeneous domains was observed in YBCO.

Based on these facts, and that the superconducting transition is accomplished by the electronic charges, we will turn our attention the hole dynamics in the Cu – O planes. Using the TDGL or CH approach, the appropriate order parameter is the normalized difference between the local $p(i, t)$ and the average electronic doping level $p$, $u(p, i, t) \equiv (p(i, t) - p)/p$. Here, in order to compare with the Poccia’s experiment, we assume the optimal doping $p = 0.16$. Clearly $u(i, t) = 0$ corresponds to the homogeneous system above $T_{ps}$, and $u(i, t) = \pm 1$ correspond to the extreme cases of full phase separation that probably is not the case for the superconductor La$_2$CuO$_{4+y}$, because the i-O mobility occurs only in a small temperature interval below the phase ordering temperature. In other similar systems like La$_{2-x}$Sr$_x$CuO$_4$ the degree of phase separation seems to be larger since AF domains (with almost zero local doping) are observed even in overdoped compounds. Consequently, in the i-O experiment it is likely that the system reaches an intermediated structure with two phases with densities around the average doping level $p$.

Then, in terms of the order parameter $u(p, i, t)$, the Ginzburg-Landau (GL) free energy functional is the usual power expansion,

$$f(u) = \frac{1}{2} \varepsilon^2 |\nabla u|^2 + V_{GL}(u, t).$$

Where the potential $V_{GL}(u, T) = -A^2(T) u^2/2 + B^2 u^4/4 + ...$, $A^2(T) = \alpha (T_{PS} - T)$, $\alpha$ and $B$ are constants. $\varepsilon$ gives the size of the boundaries between the low and high density phases. The CH equation can be written in the form of a continuity equation of the local density of free energy $f$, $\partial u/\partial t = -\nabla \cdot J$, with the current $J = M \nabla (\delta f/\delta u)$, where $M$ is the mobility or the charge transport coefficient that sets the phase separation time scale. Therefore,

$$\frac{\partial u}{\partial t} = -M \nabla^2 (\varepsilon^2 |\nabla u|^2 - A^2(T) u + B^2 u^3).$$

The parameter $\varepsilon$ determines the planar size of the boundaries and $A(T)/B$ the values of the order parameter at the minima near the transition temperature. If $A(T)$ is zero (above the phase separation temperature $T_{ps}$) there is only one solution for the free energy and for the non-vanishing case there are two solution corresponding to the two phases (high and low densities). In Fig. 2, we show same typical simulations of the density map with the two (hole-rich and hole-poor) phases given by different colors. Varying the values of the ratio $A(T)/B$ and the symmetry of original seed we can obtain these different patterns. In some previous works, we have tried to match these patterns with some experimental evidences, like the patchwork forms of the scanning tunneling microscopy (STM) local density of states (LDOS) or the stripe like patterns as measured in some systems by neutron diffraction. In theory the ratio $A(T)/B$ is zero at $T_{ps}$ a should increases as the temperature decreases but since...
FIG. 2. Different patterns derived from Eq. (2) with different parameters and different seeds. In all cases the local order parameter evolves from zero to ±A/B. The size between the walls separating the two phases is scaled by ε. We choose to work with the pattern of the bottom-right panel because it resembles the phase separation picture of Ref. (25) and Ref. (31).

the mobility also decreases with temperature we take a constant ratio A/B in the simulations. For instance, in the case of the La$_2$CuO$_{4+y}$ experiment the i-O ordered phase develops only in the small interval between 330K and 300K [20].

The simulations to the i-O experiment were made with ε = 0.08 and A(T)/B = 1 that gives the patterns shown in the button-right of Fig. (2) because it resembles the STM patterns on LASCO [31]. As in the case of YBCO where the holes seem to follow the dopant atoms [26], we assume that the planar charge follows the i-O and a similar phase separation occurs within the planes.

In the Poccia et al experiment [20], the system is heated to $T = 370$K above the mobility temperature $T_m = 330$K and quenched to low temperature. Such system does not present ordered i-O peaks and has poor superconducting order. However, by illuminating this disordered system with X-rays, they observed, after a time threshold $t_0$, the nucleation and growth of ordered domains which is accompanied of the recovery of a robust high $T_c$ state.

Therefore we simulate the appearance of the domains by the formation an EPS structure. In the simulations on a $105 \times 105$ sites, we note that below $t=250$ts (ts=time steps) the solutions of Eq. (2) have an uniform density but at $t=265$ts a disorder with a regular checkerboard pattern sets in. This solution with high and low densities evolves up to 2000ts when another domain pattern, more irregular, sets in after a transient time as it is shown on the top-right panel in Fig. (3). This pattern is consequence of more stable solution which will dominate at larger times. Consequently, we take this solution to match the ordering promoted by x-Ray illumination. Thus this stable solution, starting at the transient $t=2000$ts should correspond to the i-O ordering phase where the Bragg peaks sets in.

At 4000ts, the checkerboard order rests only on less than 1/3 of the system and the more stable irregular granular order dominates as shown in Fig. (3). This might be the situations described by Fratini et al [25], a system with two phases and different $T_c$s. Above 6000ts the granular pattern dominates and from 200000ts (button-left of Fig. (3)) to 2000000ts (button-right of Fig. (3)) the grains grow very slowly. To compare with the experiments, we take the $t_0 = 2000$ts or 0.1h, that is the onset of the stable phase, that one that will remain at larger times, as the onset or threshold time of the raise of the diffraction peaks associated with the ordered phase. This is because at $t_0 = 2000$ts that the stable phase sets in and, in the experiment, at $t_0$ is when the i-O ordering develops and remains at larger times. This connects in a phenomenological way the oxygen ordering at larger times with the raise and grow of the stable domains shown in Fig. (3). In the CH approach, another way to follow a phase separation process is through the
local densities histograms. In Fig.\textbf{ 4} we show this possibility for two selected times and as expected, the low and high local density dispersion $\Delta(t)$ decreases as time increases. This is equivalent to the phase separation into two distinct phases, evolving from just one average doping phase. We compare directly the two dispersions, the calculated and the experimental data in Fig.\textbf{ 4}, without any adjustable parameter.

III. THE LOCAL FREE ENERGY AND THE PAIR FORMATION

The phase separation process described by the CH differential equation occurs due to the minimization of the free energy given by Eq.\textbf{ 1}. Solving the CH equation, the potential $V_{GL}(i,t)$ can be calculated directly from free energy (Eq.\textbf{ 1}) through the order parameter $u(i,t)$. We performed a detailed study of this potential and found that it takes it minimum value at the domains and that is why the domains are formed. We notice that, as the time evolves, the minimum value remains practically unchanged but the height of the barriers increases slowly.

On of the main results of Poccia et al\textbf{[20]} is that the samples with more time of exposition to X-rays develops i-O ordering regions and have larger $T_c$. This is a strong indication that the formation of i-O ordering domains is associated also with the formation of charge domains in the planes where the superconducting properties develops. Consequently, the trapping of the charges in inhomogeneous domains may be connected with the superconducting properties. To explore this possibility we study in detail the energy maps of the $V_{GL}(i,t)$ for different times $t$

To start this analysis we plot a 3D view map in Fig.\textbf{ 5} for the case of $t=10h$. It is also shown in the left panel the values of $V_{GL}(i,t)$ along 25 sites in a straight line in the middle of the view map of Fig.\textbf{ 5}, for four different times of phase separation. In this way, we can visualize the regions where the charges get trapped and the inset shows the time variations of the barrier walls that, by assumption, scale the superconducting interaction\textbf{[24]}.

The calculations shown in the inset of Fig.\textbf{ 5} indicates the possibility to connect the phase separation time with the height of the $V_{GL}(i,t)$ between the domains walls, which we define as $V_{gb}(t)$. Such free energy barrier is related with probability of the planar charges be trapped in the domains as shown in a more clear way in Fig.\textbf{ 4}. The effect of $V_{gb}$ on the charges is to attract them to the grains, loosing part of their kinetic energies. This loss of kinetic energy in the presence of a two-body attractive potential favor the possibility of Cooper pair formation and the domain walls acts as a catalyst to the superconducting state\textbf{[23, 24]}. At this stage of our phenomenological approach we are not able to decide if $V_{gb}$ is the origin of the pair potential or if just strength some other fundamental interaction. The small changes on the size of $V_{gb}(t)$ with the time of phase separation $t$, as shown if Fig.\textbf{ 5}, may be the reason of the changes in the superconducting amplitudes that reproduces the experimental values $T_c(t)$. Consequently, we assume that $V_{gb}(t)$ scales the pair interaction used in the superconducting calculations of next section.

The definition and derivation of the values $V_{gb}(t)$ is essential to our calculations since its variation will be used in the Bogoliubov-deGennes calculations below to connect the time $t$ of x-ray illumination with the superconducting critical temperature $T_c(t)$. Therefore, we plot

FIG. 4. (color online) The FWHM of the i-O X-rays diffracted dispersion peaks \textbf{20} and the values of the local high and low local densities histograms dispersion $\Delta(t)$ calculated from 6 different times density maps dispersion (blue stars) as shown in Fig.\textbf{ 4}.

FIG. 5. (color online) A 3D view map of the potential $V_{GL}(i,t=10h)$ on the right panel. On the left, the values in row on 25 sites $i$ to visualize the free energy potential wells with walls defined as $V_{gb}(t)$ in the text. The values of $V_{gb}(t)$ are shown here at $t = 0.3, 3h, 5h$ and $10h$ and are very similar. In the inset we blow up the peaks and we see clearly an steady increase between $t = 0.3$ and $t = 5h$ and the saturation above $t = 5h$. Notice that the button of the energy curves, corresponding to the grains, remain fixed. The relative variations on $V_{gb}(t)$ are very small but have an important role in the BdG calculations of $\Delta_d(t)$ and on the $T_c(t)$. 
in the Fig. 6 how it is defined from a typical potential energy simulation at a given time.

![Image](77x531 to 275x706)

**FIG. 6.** (color online) The definition of the values of \(V_{gb}\), related with the height of the potential barrier among the low and high energy grains is shown in the top inset. This plot is made following \(V_{GL}(i, t = 6200)\) along the white straight line in the middle of the figure. As the time (of irradiation) increases, so does the height of the barriers (see Fig. 3) and the probability of the charges become confined also increases.

### IV. THE SUPERCONDUCTING CALCULATIONS

The CH simulations yield density maps \(p(i, t)\) on a square lattice like that of Fig. 3. They are used as the initial input and it is maintained fixed throughout the self-consistent Bogoliubov-deGennes (BdG) calculations. We use nearest neighbor hopping \(t_{ij} = 0.15eV\) and next nearest neighbor hopping of \(t_{ij}/t_{ij} = -0.27\) taken from hole doped experimental dispersion relations.\(^3\) For completeness, the BdG equations are\(^{19, 22, 34}\).

\[
\begin{pmatrix}
K & \Delta \\
\Delta^* & -K^*
\end{pmatrix}
\begin{pmatrix}
u_n(x_i) \\
v_n(x_i)
\end{pmatrix}
= E_n
\begin{pmatrix}
u_n(x_i) \\
v_n(x_i)
\end{pmatrix} \tag{3}
\]

These equations, defined in detail in Refs. 19, 34, are solved self-consistently. \(u_n, v_n\) and \(E_n \geq 0\) are respectively the eigenvectors and eigenvalues. The d-wave pairing amplitudes are given by

\[
\Delta_d(x_i) = -\frac{V_{gb}}{2} \sum_n \left( |u_n(x_i)|^2 f_n + |v_n(x_i)|^2 (1 - f_n) \right) \tanh \frac{E_n}{2k_BT}, \tag{4}
\]

and the local inhomogeneous hole density is given by

\[
p(x_i) = 1 - 2 \sum_n [ |u_n(x_i)|^2 f_n + |v_n(x_i)|^2 (1 - f_n)], \tag{5}
\]

where \(f_n\) is the Fermi function. We stop the self-consistent calculations only when all \(p(x_i) \equiv p(i)\) converges to the appropriate time CH density map like those shown in Fig. 4.

Typical solutions can be visualized in Fig. 4 where we show the local density \(p(i)\) on a square of 28x28 sites where the BdG calculations were made and the 3D map of the low temperature \(\Delta_d(i, T \approx 0)\). The pairing potential \(V_{gb}(t) \approx t_{ij} = 0.15eV\) is parametrized to match the average local density of states (LDOS) gaps measured by low temperature STM on the optimal doping \(p = 0.16\) LSCO\(^{31}\), namely, \(\Delta_d(T \approx 0) \approx 7 - 12meV\). Starting with \(V_{gb}(t = 2000ts)\), analyzing the results of \(V_{gb}(t)\) like those shown in Fig. 4, we were able to connect the time of x-ray exposure to the superconducting amplitudes.

![Image](152x725 to 275x670)

**FIG. 7.** (color online) Left panel shows a typical density view map used here on a 105x105 sites and the 28x28 square where the local superconducting amplitudes \(\Delta_d(i, t)\) are calculated by the BdG approach at \(t = 6000ts \approx 0.3h\), as an example.

With these values of \(\Delta_d(i, T \approx 0)\), we find that \(\Delta_d(i, T) \rightarrow 0\) at a single temperature \(T^* \approx 96K\) which is much larger than typical values of \(T_c(p = 0.16)\) for \(La_2CuO_4+y\), but in agreement with the pseudogap phase measured by STM\(^{31}\), or the Nernst signal on LSCO\(^{24, 35}\). The variation of the superconducting amplitudes with temperature is shown in Fig. 4. Since this value of 96K is much larger than the values of \(T_c\) for optimal \(La_2CuO_4+y\), we notice that the EPS transition, with the free energy walls and wells, makes the structure of the system similar to granular superconductors\(^3\).

In this way, it is likely that the superconducting transition occurs in two steps\(^{23, 24}\): first by intra-grain superconductivity and than by Josephson coupling with phase locking at a lower temperature. This approach provides a clear interpretation to the pseudogap phase of cuprates.

To obtain the experimental values of \(T_c(p)\), we use an approach similar to a system composed of granular superconductors\(^{36}\). Our main proposal is that the superconducting transition occurs in two steps as \(T\) decreases\(^{23, 24}\): first by intra-grain superconductivity and than by Josephson coupling with phase locking at low temperatures.

These two completely different calculations, yielding two different energy scales, are motivated by the two energy scales found in most cuprates mentioned above\(^?\).
FIG. 8. The values of $\Delta_d(i, T) \times T$ at 4 different points "i", for the case $t = 6000 \mu s = 0.3h$. The values at low temperature agree with the values measured by the LDOS from the STM data on LSCO. Notice that they vanish near $T^* = 96K$ much above the measured $T_c \approx 35K$.

], and also in the two different regimes of the fluctuation magnetoconductivity in a $YBa_2Cu_3O_7$ single crystal[37]. These systematic measurements detected an effectively two-dimensional (2D) regime far above $T_c$, that can be interpreted in our approach by the isolated superconducting grains in the $CuO$ without phase coherence. Decreasing the temperature towards $T_c$ a crossover to a three-dimensional (3D) Gaussian regime sets in as the different superconducting regions or grain become connected and increase coherence. Very close to $T_c$ a critical regime characteristic of a 3D XY university class is measured which is consistent with a granular superconductors in which each superconducting grain develops its own phase $\Phi$ that may oscillate but become locked at $T_c$, yielding long range order.

Therefore, due to the formation of the local or intragrain superconducting amplitudes at low temperatures, the system is regarded as an array of Josephson junction as shown schematically in Fig.[9]. The properties of Josephson tunnel junctions between d-wave superconductors have been studied by Bruder et al.[38]. They calculate the tunnel matrix elements in second-order perturbation theory for two superconductors (1 and 2) with superconducting amplitude $\Delta_{d,1/2}(i, T, \Phi) = \Delta(i, T) \cos[2(\Phi - \phi_{1/2})]$. We use their results to an array as schematically shown in Fig.[9], where the local amplitudes $\Delta_d(i, T)$ are represented by the size of orbitals and the phase angles $\phi$ have been drawn around x-direction. $\Phi$ is the polar angle of the first Brillouin zone.

To calculate the Josephson coupling energy that is connected with the onset of phase coherence, we recall the work of Bruder et al[38] on d-wave superconductors junctions. They found that the tunneling current behaves in a similar fashion of s-wave superconductors junction and the leading behavior is determined by tunneling from a gap node in one side of a junction into the effective gap in the other side. Consequently, as a first approximation to the Josephson coupling energy $E_J$, we adapt the theory of s-wave granular superconductors[39] to the $\Delta_d^{a\nu}(p, T)$ in the grains.

$$E_J(t, T) = \frac{\pi h \Delta_d^{a\nu}(T, t)}{4e^2 R_n} \tanh\left(\frac{\Delta_d^{a\nu}(T, t)}{2K_B T}\right). \quad (6)$$

Where $\Delta_d^{a\nu}(T, t) \equiv \sum_i \Delta_d(T, i, t)/N$, since $\Delta_d(T, i, t)$ varies with the position $i$ in the inhomogeneous systems, as shown in the right panel of Fig.[7]. $R_n$ is the normal resistance of the $La_2CuO_4+$ compound, which we assume to be independent of the time $t$ as inferred from the data of Foccia et al.[20]. It is also proportional to the planar resistivity $\rho_{ab}$ measurements[40] on the $La_{2-x}Sr_xCuO_2$ series. In Fig.[10], the Josephson
coupling $E_J(p,T)$ is plotted together with the thermal energy $K_B T$. The intersections yield $T_c(t)$.

As discussed in connection with the free energy of Eq. (1) and Fig. 3, the relative values of the grain boundary potential wall $V_{gb}(t)$ are easy to estimate, but we do not know their absolute values. Consequently we use $V_{gb}(t = 0.2h)$ that matches the 1st point of Poccia et al. [24], namely, $T_c(t = 0.2h) = 33.6K$. All the others $T_c(t)$ results for larger $t$, shown in Fig. (10), follow by the small but steady variations in $V_{gb}(t)$ shown in the inset of Fig. 5. In other words, we use $V_{gb}(t = 0.2h)$ as a parameter to calculate $T_c(t = 0.2h)$ and all the others 7 points shown in the right panel of Fig. (10) are parameter free, that is, they are calculated taking the relative variations in the free energy barriers as shown in the inset of Fig. 5. The steep increase of $T_c(t)$ during the consolidation of the stable phase between $t \approx 0.3 – 5h$ agrees well with the data as shown in Fig. (10), indicating that our triple calculations (CH simulation of $p(i)$, BdG calculation of local $\Delta_h(i,t)$ and the Josephson estimation of $T_c(t)$) provides a new way to describe the assembled of superconducting properties in La$_2$CuO$_{4+y}$.

V. CONCLUSIONS

In conclusion, we have provided a complete new description of a set of complex experiments relating the time of irradiation that booster i-O in ordering domains, with the superconducting temperature $T_c(t)$. The variation of $T_c(t)$ shows that this out of plane phase separation induces also changes or phase separation of the charges into the Cu – O planes. Consequently, we use time dependent CH approach to describe the associated charge segregation in the planes. This method allows also to follow the local variations in the free energy during the phase separation process. Analysis of the local variation of the GL potential in the charge inhomogeneous profile shows that the charge gets trapped into the high and low density domains. The confinement of the holes in these domains or puddles reinforce the possibility of local Cooper pair formation in these isolated domains as in a granular superconductor where different grains may be connected through Josephson coupling at low temperatures. Assuming that the superconducting interaction in the puddles may be strengthened or scaled by the height of the free energy barriers $V_{gb}(t)$, we were able to connect the superconducting $T_c(t)$ through the BdG approach on a charge disordered profile in the planes with the time of X-ray illumination. This procedure allows us to connect for the first time the degree of phase separation or the degree of inhomogeneities generated at high temperatures with the low temperature superconducting properties. These findings reveal a virtually unexplored line of research on how systematic variations of sample preparation may affect the superconductors properties.

I gratefully acknowledge partial financial aid from Brazilian agencies FAPERJ and CNPq.

[1] “Phase Separation in Cuprate Superconductors”, ed. by E. Sigmund and K.A. Muller (Springer-Verlag, Berlin, 1994).
[2] E. Dagotto, “Nanoscale Phase Separation and Colossal Magneto-Resistance”, (Springer, Berlin, 2002).
[3] J. D. Jorgensen et al, Phys. Rev. B38, 11337 (1988).
[4] Grenier J.C. et al, Phys. C202 269 (1992).
[5] Radaelli P.G. et al, Phys. Rev. B48, 499 (1993).
[6] B. O. Wells et al, Science 277, 1067 (1997).
[7] G. Campi et al, J. Supercond. Nov. Magn. 17, 137 (2004).
[8] Y. S. Lee et al, Phys. Rev. B69, 020502 (2004).
[9] “Stripes and related phenomena, Selected topics in Superconductivity”, A. Bianconi and N. L. Saini, (Kluwer Academic/Plenum Publishers, 2000).
[10] J. Zaanen and O. Gunnarsson, Phys. Rev. B40, 7391 (1989).
[11] H. Schulz, Phys. Rev. Lett. 64, 1445 (1990).
[12] V. J. Emery and S. A. Kivelson, Physica C209, 597 (1993).
[13] U. Löw et al Phys. Rev. Lett. 72, 1918 (1994).
[14] L. P. Gorkov and G. B. Teitel’baum, Phys. Rev. Lett. 97, 247003 (2006).
[15] L. P. Gorkov and G. B. Teitel’baum, Phys. Rev. B77, 180511 (2008).
[16] Ovchinников Yu N., Wolf S.A. and Kresin V.Z. Phys. Rev. B63, 064524 (2001).
[17] E.V.L. de Mello, E.S. Caixxiero, and J.L. González Phys. Rev. B67, 024502 (2003).
[18] Yukalov V.L. and Yukalova E.P. Phys. Rev. B70, 224516 (2004).
[19] E.V.L. de Mello et al, Phys. Rev. B70, 224517 (2004).
[20] Nicola Poccia, Nature Materials, 10, 733 (2011).
[21] E.V.L. de Mello et al, Physica A 347, 429 (2005).
[22] E.V.L. de Mello, et al J. Phys.: Condens. Matter 21, 235701 (2009).
[23] E. V. L. de Mello, R.B. Kasal, J. Supercond. Nov. Magn., 24, 1123 (2011).
[24] E. V. L. de Mello and R.B. Kasal, Phys. C472, 60 (2012).
[25] Michela Fratini et al, Nature, 466, 841 (2010).
[26] Rinat Ofer, and Amit Keren, Phys. Rev. B80 224521 (2009).
[27] S. Wakimoto et al, Phys. Rev. Lett. 98, 247003 (2007).
[28] A.J. Bray, Adv. Phys. 43, 347 (1994).
[29] E. V. L. de Mello, and D. N. Dias, J. Phys. C.M. 19, 086218 (2007).
[30] K. McElroy et al, cond-mat/0404005 and Phys. Rev. Lett. 94, 197005 (2005).
[31] Takuya Kato et al, J. Phys. Soc. Jpn., 77, 054710 (2008).
[32] Kenjiro K. Gomes et al, Nature 447, 569 (2007).
[33] M.C. Schabel, C.-H. Park, A. Matsura, Z.-X. Shen, Phys. Rev. B 57, 6090 (1998).
[34] D. N. Dias et al, Phys. C468, 480 (2008).
[35] Yayu Wang, Lu Li, and N. P. Ong, Phys. Rev. B73, 024510 (2006).
[36] L. Merchant et al, Phys. Rev. B63, 134508 (2001).
[37] Rosangela Menegotto Costa et al, Phys. Rev.B64,
2114513 (2001).

[38] C. Bruder et al, Phys. Rev. B51 R12904 (1995).

[39] V. Ambegaokar, and A. Baratoff, Phys. Rev. Lett. 10, 486 (1963).

[40] H. Takagi et al, Phys. Rev. Lett. 69, 2975 (1992).