Magnetic Properties Calculations of Cuprate Superconductors based on a Phase Separation Theory

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There is a great debate concerning the hole of the inhomogeneities in high critical temperature superconductors (HTS). In this context, there are many experiments and proposals related with a possible electronic phase separation (PS). However there is not a method to quantify how such transition occurs and how it develops. The Cahn-Hilliard (CH) theory of phase separation provides a way which we can trace the phase separation process as a function of temperature in agreement with some experiments. Here we coupled these calculations, with parameters that yield a stripe like pattern, to the Bogoliubov-deGennes (BdG) approach to an inhomogeneous superconductor in order to derive many HTS properties of the \textit{La}_{2−x}\textit{Sr}_{x}\textit{CuO}_{4} (LSCO) system. Taking the upper pseudogap as the PS transition line, we can show that; the onset of superconductivity follows close the Nernst signal, the leading edge shift is close to the zero temperature average gap and the superconducting phase is achieved by percolation or Josephson coupling. Our approach is also suitable to reproduce the experimental measurements of the $H_{c2}$ field and explain why it does not vanish above $T_{c}$.

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I. INTRODUCTION

The measurement of the pseudogap and many non-conventional properties in the normal phase\textsuperscript{1,2} of HTS has become a long standing puzzle. It is a general consensus that understanding these properties is crucial to comprehend the nature of the superconducting transition and the fundamental interaction in these materials. It is quite interesting that while low critical temperature superconductors have a well characterized normal phase, the nature of the normal or pseudogap phase of HTS is an open problem which remains a matter of intense experimental and theoretical study\textsuperscript{3,4}.

One of the possible reason why this problem remains unsolved after 20 years of intense research may be due to the uncontrolled intrinsic inhomogeneities in some HTS, which as some of us have argued\textsuperscript{5}, may also depend on the sample preparation method. Since the theoretical prediction\textsuperscript{6} and the detection of stripes\textsuperscript{7}, it is clear that at least some family of compounds exhibit some degree of non-uniformities. In fact, the role of the inhomogeneities is an open question: it seems not important in some experiments\textsuperscript{8,9}, but on the other hand, the detection and the effect of inhomogeneities have rendered many articles and books\textsuperscript{10,11}, as we will discuss in detail in this paper.

These unusual features of cuprates, like the stripes, led to theoretical proposals that PS is essential to understand their physics\textsuperscript{6,12,13,14}. Indeed PS has been observed on the \textit{La}_2\textit{CuO}_{4+δ} by x-ray and transport measurements\textsuperscript{13,14}, which have detected a spinodal phase segregation into an oxygen-rich (or hole-rich) metallic phase and an oxygen-poor antiferromagnetic (AF) phase above $T=220$K. There is also evidence of ion diffusion at room temperature in micro crystals of the Bi2212 superconductors at a very slow rate\textsuperscript{14}.

Recent angle resolved photoemission (ARPES) experiments with improved energy and momentum resolution\textsuperscript{18,19,20,21,22} have distinguished two electronic components in $k$-space associated with the \textit{La}_{2−x}\textit{Sr}_{x}\textit{CuO}_{4} (LSCO) system: a metallic quasi particle spectral weight at the $(\pi/2, \pi/2)$ nodal direction which increases with hole doping and an insulator like spectral weight at the end of the Brillouin zone straight segments in the $(\pi, 0)$ and $(0, \pi)$ antinodal regions which are almost insensitive to the doping level.

New STM data with great resolution have also revealed strong inhomogeneities in the form of a patchwork of (nanoscale) local spatial variations in the density of states which, at low temperature, is related to the local superconducting gap\textsuperscript{23,24,25,26}. More recently it was possible to distinguish two distinct behavior: well defined coherent and ill-defined incoherent peaks depending on the exactly spectra location at a \textit{Bi}_2\textit{Sr}_2\textit{CaCu}_2\textit{O}_8+δ (Bi2212) surface\textsuperscript{27,28}. STM experiments have also detected a regular low energy checkerboard order in the electronic structure of the Bi2212 family at low temperature\textsuperscript{29}, above the superconducting critical temperature ($T_{c}$)\textsuperscript{30} and in the \textit{Na}_x\textit{Cu}_{2−x}\textit{O}_4\textit{Cl}_2\textsuperscript{31}.

Bulk sensitive experiments like nuclear magnetic and quadrupolar resonance (NMR and NQR) have also provided ample evidence for spatial charge inhomogeneity in the \textit{Cu}O$_2$ of some HTS planes\textsuperscript{32,33,34}. Singer et al.\textsuperscript{33} measured a distribution of $T_{1}$ over the Cu NQR...
spectrum in bulk LSCO which can be attributed to a distribution of holes $p$ with a half width of $\Delta p/p \approx 0.5$. The increasing of $\Delta p/p$ as the temperature decreases is likely the strongest indication of a PS transition at temperatures above 600K in HTS. More recently, NMR results on La$_{1.8-x}$Eu$_{0.2}$SrCuO$_4$ were interpreted as evidence for a spatially inhomogeneous charge distribution in a system which the spin fluctuations are suppressed\[34\]. This new result is also a clear indication that the charge disorder may be due to a phase separation transition.

In this paper we work out in detail the scenario to the physics of HTS based on a PS transition at the (upper) pseudogap region given in the review of Tallon at al\[2\], which starts at very high temperatures ($\approx$ 1000K) in the underdoped region and falls to zero near the average doping level $\rho_m = 0.2$. This PS transition is treated by the CH theory\[23\], originally proposed to describe the PS transition in alloys, and yields two equilibria densities; one low and other with high values which grows apart as the temperature is lowered, exactly as seen in the NQR experiments\[29\] or, indirectly by the stripes structures. Applying the BdG theory of superconductivity to such a disordered medium we see that, as the temperature decreases, the superconductivity appears in nanoscale regions inside the high density phase. With this approach, we can show that:

i- the zero temperature average superconducting gap and the amplitude of pairing $|\Delta|$ as function of the average doping level $\rho_m$ is in reasonable agreement with the superconducting state gap\[18\] and the leading edge shift measured by ARPES\[22\].

ii- The onset temperature of superconductivity for each compound is close the lower pseudogap temperature\[1, 4, 5\] and also the recent measurements on the onset temperature of Nernst signal\[37, 38, 39\], providing a simple interpretation to these experiments.

iii-The calculation of $H_{c2}(T)$ for a system of non-uniform density regions with different local superconducting $T_c(i)$ ($T_c(i)$ will be defined below) is in excellent agreement with the measurements in the LSCO system and also provides an explanation why the $H_{c2}(T)$ field does not vanish at $T_c$.

Our proposal is an alternative scenario to the phase-disordered theory\[13, 14\] which has gained increased attention\[37, 38, 39, 40, 41, 42\]. Contrary to the familiar BCS theory in which the complex superconducting order parameter $\Psi = |\Delta|e^{i\theta}$ develops with the phase $\theta$ essentially locked, in their calculations\[13, 14\] thermally generated vortices destroy long range phase coherence at temperatures close to the superconducting critical temperature $T_c$. The temperature $T_0$ which phase rigidity is lost was estimated to be very low in the underdoped region and to increase continuously with doping\[13, 14\]. Therefore, in this scenario, the pseudogap phase is characterized by the presence of Cooper pairs with nonvanishing pairing amplitude $|\Delta|$ but, due to thermally excited vortices (in zero field), without phase rigidity.

The presence of the pairing amplitude $|\Delta|$ has been clearly detected by many spectroscopy experiments starting at a temperature that we call $T^*$, the lower pseudogap temperature, which, depending on the compound, can vary from $T^* \approx T_c$ to roughly 100K above $T_c\[4, 13, 44, 45\]$. On the other hand, Nernst effect experiments which measure a voltage transverse to a thermal gradient in the presence of a magnetic field perpendicular to the superconducting film are specially sensitive to the existence and the drift of vortices\[37, 38, 39\]. Consequently a large Nernst signal above $T_c$, which starts at $T_{onset} \approx T^*$, was taken as a strong indication of a vortex-like behavior and the presence of a large region of fluctuating superconductivity\[37, 38, 39]. Thus the important question is whether this fluctuating region is due to the thermally induced vortices of the phase disordered scenario or to some other mechanism, like a non-uniform density.

Recently, in order to address this question and to study the pseudogap region, a series of combined measurements on the Nernst effect, the upper critical field $H_{c2}$ and magnetization above the $T_c$ on different compounds were performed by Wang et al\[41\]. The results were interpreted as providing strong support to the phase-disordered theory\[41\]. On the other hand, Nernst effect studies carried on the presence of induced disorder demonstrated that $T_{onset}$ remained basically the same but $T_c$ decreased considerably with the presence of controlled defects\[42\] and they have detected fluctuations only near $T_c$, contrary to the phase disordered scenario. A possible interpretation is that the additional induced disorder hinders the percolation threshold, but does not affect the onset temperature ($T_{onset}$) of superconductivity in the nanoscale islands. This result confirms a wide variety of experimental data and theoretical investigations which have demonstrated that spatially inhomogeneities strongly affects the HTS properties\[46, 47\].

Thus, taking the spatial disorder as an intrinsic phenomena associated with a PS transition, we reproduce in this paper the main phase diagram boundaries, the upper and lower pseudogap and the superconducting phase. We also show that the results of Wang et al\[41\] are also compatible with a disordered material with non-uniform doping level which can take many forms, from random patches to stripes. For this purpose, this paper is organized as follows: In section II, we described briefly how the CH PS calculations are made (the details are in previous paper\[48, 49, 50\]). In section III, we perform the BdG superconducting calculation on a system which results from the PS. In section IV, we show the results of both methods combined. In section V, we generalize a method to calculate the $H_{c2}$ field in a non-uniform system, again applied to the CH PS results. We finish with the conclusions.
II. THE PHASE SEPARATION

At least two clearly distinct energy scales are associated with the pseudogap[4, 5, 51] and there are several indications that the upper pseudogap, which starts at very low doping and ends near $\rho_m \approx 0.2[2]$, may be a line of PS (part of this PS line is represented in Fig.(2)). The values of the upper pseudogap $T^*$, measured by susceptibility, heat capacity, ARPES, NMR and resistivity, as presented in the review by Tallon and Loram[2], or the crossover line shown in Timusk and Ststat[2] seem to be independent of the superconductivity phase[2]. In fact it was verified recently that this line falls inside the superconducting dome[52]. The very high upper pseudogap temperatures in the underdoped region led also Lee et al[2] to argue that it is very unlike any relation to the temperature $T$. On cooling down the system, the $\Delta(i, T)$ start to react with the superconductivity $T_s$, and increase as the temperature tends to zero. We find that the $\Delta(i, T)$ have basically the same value in small regions with the same charge density. This defines what we call a local superconducting temperature $T_c(i)$ on a site "i" or in a small cluster. Following the CH results, particularly those which yield stripe patterns, we have kept fixed the input local charge densities, which is an approach different than previous BdG calculations[53, 54, 55, 56]. The details can be found elsewhere[57], but just for completeness, the BdG equations are

\[
\begin{align*}
\left( \frac{\xi}{\Delta} \right) \left( \frac{\Delta^*}{-\xi} \right) \left( \frac{u_n(r_i)}{v_n(r_i)} \right) = E_n \left( \frac{u_n(r_i)}{v_n(r_i)} \right),
\end{align*}
\]

where $E_n \geq 0$ are the quasiparticles, and

\[
\begin{align*}
\xi u_n(r_i) &= -\sum_{\delta} t_{i,i+\delta} u_n(r_i + \delta) - \bar{\mu}_i u_n(r_i), \\
\Delta u_n(r_i) &= \Delta U(r_i) + \sum_\delta \Delta \delta(r_i) u_n(r_i + \delta),
\end{align*}
\]

the $t$'s are the hopping parameters and $\bar{\mu}_i$ the local chemical potential. There are also similar equations for $v_n(r_i)$. Through these equations and the positive eigenenergies it is possible to calculate the pairing amplitudes

\[
\begin{align*}
\Delta U(r_i) &= -U \sum_n u_n(r_i) v_n^*(r_i) \tanh \frac{E_n}{2K_BT}, \\
\Delta \delta(r_i) &= -\frac{V}{2} \sum_n \left[ |u_n(r_i)|^2 f_n + |v_n(r_i)|^2 (1 - f_n) \right] \tanh \frac{E_n}{2K_BT}
\end{align*}
\]

and the local hole density is given by

\[
\rho(r_i) = 1 - 2 \sum_n \left[ |u_n(r_i)|^2 f_n + |v_n(r_i)|^2 (1 - f_n) \right],
\]

where $f_n$ is the Fermi function. The BdG equations are solved self-consistently together with the equations for the pairing amplitudes (Eq.(4)) and for the local hole density(Eq.(5)) which is kept fixed throughout the entire calculation. For calculations using d-wave symmetry we have $V < 0$ and $U > 0$ and Eq.(4) can be written as[57]

\[
\begin{align*}
\Delta \delta(r_i) &= \frac{1}{4} \left[ \Delta \delta(r_i) + \Delta_{-\delta}(r_i) - \Delta \bar{\delta}(r_i) - \Delta_{-\bar{\delta}}(r_i) \right].
\end{align*}
\]

In the calculations we have used the hopping parameters up to third neighbors, close to those derived from the ARPES data for YBCO[58], that is, $t_2 = -0.61t$ and $t_3 = 0.2t$. These values are slightly different from our other work[59], which

III. THE LOCAL GAP CALCULATIONS

At temperatures below the PS transition, we can observe the possibility of the local superconducting pairing amplitude $\Delta(i, T)$ formation at a location $r_i$ inside a given cluster[3, 53, 54, 55, 56] as function of the temperature $T$. In what follows, we will take these PS results as the initial parameters. Since these parameters and the mobility of charge carriers can lead to different segregation patterns, depending on the Ginzburg-Landau (GL) free energy initial coefficients. Since these parameters and the mobility (which is related to the time scale of the PS process) are not well known, we adopt values which leads to charge stripes formation, in order to reproduce the observations in LSCO. The possibilities of other patterns, like droplets or patchwork was studied elsewhere[48]. Thus, depending on the initial parameters of the GL free energy, the phase segregation process can form patterns similar to patchwork[24, 25] or stripe[1] which are observed in HTS and in others high correlated electron systems[46, 47]. In what follows, we will take these PS results as the initial non-uniform input charge distribution on clusters followed by the BdG local superconducting calculation.
we used hopping values up to 5th neighbors following the ARPE results\[55\]. In fact we made various studies around the ARPE data, and they all give the same qualitative results, and therefore, we present the calculations that yielded the best quantitative agreement with the experiments. The potentials are $U = 1.1t$ and $V = -0.6t$ which are also close to previous calculations\[57\]. The value of $t = 0.23\text{eV}$ was chosen in order to reproduce the measurements of the zero temperature superconducting gap by Harris et al\[18\] and the ARPE leading edge shift by Ino at al\[22\]. Furthermore this value of $t$ is in the range of several experiments on HTS\[59\].

Following the charge patterns derived from the CH calculations, the 7 stripes at the left are characterized by local doping $\rho(i) \approx 0$ and the 7 at the right side have $\rho(i) \approx 2\rho_m$. This is the scheme of the three upper panel of Fig.(1). The high values of the $T^* \approx T_m$ implies that lightly doped compounds like the $\rho_m = 0.05$ has $\rho(i)$ strictly zero in the low doping region. At low temperatures, the superconducting regions for this compound, those with a finite value of $\Delta(i, T)$, develops only in the high density region and all together, they never reach more than 50% of the total sites. Consequently, the superconducting sites never percolate and there is no superconducting phase for this compound. For doping of $\rho_m > 0.06$ the low doping sites have some residual fluctuation(of the phase separation process) $\rho(i) > 0$ which grows with $\rho_m$, from $\approx 0.03$ to 0.05, what changes the properties of a sample from a disordered insulator into a disordered metal, with a superconducting phase at low temperatures. Thus, for compounds with $0.06 < \rho_m < 0.20$, at low temperatures, one can see in Fig.(1), that $\Delta(i, T)$ develops also at the very low doping regions, i.e., in the left region of the clusters represented in Fig.(1). At the temperature $T_c(\rho_m)$, when the $\Delta(i, T)$ arise at these low doping sites, the system becomes superconductor either by the percolation of the many local superconducting regions (the regions where $\Delta(i, T)$ are non-vanishing) or by Josephson coupling\[60, 61\]. The values of $T_c(\rho_m)$ are shown in each panel of Fig.(1). Consequently, below $T_c(\rho_m)$, superconducting critical temperature, the system can hold a dissipation-less current, assuming, as usual in mean field (BCS) theories, that all these superconducting regions form a conventional superconducting phase with a unique phase $\theta$ which is essential to percolation and Josephson coupling. Above $T_c(\rho_m)$ the compounds form a mixture of superconducting, insulator and normal domains and above the pairing formation temperature $T_{onset}(\rho_m)$, they are disordered metals with mixtures of normal ($\rho(i) \geq 0.03 - 0.05$) and insulator ($\rho(i) \leq 0.03 - 0.05$) regions.

From these results, we identify $T_{onset}(\rho_m)$ as the highest temperature to induce a $\Delta(i, T)$ in any region of a given compound which is easily seen from the panels of Fig.(1) (and from similar studies on others values of $\rho_m$). Thus $T_{onset}(\rho_m)$ is identified with the onset of Nernst signal because the rising of superconducting regions in a metallic matrix increases the vortices drift. The values of $T_{onset}(\rho_m)$ and $T_c(\rho_m)$ are shown in Fig.(2). The maximum pairing amplitudes for each $\rho_m$ at low temperature ($\Delta_0(\rho_m)$) is in good agreement with the ARPES zero temperature leading edge shift\[57\] or the maximum magnitude of the superconducting gap\[18, 22\].

The zero temperature gap can be also obtained by a different procedure through the study of the local density of states (LDOS), which is given by $N_i(E) = \sum_n |u_n(x_i)|^2 f_n(E - E_n) + |v_n(x_i)|^2 f'_n(E + E_n)$, where the prime is the derivative with respect to the argument. In a typical cluster of our calculations, the opening of this maximum $\Delta(i, T)$, occurs at the neighbor of site

\[\text{IV. RESULTS}\]

\[\text{FIG. 1: (color online) Temperature evolution of the local pairing amplitude } \Delta(i, T), \text{ in units of } t = 0.23\text{eV at each site } i \text{ of a } 14 \times 14 \text{ cluster with 196 sites. Because the CH phase separation for } \rho_m \leq 0.20 \text{ and the stripe pattern, the sites in the left have } \rho(i) \approx 0 \text{ and the ones in the right } \rho(i) \approx 2\rho_m. \text{ In contrast, } \rho_m = 0.22 \text{ which is beyond the phase separation limit } T_m, \text{ has just a Gaussian charge disorder and its profile is very different.}\]

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i = 127 (see, for instance, the compound with ρ_m = 0.15 in Fig. 1) and T_onset(ρ_m) was defined as the temperature which such local superconducting gap vanishes. Now, by the local density of states, we can analyze the local gaps and take the superconducting gap as the minimum value of E_n with a non-vanishing spectral weight, as shown in Fig. 3. The corresponding temperature which this superconducting gap vanishes is also shown in Fig. 2 and it is quite similar to T_onset(ρ_m), in fact, we believe they will be equal for larger clusters. Thus, both ways of defining the onset temperature of superconducting gap of the system are in good agreement with the Nernst signal onset temperature.

V. THE CRITICAL FIELD

The presence of superconducting regions with different critical temperature will affect the magnetic response. Furthermore, those regions with the local critical temperature T_c(i) above the superconducting critical temperature T_c(ρ_m) greatly affects the normal state properties. Such effects have been seen by many measurements of anomalous magnetic properties of the normal phase \[62, 63, 64, 65\]. In particular, the anomalous upper critical field H_{c2} was recently measured by Wang et al.\[41\] on the LSCO system.

A few years ago some of us have developed a way to calculate H_c2 of a disordered superconductor.\[62\]. While in that paper we have dealt with a general disorder, here we apply this method to the stripe disorder described above, appropriated to the LSCO system. To explain it, we follow along the lines described by Caixeiro et al.\[62\]. The GL upper critical field of a homogeneous superconductor may be written as\[62\]

\[
H_{c2}(T) = \frac{\Phi_0}{2\pi^2\xi_{ab}(0)} \left( \frac{T_c - T}{T_c} \right). \quad (T < T_c)
\]

Let us now apply this expression to a HTS with stripes inhomogeneities in the charge distribution. As showed in Fig. 1, when a superconducting amplitude develops in a given region “r_i”, it has a local superconducting temperature T_c(i) and it will contribute to the critical field with a local linear upper critical field H_{c2}(T) below T_c(i). Therefore, the total contribution of the various local superconducting regions to the upper critical field is the sum of all the H_{c2}(T)’s at temperatures below T_onset(ρ_m), which is the temperatures that the system starts to develop some superconducting region. In this way, the H_{c2} for a whole sample is

\[
H_{c2}(T) = \frac{\Phi_0}{2\pi^2\xi_{ab}(0)} \frac{1}{W} \sum_{i=1}^{W} \left( \frac{T_c(i) - T}{T_c(i)} \right)
\]

\[
= \frac{1}{W} \sum_{i=1}^{W} H_{c2}(T) \quad (T < T_c(i) \leq T_{onset}(ρ_m))
\]

where W is the number of superconducting regions, (the high hole densities stripes), each with its local T_c(i) ≤ T_{onset}(ρ_m). For the LSCO series a coherence length of ξ_{ab}(0) ≈ 22Å is in agreement with the measurements\[62\]. This value of ξ_{ab}(0) leads to H_{c2}(0)=Φ/2πξ_{ab}^2(0)=64T. This value is close with the extrapolated values as it is seen in Fig. 4.
In Fig. (1) we plot the results for \( \rho_m = 0.1 \) and 0.18 and compared with the experimental values of Wang et al [41] for overdoped Bi2201 (La:04 and 02). We also compare our calculations to the previous experimental values from the same group [33] on LSCO because our calculations are directed to reproduce the non-uniformities on this series. The excellent agreement indicates that LSCO compounds have indeed a distribution of local superconducting regions \( T_c(i) \) close to that derived here (see Fig. (1)). On the other hand, since the \( H_{c2} \) curves of Bi2201 are so flat near \( T/T_c \approx 1 \), according our results, it indicates that this material is highly disordered in \( T_c(i) \), with \( T_{\text{onset}}(\rho_m) \) much larger than critical temperature \( T_c(\rho_m) \).

A similar procedure, taken into account a non-uniform system with variations on the local \( T_c(i) \), was applied before to reproduce experimental values of the magnetization above \( T_c \) on LSCO single crystals [63], and the same results [64] are in good qualitative agreement with the measurements of Wang et al [41]. Recently, a distribution of local \( T_c(i) \) was also used to reproduce and to interpret the magnetization data above \( T_c \) [65].

![FIG. 4: The lines are calculations of \( H_{c2} \) considering samples with different local superconducting temperatures \( T_c(i) \), similar to Fig. (1). Left panel are comparison with the experimental points from Ref. [33] for LSCO (\( \rho_m = 0.2 \)) and the right panel with points from Ref. [41].](image)

VI. CONCLUSION

Taking the upper pseudogap line as a PS transition temperature, we have monitored the development of charge inhomogeneities by the CH theory which describes how charge segregation increases as the temperature goes down, similarly as seen in the NQR experiments [33]. In this way we have followed the process of charge segregation in the LSCO system and studied the superconducting properties of the normal and superconducting phases as function of doping. Our approach is general and could be directed to other patterns of charge disorder. Each charge domain with constant density, in general, is characterized by its local superconducting pairing amplitude \( \Delta(i, T) \) which arises at \( T_c(i) \). This introduces the new concept of a local superconducting temperature, which marks the appearance of the local pairing amplitude. The maximum local value of \( T_c(i) \) of a given compound with average doping level \( \rho_m \), as we demonstrated, can be related to the Nernst onset temperature \( T_{\text{onset}}(\rho_m) \) or lower pseudogap. This approach, with different regions or islands with local superconducting temperatures \( T_c(i) \) provides a clear explanation to the non-vanishing of \( H_{c2} \) above the critical temperature \( T_c(\rho_m) \). It also explains why early tunneling experiments [4, 18] did not see any special signal at \( T_c(\rho_m) \).

In conclusion, we have provided the steps to an interpretation of the HTS phase diagram where the disorder plays a key role. We have also shown that some physical properties, like the experimental data of Wang et al [41] on the Nernst effect and \( H_{c2} \), which were presented as evidences of the phase disordered scenario, can also be favorable interpreted as special features of conventional superconductivity which develops in spatially disordered systems at higher hole densities regions. Our calculations furnish also an interpretation to the normal phase as a disordered metal and to the three most measured phase diagram boundaries in HTS: the upper pseudogap as a phase separation transition, the lower pseudogap as the onset of islands of superconductivity and the system superconducting critical temperature as the Josephson coupling or percolation temperature among the various superconducting regions.

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