Superconductivity in the Cuprates as a Consequence of Antiferromagnetism and a Large Hole Density of States

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We briefly review a theory for the cuprates that has been recently proposed based on the movement and interaction of holes in antiferromagnetic (AF) backgrounds. A robust peak in the hole density of states (DOS) is crucial to produce a large critical temperature once a source of hole attraction is identified. The predictions of this scenario are compared with experiments. The stability of the calculations after modifying some of the original assumptions is addressed. We find that if the dispersion is changed from an antiferromagnetic band at half-filling to a tight binding \( \cosh_k x + \cosh_k y \) narrow band at \( n >= 0.87 \), the main conclusions of the approach remain basically the same i.e. superconductivity appears in the \( d_{x^2-y^2} \)-channel and \( T_c \) is enhanced by a large DOS. The main features distinguishing these ideas from more standard theories based on antiferromagnetic correlations are here discussed.

KEY WORDS: Superconductivity, t-J and Hubbard models, Mechanisms

1. INTRODUCTION

In this paper we present an informal status report of a new scenario for the cuprates proposed recently under the name of “Antiferromagnetic-van Hove” (AFVH) theory. One of the main assumptions in this scenario is that the normal state of the cuprates, at least in the underdoped region, can be approximated by a dilute gas of quasiparticles. These quasiparticles are holes heavily dressed by spin fluctuations. The dispersion of one hole in an antiferromagnetic background can be calculated with high accuracy using a variety of techniques, and in the original version of this scenario it was assumed that a finite concentration of holes does not alter substantially this dispersion. Of course, it is obvious that this is an approximation and that a rigid band filling of the hole band at hal-filling cannot be exact. But the claim is that it is a good approximation as the doping moves the system from an antiferromagnetic insulator to an optimally doped superconductor. Eventually the approximation breaks down as the AF correlations disappear. As described below and in a recent preprint, we have actually shown that changing the dispersion as the hole density increases from an AF band to a narrow tight-binding band, as suggested by numerical simulations, does not change the main qualitative properties originally observed in Ref. It is in this respect that the present theory has features of the more standard van Hove ideas discussed in the literature. Details of the AFVH theory and its comparison with experiments are given in the following sections. For lack of space we will not be able to provide all the many references to papers that have contributed to the ideas described here, and thus we apologize in advance to the readers. All the important literature can be found from the references in the papers quoted in this mini-review.

2. INTERESTING TIMES IN ANGLE-RESOLVED PHOTOEMISSION EXPERIMENTS!

Until very recently, the photoemission literature of the cuprates contained statements praising the apparent good agreement between experimental data and band structure calculations. Those results were discouraging for experts of strongly correlated electronic models because it was clear that the energy scales coming out from calculations in t-J models and band structure simulations were, and still are, very different. The t-J model near half-filling has a natural energy scale of 0.1 eV which is J, while band structure calculations are dominated by hopping amplitudes of order eV’s. However, in recent times the experimental data have improved dramatically and important “surprises” were reported. The current picture is quite different from what it was not long ago. Now the presence of strong correlations is regarded as a key feature of the physics of holes in the planes even at optimal doping where some people used to believe that the angle-resolved photoemission (ARPES) data was simply indicative of a gas of weakly interacting (1-x) electrons with a dispersion derived from band structure calculations (x is the hole concentration).

Let us here summarize the main results contained in
the ARPES data. In this authors’ opinion, there are at least four features in the recent ARPES literature that are clear indications of strong correlations affecting drastically the quasiparticle dispersion:

(i) The quasiparticle bandwidth is of order J, the Cu−Cu exchange, rather than a larger electronic scale.
(ii) An extended region of flat CuO$_2$-derived bands very near the Fermi energy exist for Bi2212, Bi2201, Y123 and Y124. This seems a universal property of the hole-doped cuprates. Again, such a behavior cannot be explained within band structure calculations which use different electronic potentials for each compound.
(iii) ARPES experiments for an AF insulator have revealed a hole dispersion with a small bandwidth also dominated by the exchange J.
(iv) Recent photoemission results by Aebi et al. in Bi2212 with Tc=85K, using sequential angle-scanning data acquisition to obtain PES intensities within a narrow energy window near the Fermi energy E$_F$, reported evidence of antiferromagnetically induced spectral weight above the naive Fermi momentum $p_F$. If confirmed, these results tell us that there are enough AF correlations in the normal state at optimal doping of Bi2212 to induce observable features in a photoemission experiment. Note that several groups have already confirmed the presence of these shadow bands in the data. Currently the debate is whether the origin of these bands is indeed antiferromagnetism or if it is caused by a superstructure effect.

3. THEORETICAL PREDICTIONS FOR THE BANDWIDTH

Let us now compare the ARPES experiments with predictions of models of strongly interacting electrons. The best model to use would be the three band Hubbard model including degrees of freedom at both Cu and O sites. However, this model is difficult to handle and to make progress simplifications are necessary. Our group and many others have mostly concentrated on the predictions arising from the 2D t-J model and from the one band 2D Hubbard model, but we believe that the results below are not much dependent on the specific model used as long as there are AF correlations in the ground state. The t − J model Hamiltonian is defined as

$$H = - t \sum_{\langle ij \rangle} (\hat{c}_{i \sigma}^\dagger \hat{c}_{j \sigma} + \text{h.c.}) + J \sum_{\langle ij \rangle} (\hat{S}_i \cdot \hat{S}_j - \frac{1}{4} n_{i \uparrow} n_{i \downarrow}),$$

where the notation is standard. The one hole dispersion in this model has been calculated in recent years by a variety of techniques both analytical and numerical. Recently, some of us in collaboration with M. Boninsenrati studied this dispersion, $\epsilon(\mathbf{k})$, using a Green Function Monte Carlo (GFMC) method on large clusters of $8 \times 8$, $12 \times 12$ and $16 \times 16$ sites minimizing finite size effects. Other techniques produce similar results.

In Fig.1a, the numerically evaluated $\epsilon(\mathbf{k})$ is shown at $J/t = 0.4$ along particular directions in the Brillouin zone. The minimum in the energy is obtained at the M point $\mathbf{k} = (\pi/2, \pi/2)$ in agreement with several previous approximate calculations. The main effective contribution to $\epsilon(\mathbf{k})$ arises from hole hopping between sites belonging to the same sublattice, to avoid distorting the AF background. The density of states (DOS) is given in Fig.1b. The total bandwidth, $W$, is severely reduced from that of a gas of non-interacting electrons due to the antiferromagnetic correlations (the vertical axis in Fig.1a,b is in units of the hopping $t$, which is $\approx 0.4 eV$).

Many features of this dispersion are in nice agreement with the experimental result (i) described above. Note also that all momenta belonging to the non-interacting 2D Fermi surface $cosk_x + cosk_y = 0$ are very close in energy in the t-J model. In the range $0.3 \leq J/t \leq 0.7$, we found that the energy difference between $(\pi/2, \pi/2)$ and $(0, \pi)$ is approximately 15% to 20% of the total bandwidth. The proximity of all the states along the $cosk_x + cosk_y = 0$ line contributes to a large peak in the density of states which is a crucial feature of the theory for the cuprates discussed below. Note also that since $W \sim J$, and more importantly since the splitting between points along the $X = (\pi, 0)$ to $Y = (0, \pi)$ line is even smaller than J, then a non-negligible temperature dependence is expected in the data. Such small energy scales in the problem produce a Hall coefficient $R_H$ in quantitative agreement with the experimental results for LSCO.

It is also interesting to notice the evolution of the Fermi surface from hole pockets to a large FS as the hole doping increases in reasonable agreement with experiments. These results were also noticed by S. Trugman time ago. For details the reader should consult Ref. and references therein. Eder and Ohta have also done important contributions to these ideas in recent papers. It is interesting to remark that mean-field spin-density-wave calculations in the literature for the one band Hubbard model do not remove the degeneracy along the $(\pi, 0)$ to $(0, \pi)$ model, affecting severely the results. The removal of this degeneracy is very important to properly describe the physics of the model.

4. FLAT REGIONS IN THE CUPRATES

An interesting detail of Fig.1a is the near flatness of the energy in the vicinity of $\mathbf{k} = (\pi, 0)$. This feature is similar to the ARPES results described in (ii) above. Actually, in Refs. the theoretically observed flat region of Fig.1a was explicitly compared with ARPES experiments finding a good agreement. The flatness of the $\mathbf{k} = (\pi, 0)$ region in the cuprates has a many-body origin, rather than being induced by band effects (see also Refs. ). Intuitively, it is the presence of saddle-points near X and Y (also noticed in Ref. ) plus the presence of
a near degeneracy along \((\pi, 0)-(0, \pi)\) which is responsible for the abnormal flatness of the hole dispersion. These combined effects produce a density of states DOS with a robust peak at the bottom of the hole band (top of the valence electronic band) and a van-Hove (vH) singularity (Fig. 1b). This large DOS was used by some of us to boost the critical temperature once a pairing mechanism was identified. As remarked before, the presence of this van Hove singularity and the large DOS has strong similarities with vH scenarios discussed before in the literature. In the previous vH ideas the dispersion is usually generated by band effects, while here many-body effects in the CuO\(_2\) planes are crucial, and thus our predictions are universal for all hole-doped cuprates.

5. ARPES DATA FOR A HOLE IN AN ANTI-FERROMAGNETIC INSULATOR

In this section, we will discuss the interesting results obtained by Wells et al. for the AF insulator Sr\(_2\)CuO\(_2\)Cl\(_2\). The main conclusion of the experimental effort is that the theory for one hole in the 2D t-J model describe very well the data in almost all directions in momentum space. In particular, the agreement along the \((0,0)\) to \((\pi, \pi)\) line is remarkable. This result is encouraging since it shows that indeed the 2D t-J model is suitable for a first principles description of the CuO\(_2\) planes. However, there are discrepancies in the vicinity of the \((0, \pi)\) and \((\pi, 0)\) points. The prediction of the t-J model would indicate a flat energy close to the top of the valence band as described before. However, the ARPES result has a larger binding energy. In the opinion of the authors, we have to keep in perspective that this discrepancy cannot be labeled as a failure of the model since it is clear to all of us that the t-J model is only a rough approximation and the hope is that it captures some of the essential features of the experiments. Asking for a perfect agreement with the data is too much. With this caveat, however let us also say that the absence of flat regions near the \((0, \pi)\) and \((\pi, 0)\) is an issue to worry about since they are a very clear feature of the other cuprates at optimal doping. Then, an important question arises: is the absence of flat regions in Sr\(_2\)CuO\(_2\)Cl\(_2\) an indication that this material is different from the rest? After all Sr\(_2\)CuO\(_2\)Cl\(_2\) is not a superconductor since it is difficult to dope. A possibility raised by some of us is that small modifications around the t-J model may account for the ARPES dispersion of this compound. The modification amounts to the addition of a hopping amplitude for next to nearest neighbor sites. This modified model describes better the data than the t-J model. However, recent preliminary ARPES results by the Stanford group for underdoped Bi2212 suggest that as a function of doping, moving from the AF insulator to optimal doping, the region from \((0, 0)\) to \((\pi, \pi)\) remain the same while the neighborhood of \((0, \pi), (\pi, 0)\) is much affected.

The flat regions seem to emerge as the doping grows towards its optimal value. Work is in progress to analyze this crucial aspect of the new ARPES data. Results will be presented soon.

6. SHADOW BANDS

As described in Sec.2, recent experiments by Aebi et al. have generated considerable excitement. A feature presumably caused by antiferromagnetic correlations was reported in their ARPES data for Bi2212. This result is compatible with the “shadow bands” scenario of Kampf and Schrieffer which is a consequence of antiferromagnetic correlations in the normal state. At half-filling, these bands, which appear at momenta above the naive Fermi momentum \(p_F\), are caused by the enlarged magnetic unit cell of the CuO\(_2\) planes produced by the long range antiferromagnetic order in the ground state. This effective reduction in the size of the Brillouin zone (BZ) has interesting implications for PES experiments. For example, along the diagonal \(p_x = p_y = p\), and assuming long-range order, peaks at momenta \(p_1 = (p, p)\) and \(p_2 = (\pi - p, \pi - p)\) should appear at the same energy location, for any value of \(p\). The PES weight \((\omega < 0)\) observed in the region above the non-interacting \(p_F\) is induced by strong magnetic correlations. How important is this antiferromagnetically generated PES weight at finite density? Only recently Quantum Monte Carlo and Exact Diagonalization calculations in the proper regime of strong coupling have been discussed. At density \(\langle n \rangle = 0.88\) and coupling \(J/t = 0.4\), the AF correlation is of only two lattice spacings as in optimal YBCO. In spite of this small correlation, a sharp peak in the hole spectral function was observed in Ref. near the chemical potential even for momenta \((2\pi/3, 2\pi/3)\) i.e. above the naive Fermi momentum. This peak is correlated with AF and disappears with further increasing of the density. But at \(\langle n \rangle = 0.88\) it is still observable, giving more support to the AF interpretation of Aebi et al.’s data and to theoretical scenarios based on AF. In short, an antiferromagnetic correlation of two lattice spacings can produce observable results in PES experiments for the cuprates! This remarkable result was unexpected since the previous intuitive perception was that very short range correlations are mostly irrelevant. Our results show that this is incorrect and, specially for the dispersion of holes, the spin ordering in its immediate vicinity is important. If the “shadow bands” found in Bi2212 turn out to have a superstructure explanation rather than an AF origin, then the numerical simulation results can be used to conclude that the AF correlation of Bi2212 should be smaller than a couple of lattice spacings, making it negligible. Either way, the study of shadow bands in the cuprates is important.

7. d-WAVE SUPERCONDUCTIVITY
The overall conclusion of the previous sections is that the quasiparticles described by the 2D t-J model are in many respects in good agreement with ARPES data. Let us now introduce interactions among the quasiparticles. We will follow ideas based on antiferromagnetism to produce the pairing attraction needed for superconductivity. However, there is an important distinction with respect to previous “AF-oriented” literature [6]: in the AFVH scenario the DOS of the quasiparticles has a large peak that in a natural way induces the existence of an optimal doping i.e. a density at which the critical temperature is maximized.

To build up a model for the cuprates we construct the interaction between the quasiparticles based on the 2D t-J model, where it is well-known that in an antiferromagnet an effective attractive force exists between two holes leading to a bound state in the d_{x^2−y^2}−wave channel. [8] As shown numerically in many studies, the dominant effective attraction is between nearest-neighbors sites. Thus, the model we will use in our analysis is

\[ H = - \sum_{p,\alpha} c_p^\dagger c_p c_{p,\alpha} - |V| \sum_{\langle ij \rangle} n_i n_j, \]  

where \( c_{p,\alpha} \) is an operator that destroys a quasiparticle with momentum \( p \) in sublattice \( \alpha = A, B; n_i \) is the number operator at site \( i \); \( |V| = 0.6J \) (which can be deduced from the \( t-J \) model [1]), and \( c_p \) the dispersion evaluated in Ref. [3]. No double occupancy is allowed. Since in the original \( t-J \) language quasiparticles with spin-up(down) have already been taken into account in the construction of Sec.7. it was assumed that other phenomenological models of d-wave superconductivity do not have. [17] This issue has been discussed in a recent publication where exact diagonalization results on a 32 site lattice have shown the existence of d-wave superconductivity in the AFVH model analyzed beyond the BCS gap equation. [13]

The ratio \( R(T) = 2\Delta_{\text{max}}(T)/kT_c \) can be calculated from the gap equation, (for a \( d_{x^2−y^2} \)-wave condensate, \( \Delta_{\text{max}}(T) \) is defined as the maximum value of the gap). At \( T = 0 \), the AFVH model predicts \( R(0) = 5.2 \) while recent tunneling experiments [19] give 6.2. Other experiments have reported a smaller value for \( R(0) \). For example, ARPES data by Ma et al. [20] obtained \( R(0) = 4.6 \), while an average over the pre-1992 literature [21] suggested \( R(0) = 5 \pm 1 \) supporting the results of the AFVH model. We have also verified that an important feature of previous vH scenarios [4] also exists in our model, i.e. a quasiparticle lifetime linear with frequency at the optimal doping [1].

A standard concern of any scenario that makes use of a van Hove singularity is its stability after the addition of disorder that tend to rapidly smear the logarithmic singularity and reduce drastically its effects. Also in models where the van Hove singularity appears in the non-interacting limit, the presence of strong correlations tend to destroy such a singularity. In our AFVH scenario none of these effects are important. Note that strong correlations have already been taken into account in the construction of the quasiparticle dispersion and the expectation is that these q.p.’s are weakly interacting. Note also that the van Hove singularity of the DOS at half-filling appears on top of a large accumulation of weight naturally caused by features of a hole in an antiferromagnet as described before. Then, although the actual log-singularity may disappear with disorder, the robust peak in the DOS remains, as was shown explicitly in Ref. [1]. Then, this model does not have the weaknesses of other van Hove based models in the literature.

8. EFFECT OF A FINITE HOLE DENSITY ON THE HOLE DISPERSION

An immediate concern about the AFVH scenario is the issue of the influence of hole density over the quasiparticle dispersion. In the construction of Sec.7. it was assumed
that holes still move as they were moving in a Néel state even with other holes present. It is obvious that this assumption cannot be exact i.e. as the density diminishes from half-filling changes must occur in the hole dispersion since the AF correlation length diminishes as the number of holes grow. In Ref. [22] this issue was addressed numerically using the exact diagonalization technique on a finite lattice. There, working at $< n > = 0.87$ the result shown in Fig.3 was found. The PES part of the spectrum is very similar to that found at half-filling giving support to the assumptions of Sec.7. The near flat region seems still present in the PES data, although now the error bars and finite size effects are more severe than they were at half-filling. On the other hand, note that there is a substantial IPES region that contributes appreciably to the dispersion (see also Ref. [1]). In Fig.4 we show that the hole DOS at finite density still has a large peak at the top of the band as at half-filling. This peak is crossed by the chemical potential as the doping is moved away from half-filling. [23,24]

To study whether our scenario will be modified by the IPES contribution, we carried out the following exercise: instead of using the AFVH dispersion in the kinetic energy of Eq.(2), we used a $\cosh_k x + \cosh_k y$ dispersion to mimic the broad features of Fig.3 with the amplitude $t_{eff}$ as a fitting parameter ($t_{eff}$ is still much smaller than the bare hopping $t$). Using this dispersion, i.e. entirely neglecting the “AF-induced” part of the spectrum observed in Fig.3 we carried out the calculation of the critical temperature using the same interaction as before i.e. a nearest neighbor attraction of order $J$. As shown by inspection in Fig.3 the chemical potential in this quasiparticle band is near the flat region and in the language of the tight-binding “cos+cos” dispersion it amounts to working with a half-filled q.p. band. Then, effectively the superconductivity that will arise after hole attraction is introduced will correspond to that of a narrow band “$t$-$U$-$V$ model” at half-filling which we know leads to a d-wave condensate. [1] The new $T_c$ is shown in Fig.5. Although much reduced with respect to the original AFVH result [1], it still has a robust value of $\sim 35K$ since the density of states is again large due to the approximate flat regions near the saddle points of the tight-binding dispersion. In Ref. [22] we have also introduced a dispersion that interpolates between the two extreme cases (AFVH and tight binding). The $T_c$ in this case is also shown in Fig.4 and it reaches $\sim 60K$. Then, the main quantitative conclusions of the AFVH scenario remain unaltered i.e. even using a dispersion obtained numerically and removing the AF induced shadow part, the robust peak in the DOS still produces a robust $T_c$, and the channel remains $d_{x^2-y^2}$-wave. Details are presented in a recent preprint [25]. These results show that our scenario is robust under reasonable modifications of the main assumptions. Such stability is important. Our ideas are general and do not correspond to a fine tuning of parameters to fit the data.

We have also done the following exercise: using the AFVH dispersion, we added to the one particle Green functions that enter into the gap equation a factor $Z_k$ in the numerator to account for the fact that the quasiparticles do not carry 100% of the weight in $\Lambda(k,\omega)$. Actually to study a drastic influence of $Z_k$, we made zero the weight of those states which were at a distance larger than 20 meV from the flat regions. This trick can also account for the fact that the quasiparticle peaks away from the Fermi surface become broad with a width growing like the square of the energy distance from the Fermi surface, as in any Fermi liquid. The results, recently discussed in Ref. [25], are given in Fig.5. The main features of the original AFVH result remain qualitatively the same after these modifications are introduced. It is becoming clear that the main factor contributing to the large $T_c$ are the flat regions at the top of the valence band where most of the spectral weight is accumulated. The rest of the dispersion, and with it most of the AF-induced shadow band, is not as important. Then, as it happened before for the case of disorder and strong correlations, our approach seems stable against changes in the quasiparticle dispersion to account for the finite hole density.

9. PHASE SEPARATION:

It has been known since the early studies of the t-J model that as $J/t$ grows at any finite hole density, the system will eventually phase separate. Near half-filling this is caused by the attraction between holes coming from the minimization of broken antiferromagnetic links. [8] The presence of a tendency to form large domains of holes has been detected in several high-Tc materials in their normal state. [26,27] The philosophy of our group is that phase separation mechanisms and AF-based mechanisms correspond to different sides of the same coin. In the general phase diagram of the t-J model it is well-known that, at a fixed density, as $J/t$ grows we move from a metallic phase, to a superconducting phase, to a phase separated regime. [8] The force leading to superconductivity and phase separation is basically the same in this model. The region of major interest, i.e. the superconducting regime, can be accessed from the paramagnetic region by developing AF correlations or from the phase separated regime by reducing these correlations, i.e. improving the hole mobility. [28] Then, to understand the superconducting phase both approaches are supposed to lead to the same result.

10. IS RETARDATION IMPORTANT? CAN PHONONS MATTER AFTER ALL?

A feature of theories of high-Tc which is rarely addressed is the importance of “retardation” effects. In the old superconductors described by a phononic mechanism these effects are clearly crucial since the delay in the interaction introduced by the exchange of phonons (with
a typical velocity related to Debye energies rather than to Fermi energies) manages to avoid the instantaneous Coulomb repulsion between the two electrons forming a Cooper pair. In theories of high-Tc, somehow we should also be able to avoid the repulsion between holes in the pair. However, an immediate problem arises related to the fact that the spin-wave velocity is governed by the exchange J, while near half-filling the bandwidth of the hole band is also of order J, as shown before. Thus, the Fermi velocity is not obviously larger than the spin-wave velocity i.e. there is no clear distinction between the velocities of the (rather heavy) dressed quasiparticles and the bosons mediating the attraction. In order to avoid the Coulomb repulsion one may use the following argument: a pair of holes in an antiferromagnet have a natural finite distance between the members of the pair since the attractive channel is d-wave. The pair cannot be “on-site”. However, this is not enough to avoid entirely the problem since at a distance of one lattice spacing the naive bare Coulomb repulsion is large enough to destroy the weak attraction used in our AFVH Hamiltonian. A possible way to avoid this problem is by invoking a large polarization (i.e. a large dielectric constant) or a strong screening effect. But a more interesting possible explanation is that the hole attraction in the t-J model indeed has some important but somewhat hidden retardation effects. Suppose that a hole in an AF produces “string” states i.e. once the hole is injected at a given site its movement leads to the creation of a string of spins that are not correctly aligned with respect to the staggered background. \[ \text{This effect costs energy and the only way to avoid it is by the hole to retrace its path, unless quantum spin fluctuations destroy the string. Let us imagine what occurs in the small J/t limit. Here a hole can move a large distance since the energy paid by the string creation grows like J, while the mobility is regulated by t. But eventually the hole feels the string which makes it return to the origin. But a second hole added to the problem would improve its energy by taking advantage of this string, i.e. moving along the path opened by the first hole is energetically favorable since the string is erased. Then, we can roughly envision a hole pair as one hole that leads the way creating a string and a second hole that follows through exactly the same path, healing the damage. The two holes remain at some prudent distance to avoid the Coulomb repulsion. We believe that this picture may lead to an interesting retardation effect that may solve the Coulomb repulsion problem in AF scenarios for the cuprates.}

There is another way to avoid the Coulombic interaction that we have recently studied. It may occur that the strength of the AF correlations in the normal state at optimal doping is enough to affect the quasiparticle dispersion, as described before, but it may not be strong enough to produce pairing. Then, a model where the holes approximately have the dispersion arising from AF, but with the pairing mediated by phonons would be a possibility. The main trouble that immediately arises is that the natural channel for phononic mechanisms is s-wave. However, we found that the buckling mode of YBCO can produce attraction in the d-channel.\[29\] This fact was also observed by Song and Annett.\[30\] One of the clear advantages of this approach is that a nonzero isotope effect can be explained in a natural way. Current experimental information indeed favors the presence of a nonzero isotope coefficient away from optimal doping. Although the idea of mixing AF concepts with phonons is not in such a developed state as those based on AF mediated pairing, the possibility of phonons for d-wave deserves further study.

11. CONCLUSIONS

Recent ARPES experimental results have provided evidence that strong correlations are important to properly describe the physics of the quasiparticle carriers in the cuprates even at optimal densities. We attribute the features observed in ARPES data to strong AF correlations and based on them, we have built a theory of high-Tc combining van Hove and AF scenarios. Concrete predictions come out from our approach namely \(d_{xz-yp}\)-wave superconductivity, and the concept of optimal doping when the chemical potential reaches the large peak in the DOS. The results are not much affected if the rigid band filling of the hole dispersion at half-filling is relaxed by using a more standard tight-binding quasiparticle dispersion as given by numerical studies of the 2D t-J model. The theory is also robust after the introduction of disorder, and it produces a Hall coefficient which agrees well with experiments.\[{3}\] A long paper with the details of our calculations will be presented soon.

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REFERENCES

[1] E. Dagotto, A. Nazarenko, and A. Moreo, Phys. Rev. Lett. 74, 310 (1995).
[2] D. J. Scalapino, Phys. Rep. 250, 331 (1995).
[3] E. Dagotto, A. Nazarenko and M. Boninsegni, Phys. Rev. Lett. **73**, 728 (1994).
[4] C. C. Tsuei et al., Phys. Rev. Lett. **65**, 2724 (1990); R. S. Markiewicz, J. Phys. Condens. Matt. **2**, 6223 (1990); D. M. Newns, P. C. Pattanaik and C. C. Tsuei, Phys. Rev. B **43**, 3075 (1991); A. A. Abrikosov, J. C. Campuzano, and K. Gofron, Physica C **214**, 73 (1993).
[5] D. S. Dessau et al., Phys. Rev. Lett. **71**, 2781 (1993); K. J. Gofron et al., J. Phys. Chem. Solids **54**, 1193 (1993); K. J. Gofron, thesis (1993); Z.-X. Shen and D. S. Dessau, preprint (1994).
[6] B.O. Wells, et al., Phys. Rev. Lett. **74**, 964 (1995).
[7] P. Aebi et al., Phys. Rev. Lett. **72**, 2757 (1994); J. Ostervalder et al., preprint.
[8] For a comprehensive review of this issue, see E. Dagotto, Rev. Mod. Phys. **66**, 763 (1994).
[9] S. Trugman, Phys. Rev. Lett. **65**, 500 (1990); Phys. Rev. B **37**, 1597 (1988).
[10] R. Eder and Y. Ohta, Phys. Rev. B **50**, 10043 (1994), and references therein.
[11] N. Buitun, D. J. Scalapino and S. R. White, Phys. Rev. B **50**, 7215 (1994); R. Putz, R. Preuss, A. Muramatsu, and W. Hanke, preprint.
[12] A. Nazarenko, K. Vas, S. Haas, E. Dagotto, and R. Gooding, Phys. Rev. B **51**, 8676 (1995).
[13] D. Dessau and Z.X. Shen, private communication.
[14] A. Kampf and J. R. Schrieffer, Phys. Rev. B **41**, 6399 (1990); Phys. Rev. B**42**, 7967 (1990).
[15] S. Haas, A. Moreo and E. Dagotto, Phys. Rev. Lett. **74**, 4281 (1995). See also R. Preuss, W. Hanke and W. von der Linden, Dec. 1994, preprint.
[16] N. E. Bickers, D. J. Scalapino, and S. R. White, Phys. Rev. Lett. **62**, 961 (1989); E. Dagotto, J. Riera and A. P. Young, Phys. Rev. B **42**, 2347 (1990); P. Monthoux and D. Pines, Phys. Rev. Lett. **69**, 961 (1992); E. Dagotto and J. Riera, Phys. Rev. Lett. **70**, 682 (1993); Y. Ohta et al., Phys. Rev. Lett. **73**, 324 (1994).
[17] R. Micnas et al., Rev. Mod. Phys. **62**, 113 (1990); E. Dagotto et al., Phys. Rev. B**49**, 3548 (1994).
[18] A. Nazarenko et al., preprint.
[19] S. I. Vedeneev et al., Phys. Rev. B **49**, 9823 (1994).
[20] Jian Ma et al., Madison preprint, May 1994.
[21] B. Batlogg, Springer Series in Solid-State-Sciences, Vol. 106, Eds.: S. Mackawa and M. Sato, page 219 (1992).
[22] A. Moreo, S. Haas, A. W. Sandvik and E. Dagotto, Phys. Rev. B **51**, 12045 (1995).
[23] A. Moreo et al., to appear in the Proceedings of the Stanford Conference on High-Tc Superconductivity, March 1995.
[24] The presence of a large peak in the DOS of the t-J model has also been obtained recently by N. Plakida, V. Oudovenko, P. Horsch and A. Liechtenstein, preprint.
[25] A. Nazarenko et al., preprint.
[26] J. D. Jorgensen et al., Phys. Rev. B**38**, 11337 (1988); D. R. Harshman, et al., Phys. Rev. Lett. **63**, 1187 (1989); P. C. Hammel, et al., Phys. Rev. B **42**, 6781 (1990); Physica C **185-189**, 1095 (1991); Phys. Rev. Lett. **71**, 440 (1993); J. H. Cho, F. C. Chou, and D. C. Johnston, Phys. Rev. Lett. **70**, 222 (1993); J. H. Cho, F. Borsa, D. C. Johnston, and D. R. Jorgeson, Phys. Rev. B **46**, 3179 (1992); D. E. Rice, and D. J. Buttrey, J. Solid State Chem. **105**, 197 (1993); S. Hosoya et al., Physica C **202**, 188 (1992); J. M. Tranquada, D. J. Buttrey, and D. E. Rice, Phys. Rev. Lett. **70**, 445 (1993); C. H. Chen, S-W. Cheong, and A. S. Cooper, Phys. Rev. Lett. **71**, 2461 (1993); S-W. Cheong, et al., Phys. Rev. B **49**, 7088 (1994); S. M. Hayden, et al., Phys. Rev. Lett. **68**, 1061 (1992).
[27] U. Löw, V. J. Emery, K. Fabricius, and S. A. Kivelson, Phys. Rev. Lett. **72**, 1918 (1994); S. Haas, E. Dagotto, A. Nazarenko and J. Riera, Phys. Rev. B **51**, 5980 (1995).
[28] V. J. Emery, S. A. Kivelson, and H.-Q. Lin, Phys. Rev. Lett. **64**, 475 (1990).
[29] A. Nazarenko and E. Dagotto, preprint 1995.
[30] J. Song and J. F. Annett, Phys. Rev. B **51**, 3840(1995); *Erratum*, Phys. Rev. B **52**, 6930 (1995).

**Figure Captions**

1. (a) Energy of a hole in the t – J model, $\epsilon(k)$, vs momentum obtained with the GFMC method on a $12 \times 12$ lattice (open squares) and $J/t = 0.4$ (in units of $t$). Results for an $8 \times 8$ cluster (open triangles) and a $16 \times 16$ cluster (full squares) are shown. (b) Density of states obtained from our fit of the numerical data Fig.1a showing the van-Hove singularity between $\bar{M}$ and $X$. The unit of energy is $t$ (from Ref. [2]).

2. Critical temperature $T_c$ of the AFVH model as a function of hole density $x (= 1 - \langle n \rangle)$ (using the BCS gap equation). The superconducting state is $d_{x^2-y^2}$-wave (from Ref. [3]).

3. Dispersion of the hole quasiparticle in the 2D t-J model at $J/t=0.4$ and density $\langle n \rangle = 0.87$. The chemical potential is at zero. $\omega > 0$ is the IPES region. The size of the open and full circles is proportional to the intensity of the quasiparticle peaks. The technique used is exact diagonalization. For details see Ref. [4].

4. Density of states of the 2D t-J model at finite electronic density, and $J/t=0.4$. The results were obtained with exact diagonalization. For details see Ref. [5].

5. Critical temperature using the AF original dispersion used in Ref. [1] (dashed line), using the tight-binding dispersion described in Sec.8 and Ref. [2] (dot-dashed line) and also using a combination of both as in Ref. [3] (solid line).