Magnetic susceptibility in the Millis-Monien-Pines model

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The temperature dependence of the susceptibility of electrons interacting with antiferromagnetic spin excitations has been calculated using the Millis-Monien-Pines model. The deviation from the Pauli paramagnetism is in agreement with the measurements of $\chi(T)$ for the normal state in the low doping region in the high-critical-temperature superconductors. [S0163-1829(97)01806-7]

I. INTRODUCTION

The high-T_c superconductors (HTS) have anomalous normal state properties. At the present time there are two essentially different explanations of the normal state of the HTS.

In one class of theories it is assumed that Landau Fermi-liquid theory breaks down completely and an exotic metallic state described by the Luttinger-liquid theory is realized.[1] In the second class of theories it is assumed that the Landau quasiparticle concept does work but the normal Fermi liquid has some peculiar properties. In this second class of theories the most important models are the van Hove scenario developed by Fridel, Labbe, Bok, and the IBM group[2,3] and the Millis-Monien-Pines (MMP) model.[4] In the model based on the van Hove scenario the deviations from the usual metallic behavior are associated with anomalous scattering near the saddle points of the Fermi surface. The MMP model is based on the existence of antiferromagnetic excitations which are described by a dynamic susceptibility with relaxational dynamics and the imaginary part of the spin susceptibility Im $\chi(\mathbf{q},\omega)\sim\omega$ for all $\mathbf{q}$ measured from the zone center.

In the first class of theories, called non-Fermi-liquid (NFI) models, the temperature dependence of the resistivity, as well as the optical properties, can be explained if we consider that the excitations are on the low-energy scale. These models present many difficulties if doping effects are taken into consideration and Levine[5] presented a scaling hypothesis for the spectral density of excitations in order to explain the departure from the non-Fermi behavior of the doped HTS. This idea was also considered by Barzykin and Pines[4] in order to get the phase diagram of the HTS and the main point of these investigations is that antiferromagnetic excitations are very sensitive to the concentration of impurities.

Recently Pines[6] introduced an additional contribution to $\chi(\mathbf{q},\omega)$, considered initially in Ref. 4, containing the contribution of the excitation which has a peak at the commensurate wave vector $\mathbf{Q}=(\pi,\pi)$, and in this way he correlated magnetic and transport experiments supporting the *d* pairing. The unusual temperature dependence of the magnetic susceptibility of HTS has been considered by Wang and Franz[7] using the linear dependence of the density of states on the energy. For small doping they obtained the linear dependence of the temperature T and for large doping they obtained a logarithmic dependence of T. The calculations have been performed using a t-J model taking a spin liquid and the results have been compared with the measurements performed on $La_{2-x}Sr_xCuO_4$. The results have been compared with the density of states and for k_BT smaller than the characteristic energy E_v ($E=E_v$ is the van Hove singularity) the calculations are in agreement with the experimental data. We have to mention that the linear prediction is not the best dependence at small doping as it can be observed from the NMR data which are more accurate than the static measurements.

Recently Altshuler *et al.*[9] reanalyzed the two-dimensional (2D) spin liquid with a gap and one important result was that even in such a Fermi system, part of the magnetic response is given by the particle-hole continuum of spin-1/2 fermions.

In this paper we calculated the magnetic susceptibility $\chi(T)$ for the MMP taking into consideration the vertex corrections in the self-energy due to the magnetic field. We expect that these corrections are important for a Fermi system interacting with antiferromagnetic excitations. In fact, Mitrovic and Picket[10] considered this correction for the A-15 superconductors with an electron-phonon interaction, and showed that the magnetic susceptibility is enhanced at low temperatures.

On the other hand, Coffey[11] showed that the quasiparticle spectra of a 2D Fermi liquid is changed by the dynamical effect. The dynamical quasiparticle spectrum considered for a 3D Fermi liquid by Corneiro and Pethick[12] gives similar effects in a 2D Fermi liquid by introducing a term of the form $\varepsilon^3(p)\ln\varepsilon(p)$ associated with $T^3\ln T$ in the entropy.

If such a correction in the spectrum of quasiparticles is important for thermal properties we expect that the corrections given by the vertex are important for the magnetic response. However, we have to mention that in the case of the MMP model, the results will be relevant only for the small doping where the particle-hole continuum of the spin-1/2 fermion is well defined. In the strong doping region the localization effects[13,14] are important and the system is not a ''good'' metal.

The paper is structured as follows: in Sec. II we calculate the self-energy of the 2D electronic system interacting with spin excitations described by the dynamic susceptibility $\chi(\mathbf{q},\omega)$. The vertex correction given by the external magnetic field was expressed by the Hartree-Fock correction in the self-energy. This general result has been applied for the MMP model and in Sec. III we calculated the magnetization and magnetic susceptibility for $T\neq 0$. Using realistic parameters for the MMP model we showed that the obtained T^2 correction is important for the low doping region. In Sec. IV we discussed the result in connection with different calculations and models.

II. SELF-ENERGY AND VERTEX CORRECTIONS

A. General expression

In order to calculate the magnetic susceptibility of the electrons interacting with the antiferromagnetic spin fluctuations in the MMP model we will consider in the Green's functions the corrections given by the self-energy and by the vertex due to the interactions with the external field. We neglect the vertex corrections in the electron spin fluctuation energy because it was shown[8] that these corrections are small.

The Hamiltonian which describes the electron-spin fluctuation interaction has the form

$$\mathcal{H}=\sum_{\mathbf{p},\alpha} c^{\dagger}_{\mathbf{p},\alpha}[\varepsilon(\mathbf{p})-\tau_3 H]c_{\mathbf{p},\alpha} - \frac{U^2}{2}\sum_{\mathbf{k},i,j} S_i(\mathbf{k})\chi^{ij}(\mathbf{k})S_j(-\mathbf{k}), \tag{1}$$

where τ_i ($i=1,2,3$) are the Pauli matrices, U is the coupling constant, $S_i(\mathbf{k})$ is the spin density operator,

$$S_i(\mathbf{k})=\sum_{\mathbf{p}} c^{\dagger}_{\mathbf{k}+\mathbf{p}}\tau_i c_{\mathbf{p}}, \tag{2}$$

and $\chi^{ij}(\mathbf{k})$ is the dynamic susceptibility of the spin fluctuations which will be considered as

$$\chi^{ij}(\mathbf{k})=\chi(\mathbf{k},i\omega_m)\delta_{ij},$$

where $\chi(\mathbf{k},i\omega_m)$ has to be specified by the model.

The self-energy correction due to the interaction with the spin fluctuations has the general form

$$\Sigma_1(\mathbf{p},i\omega_n)=-\frac{U^2}{\beta}\sum_{m,\mathbf{k}} t_{ij}(\mathbf{k},i\omega_m)\tau_i G(\mathbf{p}-\mathbf{k},i\omega_m-i\omega_n)\tau_j, \tag{3}$$

where

$$t_{ij}(\mathbf{k},i\omega_m)=\chi(\mathbf{k},i\omega_m)\delta_{ij}. \tag{4}$$

From these equations we obtain, using the spectral representation for $\chi(\mathbf{k},i\omega_m)$ and $G(\mathbf{p},i\omega_m)$, the expression

$$\Sigma_1(\mathbf{p},\omega+i\delta)=6U^2\sum_{\mathbf{k}}\int_{-\infty}^{\infty}\frac{d\omega'}{2\pi}\int_{-\infty}^{\infty}\frac{d\omega_1}{2\pi}\frac{\mathrm{Im}\,G(\mathbf{p}-\mathbf{k},\omega_1)\mathrm{Im}\,\chi(\mathbf{p},\omega')}{\omega'+\omega_1-\omega-i\delta}\left[\tanh\frac{\omega_1}{2T}+\coth\frac{\omega'}{2T}\right]. \tag{5}$$

In a 2D electronic system we transform $\Sigma_{\mathbf{k}}\rightarrow(2\pi)^{-2}\int k\,dk\int_0^{2\pi}d\theta$ and using the approximations from Ref. 9 we obtain

$$\begin{aligned}\Sigma_1(\mathbf{p},\omega+i\delta)=&-\frac{3U^2}{(2\pi)^2}\frac{2\pi}{v_F}\int_{-\infty}^{\infty}\frac{d\omega'}{2\pi}\Bigg\{\int_0^{\infty}\frac{d\omega_1}{2\pi}\int_{\omega_1/v_F}^{2p_F}dk\,\frac{\mathrm{Im}\chi(\mathbf{k},\omega')}{\omega'+\omega_1-\omega-i\delta}\frac{1}{\sqrt{1-(k^2/4p^2)(1-2m\omega_1/k)^2}}\\&\times\left[\tanh\frac{\omega_1}{2T}+\coth\frac{\omega'}{2T}\right]-\int_0^{\infty}\frac{d\omega_1}{2\pi}\int_{\omega_1/v_F}^{2p_F}dk\,\frac{\mathrm{Im}\chi(\mathbf{k},\omega')}{\omega'+\omega_1+\omega+i\delta}\frac{1}{\sqrt{1-(k^2/4p^2)(1-2m\omega_1/k)^2}}\\&\times\left[\tanh\frac{\omega_1}{2T}+\coth\frac{\omega'}{2T}\right]\Bigg\},\end{aligned} \tag{6}$$

where p_F is the Fermi momentum and v_F the Fermi velocity.

In order to evaluate the real and imaginary parts of the self-energy we use the Kramers-Kronig relations and the approximation

$$\sqrt{1-\frac{k^2}{4p^2}\left(1-\frac{2m\omega_1}{k}\right)^2}\simeq\frac{2p_F}{\sqrt{4p_F^2-k^2}} \tag{7}$$

which is valid if $p\simeq p_F$ and $\omega_1\ll E_F$ where E_F is the Fermi energy. We get for the real part of the self-energy

$$\mathrm{Re}\,\Sigma_1(\mathbf{p},\omega)=\frac{3U^2}{(2\pi)^2}\frac{2\pi p_F}{v_F}\int_{-\infty}^{\infty}\frac{d\omega_1}{2\pi}\int_{\omega_1/v_F}^{2p_F}dk\,\frac{\mathrm{Re}\,\chi(\mathbf{k},\omega_1)}{\sqrt{4p_F^2-k^2}}\left[\tanh\frac{\omega_1-\omega}{2T}-\tanh\frac{\omega_1+\omega}{2T}\right] \tag{8}$$

and for the imaginary part of the self-energy

$$\mathrm{Im}\,\Sigma_1(\mathbf{p},\omega)=-\frac{3U^2}{(2\pi)^2}\frac{4\pi^2 p_F}{v_F}\int_0^{\infty}\frac{d\omega_1}{2\pi}\int_{\omega_1/v_F}^{2p_F}dk\,\frac{\mathrm{Im}\chi(\mathbf{k},\omega_1)}{\sqrt{4p_F^2-k^2}}\left[2\coth\frac{\omega_1}{2T}-\tanh\frac{\omega_1-\omega}{2T}-\tanh\frac{\omega_1+\omega}{2T}\right]. \tag{9}$$

The vertex corrections given by the external magnetic field H gives the contribution

$$\Sigma_v(\mathbf{p},i\omega_n)=-\frac{U^2}{\beta}\sum_{\mathbf{k}}\sum_m\sum_i\chi(\mathbf{p}-\mathbf{k},i\omega_n-i\omega_m)\overline{H}\tau_3\tau_i G(\mathbf{k}+\mathbf{q},i\omega_m+i\omega_n)G(\mathbf{k},i\omega_m)\tau_i, \tag{10}$$

where $\overline{H}=\mu_B H$ and for the Green's function we will take $G=G_0$. Using now the identity

$$G_0(\mathbf{k}+\mathbf{q},i\omega_m+i\omega_n)G_0(\mathbf{k},i\omega_m)=\frac{1}{\varepsilon(\mathbf{k}+\mathbf{q})-\varepsilon(\mathbf{k})-i\omega_n}[G_0(\mathbf{k}+\mathbf{q},i\omega_m+i\omega_n)-G_0(\mathbf{k},i\omega_m)] \tag{11}$$

and the spectral representation for χ and G_0 we get from Eq. (10) the general expression

$$\Sigma_v(\mathbf{p},i\omega_n)=\overline{H}\tau_3U^2\int\frac{d^2\mathbf{k}}{(2\pi)^2}\frac{1}{\beta}\sum_m\int_{-\infty}^{\infty}\frac{d\omega'}{\pi}\int_{-\infty}^{\infty}\frac{d\omega_1}{\pi}\frac{\text{Im }\chi(\mathbf{p}-\mathbf{k},\omega_1)}{i\omega_n-i\omega_m-\omega_1}\left[\frac{\text{Im }G_0(\mathbf{k}+\mathbf{q},\omega')}{i\omega_m+i\omega_n-\omega'}-\frac{\text{Im }G_0(\mathbf{k},\omega')}{i\omega_m-\omega'}\right]. \tag{12}$$

In this expression we can perform the summation over m and we get

$$\Sigma_v(\mathbf{p},i\omega_n)=2\overline{H}\tau_3U^2\int\frac{d^2\mathbf{k}}{(2\pi)^2}\int_{-\infty}^{\infty}\frac{d\omega'}{2\pi}\int_{-\infty}^{\infty}\frac{d\omega_1}{2\pi}\frac{\text{Im }\chi(\mathbf{p}-\mathbf{k},\omega')\text{Im }G_0(\mathbf{k},\omega_1)}{(i\omega_n+\omega'-\omega_1)^2}\left[\tanh\frac{\omega_1}{2T}-\coth\frac{\omega'}{2T}\right]. \tag{13}$$

Taking $i\omega_n\to\omega+i\delta$ in Eq. (13) we can see that

$$\Sigma_v(\mathbf{p},\omega)=-\frac{1}{3}\overline{H}\tau_3\frac{\partial}{\partial\omega}\Sigma_1(\mathbf{p},\omega), \tag{14}$$

an equation which gives the vertex correction due to the external field as a function of the self-energy correction Σ_1.

Using these results we can calculate the magnetic susceptibility for a model which is in fact defined by $\chi(\mathbf{k},\omega)$.

B. Self-energy for the Millis-Monien-Pines model

We consider the low-energy region where

$$\omega<T<\omega_{SF}, \tag{15}$$

ω_{SF} is the energy of the antiferromagnetic spin fluctuations. The dynamical susceptibility $\chi(\mathbf{k},\omega)$ for the MMP model has the form[6]

$$\chi(\mathbf{k},\omega)=\frac{\chi_Q(T)}{1+\xi^2k^2-i(\omega/\omega_{SF})}, \tag{16}$$

where $\chi_Q(T)$ is a temperature-dependent contribution and ξ is the antiferromagnetic correlation length and is also temperature dependent.

In this region we approximate

$$\tanh\frac{\omega_1-\omega}{2T}-\tanh\frac{\omega_1+\omega}{2T}\simeq-\frac{\omega}{T} \tag{17}$$

and Eq. (8) becomes

$$\text{Re }\Sigma_1(\omega,p_F)=-3\omega A(p_F), \tag{18}$$

where

$$A(p_F)=\frac{U^2N(0)}{4}\frac{\chi_Q(T)}{\sqrt{1+4p_F^2\xi^2}}. \tag{19}$$

The imaginary part of the self-energy given by Eq. (9) can be evaluated using as

$$\text{Im }\chi(\mathbf{k},\omega)=\chi_Q(T)\frac{\omega/\omega_{SF}}{(1+\xi^2k^2)^2+(\omega/\omega_{SF})^2} \tag{20}$$

and for $\omega\ll\omega_{SF}$ we take

$$\text{Im }\chi(\mathbf{k},\omega)=\chi_Q(T)\frac{\omega}{\omega_{SF}}\frac{1}{(1+\xi^2k^2)^2}. \tag{21}$$

The integral over ω_1 can be performed and we get

$$\int_0^{\infty}d\omega_1\omega_1\left[2\coth\frac{\omega_1}{2T}-\tanh\frac{\omega_1-\omega}{2T}-\tanh\frac{\omega_1+\omega}{2T}\right]=\omega^2+(\pi T)^2,$$

which leads to the result

$$\text{Im }\Sigma_1=-[\omega^2+(\pi T)^2]\frac{3mU^2}{2\omega_{SF}}\chi_Q(T)\frac{1+2p_F^2\xi^2}{(1+4p_F^2\xi^2)^{3/2}}. \tag{22}$$

Using now Eq. (15) we approximate Eq. (22) as

$$\text{Im}\Sigma_1(p_F)=-\omega_{SF}^2B(p_F), \tag{23}$$

where

$$B(p_F)=\frac{3}{2}\frac{N(0)U^2}{\omega_{SF}}\chi_Q(T)\frac{1+2p_F^2\xi^2}{(1+4p_F^2\xi^2)^{3/2}}. \tag{24}$$

III. MAGNETIZATION AND MAGNETIC SUSCEPTIBILITY

A. Green's functions

In order to calculate the magnetic susceptibility we calculate the Green's functions from the equation

$$\hat{G}^{-1}(\mathbf{p},i\omega_n)=i\omega_n\hat{\mathbf{1}}-\varepsilon(\mathbf{p})\hat{\mathbf{1}}+\overline{H}\hat{\tau}_3-\hat{\Sigma}(\mathbf{p},i\omega_n), \tag{25}$$

where

$$\hat{\Sigma}(\mathbf{p},i\omega_n)=\hat{\Sigma}_1(\mathbf{p},i\omega_n)+\hat{\Sigma}_v(\mathbf{p},i\omega_n) \tag{26}$$

and

$$\hat{\Sigma}_1(\mathbf{p},i\omega_n)=-3Ai\omega_n\hat{\mathbf{1}}-i\omega_{SF}^2B\hat{\mathbf{1}}\,\text{sgn }\omega_n$$

$$\hat{\Sigma}_v(\mathbf{p},i\omega_n)=\overline{H}\hat{\tau}_3A, \tag{27}$$

where we considered $A=A(p_F)$ and $B=B(p_F)$. From Eqs. (25)–(27) we get

$$G_+(\mathbf{p},i\omega_n)=\frac{1}{1+3A}\,\frac{1}{[i\omega_n-\widetilde{\varepsilon}(\mathbf{p})+i\widetilde{B}]\hat{\mathbf{1}}+\widetilde{H}\hat{\tau}_3},\quad (28)$$

$$G_-(\mathbf{p},i\omega_n)=\frac{1}{1+3A}\,\frac{1}{[i\omega_n-\widetilde{\varepsilon}(\mathbf{p})-i\widetilde{B}]\hat{\mathbf{1}}+\widetilde{H}\hat{\tau}_3},\quad (29)$$

where

$$\widetilde{\varepsilon}(\mathbf{p})=\frac{\varepsilon(\mathbf{p})}{1+3A},\quad \widetilde{H}=\overline{H}\,\frac{1-A}{1+3A},\quad \widetilde{B}=\omega_{\rm SF}^2\,\frac{B}{1+3A}$$

and the magnetization $M(T,H)$ will be defined as

$$M(T,H)=\mu_B\sum_{\mathbf{p}}\left[\frac{1}{\beta}\sum_{\omega_n<0}\mathrm{Tr}[\tau_3G_-(\mathbf{p},i\omega_n)]+\frac{1}{\beta}\sum_{\omega_n>0}\mathrm{Tr}[\tau_3G_+(\mathbf{p},i\omega_n)]\right].\qquad (30)$$

In this equation we can perform the summation over ω_n and we get

$$M(T,H)=-\frac{\mu_B}{\pi(1+3A)}\sum_{\mathbf{p}}\int_{-\infty}^{\infty}dz\,f(z)\left[\frac{\widetilde{B}}{[z-\widetilde{\varepsilon}(\mathbf{p})-\widetilde{H}]^2+\widetilde{B}^2}-\frac{\widetilde{B}}{[z-\widetilde{\varepsilon}(\mathbf{p})+\widetilde{H}]^2+\widetilde{B}^2}\right].\qquad (31)$$

B. Magnetic susceptibility

The magnetic susceptibility $\chi(T)$ defined as

$$\chi(T)=\left(\frac{\partial M(T,H)}{\partial H}\right)_{H=0}\qquad (32)$$

was obtained from Eq. (31) as

$$\chi(T)=\frac{4\mu_B^2}{\pi}\sum_{p}\overline{B}(1-A)\int_{-\infty}^{\infty}dz\,f(z)\,\frac{\varepsilon(\mathbf{p})-z(1+3A)}{\{[\varepsilon(\mathbf{p})-z(1+3A)]^2+\overline{B^2}\}^2},\qquad (33)$$

where $\overline{B}=\omega_{\rm SF}^2B$ and $f(z)$ is the Fermi distribution function.

In order to perform the integral over z in Eq. (33) we approximate for low-temperature values

$$f(z)=\begin{cases}\exp\left[-\dfrac{z-\varepsilon_F}{T}\right], & z>\varepsilon_F,\\[2mm] 1-\exp\left[\dfrac{z-\varepsilon_F}{T}\right], & z<\varepsilon,\end{cases}\qquad (34)$$

and

$$I(\varepsilon)=\int_{-\infty}^{\infty}dz\,f(z)\,\frac{\varepsilon(\mathbf{p})-z(1+3A)}{\{[\varepsilon(\mathbf{p})-z(1+3A)]^2+\overline{B^2}\}^2}\qquad (35)$$

becomes

$$I=\frac{1}{2(1+3A)}\left[\frac{-1}{[\varepsilon(\mathbf{p})-\varepsilon_F(1+3A)]^2}+\int_0^{\infty}\frac{du\,e^{-u}}{[\varepsilon(\mathbf{p})-(Tu+\varepsilon_F)(1+3A)]^2+\overline{B^2}}+\int_{-\infty}^{0}\frac{du\,e^{u}}{[\varepsilon(\mathbf{p})-(Tu+\varepsilon_F)(1+3A)]^2+\overline{B^2}}\right]\qquad (36)$$

and in the limit of small temperature Eq. (36) will be approximated as

$$I=\frac{1}{2(1+3A)}\,\frac{1}{[\varepsilon(\mathbf{p})-\varepsilon_F(1+3A)]^2+\overline{B^2}}\left[1-\frac{4(1+3A)^2T^2}{[\varepsilon(\mathbf{p})-\varepsilon_F(1+3A)]^2+\overline{B^2}}\right].\qquad (37)$$

From Eqs. (33) and (37) we obtain

$$\chi(T)=\frac{4\mu_B^2}{\pi}\sum_{\mathbf{p}}\frac{\overline{B}(1-A)}{1+3A}\,\frac{1}{[\varepsilon(\mathbf{p})-\varepsilon_F(1+3A)]^2+\overline{B^2}}\left[1-\frac{4(1+3A)^2T^2}{[\varepsilon(\mathbf{p})-\varepsilon_F(1+3A)]^2+\overline{B^2}}\right].\qquad (38)$$

If we transform the summation over **p** in Eq. (38) in a 2D integral we calculate the magnetic susceptibility as

$$\frac{\chi(T)}{\chi(0)}=1-\frac{4A}{1+3A}-\frac{2(1-A)(1+3A)}{\overline{B^2}}\,T^2, \tag{39}$$

where $\chi(0)=\mu_B^2N(0)$ is the Pauli susceptibility. From this equation we can see that the first correction to the magnetic susceptibility due to the electron-spin excitation interaction is quadratic in temperature, and for $U=0$ we obtain the Pauli paramagnetism $\chi(0)=\mu_B^2N(0)$.

In the approximation $p_F\xi\gg1$ the parameters A and B given by Eq. (9), respectively, Eq. (24), becomes

$$A=\frac{U^2N(0)}{8p_F\xi}\,\chi_Q(T), \tag{40}$$

$$B=\frac{3\pi U^2N(0)}{8p_F\xi}\,\frac{\chi_Q(T)}{\omega_{SF}}, \tag{41}$$

where $\chi_Q(T)$ is given in the MMP model[6] as

$$\chi_Q(T)=\alpha\xi^2(T), \tag{42}$$

where α is an independent temperature constant. The coherence length $\xi(T)$ is given in this model by

$$\left(\frac{\xi(T)}{a}\right)^2=\left(\frac{\xi}{a}\right)^2_{T=0}\frac{\Theta}{T+\Theta}, \tag{43}$$

where $\Theta\simeq100$ K and a is the lattice constant. If we take for $\omega_{SF}=350$ K, in the condition of Eq. (15), where we can take the results from Ref. 10 which are well approximated by $\xi^{-1}(T)\rightarrow0$, we can approximate Eq. (39) as

$$\frac{\chi(T)}{\chi(0)}=1-\frac{4A}{1+3A}+\frac{2}{3\pi^2}\left(\frac{T}{\omega_{SF}}\right)^2. \tag{44}$$

The temperature dependence of $\chi(T)$ is given in Fig. 1. Using for $\chi(0)\simeq0.95\times10^{-4}$ emu/mol we calculate $\chi(T)$ for different values of $UN(0)$.

The experimental data obtained in Ref. 8 for $La_{2-x}Sr_xCuO$ with $0.08<x<0.15$ represented in Fig. 1 are in good agreement with our calculations and showed that the density of states $N(0)$ is decreasing with the tendency of the localization effects[13,14] observed in the transport measurements. Our calculations will be modified to take into consideration at the same time the temperature and disorder dependence of the magnetic susceptibility.

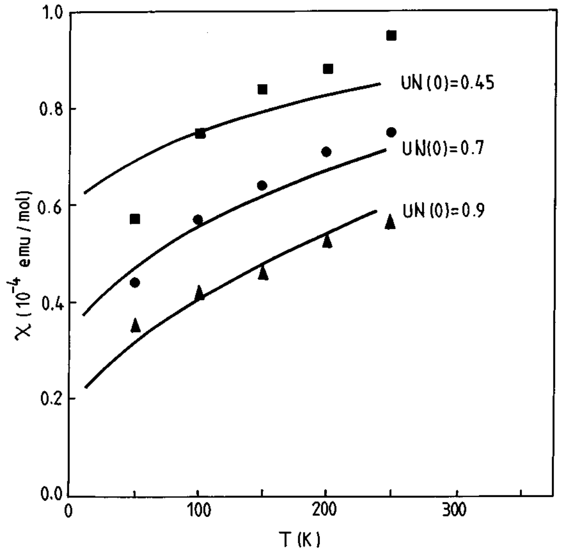

FIG. 1. Comparison of the calculated susceptibility to the experimental data of Refs. 11 and 12. Fits of the susceptibility for different values of $UN(0)$ correspond to the Sr concentration as follows: $x=0.08$ [$UN(0)=0.9$], $x=0.12$ [$UN(0)=0.7$], and $x=0.15$ [$UN(0)=0.45$].

IV. DISCUSSION

We calculated the magnetic susceptibility of a 2D electron gas interacting with antiferromagnetic excitations taking in the spectrum of the energy excitations the vertex corrections due to the magnetic field. This contribution to the self-energy has been expressed by the Hartree-Fock self-energy of the electrons interacting with the magnetic excitations which have the dynamic susceptibility $\chi(\mathbf{q},\omega)$. This result, which can be applied to other models, has been applied for the MMP model. In this model $\chi(\mathbf{q},\omega)$ is considered of the form given by Eq. (16) and in fact all these calculations have a phenomenological character due to the form of the dynamical susceptibility. However all the calculations can be performed analytically, even for the 2D system, and we obtained at $T=0$ an enhancement of the susceptibility which depends on the parameters of the MMP model and the electron excitation interaction. For $T\neq0$ the correction is quadratic in temperature and is also dependent on these parameters. We mention that for a free-electron gas such a correction is given by the temperature dependence of the chemical potential but in this case it is very small because has the order of $(k_BT/E_F)^2$.

This calculation is expected to be relevant for the small doping region where the coherence length $\xi(T)$ is not affected very much by impurities. The density of states was also considered as a parameter but we considered values of $UN(0)$ which are realistic for HTS. The linear and logarithmic dependence obtained in Ref. 7 can be given by the approximations in the density of states and it is expected if the energy spectrum gives van Hove singularities. Our comparison with the experimental data was presented only to show the relevance of the vertex correction in the problem of interacting electrons with magnetic excitations. The MMP model is the most appropriate for this aim but a realistic calculation has to consider the van Hove singularities in the 2D spin-excitation model as was suggested in Ref. 15. The generalization for the layered model could also improve the relevance of the present calculations.

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