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Ž.Kovačević, N.M.Plakida

SPIN-FLUCTUATION LINEWIDTH
OF THE 4f-ELECTRON CRYSTAL
FIELD LEVELS IN CUPRATES

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1 Introduction

The effect of sharp reduction of crystal-field (CF) linewidth for $4f$ -electrons at the superconducting transition temperature T_c in metallic alloys with rare-earth (RE) impurities (e.g. $\text{Tb}_x\text{La}_{1-x}\text{Al}_2$) is a well established phenomena [1].

In order to get more information about the spin dynamics in the CuO_2 planes, temperature dependence of linewidth $\Gamma_{cf}(T)$ of CF transitions in RE doped high T_c superconductors has been also investigated [2, 3]. But it was observed that the linewidth sharply decreases at some temperature T_s well above T_c .

The existence of antiferromagnetic (AF) correlations in high- T_c superconducting cuprates is widely accepted [4-8]. Suggesting that spin fluctuations provide a primary mechanism for the relaxation of the excited f -electrons, in the present paper we consider the model Hamiltonian of the RE ions and the spins at the Cu2 sites with the indirect-exchange coupling [9]. Using the pseudospin formalism and the method of the two-time Green functions (GF), we have derived the expression for $\Gamma_{CF}(T)$ (similar to that in Ref.1) of the first excited level $\Gamma_4^{(1)}$ RE ion Tm^{3+} in the superconducting $\text{Tm}_{0.1}\text{Y}_{0.9}\text{Ba}_2\text{Cu}_3\text{O}_{6.9}$ (Tm-TBCO_{6.9})-compound [3]. Using the results of Rossat-Mignod et al. [5] of the temperature dependence of the imaginary part of the magnetic susceptibility of YBCO_{6.92} near the AF wave vector $\mathbf{Q}_{AF}=(1/2, 1/2, 1.6)$ for the energy $\hbar\omega = 10$ meV, we have made a conclusion that dynamic spin fluctuations in CuO_2 dominate in the line broadening.

For the nonsuperconducting compound Tm-YBCO_{6.1}, using spin-wave approximation it has been shown that the main contribution to $\Gamma_{CF}(T)$ arises from a one-magnon process, which means that the spin gap is small compared to the $4f$ level splitting [10].

The paper is organized as follows. In the next Section, we present the model of s - f coupling. In Sec. III we introduce pseudospin formalism and derive the expression for linewidth $\Gamma_{CF}(T)$. In Sec. IV we discuss the numerical results and related works. In Sec. V we present our conclusions.

2 Model of s - f Interactions

Adopting the model of the one-component AF Fermi-liquid [4], [11], we can write the model of RE ions and spins $S = 1/2$ at the Cu2 sites in the following form:

$$H = H_{cf} + H_{s-s} + H_{s-f}, \quad (1)$$

where the Hamiltonian of CF for Tm^{3+} ions into the bilayers $\text{CuO}_2\text{-Tm}^{3+}\text{-CuO}_2$ (Fig. 1) can be presented in the following way:

$$H_{cf} = \sum_{n,i} \omega_n K_{nn}^{(i)} \quad (2)$$

where $K_{nn}^{(i)} = (|m\rangle\langle n|)_i$ are the transitions operators for the n, m levels of the CF of Tm^{3+} ions at the site i , and ω_n is the appropriate energy of the level n . H_{s-s} is the spin Hamiltonian describing doped holes in the CuO_2 plane and spin-spin interactions of the spins $\mathbf{S}_i$ at the copper sites. We are not going to discuss the problem of calculation the dynamical spin susceptibility $\chi(\mathbf{q}, \omega)$ for any explicit form of H_{s-s} but adopt some models for $\chi(\mathbf{q}, \omega)$ in our numerical calculations.

The Hamiltonian of the s - f interactions describing coupling between spins at Cu2 sites and $4f$ -electrons, we present in the following manner:

$$H_{s-f} = - \sum_{i,j} I_{s-f}^\alpha J_i^\alpha S_j^\alpha, \quad (3)$$

where $\mathbf{J}_i$ is the operator of the total angular momentum of the Tm^{3+} ion at site i , $\mathbf{S}_j$ is the operator of the spin at the copper sites j nearest to the site i and I_{s-f}^α , in the general case, the anisotropic indirect-exchange coupling constant, $\alpha = (x, y, z)$.

Due to a local character of $4f$ -electrons, we ignore the interaction between them and holes in the CuO_2 planes.

3 Calculation of the linewidth in the pseudospin representation

Let us recall that for polycrystalline samples, in the dipole approximation (for small scattering vectors of neutrons κ), the partial differential cross-section of transversal magnetic inelastic neutron scattering (INS) per ion of RE target can be written as [15]:

$$\left(\frac{d^2\sigma}{d\Omega dE'} \right)_\perp = \frac{1}{6} (r_0 \gamma)^2 \frac{k'}{k} \left[\frac{g}{2} F(\vec{\kappa}) \right]^2 \frac{e^{\beta\omega}}{1 - e^{\beta\omega}} \frac{1}{\pi} \text{Im}(\langle J_i^- | J_i^+ \rangle)_{\omega + i\epsilon}, \quad (4)$$

where $r_0 = \frac{e^2}{m_e c^2}$ is the electromagnetic radius of electron, $\gamma = -1.91$ is the magnetic moment of neutron in units of the nuclear magneton $\mu_N = \frac{eh}{2m_p c}$, $\vec{\kappa} = \vec{k} - \vec{k}'$, where $\vec{k}$ and $\vec{k}'$ are incident and scattered neutron wave vectors,

respectively, $F(\vec{k})$ is the free-ion form factor, g is the Landé splitting factor and where $\text{Im}\langle\langle J_i^- | J_i^+ \rangle\rangle_{\omega+i\epsilon}$ is the Fourier transform of the two-time GF [16].

The ground-state multiplet 3H_6 of Tm^{3+} in CF of orthorhombic symmetry D_{2h} splits into 13 singlets [13]: $4\Gamma_1, 3\Gamma_2, 3\Gamma_3$ and $3\Gamma_4$. The wave functions of the irreducible representations Γ_i can be given by [14]:

$$|n\rangle \equiv |\Gamma_i^{(j)}\rangle = \sum_{M=-J}^J a_{ij}^{(M)} |M\rangle, \quad (5)$$

where index j represents dimension of the Γ_i , along with

$$J^z |M\rangle = M |M\rangle. \quad (6)$$

Since the first excited level $\Gamma_4^{(1)}$ of CF is non-degenerate and its energy is much lower than the energy of the second one $\Gamma_2^{(1)}$, it is possible to approximate the local CF scheme of Tm^{3+} ions in $\text{Tm-YBCO}_{6.9}$ by two levels [1], [3], [13].

Let us define the wave functions of the ground state of H_{cf} by:

$$|-\rangle \equiv |\Gamma_3^{(1)}\rangle = a_{31}^{(6)} |6\rangle + a_{31}^{(2)} |2\rangle, \quad (7)$$

and the first excited one as

$$|+\rangle \equiv |\Gamma_4^{(1)}\rangle = a_{41}^{(5)} |5\rangle + a_{41}^{(3)} |3\rangle + a_{41}^{(1)} |1\rangle. \quad (8)$$

respectively. Then, it is possible to introduce an operator of pseudospin σ^α whose components satisfy the following relations:

$$\sigma^z |\pm\rangle = \pm \frac{1}{2} |\pm\rangle \quad \text{and} \quad \sigma^\pm |\mp\rangle = |\pm\rangle. \quad (9)$$

In this pseudospin representations H_{cf} can be written as:

$$\hat{H}_{cf} = \omega_0 \sum_i \sigma_i^z \quad (10)$$

where $\omega_0 = \omega_+ - \omega_- = 11.8$ meV is the energy of the first excited CF level.

By expanding the components of the total angular momentum $\mathbf{J}$ into the basical operators of the components of pseudospin, H_{s-f} can be written as

$$H_{s-f} = - \sum_{i,j} \{ I_{ij}^{zz} [A \cdot S_j^z + B \cdot \sigma_i^z S_j^z] + \frac{1}{2} I_{ij} [C \cdot (\sigma_i^- S_j^- + \sigma_i^+ S_j^+) + D \cdot (\sigma_i^+ S_j^- + \sigma_i^- S_j^+)] \}, \quad (11)$$

where the coefficient are

$$A = \frac{1}{2} \{ 6(a_{31}^{(6)})^2 + 2(a_{31}^{(2)})^2 + 5(a_{41}^{(5)})^2 + 3(a_{41}^{(3)})^2 + (a_{41}^{(1)})^2 \} \approx 1.05$$

$$B = 5(a_{41}^{(5)})^2 + 3(a_{41}^{(3)})^2 + (a_{41}^{(1)})^2 - 6(a_{31}^{(6)})^2 - 2(a_{31}^{(2)})^2 \approx -0.38$$

$$C = a_{31}^{(6)}a_{41}^{(5)}\sqrt{12} + a_{31}^{(2)}a_{41}^{(1)}\sqrt{40} \approx 2.44$$

$$D = 6a_{41}^{(3)}a_{31}^{(2)} \approx 1.69$$

Keeping only the resonance terms, H_{s-f} becomes

$$\hat{H}_{s-f} = -\frac{1}{2} \sum_{i,j} \tilde{I}_{ij} (\sigma_i^- S_j^+ + \sigma_i^+ S_j^-), \quad (12)$$

where $\tilde{I}_{ij} = I_{ij}D$ and $I_{ij}^{xx} \approx I_{ij}^{yy} = I_{ij}$.

The differential cross section (4) in terms of the pseudospin operators can be written as:

$$\left(\frac{d^2 \sigma^i}{d\Omega d\omega} \right)_\perp \propto \frac{e^{\beta\omega_0}}{1 - e^{\beta\omega_0}} \frac{1}{\pi} \text{Im} \langle \sigma_i^- | \sigma_i^+ \rangle_{\omega_0 + i\epsilon}. \quad (13)$$

Using the technique of differentiating with respect to two times, t and t' , in the equation-of-motion method for the two-time GF $\langle \langle \sigma_i^-(t), \sigma_i^+(t') \rangle \rangle$, we find:

$$(\omega - \omega_0)^2 \langle \langle \sigma_i^- | \sigma_i^+ \rangle \rangle_\omega = -2\langle \sigma^z \rangle (\omega - \omega_0) + \sum_{j,j'} \tilde{I}_{ij} \langle \langle \sigma_i^z S_j^- | \sigma_i^z S_{j'}^+ \rangle \rangle_\omega \tilde{I}_{ij'}. \quad (14)$$

Since the s - f coupling is very weak, we consider only the second order terms which are allowing for by the decoupling:

$$\langle \sigma_i^z(t) S_j^-(t) \sigma_i^z S_{j'}^+ \rangle \simeq \langle \sigma_i^z(t) \sigma_i^z \rangle \langle S_j^-(t) S_{j'}^+ \rangle \simeq \frac{1}{4} \langle S_j^-(t) S_{j'}^+ \rangle. \quad (15)$$

In this approximation we neglect the longitudinal relaxation :

$$\langle \sigma_i^z(t) \sigma_i^z \rangle \simeq \langle \sigma_i^z \sigma_i^z \rangle = \frac{1}{4}. \quad (16)$$

It results in the following equation for the GF:

$$\langle \langle \sigma_i^- | \sigma_i^+ \rangle \rangle_\omega = -\frac{2\langle \sigma^z \rangle}{\omega - \omega_0 - \Sigma_i(\omega)/(-2\langle \sigma^z \rangle)}, \quad (17)$$

where in the self-energy operator

$$\Sigma_i(\omega) = \frac{1}{4} \sum_{j,j'} \tilde{I}_{ij} \langle \langle S_j^- | S_{j'}^+ \rangle \rangle_\omega \tilde{I}_{ij'}. \quad (18)$$

The summation runs over the j, j' copper sites in the neighbouring CuO_2 planes and

$$\langle \sigma^z \rangle \simeq -\frac{1}{2} \text{th} \left(\frac{\omega_0}{2kT} \right). \quad (19)$$

The linewidth $\Gamma_{cf}(T)$ is determined by the imaginary part of the self-energy operator

$$\Gamma_{cf}(\omega_0) = \coth\left(\frac{\omega_0}{2kT}\right) \text{Im}\{\Sigma_i(\omega_0 + i\varepsilon)\}. \quad (20)$$

Translational invariance allows the spatial Fourier transformation:

$$\langle\langle S_j^- | S_{j'}^+ \rangle\rangle_\omega = \frac{1}{N} \sum_{\mathbf{q}} e^{i\mathbf{q}(\mathbf{R}_j - \mathbf{R}_{j'})} \langle\langle S^- | S^+ \rangle\rangle_{\mathbf{q}, \omega}. \quad (21)$$

and (19) becomes:

$$\Gamma_{cf}(\omega_0) \propto \coth\left(\frac{\omega_0}{2kT}\right) \sum_{\mathbf{q}} |F(\mathbf{q})|^2 \text{Im}\{\chi^{-+}(\mathbf{q}, \omega_0 + i\varepsilon)\}, \quad (22)$$

where the imaginary part of the dynamical spin susceptibility in the CuO_2 planes is given by :

$$\text{Im}\chi^{-+}(\mathbf{q}, \omega_0) \equiv -\text{Im}\langle\langle S^- | S^+ \rangle\rangle_{\mathbf{q}, \omega_0} \equiv \chi''_{-+}(\mathbf{q}, \omega_0), \quad (23)$$

and

$$F(\mathbf{q}) = 8 \cos\left(\frac{aq_x}{2}\right) \cos\left(\frac{bq_y}{2}\right) \cos\left(\frac{cq_z}{6}\right) \quad (24)$$

is the form factor reflecting the local symmetry of the Tm^{3+} ion in the $\text{TmBa}_2\text{Cu}_3\text{O}_7$ unit cell with the lattice constants a, b and c (Fig. 1).

4 Numerical Results and Discussion

At the present time, there is no well justified model for spin susceptibility in the CuO_2 planes. Therefore we have used some experimental data and a theoretical model for $\chi''(\mathbf{q}, \omega)$ in our numerical calculations to compare them with the results of the experiment [3] on $\Gamma_{cf}(T)$ in an effort to elucidate spin dynamics in the CuO_2 planes.

4.1 Millis–Monien–Pines (MMP) model

Let us consider first the phenomenological model of AF Fermi liquid proposed by Millis, Monien and Pines [4], where the dynamical spin susceptibility $\chi^{+-}(\mathbf{q}, \omega)$ is given by the formula:

$$\chi_{AF}(\mathbf{q}, \omega) = \frac{\chi Q}{1 + \xi^2(\mathbf{Q} - \mathbf{q})^2 + i\left(\frac{\omega}{\omega_{SF}}\right)}, \quad (25)$$

where χ_Q is the static spin susceptibility at the AF wave vector $\mathbf{Q} = (\pi/a, \pi/a)$. $\xi(T)$ is the temperature dependent AF correlation length, and $\hbar\omega_{SF}$ is a typical energy scale for the AF spin dynamics.

Though the MMP model was introduced to describe the nuclear magnetic resonance (NMR) experiments in the region of a very low frequency of order of μeV , we suggest that it can be used also in the range of $\hbar\omega \simeq 12$ meV.

Using the same transformation of the variables in the corresponding integrals like in Appendix C of Ref. [4], we find:

$$\Gamma_{cf}(\omega_0) \propto \coth\left(\frac{\omega_0}{2kT}\right) \frac{\chi_0(T)}{\Gamma(T)} (2\dot{I}_1 - \dot{I}_3), \quad (26)$$

where

$$\begin{aligned} \dot{I}_1 &= 4 \int_0^{1/2} dx \int_0^{1/2} dy \frac{1 - \cos(2\pi x)}{\{x^2 + y^2 + \eta^2\}^2 + (\frac{\omega}{\omega_{SF}})^2}, \\ \dot{I}_3 &= 8 \int_0^{1/2} du \int_0^{(1/2)-u} dv \frac{1 - \cos(4\pi u)}{\{2u^2 + 2v^2 + \eta^2\}^2 + (\frac{\omega}{\omega_{SF}})^2}, \end{aligned} \quad (27)$$

where $\eta = \frac{1}{2\pi} \left(\frac{a}{\xi}\right)$, $\chi_Q = \frac{\sqrt{\beta}\chi_0}{4\pi^2\eta^2}$, $\beta \approx \pi^2$ and $\omega_{SF} = \frac{4\pi\Gamma}{\beta^{1/2}}\eta^2$, where $\chi_0(T)$ is the strong temperature dependent static spin susceptibility at $q = 0$, and $\hbar\Gamma(T)$ is a weakly temperature dependent spin-fluctuation energy of the electronic system.

As the value of the $(2\dot{I}_1 - \dot{I}_3)$ changes only by 5% and the value of the $\hbar\Gamma(T)$ by 7% in the considered temperature range $75 < T < 170K$, in this approximation the main contribution to the temperature dependence of $\Gamma_{cf}(\omega_0)$ comes from $\chi_0(T)$. The latter one can be extracted from the temperature dependent spin part of the Knight shifts $^{\alpha}K_S(T)$, $\alpha = (63, 89, 17)$. Using the result of $\chi_0(T)$ from Ref. [4] and experimental result of Knight shift $-\Delta K(T)$ from Ref. [7], in this approximation, we get theoretical curves (short and large dashed line, respectively, in the Fig.3), which are not consistent with experimental results [3] for linewidth $\Gamma_{CF}(T)$.

By considering another model for dynamical spin susceptibility the authors of Ref. [10] have concluded that the temperature dependence of the linewidth $\Gamma_{CF}(T)$ is determined by the temperature dependence of the uniform static susceptibility $\chi_0(T)$. But this assumption has not permitted them to obtain a good agreement between their theoretical curve and experimental data [3].

4.2 Models for $\chi(\mathbf{q}, \omega)$ based on experimental studies

According to the experimental results obtained by Rossat-Mignod et al. [5], [17], magnetic scattering in metallic phase of YBCO -system remains concentrated around the AF-rod, and there is no sign of any incommensurability. The spin excitation spectrum is isotropic in the metallic state ($\chi^{zz} = \chi^{xx}$) and the dynamical structure factor can be written as:

$$S(\mathbf{Q}, \omega) = \frac{2}{\pi} \frac{1}{1 - e^{-\hbar\omega/(kT)}} \text{Im}\chi(\mathbf{Q}, \hbar\omega). \quad (28)$$

By assuming that the line shape of magnetic intensity is of the Gaussian-type and using the value of the full width at half maximum (FWHM) i.e. "q-width" $\Delta q = 0.27$ in $2\pi\sqrt{2}/a$ units [5] in $\text{YBa}_2\text{Cu}_3\text{O}_{6.92}$ at $T = 150\text{K}$ at the energy $\hbar\omega = 10\text{meV}$, we can estimate a contribution to the line-width from AF spin fluctuations by the ratio:

$$\gamma = \frac{\int d^2q |F(\mathbf{q})|^2 \chi''(\mathbf{Q}, \omega)}{\int d^2q |F(\mathbf{q})|^2 \int d^2q \chi''(\mathbf{Q}, \omega)} \simeq 0.16 \quad (29)$$

where the $\mathbf{q}$ -integration is done over the first B.Z. Since the spin susceptibility at $\mathbf{q} = \mathbf{Q}$ is much larger than at $q = 0$ (e.g. in the MMP model $\chi''(\mathbf{Q}, \omega)/\chi''(0, \omega) \simeq \beta(\xi/a)^4 \simeq 300$), we propose that the main contribution to the linewidth arises from the AF spin fluctuations, estimated by (29).

Berthier et al. [6] have recently measured the temperature dependence of the NMR relaxation rates

$$({}^\alpha T_1 T)^{-1} \propto \sum_{\mathbf{q}} |{}^\alpha A(\mathbf{q})|^2 \frac{\chi''(\mathbf{q}, \omega_n)}{\omega_n} \quad (30)$$

in $\text{YBa}_{1.93}\text{Sr}_{0.07}\text{Cu}_3\text{O}_{6.92}$ where ω_n is the NMR frequency and $|{}^\alpha A(\mathbf{q})|^2$ is squared modulus of the Fourier-transferred hyperfine coupling constants for different nuclear sites $\alpha = (63, 17, 89)$. This dependence for ${}^{63}\text{Cu}$ can be approximated with good accuracy for $T > 75\text{K}$ by:

$$({}^{63}T_1 T)^{-1} \simeq a(T - 75)^b \exp[c(T - 75)], \quad (31)$$

where the parameters have the values $a \simeq 0.08 \text{ s}^{-1} \cdot \text{K}^{-b-1}$, $b \simeq 1.27$, $c \simeq -0.02 \text{ K}^{-1}$.

According to Horvatić et al. [6], the temperature dependence of $({}^{63}T_1 T)^{-1}$ and $\chi''(Q_{AF}, \hbar\omega \simeq 10 \text{ meV})$ are quite similar in the considered temperature range. Therefore we can assume that the temperature dependence of the sum over $\mathbf{q}$ in (22) due to our estimation (29) corresponds to (31), i.e.

$$\sum_{\mathbf{q}} |F(\mathbf{q})| \chi''(\mathbf{q}, \omega) \propto ({}^{63}T_1 T)^{-1}. \quad (32)$$

Fig. 1.
Positions of ions in $\text{CuO}_2\text{-Tm-CuO}_2$ bilayer.

Fig. 2.
Temperature dependence of the linewidth for CF excitation $\Gamma_3^{(1)} \rightarrow \Gamma_4^{(1)}$ ($\varepsilon = 11.8 \text{ meV}$) of the Tm^{3+} ion in $\text{Tm-YBCO}_{6.9}$: points – experimental data [3], curves – theoretical results for some models of $\chi(\mathbf{q}, \omega)$ (see text).

Fig. 3.
 Comparison of theoretical results for $\Gamma_{CF}(T)$: based on MMP model [4] with different $\chi_0(T)$ (large [4] and short dashed line [7]), and experiments for NMR relaxation rate $1/(T_1T)$ for ^{63}Cu [6] (full line).

By introducing a constant component Γ_0 of linewidth which is not caused by dynamic spin fluctuations, we find the following expression for the linewidth:

$$\Gamma_{cf}(T) = \Gamma_0 + A \coth\left(\frac{\omega_0}{2kT}\right) ({}^{63}\text{T}_1 T)^{-1}. \quad (33)$$

The best agreement with the experimental data [3] can be obtained for the parameter values $\Gamma_0 = 0.189 \pm 0.008$ meV and $A = 0.019 \pm 0.002$ a.u.

In Fig.2 the full line represents our theoretical results (33) for temperature dependence of the linewidth $\Gamma_{cf}(T)$. If we adopt that $\sum_{\mathbf{q}} |F(\mathbf{q})|^2 \chi''(\mathbf{q}, \omega) \propto {}^{89}\text{T}_1 T)^{-1}$ we get the result which is represented by long-dashed line. For the temperature independent $\chi''(\mathbf{q}, \omega)$ one can get the result represented by the short-dashed line. Experimental data [3] are shown by points (different symbols means different energy of incident neutrons). One can see that only the full line is in agreement with experimental data.

Fig. 3 compares our theoretical results for $\Gamma_{CF}(T)$ by using the experimental model of $\chi(\mathbf{q}, \omega)$ (full line – the same as in Fig.2) and by using the MMP model (dashed lines – see above given discussion).

From our analysis one can conclude that dynamic spin fluctuations in CuO_2 dominate the line broadening. Excited f -electrons can relax through the s - f interaction with the Cu- spin system. Opening of a pseudo-gap E_g in the spectrum of spin excitations observed in neutron experiments [5], [17] results in a reduction of the low-energy spin fluctuations and corresponding sharp decrease in the linewidth for CF excitation with energy $\hbar\omega_0 < E_g$ at the temperature of the onset of the gap. If the energy of CF $\hbar\omega_0 > E_g$, there is no sharp decrease in the linewidth that permits one, in principle, to measure the value of E_g by using compounds with different RE doped ions.

5 Conclusions

In the present paper we have proposed a model describing the relaxation of CF excitations for $4f$ -electrons in cuprates due to spin fluctuations on Cu-sites. A general expression (22) for Tm^{3+} in (Y-Tm)BCO-compound has been derived and estimations for $\Gamma_{CF}(T)$ has been done for some models of dynamical spin susceptibility $\chi(\mathbf{q}, \omega)$.

We cannot explain a sharp decrease of $\Gamma_{cf}(T)$ observed experimentally for Y-Tm $\text{Ba}_2\text{Cu}_3\text{O}_{6.9}$ [3] by employing the MMP-model [4] for $\chi(\mathbf{q}, \omega)$ as well as considering the temperature-dependent NMR relaxation rate $1/(T_1 T)$ for ${}^{89}\text{Y}$ [6]. To fit the experimental data [3] one has to adopt that AF spin fluctuations measured by inelastic neutron scattering [5] at $\hbar\omega_0 \simeq 10\text{meV}$ [9] or by NMR relaxation rate $1/(T_1 T)$ for ${}^{63}\text{Cu}$ [6] give an essential contribution to $\Gamma_{cf}(T)$, as justified by our estimation (29). Unfortunately, we cannot

present at this time a full self-consistent calculation for the linewidth $\Gamma_{cf}(T)$ (22) , since now there is no reliable theory of the dynamical spin susceptibility in strongly correlated electronic systems which cuprates belongs to .

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Спин-флуктуационная ширина уровней $4f$ -электронов
в кристаллическом электрическом поле в купратах

Вычислена ширина линии $\Gamma_{cf}(T)$ возбуждений $4f$ -электронов в кристаллическом поле в Tm-YBCO соединениях, обусловленная $s-f$ взаимодействием. Расчеты проведены для двухуровневой модели методом двухвременных функций Грина. Показано, что антиферромагнитные флуктуации в CuO_2 плоскостях важны для объяснения температурной зависимости Γ_{cf} .

Работа выполнена в Лаборатории теоретической физики им. Н.Н. Боголюбова ОИЯИ.

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Kovačević Ž., Plakida N.M.

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Spin-Fluctuation Linewidth of the $4f$ -Electron Crystal Field
Levels in Cuprates

The crystal field excitation linewidth $\Gamma_{cf}(T)$ in Tm-YBCO system is calculated due to $s-f$ interactions. The method of two-time Green function was used in the two-level approximation for crystal field excitations. It is shown that the antiferromagnetic fluctuations in CuO_2 planes are important to explain the temperature dependence of Γ_{cf} .

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR.

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