Effect of magnetic fluctuations on the normal state properties of Sr$_2$RuO$_4$

Canio Noce, Gaetano Busiello, and Mario Cuoco
I.N.F.M. - Unità di Salerno
Dipartimento di Scienze Fisiche "E.R. Caianiello",
Università di Salerno
I-84081 Baronissi (Salerno), ITALY

We investigate the normal state transport properties of Sr$_2$RuO$_4$ and we show that a consistent explanation of the experimental results can be obtained assuming that the system is near a quantum phase transition. Within the framework of a self-consistent spin fluctuation theory, we calculate the temperature variation of some relevant physical quantities and we discuss a possible microscopic origin of the quantum phase transition.

Since the discovery of superconductivity in the layered perovskite oxide Sr$_2$RuO$_4$ much attention has been paid to the electronic, magnetic and superconducting properties of this compound. In its stoichiometric composition Sr$_2$RuO$_4$ is metallic, shows a Fermi liquid behavior below a certain temperature, undergoes to a superconducting transition at the rather low transition temperature of ~1K.

Recent experiments lead to speculate that the electrons in the Cooper pairs would have aligned spins indicating a triplet superconductivity, and an odd orbital wavefunction as for example p-wave, in contrast with the spin-singlet pairing of conventional superconductors as well as of the high-$T_c$ copper oxides.

Its electronic properties are mainly determined by three bands crossing the Fermi level produced by antibonding Ru 4d (xy,yz,xz) and O 2p$_x$ orbitals.

It is found that the electrons belonging to the xy band play an important role determining the normal state properties. From $^{17}$O NMR in $^{17}$O isotope-enriched measurements, spin correlations in Ru d$_{xy}$ and d$_{xz,yz}$ orbitals are probed separately. They provide the evidence that only the spin susceptibility $\chi_{xy}$ from the electrons in the d$_{xy}$ orbital shows significant temperature dependence. $\chi_{xy}$ increases monotonically with decreasing temperature down to about 40K, turns over, and then tends to level below $T_{FL} \approx 25K$ in the canonical Fermi liquid state, implying that the spin correlations are predominantly ferromagnetic in origin, and orbital dependent. We point out that, below $T_{FL}$ the out-of-plane and in-plane resistivity have a quadratic temperature dependence indicating that a crossover to a Fermi-liquid state takes place below 25K prior to the superconducting transition. On the other hand, above $T_{FL}$ the in-plane resistivity shows a superlinear behaviour which may be related to scattering due to spin fluctuations. These experimental results indicate a clear connection to the crossover in the magnetic transport measurements.

The demonstration that spin correlations in the RuO$_2$ planes are predominantly ferromagnetically come also from measurements of nuclear spin-lattice relaxation rate. The hyperfine form factor for the $^{101}I/2T_1T$ at the Ru site is constant in the reciprocal space, while is proportional to $\cos(q_{x,y}/2)^2$ for $^{17}I/2T_1T$ at the planar oxygen O site. This means that the $^{101}I/2T_1T$ can probe both ferromagnetic and antiferromagnetic spin fluctuations. On the other hand, since the form factor for the planar O site is zero at the staggered wave vector $\mathbf{q} = \{ \pi, \pi \}$, antiferromagnetic spin fluctuations do not contribute to $^{17}I/2T_1T$. Hence, one can probe whether the spin correlations are ferromagnetic or antiferromagnetic by comparing the $^{101}I/2T_1T$ and $^{17}I/2T_1T$. It turns out that both $^{101}I/2T_1T$ and $^{17}I/2T_1T$ increase monotonically down to $T_{FL}$, and almost saturate in a Korringa-like behaviour.

Besides, inelastic neutron scattering measurements in the normal state reveal the existence of incommensurate magnetic spin fluctuations located at $\mathbf{q} = (\pm 0.4\pi/a, \pm 0.6\pi/a, 0)$ due to the pronounced nesting properties of the almost one-dimensional $d_{xz,yz}$ bands. In fact, the 1D sheets can be schematically described by parallel planes separated by $\hat{q} = \pm 2\pi/3a$, running both in the x and in the y directions which give rise to dynamical nesting effects at the wave vectors $\mathbf{k} = (q_x, \hat{q})$, $\mathbf{k} = (k_x, \hat{q}_y)$, and in particular at $\hat{q} = (\hat{q}, \hat{q})$.

Combining the results of NMR, nuclear spin-lattice relaxation rate, and inelastic neutron scattering measurements, it is possible to draw the following physical picture for the Sr$_2$RuO$_4$. There is a strong enhancement of ferromagnetic spin correlations above $T_{FL}$ mainly due to ferromagnetic correlations between the electrons in the $d_{xy}$ band as revealed from Knight shifts experiments. These contributions are in competition with incommensurate spin fluctuations due to the nesting properties of the almost 1D $d_{xz,yz}$ bands. Hence, the main features of the magnetic response turn out to be decoupled for the electrons in the $d_{xz}$ and in the $d_{xz,yz}$ bands, respectively.

The aim of this Letter is to propose an explanation of the non Fermi liquid behaviour observed in the $\chi_{xy}$ and in the $1/T_1T$ experiments of the Sr$_2$RuO$_4$ assuming that this compound is close to a 2D ferromagnetic quantum critical point. Then, we will discuss how it might be possible to drive the system from a magnetic to a non-magnetic state considering the interplay between the lowering of the crystal symmetry and the magnetic correlations. Let consider the effect of ferromagnetic fluctuations in the correlated $d_{xy}$ band considering the system as a 2D ferromagnet with vanishing critical temperature.
The starting point in our case is represented by the correlated dynamics in the RuO$_2$ planes of the $d_{xy}$ electrons, which we consider responsible for ferromagnetic fluctuations as suggested from NMR and nuclear spin-lattice relaxation rate.

In this case as in many others metallic systems at low temperatures [4], it has been observed the signature for a non-Fermi-liquid behavior near a quantum phase transition. The proximity to a quantum critical point is usually marked by enhancement in the effective mass, and in spin and charge response at low temperatures. This in turn introduces a low energy scale which marks a crossover from quantum to a classical behavior in the temperature dependence of various physical properties.

Now, to calculate some relevant physical properties, we consider the self-consistent spin fluctuation theory developed by Ramakrishnan et al [13] and many others [14] for the $d_{xy}$ band.

The main motivation for the use of spin-fluctuation theory is the largeness of the Stoner enhancement factor for the itinerant ferromagnets depending on the approximation. In the mean field theory of itinerant ferromagnets $\alpha_{MF}(T) = 1 - U \rho(\epsilon_F)$ and $\beta$ is constant, $\rho(\epsilon_F)$ being the density of states at the Fermi level. As the temperature dependence is weak, of the order of $(T/T_F)^2$, one cannot yield a Curie-Weiss form of the spin-susceptibility. Here $T_F$ is the Fermi temperature. This issue is overcome in the spin fluctuation theory where $\alpha(T)$ is given by [13,14]:

$$\alpha(T) = \alpha(0) + u(2D^T + 3D^L),$$

where $\alpha(0)$ is the susceptibility enhancement factor at $T = 0$, which includes the mean field part of Eq. [4] and the zero-temperature part of the fluctuation self-energy. Still, $D^T$ and $D^L$ are the transverse and longitudinal spin fluctuation amplitudes obtained by a diagrammatic expansion of the effective Hamiltonian, after integrating over the electronic degrees of freedom. The factor $u$ is a dimensionless short range fluctuation coupling constant [13]. In this framework, the susceptibility for the ferromagnetic case has the following form:

$$\chi(q,\omega) = \frac{\rho(\epsilon_F)}{\alpha(T) + \delta q^2 \frac{\alpha(T)}{\gamma q^2}},$$

where the parameters $\delta$ and $\gamma$ depend on the diagrammatic expansion.

It is found that there are two different regimes which for a 2D ferromagnet read as follows: when $\tau < \alpha(0)$, one has an enhanced Pauli susceptibility behaviour, while at higher temperatures, i.e. for $\alpha(0) < \tau < 1$, the susceptibility follows the classical Curie Weiss behavior. Here, $\tau = T/T_F$. Therefore, the quantity $\alpha(0)T_F$ plays the role of the low energy scale and naturally comes out from the fluctuation theory. The comparison between the experimental data from Imai et al [5] and the $xy$ spin susceptibility calculated within the above assumptions, is reported in Fig.4. As we can see, there is a good agreement between the experimental results and the theoretical prediction. It is worth stressing that using the experimental data for the spin magnetic susceptibility and the Fermi temperature, calculated using the Fermi wavevector and the effective mass reported by Mackenzie et al...
Hall coefficient and the magnetoresistance, respectively have been determined in a way to reproduce the in-plane transport properties are affected by spin-fluctuation theory is in progress. Furthermore, we expect that considering the multi-orbital system within the spin fluctuation, looking at the problem from a more general point of view.

One argument on why the ferromagnetic spin fluctuations play an important role in determining the transport properties of Sr$_2$RuO$_4$ is the following. The Rudmose-Popper series Sr$_{n+1}$Ru$_n$O$_{3n+1}$ contains multilayer compounds with $n$ as the number of RuO$_2$-planes per unit cell. In particular, there is a series of ferromagnetic compound related to Sr$_2$RuO$_4$: the infinite-layer (3D) SrRuO$_3$ is ferromagnetic with $T_c \approx$165K [14] for $n=3$ one finds $T_c \approx$148K [20] and for $n=2$ $T_c \approx$104K [21], although the ferromagnetism in this last case is still controversial. These values indicate the tendency that with decreasing the layer number $n$, $T_c$ is reduced and finally vanishes [22], since for $n=1$ the system is paramagnetic at all temperatures before becoming superconductor below $\sim 1K$.

Since $n$ is varying in a discrete way, it is meaningless to consider it as the direct parameter whose continuous change controls the transition from a paramagnetic to a ferromagnetic phase. On the other hand, it is possible to image stacks of multilayer Sr$_{n+1}$Ru$_n$O$_{3n+1}$ compounds with different $n$ so that the final system has an average number of planes which may be varied continuously. In this framework, the average number of RuO$_2$ planes can represent the parameter controlling a quantum phase transition. This kind of ideal system can in principle be realized by performing a molecular beam epitaxial growth.

An important point on the changes induced by $n$ is that when we move from the cubic SrRuO$_4$ compound to the tetragonal Sr$_2$RuO$_4$, the modification of the magnetic ground state is accompanied by the lowering of the lattice symmetry.

We know other examples within the metal transition oxides whose magnetic properties are strictly related to structural changes. These cases are mainly insulators systems where the Jahn-Teller effect cause structural phase transitions, and gives rise to orbital ordering and new magnetic structure.

In our situation, the removal of the degeneracy due to crystal field effects without Jahn-Teller distortions produces a subtle change in the magnetic properties. Due to the peculiar filling of the 4$d$ level in the SrRuO systems, we will show that the ground state switches from a paramagnetic to a ferromagnetic configuration depending on the way one lowers the lattice symmetry, i.e. by elongating or compressing the RuO$_6$ octaedra along the c-axis.

This effect might be experimentally fulfilled by applying an external uniaxial pressure and/or by means of sub-

\[ \rho_x(\mu \Omega \text{cm}) \]

\[ T(K) \]

FIG. 3. In plane resistivity vs temperature: the circles are the experimental results from [18] while the solid line is the theoretical curve.

\[ \alpha(0)T_F \]

we obtain for $\alpha(0)T_F$ the value $\sim 70K$ which gives the right order of magnitude for the temperature $T_{FL}$ of the crossover into a Fermi liquid state.

Within the same approach it is easy to obtain the temperature dependence of the nuclear spin-lattice relaxation rate.

One gets $(T/T_F)^{-1} \sim \alpha(T)^{3/2}$ [13]: for a normal Fermi-liquid $\alpha(T)$ is constant and gives the usual Korringa law, while for a 2D ferromagnet varies as $T^{-1}$.

Assuming the previous temperature dependence for $(T_1T)^{-1}$ for the xy electrons and a usual Korringa law for the other two bands, we obtain a fair fit, shown in Fig.2, to the experimental results of Imai et al [6] for temperatures larger than $T_{FL}$.

It is worth pointing out that though the contributions of the $d_{xz,yz}$ contain the effect of dynamical nesting, in the present calculation they have been added at a mean field level so that there is a weak temperature dependence of the order of $\sim (T/T_F)^2$ in the range examined. If we consider the correction due to spin fluctuations instead at $\mathbf{q} = 0$ around the nesting vector $\mathbf{q} = (q, \bar{q})$ we would expect a contribution to $(T_1T)^{-1}$ with a temperature dependence $\sim T^{-1}$. A more detailed analysis considering the multi-orbital system within the spin fluctuation theory is in progress. Furthermore, we expect that the transport properties are affected by spin-fluctuation above $T_{FL}$ and that this effect should manifest mainly in the in-plane quantities. Therefore, we have calculated the in-plane resistivity using the Boltzmann equation for a multi-band anisotropic electronic system assuming for the relaxation rates, two Fermi liquid ($\tau_f^{-1} \sim T^2$) behaviors and a two-dimensional ferromagnetic decaying time $\tau_f^{-1} \sim T$ as due to the scattering of the spin fluctuations with the electrons in the $d_{xy}$ band [13][16].

It is worth pointing out that the relaxation rates $\tau_f$ have been determined in a way to reproduce the in-plane Hall coefficient and the magnetoresistance, respectively [17]. The fit to the experimental data reported in Fig.4, where the experimental data are taken from [18], indicates that the assumption of linear temperature dependence in the decaying relaxation rate of the xy electrons is essentially correct.

Let consider now the origin of the ferromagnetic spin fluctuations looking at the problem from a more general point of view.

A more detailed analysis considering the multi-orbital system within the spin fluctuation, looking at the problem from a more general point of view.

One argument on why the ferromagnetic spin fluctuations play an important role in determining the transport properties of Sr$_2$RuO$_4$ is the following. The Rudmose-Popper series Sr$_{n+1}$Ru$_n$O$_{3n+1}$ contains multilayer compounds with $n$ as the number of RuO$_2$-planes per unit cell. In particular, there is a series of ferromagnetic compound related to Sr$_2$RuO$_4$: the infinite-layer (3D) SrRuO$_3$ is ferromagnetic with $T_c \approx$165K [14]: for $n=3$ one finds $T_c \approx$148K [20] and for $n=2$ $T_c \approx$104K [21], although the ferromagnetism in this last case is still controversial. These values indicate the tendency that with decreasing the layer number $n$, $T_c$ is reduced and finally vanishes [22], since for $n=1$ the system is paramagnetic at all temperatures before becoming superconductor below $\sim 1K$.

Since $n$ is varying in a discrete way, it is meaningless to consider it as the direct parameter whose continuous change controls the transition from a paramagnetic to a ferromagnetic phase. On the other hand, it is possible to image stacks of multilayer Sr$_{n+1}$Ru$_n$O$_{3n+1}$ compounds with different $n$ so that the final system has an average number of planes which may be varied continuously. In this framework, the average number of RuO$_2$ planes can represent the parameter controlling a quantum phase transition. This kind of ideal system can in principle be realized by performing a molecular beam epitaxial growth.

An important point on the changes induced by $n$ is that when we move from the cubic SrRuO$_4$ compound to the tetragonal Sr$_2$RuO$_4$, the modification of the magnetic ground state is accompanied by the lowering of the lattice symmetry.

We know other examples within the metal transition oxides whose magnetic properties are strictly related to structural changes. These cases are mainly insulators systems where the Jahn-Teller effect cause structural phase transitions, and gives rise to orbital ordering and new magnetic structure.

In our situation, the removal of the degeneracy due to crystal field effects without Jahn-Teller distortions produces a subtle change in the magnetic properties. Due to the peculiar filling of the 4$d$ level in the SrRuO systems, we will show that the ground state switches from a paramagnetic to a ferromagnetic configuration depending on the way one lowers the lattice symmetry, i.e. by elongating or compressing the RuO$_6$ octaedra along the c-axis.

This effect might be experimentally fulfilled by applying an external uniaxial pressure and/or by means of sub-
stitution of the Sr$^{+2}$ with a larger ion with the same valence. In this way, it might be possible to induce changes in the local crystal field driving the system from a magnetic state to a non-magnetic one or vice versa.

To have a quantitative insight on these considerations, we study the effect of the removal of the cubic symmetry for a $d^2$ system (two holes in the $t_{2g}$ orbitals).

The Hamiltonian is given by:

$$H = \sum_{i,\alpha} \epsilon_{i,\alpha} n_{i,\alpha} + (U + 2J_H) \sum_{i,\alpha} n_{i,\alpha\uparrow} n_{i,\alpha\downarrow} + (U - \frac{1}{2}J_H) \sum_{i,\alpha<\beta} n_{i,\alpha} n_{i,\beta} - 2J_H \sum_{i,\alpha<\beta} S_{i,\alpha} S_{i,\beta} + J_H \sum_{i,\alpha,\beta} d_{i,\alpha\uparrow}^\dagger d_{i,\beta\uparrow} d_{i,\beta\downarrow} d_{i,\alpha\downarrow} + \sum_{<i,j>\neq 0} t_\sigma (d_{i,\alpha,i\sigma}^\dagger d_{j,\alpha,j\sigma} + H.c.)$$

where the Hamiltonian contains intrasite terms, and the diagonal hopping between electrons in the different $t_{2g}$ orbitals.

The operator $d_{\alpha,i\sigma}$ destroys an electron with spin $\sigma$ in the orbital $\alpha$ on site $i$, $n_{i,\alpha\sigma}$ is the electron density with spin $\sigma$ on the orbital $\alpha$, and $S_{i,\alpha}$ is the spin of the electron in the $\alpha$ orbital on site $i$, respectively. Here, $\epsilon_{i,\alpha}$ denotes the on-site energy of the $\alpha$ $t_{2g}$ orbital on the site $i$, $U$ and $J_H$ stands for the Coulomb and Hund’s exchange interaction, respectively, and $t$ denotes the hopping amplitude.

The cubic-tetragonal symmetry crossover is controlled by means of the zero energy splitting $\Delta \equiv (\epsilon(d_{xy}) - \epsilon(d_{yz}))$ between the $d_{xy}$ and $d_{xz,yz}$ orbitals.

In particular, the variations of $\Delta$ describe the interplay between ionic and covalent effects induced by the oxygens surrounding the Ru ion and thus simulate the effect of compressing and/or elongating the RuO$_6$ octaedra along the c-axis.

The phase diagram is obtained considering two effective ruthenium atoms. The results of this numerical simulation are reported in Fig. 4 with $J_H/U$ vs $\Delta/t$.

For the cubic case, i.e. when $\Delta=0$, the ground state is ferrimagnetic (total spin is equal to one) in a very small region, above that it becomes ferromagnetic passing through a spin zero (paramagnetic) configuration. When the value of the exchange interaction $J_H$ is large enough, crystal field effects, associated with the elongation of the RuO$_6$ octaedra ($\Delta>0$), tend to stabilize ferromagnetic spin configurations.

Indeed, for positive $\Delta$, the $d_{xy}$ orbital is lower in energy than the others two degenerate $d_{xz,yz}$. Then, if the Coulomb repulsion is larger respect to $\Delta$ and the other parameters involved, one would occupy the first lower energy orbital and put the other hole in one of the two degenerate $d_{xz,yz}$. In this case there is a gain in the kinetic energy if the holes on the neighbour site have the same spin of the hole moving. We have a kind of dynamical double-exchange mechanism since the spin of the neighbour site is fluctuating in amplitude and phase, instead of having only phase fluctuation as happens in the manganite oxides. Still, strictly speaking, the exchange mechanism does not occur between localized spins.

On the other hand, the gain in kinetic energy due to the large $d-p$ hybridization, inverting the order of the molecular orbitals respect to the result of crystal field and/or the compression of the RuO$_6$ octaedra, would produce negative value for $\Delta$ and stabilize a paramagnetic configuration.

Indeed, for negative $\Delta$, the lowest energy configuration is realized by occupying with two holes the $d_{xz,yz}$ orbitals. In this case for large Coulomb repulsion we would have and effective Heisenberg antiferromagnetic Hamiltonian with a net exchange $J \sim 4t^2/U$ which sets the lowest spin configuration in the ground state.

These two limiting cases come in competition when $|\Delta|$ is small and of the order of $t$. In this case the gain in the kinetic energy allow to have configurations with non integer occupation number on each $t_{2g}$ orbital. This is the relevant situation which occurs in the ruthenium oxides either for the cubic and the tetragonal compound. Some comments on the limits of this cluster calculation are worthwhile. Within this two-sites problem one could not include any band effect which, for example, is relevant to understanding the dynamical nesting at incommensurate wave vector in the Sr$_2$RuO$_4$. Nevertheless, the present calculation yields useful insights on the interplay between the magnetic correlations and the orbital degrees of freedom in the complete series of the SrRuO compounds. We point out that the study of the electron dynamics in a
configuration have been attracted new interest also in other compounds like the V$_2$O$_3$, suggesting more detailed analysis in this direction.

In conclusion, in this paper we described the non-Fermi liquid behaviour observed in the normal state properties of Sr$_2$RuO$_4$. We have shown that, assuming that this compound lies very near to a quantum critical point, the temperature variation of various physical quantities is governed by spin fluctuations, whose effect is observed over a wide temperature range. A consistent explanation of the experimental results is obtained within this picture and assuming that only the electrons belonging to $d_{xy}$ band are involved in this mechanism. Moreover, we have given indication how to drive the system from a non-magnetic to a magnetic configuration both on the theoretical and experimental side which follows directly from the peculiar interplay between the lowering of the crystal symmetry, which involves the orbital degrees of freedom, and the spin correlations.

[1] Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita, J.G. Bednorz, and F. Lichtenberg, Nature 372, 532 (1994).
[2] A.P. Mackenzie, R.K. Haselwimmer, A.W. Tyler, G.G. Lonzarich, Y. Mori, S. Nishizaki, and Y. Maeno, Phys. Rev. Lett. 80, 161 (1998).
[3] G.M. Luke, Y. Fudamoto, K.M. Kojima, M.I. Larkin, J. Merrin, B. Nachumi, Y.J. Uemura, Y. Maeno, Z.Q. Mao, Y. Mori, H. Nakamura, and M. Sigrist, Nature 394, 558 (1998).
[4] K. Ishida, H. Mukuda, Y. Kitaoka, K. Asayama, Z.Q. Mao, Y. Mori, and Y. Maeno, Nature 396, 658 (1998).
[5] T. M. Riseman, P.G. Kealey, E. M. Forgan, A. P. Mackenzie, L. M. Garvin, A. W. Tyler, S. L. Lee, C. Ager, D. McK. Paul, C. M. Aegerter, R. Cubitt, Z. Q. Mao, T. Akima, and Y. Maeno, Nature 396, 242 (1998).
[6] A.P. Mackenzie, S.R. Julian, A.J. Diver, G.J. McMullan, M.P. Ray, G.G. Lonzarich, Y. Maeno, S. Nishizaki, and T. Fujita, Phys. Rev. Lett. 76 1996 3786; A.P. Mackenzie, S. Ikeda, Y. Maeno, T. Fujita, S. R. Julian, and G. G. Lonzarich, J. Phys. Soc. Japan 67, 385 (1998).
[7] T. Imai, A. W. Hunt, K. R. Thurber, and F. C. Chou, Phys. Rev. Lett. 81, 3006 (1998).
[8] H. Mukuda, K. Ishida, Y. Kitaoka, K. Asayama, Z. Q. Mao, Y. Mori, and Y. Maeno, J. Phys. Soc. Japan 67, 3945 (1998).
[9] K.R. Thurber, A. W. Hunt, T. Imai, F. C. Chou, and Y. S. Lee, Phys. Rev. Lett. 79, 171 (1997).
[10] Y. Sidis, M. Braden, P. Brouges, B. Hennion, S. NishiZaki, Y. Maeno, and Y. Mori, Phys. Rev. Lett. 83, 3320 (1999).
[11] I. I. Mazin and D.J. Singh, Phys. Rev. Lett. 82, 4324 (1999).
[12] C. Pfleiderer, G. J. McMullan, S. R. Julian, and G. G. Lonzarich, Phys. Rev. B 55, 8330 (1997); S. R. Julian, C. Pfleiderer, F. M. Grosche, N. D. Mathur, G. J. McMullan, A. J. Diver, I. R. Walker, and G. G. Lonzarich, J. Phys.: Condens. Matter 8, 9675 (1996).
[13] T. V. Ramakrishnan, Solid State Commun. 14, 449 (1974); T. V. Ramakrishnan, Phys. Rev. B 10, 4014 (1974); S. G. Mishra and T. V. Ramakrishnan, Phys. Rev. B 10, 4014 (1985).
[14] See for example: T. Moriya, Spin Fluctuations in Itinerant Electron Magnetism (Springer Verlag, Heidelberg) 1985.
[15] M. Ziman, Electrons and Phonons (Oxford University Press, London) 1960.
[16] J. Mathon, Proc. R. Soc. London, Ser. A 306, 355 (1968).
[17] C. Noce and M. Cuoco, to appear on Physica B (2000).
[18] N.E. Hussey, A.P. Mackenzie, J.R. Cooper, Y. Maeno, S. Nishizaki, and T. Fujita, Phys. Rev. B 57, 5505 (1998).
[19] T. C. Gibb, J. Solid State Chem. 11, 17 (1974).
[20] G. Cao, S. K. McCall, J. E. Crow, and R. P. Guertin, Phys. Rev. B 56, 5740 (1997).
[21] G. Cao, S. K. McCall, and J. E. Crow, Phys. Rev. B 55, 672 (1992); S. Ikeda, Y. Maeno, and T. Fujita, Phys. Rev. B 57, 978 (1998).
[22] M. Sigrist, D. Agerberg, A. Furasaki, C. Honerkamp, K. K. Ng, T. M. Rice, and M. E. Zhitomirsky, Physica C 317-318, 134 (1999).
[23] K.I. Kugel and D.I. Khomskii, Sov. Phys. Usp. 25, 231 (1982).
[24] C. Noce and M. Cuoco, Phys. Rev. B 59, 1189 (1999).