TO THE THEORY OF MAGNETIC PROPERTIES OF HIGH – TEMPERATURE SUPERCONDUCTORS

M.B. GUSEYNOV, A.M. SULEYMANOV, K.M. SULTANOV, V.S. TAGIEV

Institute of Physics of Academy of Sciences of Azerbaijan

370143, Baku, JH.Javid av., 33

Magnetic properties and energetic spectrum of high – temperature superconductors (HTSC) with structure La2CuO4 are considered. The value of critic field strength is obtained.

A number of high-temperature superconductors (HTSC) are magnet-ordered crystals [1-13]. Magnetic properties of such crystals can play an important role pairing mechanism [2,4-8]. Therefore investigations of HTSC properties are of certain interest. Antiferromagnetic HTSC with La_2CuO_4 structure are subject of our invert. La_2CuO_4 is the ancestor of metal-oxide HTSC series and quasi-two-dimensional four-sublattice antiferromagnetic.

A number of papers are dedicated to theoretical investigation of given problem (1-3, 9-12). In (1-3, 9) there have been considered homogenous case ($\vec{k}$ =0, k= wave vector). In (9-12) case $\vec{k}\neq 0$ is treated but dispersion of magnon spectrum is treated in the absence of external magnetic field. In (11) La_2CuO_4 is given as two-sublattice system but such model can't adequately describe the pattern of magnetic properties of four- sublattice system as La_2CuO_4.

This paper deals with energy spectrum, thermodynamic and high-frequency properties of antiferromagnetic HTSC with La_2CuO_4 structure by method of Green function at ($\vec{k}\neq 0$ and $H\neq 0$ (H- external constant magnetic field). Quantum-mechanical Hamiltonian of system in question is chosen as:

$$H_I = J_I\sum_{m,m'}\left[\mu_I\left(S_{mx}S_{m'x}+S_{my}S_{m'y}\right)+S_{mz}S_{m'z}\right]+ \\ +J_2\sum_{mlr}\left[\eta_2\left(S_{mx}S_{rx}+S_{my}S_{ry}\right)+S_{mz}S_{rz}\right]-d\sum_{mlm'}\left(S_{my}S_{m'z}-S_{mz}S_{m'y}\right)-H\sum_r S_{ry} \tag{1}$$

where J_I>0 and J_2 – parameters of exchange interaction inside and between the layers, respectively ($J_I >> |J_2|$ due to La_2CuO_4 has quasi-two-dimensional magnetic structure as it is mentioned) d – Dzyaloshinsky parameter giving rise deviation of spins from layer plain on angle θ, S – spin operator; η_1, η_2 are characterized anisotropy of exchange parameters ($0\le\eta_1, \eta_2\le 1$), H-external constant magnetic field in units of $g\mu_b$ (g-factor Lande, μ_b-Bors magneton), indexes m, m' refer to one layer, and indexes m, r- to different layers. As it shown from figure, $(m, m')\equiv(1,2), (3,4)$; $(m,r)\equiv(1,3), (1,4), (2,3), (2,4)$. For spin pairs (1,3) and (2,4)- J_2>0, but for spin pairs (1,4) and (2,3) J_2<0.

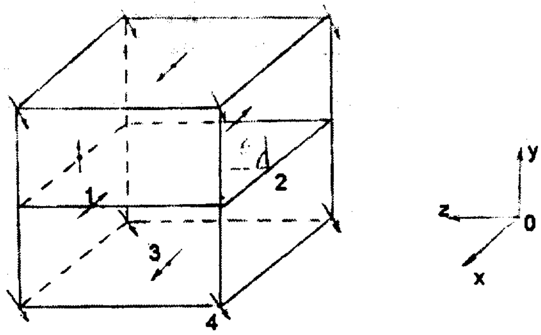

Fig. Magnetic structure of the crystal La_2CO_4

In intrinsic coordinate system of sublattices (15), gamiltonian (1), expressed as bose – operators appears as:

$$H=\sum_{n=0}^{n}H_n \tag{2}$$

where H_n- value of n – order with respect to bose – operators. According to requirements of main state H_I=0, terues H_3 and H_4 play a role in kinetics and we don't consider them here.

H_0- Hamiltonian of main state and such that $\sigma H_0/\sigma\theta$ = 0 for equilibrium value of angle θ we have:

$$tg\theta=\frac{d}{J_I(1+\eta_I)+2J_2} \tag{3}$$

It is shown from (3) – that θ=0 at d=0 and magnetic field H don't appear in this expression. So at $H||y$ magnetic field does not influence on main state. Frequencies of spin waves appears as:

$$\omega_{1,2}(k)=\left\{(\Gamma+2\beta_I)(\Gamma-2\alpha_I)+h^2\pm 2\sqrt{h^2(\Gamma-\alpha_I+\beta_I)^2+4\alpha_2^2\left[(\Gamma+2\beta_I)^2-h^2\right]}\right\}^{\frac{1}{2}} \tag{4}$$

$$\omega_{3,4}(k)=\left\{(\Gamma+2\alpha_1)(\Gamma-2\beta_1)+h^2\pm2\sqrt{h^2(\Gamma+\alpha_1+\beta_1)^2+\beta_2^2\left[(\Gamma+2\alpha_1)^2-h^2\right]}\right\}^{\frac{1}{2}} \tag{5}$$

where $\alpha_i=\beta_i\cos^2\theta$ $(i=1,2)$,

$$\Gamma=\frac{1}{2}(J_1+J_2)\cos^2\theta+d\sin\theta\cos\theta;$$

$$\beta_I=\frac{1}{4}\eta_i J_i\ (I=1,2)$$

It's easy to check that ω_1, ω_3 are the optical branches, but ω_2, ω_4 – acoustic branches.

In [12], where case $H=0$ is considered, it was established, that:

(1) – at $J_2=0$, $d\neq0$ $\omega_1=\omega_2$, $\omega_3=\omega_4$ takes place
(2) – at $J_2\neq0$, $d=0$ $\omega_1=\omega_3$, $\omega_2=\omega_4$ takes place
(3) –at $J_2=d=0$ $\omega_1=\omega_2=\omega_3=\omega_4$ takes place

As it is shown, in cases (1) and (2) there have been taken place two–fold degeneracy, but in case (3) – four-fold degeneracy. But in case we consider, only in one case exactly at $J_2=d=0$ we have degeneration: $\omega_1=\omega_3$, $\omega_2=\omega_4$. This result coincides in case (2) at $H=0$.

At $\theta\to0$ one can assume in future calculation $\alpha_1=\beta_1$, $\alpha_2=\beta_2$.

Then $\omega_1=\omega_3$, $\omega_2=\omega_4$

For magnetization of sublattice we have

$$<S^z>=\frac{1}{2}-\varphi(0)-\varphi(T) \tag{6}$$

In (6)

$$\varphi(0)=\frac{1}{2N}\sum_{\bar{k}}\left[-1+\frac{\Gamma}{\omega_1+\omega_2}+\frac{\Gamma(\Gamma^2-4\alpha_1^2)-8\alpha_2^2(\Gamma+2\alpha_1)}{\omega_1\omega_2(\omega_1+\omega_2)}\right] \tag{7}$$

describes magnetization deviation from saturation at $T=0$ at the expense of zero oscillations in system (quantum spin reduction), and

$$\varphi(T)=\frac{1}{2N}\sum_{\bar{k}}\left\{\frac{1}{\omega_1^2-\omega_2^2}\left[\frac{\omega_1^3+\omega_1^2-\mu_1\omega_1-\mu_2}{\omega_1}f(\omega_1)-\frac{\omega_2^3+\Gamma\omega_2^2-\mu_1\omega_2-\mu_2}{\omega_2}f(\omega_2)\right]\right\} \tag{8}$$

magnetization deviation at the expense of thermal oscillations of spin (magnons) at $T\neq0$,

$$\mu_1=\Gamma^2-4\alpha_1^2;\ \mu_2=\Gamma(\Gamma^2-4\alpha_1^2)-8\alpha_2^2(\Gamma+2\alpha_1)$$

$$f(\omega)=\left[exp\left(\frac{\omega}{T}-1\right)\right]^{-1},\quad (k_B=1)$$

At low temperatures

$$<S^z>=\frac{1}{2}-\varphi(0)-\frac{\Gamma}{4\pi^2}\left[\frac{R_5^{3/2}-R_4^{3/2}}{(R_1R_4R_5)^{3/2}}\right]T^2 \tag{9}$$

if $(R_1R_3)^{1/2}<<T<<T_N$. At $T<<(R_1R_3)^{1/2}$ both branches give exponentially small corrections.

In (9)

$$R_1=J_1(0)\eta_1+J_2(0)\eta_2;\ R_4=[J_1(0)\eta_1-2J_2(0)\eta_2];\ R_5=\frac{1}{12}[J_1(0)\eta_1+2J_2(0)\eta_2]$$

In the neighborhood T_N $(T<T_N)$ at $H=0$

$$<S^z>=\sqrt{\frac{T_N}{F}\left(1-\frac{T}{T_N}\right)} \tag{10}$$

where $F=\frac{2}{N}\sum\frac{\Gamma+2\alpha_2}{6}$, but

$$T_N=\left\{\frac{2}{N}\sum_{\vec{k}}(\Gamma+\alpha_2)\left[\frac{1}{\omega_1^2}+\frac{1}{\omega_2^2}\right]\right\}^{-1}$$

Neel temperature. At $T_1\sim10^3$ K $\left(T\approx\frac{J_1}{K_Б}\right)$ we have $T_N\approx270$K.

Magnetic heat capacity, is defined in the following way:

$$C_m=\left(\frac{NV}{4\pi^2}\right)\frac{1}{T^2}\int_0^\infty\sum_{i=1}^{2}\frac{\omega_i^2e^{\omega_i/T}k^2dk}{\left(e^{\omega_i/T}-1\right)^2} \quad (11)$$

At low temperatures

$$C_m=\left(\frac{NV}{\pi^2}\right)\frac{1}{R_1^{3/2}}\left(\frac{1}{R_4^{3/2}}+\frac{1}{R_5^{3/2}}\right)T^3 \quad (12)$$

if $(R_1R_3)^{1/2}<<T<<T_N$

$$C_m=\left(\frac{NV}{4\pi^2}\right)\left(\frac{\pi}{2}\right)^{1/2}\left[\frac{P_1^{7/2}}{\gamma_1}e^{-\frac{P_1}{T}}+\frac{P_2^{7/2}}{\gamma_2}e^{-\frac{P_2}{T}}\right]T^{-\frac{1}{2}}+3\left[\frac{P_1^{5/2}}{\gamma_1}e^{-\frac{P_1}{T}}+\frac{P_2^{5/2}}{\gamma_2}e^{-\frac{P_2}{T}}\right]T^{1/2}+$$
$$+\frac{15}{4}\left[\frac{P_1^{3/2}}{\gamma_1}e^{-\frac{P_1}{T}}+\frac{P_2^{3/2}}{\gamma_2}e^{-\frac{P_2}{T}}\right]T^{3/2} \quad (13)$$

if $T<<(R_1R_3)^{1/3}$. In (9), (12) and (13) $P_1=(R_1R_5-R_2d)^{3/2}$, $P_2=(dR_1)^{1/2}$, $\gamma_1=(R_1R_4-R_2R_3)^{3/2}$, $\gamma_2=(R_1R_5-R_2d)^{3/2}$.

The dependences (14) and (15) agree to the experimental data on heat capacity investigations [9].

Transversal (dynamical) magnet susceptibility is the following:

$$\chi_\perp\left(\vec{k},\omega\right)=-4\mu^2\frac{\omega^3+\Gamma\omega^2-\mu_1\omega-\mu_2}{\left(\omega_1^2-\omega^2\right)\left(\omega_2^2-\omega^2\right)} \quad (14)$$

(14) describes resonance behavior of system La_2CuO_4.

Having expanded ω in terms of k at low temperatures and integrating (14) we can show that $\chi_1\sim T$, which accords with the results of paper [9].

We note, that as the external magnetic field is increasing (at a certain value of this field). First the spins change from antiparallel state into the state of spin-flop phase and make an angle $\varphi\ (0<\varphi<2\pi)$ and then they come together. These values of the magnetic field are called critical and determined when the acoustic branch is ignored (in our case it is ω_2) at k=0.

So we have

$$h_{K1}=\sqrt{\left(\Gamma-2\alpha_1\right)^2-16\alpha_2^2} \quad (15)$$

is the critical field, corresponding to the change from the parallel state of spins into the spin-flop-phase and $h_{k2}=\Gamma+2\alpha_1$ – is the critical field, corresponding to the change from spin-flop-phase into the state of parallel spins.

Results

1. Unlike paper [11], where La_2CuO_4 is considered as two-sublattice system in the present paper La_2CO_4 is considered as four-sublattice anti ferromagnetic system, which is taken place.
2. It was established that if the external magnetic field is perpendicular to the direction S_7, it doesn't influence on the basic state.
3. Considering the external magnetic field results in taking off degeneracy in the energetic spectrum of spin excitations of anti ferromagnetic HTSC La_2CuO_4. Just in one case, particularly when $J_2<<J_1$, $J<<J_1$, the following degeneracy $\omega_2=\omega_3$, $\omega_2=\omega_4$ is true one. This result coincides with the case of the work [2] at H=0.
4. For the first time there have been obtained the expression for critical fields in anti ferromagnetic crystal La_2CuO_4.

[1] *A.S. Borovik – Romanov, A.I. Buzdin, N.M. Kreines, S.S. Krotov*. JETT Letters, 1988, 47, ext. 11 p.60
[2] *V.G. Baryakhtar, V.M. Loktev, D.A. Yablonskyi*. Preprint ITF-88 81P, ITF Ukrainian Acad of Sc., Kiev., 1988
[3] *S.S. Krotov, R.M. Farzeddinova*. SFHT, 1989, vol. 2 N-2, p.60
[4] *P.W. Anderson*. Science, 1987, v.235, N-4794, p. 1196
[5] *V.J. Emeru*. Phys. Rev. Lett., 1987, v. 59, N-26, p. 2794
[6] *T.E. Hirsch*. Phys. Rev. Lett., 1987, v. 59, N-2, p.228
[7] *V.I. Pokrovsky, G.V. Uimin, D.V. Khvetshenko*. JETT Letters, 1987, v.46, Appendix, p. 136
[8] *T.R. Schrieffer, X.G. Wen, S.C. Zhang*. Phys. Rev. Lett., 1988, v. 60, N-10, p. 944
[9] *V.G. Baryakhtar, V.M. Loktev, D.A. Yablonskyi*. SFHT, 1989 vol. 2 N-1, p.16
[10] *V.G. Baryakhtar, V.A. Lvov, V.M. Loktev, D.A. Yablonskyi*. SFHT, 1989 vol. 2 N-8, p.59

[11] *M. Takahashi.* J. Phys. Soc. Japan, 1989 vol. 58 N-5, p.1524

[12] *N.G. Guseynov, Kh.M. Pashayev, M.B. Guseynov*, Preprint, N-337, Institute of Physics Academy of Sc. of Azerbaijan Republic, Baku, 1989, p.11

[13] Comments. Cond. Mat. Phys., 1988, v. 14, N-2, p-65

[14] *E.A. Turov*. Physical properties of magneto-ordered crystals., M., Academy of Sciences of USSR, 1963, p..325

[15] *S.V. Tyablikov*. Metodi kvantovoy teori magnetizma. M., Nauka, 1975, p.527

M.B. Hüseynov, A.M. Süleymanov, K.M. Sultanov, V.C. Tağıyev

YÜKSƏK TEMPERATURLU İFRAT KEÇİRİCİLƏRİN MAQNİT XASSƏLƏRİNƏ DAİR

Yüksək temperaturlu antiferromaqnit ifrat keçiricilərin maqnit xassələri və enerji spektri təqdim edilmişdir. La_2CuO_4 tipli kristallara baxılmışdır. Kritik sahə gərginliyinin faza sərhəddinə uyğun olan qiymətləri alınmışdır.

М.Б. Гусейнов, А.М. Сулейманов, К.М. Султанов, В.С. Тагиев

К ТЕОРИИ МАГНИТНЫХ СВОЙСТВ ВЫСОКОТЕМПЕРАТУРНЫХ СВЕРХПРОВОДНИКОВ

Ряд ВТСП являются магнитоупорядоченными кристаллами. Объектами исследования данной работы являются антиферромагнитные ВТСП со структурой La_2CuO_4. Получен спектр возбуждения спиновых волн исследован в разных случаях магнитного поля. Получено значение критического поля, соответствующей фазовой границе.

Дата поступления: 08.08.2000 *Редактор: Ф. М Гашимзаде*