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STATIC MAGNETIC AND ELECTRON PARAMAGNETIC RESONANCE STUDIES OF HIGH TEMPERATURE SUPERCONDUCTORS AND RELATED COMPOUNDS

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Summary. The paper reviews possible applications of static magnetic and Electron Paramagnetic Resonance measurements in studies of high temperature superconductors and related compounds. Particular examples of these applications are given and discussed. It is shown that magnetic measurements reveal the existence of different magnetic phase transitions, whereas the EPR measurements yield unique information about the coupling of a variety of paramagnetic centers with their crystalline environment.

Key words: superconductors – static magnetic measurements – Electron Paramagnetic Resonance – transition ions – electric conductivity.

INTRODUCTION

Since the discovery of high temperature superconductivity (HTS) in ceramics [2, 18] great effort has been done to understand the origin of this phenomenon. A great deal has been learned about magnetic properties, crystal structure, phase composition and the electronic structure of magnetic ions being present in superconducting and related compounds. Many experimental techniques were applied (some of them are very much sophisticated) in order to get the information useful in the microscopic interpretation of the HTS.

In this paper we shall review some results of our experimental studies of magnetic properties of the compounds under discussion derived from static magnetic and EPR methods. We shall also try to interpret some mechanisms of conductivity. As deduced from the results of magnetic measurements...
we were able to discover many unusual phase transitions occurring in phases related to superconducting ones. The EPR measurements supplied important information about the electronic structure of different magnetic ions and their interactions with the surrounding.

The results described in the paper are reported in many of our previous publications and therefore it may be difficult, even for a specialist, to work out a general view about the conclusions resulting from them. This paper is intended to help a reader interested in superconductors to overcome these difficulties.

INFORMATION ABOUT EXPERIMENTAL METHODS

All ceramics studied by us were prepared by the standard solid state reaction technique. Appropriate amounts of Re$_2$O$_3$ (Re stands here for a rare-earth element), Cu and BaCo$_3$ were carefully mixed and pelleted. The pellets were then annealed in flowing oxygen at the following four step reaction:

$$920^\circ C(20hs) \rightarrow 925^\circ C(20hs) \rightarrow 930^\circ C(30hs) \rightarrow 940^\circ C(20hs).$$

After this procedure the samples were powdered and recalcinated at $940^\circ C(12hs)$. In order to increase the content of oxygen the pulverized samples were kept in a hot furnace ($920^\circ C$) with flowing oxygen. When thermal equilibrium was reached the temperature was reduced to $450^\circ C(6hs)$ and then the samples were kept for other 6 hours at $400^\circ C$. In order to obtain the tetragonal phase, a part of the oxygenated powders was annealed at $650^\circ C(6hs)$ in flowing He and then cooled fast to room temperature in a reducing atmosphere.

The phase composition and structure characterization of the obtained samples were done using a Philips X-ray powder diffractometer with a Co - K$_\alpha$ cathode. An example of the X-ray diffraction pattern (NdBa$_2$Cu$_3$O$_{7-\delta}$) for superconducting (orthorhombic) and non-superconducting (tetragonal) phases is shown in Fig. 1 [5]. For this particular case the major phase in

![Fig. 1. X-ray diffraction pattern for orthorhombic (a) and tetragonal (b) phases of NdBa$_2$Cu$_3$O$_{7-\delta}$](image-url)
high temperature superconducting sample could be indexed on a base of an orthorhombic unit cell with the lattice constants: $a = 0.38661(5)\ \text{nm}$, $b = 0.391632(2)\ \text{nm}$ and $c = 1.17607(9)\ \text{nm}$.

The major phase in the non-superconducting sample could be indexed on a basis of a tetragonal phase with $a = b = 0.38915(4)\ \text{nm}$ and $c = 1.18390(10)\ \text{nm}$.

The magnetization measurements vs. temperature were carried out using a PAR 155 vibrating sample magnetometer in the temperature range from 4.2 K to 300 K. The applied magnetic field induction was usually 1 or $2 \times 10^{-2}$ T. The measurements were carried out both in zero-field-cooled (ZFC) and field-cooled (FC) modes.

The EPR measurements were done using a Varian E-4 X-band spectrometer working with a 100 kHz frequency modulation of the steady magnetic field. EPR spectra were taken in the first derivative mode. DPPH standard was used as a frequency marker and the magnetic field was scaled using a precision NMR magnetometer.

**STATIC MAGNETIC MEASUREMENTS**

For the samples in orthorhombic symmetry the magnetic measurements are usually performed in order to obtain quick information about the transition temperature to the superconducting state by the observation of the Meissner signal.

![Fig. 2. Temperature dependence of the magnetization for GdBa$_2$Cu$_3$O$_{7-\delta}$](image)

An example of the magnetization vs. temperature for such samples is given in Fig. 2 for a particular case of the GdBa$_2$Cu$_3$O$_{7-\delta}$ sample [6]. For this sample the $T_c$ outset was 83 K. From the FC line and the ratio $L = -4\pi M/H$ one can calculate the percentage of the superconducting phase estimated in this case to be about 13%. Such measurements are standard ones and therefore
need not be described here in detail. The results for the samples with tetragonal symmetry are much more interesting. This phase is non-superconducting and normally exhibits an antiferromagnetic ordering below $T_N$. However, Masuda et al. [15] reported that for LaBa$_2$Cu$_3$O$_{7-\delta}$ prepared in a reducing atmosphere one detects, at low temperatures, an anomalous behaviour of the inverse susceptibility vs. temperature. The origin of this behaviour was explained to be due to the existence of an impurity phase La$_4$Ba$_2$Cu$_2$O$_{10}$ (4:2:2 phase). However, we found [7] that for YbBa$_2$Cu$_3$O$_x$ similar anomalies are detected although the data derived from XRD and EPR measurements excluded the existence of the 4:2:2 phase.

![Fig. 3. The plot of the inverse magnetic susceptibility versus temperature for YbBa$_2$O$_3$O$_x$](image)

The plot of the reciprocal static magnetic susceptibility for YbBa$_2$Cu$_3$O$_x$ as a function of temperature is shown in Fig. 3. Three main regions can be distinguished from the plot. From high temperatures down to 60 K, $\chi^{-1}$ obeys the Curie-Weiss law. The line extrapolated from these data crosses the abcissa at a negative temperature $\Theta = -25$ K indicating the antiferromagnetism of the system. The effective number of Bohr magnetons determined from the slope is 3.85. In the region between 60 and 30 K a clear deviation of $\chi^{-1}$ from the linear run was detected. From 30 K down to 4.7 K one again detects a linear run of $\chi^{-1}$ but the line extrapolated crosses the abcissa at about 1 K which indicates a positive divergency of the magnetic susceptibility at a finite temperature. This would mean that below 1 K the substance exhibits an ordering of the ferromagnetic type. This suggestion was partially supported by the results obtained from EPR measurements of Cu$^{2+}$ ions. It proved that below 20 K one detects a gradual increase in the value of $g$. At 4.7 K this value reached as much as 2.205(3). At the same time when approaching the lowest
temperatures investigated from above we noticed a phenomenon of a substantial increase in the linewidth. All these facts can be interpreted within the framework of the fluctuation theory for magnetization (see e.g. [16]).

Other examples of possibly new magnetic phase transitions in tetragonal phases of ReBa$_2$Cu$_3$O$_{6+x}$ (where Re = Nd, Sm or Tm) were given in [3]. This paper gives clear evidence that for all investigated samples a pronounced change in the slope of $\chi^{-1}$ versus $T$ is observed. The plots exhibited a positive divergency which again indicated a ferromagnetic behaviour.

Interesting data about magnetic properties of EuBa$_{2-x}$Eu$_x$Cu$_3$O$_{7-\delta}$ in tetragonal phase are reported in [8]. The plot of the reciprocal statistic magnetic susceptibility for this compound is presented in Fig. 4.

![Fig. 4. The plot of the inverse magnetic susceptibility versus temperature for EuBa$_{2-x}$Eu$_x$Cu$_3$O$_{7-\delta}$](image)

As results from the Hund rules, the ground state of the 4f$^6$ configuration of Eu$^{3+}$ is $^7F_0$ implying that the magnetic moment $\mu$ should be zero. However, one measures the experimental value of $\mu$ equal to 3.4$\mu_B$. This behaviour can be very well interpreted taking into account the fact that the first excited state $^7F_1$ has the energy equal to only $\Delta/k_B = 350$ K above the ground state being thus quite considerably populated at higher temperatures [18]. For EuBa$_2$Cu$_3$O$_{7-\delta}$ a paramagnetic susceptibility was reported by Xiao et al. [19]. They could, indeed, explain their data based on the above-mentioned fact. Our magnetic susceptibility measurements indicate a Curie-Weiss behaviour above 200 K. The effective magnetic moment $\mu_{\text{eff}}$ obtained by least-square fitting is 4.10 $\mu_B$ per formula unit. This value is clearly different from that expected for Eu$^{3+}$ ions including contributions from thermally excited states. The discrepancy can, however, be explained assuming that a small fraction of Ba$^{2+}$ ions is substituted by Eu$^{2+}$ ones with $\mu_{\text{eff}} = 7.94 \mu_B$. This explanation was
also supported by the EPR data. From the contribution of Eu$^{2+}$ to the total magnetic susceptibility $x \simeq 0.07$ was estimated.

Below 200 K the plot deviates from the Curie-Weiss law and below 50 K one detects that there exists a strong decrease in $\chi^{-1}$ with the temperature decrease. The behaviour below 50 K may be explained by the crystal field effect.

**EPR MEASUREMENTS**

EPR measurements are mainly devoted to the investigations of two problems: the Josephson effect and the electronic structure and local symmetry of paramagnetic ions in HTS and related compounds [17]. Due to the intrinsic sensitivity of the method a great deal of important information enabling a better understanding of the nature of superconductivity can be derived. In this chapter we shall limit ourselves only to the discussion of chosen aspects of the EPR application in studies of HTS and related compounds paying particular attention to the electronic structure and local symmetry of paramagnetic ions involved.

Let us begin with a short discussion on the results obtained for Cu$^{2+}$ ions. Typical EPR spectra for these ions in orthorhombic and tetragonal phases are shown in Figs. 5—7 for the case of TmBa$_2$Cu$_3$O$_{7-\delta}$. The signal presented in Fig. 5 clearly results from Cu$^{2+}$ ions feeling the action of the crystal field of rhombic symmetry. The components of the $g$-tensor were estimated to be:

$$
g_x = 2.099 (5), \quad g_y = 2.029 (5) \quad \text{and} \quad g_z = 2.235 (5).$$

Below the transition temperature $T_c = 91$ K basically the same line was observed and slight changes detected (see Fig. 6) could be ascribed to the increased conductivity of the sample.

![Fig. 5. EPR spectrum of Cu$^{2+}$ for TmBa$_2$Cu$_3$O$_{7-\delta}$ in orthorhombic phase taken at room temperature](image_url)
Fig. 6. EPR spectrum of Cu\(^{2+}\) for TmBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) in orthorhombic phase taken at 77 K

Fig. 7. EPR spectrum of TmBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) in tetragonal phase

Similar pattern was seen for many other samples indicating that Cu\(^{2+}\) ions detected by EPR are not directly involved in superconductivity. Fig. 7 presents the EPR spectrum for the tetragonal phase of the compound. As seen from the figure the signal reflects an axial local symmetry. Thus, we may claim that although Cu\(^{2+}\) ions observed by EPR are not involved in superconductivity nonetheless the EPR spectra of these ions identify unequivocally the type of the sample i.e. they differentiate superconducting and non-superconducting samples.

Temperature dependences of the EPR spectra of Cu\(^{2+}\) ions supplied also additional information about the exchange interaction between these ions. As seen from Figs. 8 and 9 at low temperatures, typically below 25 K, one observes a relatively symmetrical line, the intensity of which increases strongly with the temperature decrease. It is suggested that this line may result from the pair interaction, involving oxygen bridges, of divalent
Fig. 8. Low temperature EPR signals due to exchange coupled pairs of Cu$^{2+}$ for Pr$_{0.5}$Dy$_{0.5}$Ba$_2$Cu$_3$O$_{7-\delta}$

Fig. 9. Low temperature EPR signals due to exchange coupled pairs of Cu$^{2+}$ for Gd$_{0.3}$DyBa$_2$Cu$_3$O$_{7-\delta}$

copper – copper ions. This interaction can be described by the following spin-Hamiltonian [1]:

$$\chi = g_1 \mu_B \vec{B} \cdot \vec{S}_1 + g_2 \mu_B \vec{B} \cdot \vec{S}_2 + J \vec{S}_1 \cdot \vec{S}_2,$$

(1)

where $J$ is the exchange integral and the rest of the symbols have their usual meaning.
If one assumes an isotropic exchange interaction then the energy $W$ of the triplet state is:

$$W = J/4 \pm 1/2(g_1 + g_2)\mu_B B$$  \hspace{1cm} (2)$$

and it is different from that corresponding to the singlet $S = 0$ state. For example, for the case of GdBa$_2$Cu$_3$O$_{7-\delta}$ a single EPR line (shown in Fig. 8) with the $g$-factor equal to $g = 1/2(g_1 + g_2) = 2.27$ was observed [9].

The value of $J$ can be estimated from the temperature dependence of the EPR line intensity. The intensity should increase with the temperature decrease due to the fact that the ground state becomes more populated as the temperature is lowered. The functional dependence of the EPR line intensity $I_s$ on temperature is given in [1]:

$$I_s = \frac{\exp \left[-\frac{1}{2}JS(S+1)/k_B T\right]}{\sum_s (2S+1) \exp \left[-\frac{1}{2}JS(S+1)/k_B T\right]}.$$  \hspace{1cm} (3)$$

Fitting the experimental data on the intensity changes with temperature, the value of $J = 5.0(5)$ cm$^{-1}$ was obtained for GdBa$_2$Cu$_3$O$_{7-\delta}$ [9] and $J \simeq 20$ to 30 cm$^{-1}$ for Gd$_{0.5}$Nd$_{0.5}$Ba$_2$Cu$_3$O$_{7-\delta}$ [10].

Apart from the EPR spectra corresponding to Cu$^{2+}$ ions one also detects the spectra of rare earth ions when they are the Kramers ones. The spectrum of Tm$^{2+}$ in TmBa$_2$Cu$_3$O$_{7-\delta}$ was reported in [11] and is presented in Fig. 7 (low field portion of the spectrum). The analysis of this signal, carried out in the theory of Lea et al. [14] leads to the conclusion that the signal is due to the $I_7$ doublet resulting from $4f^{13}(2F_{7/2})$ ground state split by a cubic crystalline field. The measured $g$ – factor could be explained assuming that the phenomenon of the reduction of the orbital moments is essential.

The EPR signal of Nd$^{3+}$ in NdBa$_2$Cu$_3$O$_{7-\delta}$ was reported in [12]. From the measured $g$-factors and the theory of Lea et al. it was deduced that the observed signal is due to the $I_{9/2}^{(2)}$ component of the ground state $4I_{9/2}$ split by a crystal field of a cubic symmetry. This doublet can be built from the $|\pm 1/2\rangle$, $|\pm 7/2\rangle$, and $|\pm 9/2\rangle$ wavefunctions as follows:

$$a_1|\pm 9/2\rangle + a_2|\pm 1/2\rangle + a_3|\pm 7/2\rangle$$  \hspace{1cm} (4)$$

with $a_1 = 0.75$, $a_2 = -0.60$ and $a_3 = 0.25$. The values of these parameters imply that the type of coordination of Nd$^{3+}$ is that of a four coordinated tetrahedral or eight – coordinated cubic one, and that the ground state zero-field splitting is dominated by the six degree crystal field terms.

Yet another interesting case of the observation of an EPR spectrum of Tm$^{2+}$ in the tetragonal phase of the (Lu, Tm) — Ba — Cu — O system has recently been reported in [13]. The EPR signal of this ion is presented in Fig. 10.
in the low-field part of the spectrum. The observed EPR line could be described by the following spin-Hamiltonian:

$$\chi = \mu_B S g B + IAS$$

with the effective electron spin $S = 1/2$ and the nuclear spin $I = 1/2$. The spin-Hamiltonian parameters determined directly from the observed spectrum were: $g = 3.12(1)$ and $A = -952$ MHz. These values are somewhat smaller than those found experimentally for Tm$^{2+}$ in CaF$_2$ and those which could be deduced from the crystal field theory of Lea et al. applied to the $^8F_{7/2}$ ground state of Tm$^{2+}$. This fact again supports the idea that the reduction of the orbital angular momentum, lowering both the value of $g$ and hyperfine structure parameters, is essential in the discussed compounds. Physically, such reduction is due to the delocalization of magnetic electrons into neighbouring orbitals of ligands, or in the other words, is due to rather pronounced effects caused by overlap and covalency.

**EPR MEASUREMENTS OF CONDUCTIVITY**

A generalized molecular crystal model (GMCM) developed by Triberis and Friedman [17] is used to study the small-polaron hopping motion in disordered systems such as discussed here.

The treatment is based on a generalized „hopping-model” Hamiltonian of the following form:

$$\langle m | H | n \rangle = \langle m | H_0 + V | n \rangle = E_{i,(n_k)} \delta_{ij} \delta_{(n_k),(n'_k)} + \langle m | V | n \rangle.$$  

Here $\langle m | V | n \rangle$ describes the overlap interaction, $|n\rangle = |i, \{n_k\}\rangle$ are the eigenstates of $H$, and $H$ is the zeroth-order Hamiltonian of Holstein the eigenvalues
of which are:

\[ E_{i,(n_k)} = \varepsilon_i(o) - E_b(i) + \sum_k \hbar \omega_k \left( n_k + \frac{1}{2} \right), \]  

(7)

where \( \{n_k\} \) represents the totality of the vibrational quantum numbers \( (\ldots, n_k, \ldots) \) for the occupation at \( \bar{r}_i \),

\[ E_b(i) = \frac{1}{N} \sum_k A_i^2/2M\omega_k^2 \]  

(8)

is the small-polaron binding energy, and \( \varepsilon_i(o) \) is the local electronic energy. \( N \) is the number of lattice sites and \( A_i \) the electron-lattice interaction energy.

The GMCM has essentially two advantages:

(i) the local electronic energy \( \varepsilon_i(o) \) is site-dependent,

(ii) the electron-lattice interaction parameter \( A_i \) and the binding energy \( E_b(i) \) are also site-dependent.

According to Triberis and Friedman for the high-temperature regime the conductivity varies with temperature as:

\[ \sigma \sim \exp\left[ -(T_o'/T)^{2/5} \right] \]  

(9)

with

\[ T_o' = 8.5N_s^{1/2}\alpha^{3/2}/k_B N_o', \]  

(10)

where \( N_s \) is the concentration of sites, \( \alpha^{-1} \) is the spacial extent of electronic wave function localized at a single site, and \( N_o' \) is the density of states.

In the low temperature range the conductivity varies as:

\[ \sigma \sim \exp\left[ -(T_o/T)^{1/4} \right] \]  

(11)

where

\[ T_o = 6.49\alpha^2/k_B N_o. \]  

(12)

Direct measurements of the resistance for \( \text{Pr}_{0.5}\text{RE}_{0.5}\text{Ba}_2\text{Cu}_3\text{O}_x \) (where \( \text{RE} = \text{Tm}, \text{Lu}, \text{Er}, \text{Yb} \)) shown in Fig. 11 supported unequivocally the applicability of the discussed model [13].

As it is well known the increase of the conductance affects strongly the EPR line intensities. This phenomenon is mainly caused by the skin effect which reduces an effective sample volume for penetration by microwave radiation. The skin depth \( \delta \) for microwave penetration is inversely proportional to the sample conductivity:

\[ \delta = (2/\mu_o \omega \sigma)^{1/2}. \]  

(13)
Semiconducting behaviour was observed for samples with large oxygen deficiency. The relative intensity changes of the EPR line for semiconductors can be described by a formula given by Godlewski et al. [4]:

$$\frac{I}{I_0} = \frac{2 \exp(-w) + [1 - \exp(-2w)] w^{-1}}{[1 + \exp(-w)]^2},$$  \hspace{1cm} (14)

where: \(w = d/\delta\) (here \(d\) is the thickness of a sample). This expression was used, for example, to study the mechanism of the conduction for GdBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) in its tetragonal phase [5]. Table 1 presents the measured and calculated from (13) and (14) parameters for this system.

**Table 1. Measured and calculated parameters appearing in (13) and (14)**

| Temperature [K] | Relative intensity | \(w\) \[mm\] | \(\delta\) \[mm\] | \(\sigma\) \[\Omega^{-1} \text{cm}^{-1}\] |
|-----------------|--------------------|--------------|----------------|------------------|
| 30              | 0.92               | 0.72         | 2.78           | 0.23             |
| 60              | 0.75               | 1.39         | 1.44           | 0.86             |
| 90              | 0.62               | 1.82         | 1.12           | 1.42             |
| 120             | 0.56               | 2.14         | 0.93           | 1.80             |
| 150             | 1                  | –            | –              | –                |

The conductivity \(\sigma\) was calculated from the measured intensity ratio \(I/I_0\) and from equation (14). Table 2 presents the ratios \(\ln \sigma_i/\ln \sigma_j\), both experimental and those implied from the model of Triberis and Friedman, for different temperatures \(T_i \neq T_j\).

Good agreement with the theory of Triberis and Friedman is observed. This agreement is partially due to the fact that the non-stoichiometry
Table 2. Experimental and calculated rations of $\ln \sigma_i/\ln \sigma_j$

| $\ln \sigma_i/\ln \sigma_j$ | experiment | theory |
|-------------------------------|------------|--------|
| $\ln \sigma_{50}/\ln \sigma_{90}$ | 1.27(10)   | 1.17   |
| $\ln \sigma_{90}/\ln \sigma_{120}$ | 1.12(5)    | 1.12   |
| $\ln \sigma_{120}/\ln \sigma_{150}$ | 1.09(5)    | 1.06   |

of GdBa$_2$Cu$_3$O$_{7-\delta}$ introduces disorder in the system. Taking the random arrangement of the constituents and the above results into account one is entitled to claim that the conduction process in this material can be attributed to small-polaron hopping motion between copper ions in different valence states.

These results seem also to be in good compliance with the idea that the presence of small-polarons prevents the appearance of superconductivity.

CONCLUSIONS

1. The static magnetic measurements give fairly exact information about the critical temperature for high $T_c$ compounds. For the compounds with large deficiency of oxygen (i.e. for the compounds in tetragonal phase) the static magnetic measurements revealed the existence of many unusual types of magnetic phase transitions and long-range magnetic orderings.

2. EPR studies of Cu$^{2+}$ ions indicate the fact that the local symmetry of these ions is orthorhombic for superconducting samples and axial for the samples with large oxygen deficiency.

3. At low temperatures, usually below 25 K, one is able to detect the EPR signal resulting from exchange interactions between Cu$^{2+}$ pairs. The temperature dependence of the signal intensity allows the estimation of the value of exchange integrals.

4. The Kramers rare-earth ions are also frequently detected by EPR even at high temperatures. The common feature resulting from such studies is the reduction of the angular momentum hyperfine parameters. This phenomenon suggests that the rare-earth ions in the studied systems are bound with its ligands not purely ionically but there is a contribution from overlap and covalency effects.

5. The EPR studies of the temperature dependence of the line intensity carried out at high temperatures for the samples with large oxygen deficiency can be explained in terms of the skin effect. The deduced values of temperature variations of the conductivity are in good agreement with the theory of Triberis and Friedman suggesting that the small-polaron hopping mechanism is responsible for the conduction process in these samples.
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BADANIA STATYCZNE MAGNETYCZNE
I BADANIA
ELEKTRONOWYM REZONANSEM PARAMAGNETYCZNYM
WYSOKOTEMPERATUROWYCH NADPRZEWODNIKÓW
I ZWIĄZKÓW POKREWNYCH

Streszczenie

Praca stanowi przegląd możliwych zastosowań statycznych pomiarów magnetycznych i elektronowego rezonansu paramagnetycznego w badaniu wysokotemperaturowych nadprzewodników i związków pokrewnych. Podano i przedyskutowano szczególne przypadki tych zastosowań. Wykazano, że pomiary magnetyczne ujawniają istnienie różnych magnetycznych przejść fazowych, natomiast pomiary EPR dają unikalną informację o oddziaływaniu szeregu centrów paramagnetycznych z ich krystalicznym otoczeniem.

ГУСКОС НИКОС, КУРИАТА ЯРЫ, ЛИКОДИМОС ВЛАСИС, САДЛОВСКИ ЛЮЦИАН, ВАБЯ МАРИАН,
ЛЕМБИЧ ФРАНЦИШЕК, ВИТОЛЬД ДУЛАК

СТАТИЧЕСКИЕ МАГНИТНЫЕ ИССЛЕДОВАНИЯ
И ИССЛЕДОВАНИЯ
ЭЛЕКТРОННЫМ ПАРАМАГНИТНЫМ РЕЗОНАНСОМ
ВЫСОКОТЕМПЕРАТУРНЫХ СВЕРХПРОВОДНИКОВ
И РОДСТВЕННЫХ СОЕДИНЕНИЙ

Резюме

Работа является обзором возможных применений магнитных и ЭПР измерений при исследовании сверхпроводников и родственных соединений. Обсуждаются особые случаи таких применений. Представлено, что магнитные измерения проявляют присутствие магнитных фазовых переходов, а измерения ЭПР дают уникальную информацию о взаимодействии ряда парамагнитных центров с их кристаллическими окрестностями.

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