c-axis phase coherence and spin fluctuations in cuprates

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Abstract. - There is a consensus that superconductivity (SC) in cuprates is two-dimensional. It is widely believed that the long-range phase coherence appears at $T_c$ due to the Josephson coupling between SC CuO$_2$ (bi-, tri-, ...) layers. Recent $T_c$ and resistivity measurements in Tl$_2$Ba$_2$CaCu$_2$O$_8$ as a function of applied pressure (Salvetat J.-P. et al., Europhys. Lett., 52 (2000) 584) show that the interlayer Josephson-coupling mechanism does not fit the data. Here we analyze data obtained in Andreev reflection, neutron scattering, microwave, muon spin relaxation, tunneling and resistivity measurements performed on different cuprates, mainly, on YBa$_2$Cu$_3$O$_{6+x}$, Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ and La$_{2-x}$Sr$_x$CuO$_{4+y}$. The analysis of the data shows that the long-range phase coherence in the cuprates intimately relates to antiferromagnetic interactions along the c axis. At the same time, it seems that the in-plane mechanism of the SC has no or little relations to the magnetic interactions along the c axis.

74.25.-q; 74.72.-h; 74.25.Ha

I. INTRODUCTION

Superconductivity (SC) and magnetism were earlier considered as mutually exclusive phenomena. Recent research revealed a rich variety of extraordinary SC and magnetic states and phenomena in novel materials that are due to the interaction between SC and magnetism [1]. The coexistence of SC and long-range antiferromagnetic (AF) order was first discovered in RMo$_6$Se$_8$ ($R = $ Gd, Tb and Er), $RRhB_4$ ($R = $ Nd, Sm and Tm), and $RMo$_6$S$_8$ ($R = $ Gd, Tb, Dy and Er) [1]. Later, coexistence of SC and AF order was found in U-based heavy fermions (UPt$_3$, URu$_2$Si$_2$, UNi$_2$Al$_3$, UPd$_2$Al$_3$, U$_6$Co, and U$_6$Fe), in heavy fermions $RRhB_2$ ($R = $ La and Y), Cr$_{1-x}$Re$_x$, CeRu$_2$, CeRu$_2$ in borocarbides $RNi_2B_2$ ($R = $ Tm, Er, Ho, Dy), in organic SCs [1,2] and in the new heavy fermion CeRh$_{1-x}$Ir$_x$In$_5$ [3]. In CeRh$_{1.5}$Ir$_0.5$In$_5$, the bulk SC coexists microscopically with small-moment magnetism ($\leq 0.1 \mu_B$) [3]. In all other heavy fermions, there are strong AF correlations present in the SC state [1,2,3]. Another class of materials in which SC and AF coexist are copper oxides (cuprates) such as YBa$_2$Cu$_3$O$_{6+x}$ (YBCO) and La$_{2-x}$Sr$_x$CuO$_{4+y}$ (LSCO) compounds [1]. Coexistence of SC and ferromagnetic (FM) order is found in the heavy fermion UGe$_2$ [4], and in Ru-based compounds, for example, in RuSr$_2$GdCu$_2$O$_8$ [1,2].

In SC heavy-fermion systems, spin fluctuation (electron-electron interactions) are believed to mediate the electron pairing that leads to SC [1]. For the heavy fermions CeIn$_3$, CePd$_2$Si$_2$ [4], UPd$_2$Al$_3$ [8] and UGe$_2$ [1,2], there is an indirect evidence for spin-fluctuation mechanism of SC. This intimate relationship between the SC and magnetism also appears to be central to cuprates [1] which inherited magnetic properties from their parent compounds, AF Mott insulators. Many theoretical studies suggest that the SC in cuprates is mediated via the exchange of AF spin fluctuations [1].

There is a consensus that, in the underdoped regime of cuprates, there are two energy scales [10]: the pairing energy scale, $\Delta_p$, and the phase-coherence scale, $\Delta_c$, observed experimentally [10,11]. The two energy scales have different dependences on hole concentration, $p$, in CuO$_2$ planes (see fig. 2): $\Delta_p$ increases linearly with decrease of hole concentration, whereas $\Delta_c$ has approximately the parabolic dependence on $p$ and scales with $T_c$ as $2\Delta_c \approx 5.4k_BT_c$ [11].

There is a consensus that the SC in cuprates is two-dimensional (2D). It is widely believed that the long-range phase coherence occurs at $T_c$ due to the Josephson coupling between SC CuO$_2$ (bi-, tri-, ...) layers. Recent measurements of the in-plane ($\rho_{ab}$) and out-of-plane ($\rho_c$) resistivities in Tl$_2$Ba$_2$CaCu$_2$O$_8$ as a function of applied pressure show that $\rho_c(T)$ shifts smoothly down with increase of pressure, however, $T_c$ first increases and then decreases [7]. This result can not be explained by the interlayer Josephson-coupling mechanism. The authors conclude [12]: “Any model that associates high-$T_c$ with the interplane Josephson coupling should therefore be revisited.” In this paper, we analyze data obtained in Andreev reflection, inelastic neutron scattering (INS), microwave, muon spin relaxation ($\mu$SR), tunneling and resistivity measurements performed on different cuprates, mainly, on YBCO, Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi2212) and LSCO. The analysis of the data shows that the long-range phase coherence in the cuprates intimately relates to AF interactions along the c axis [13]. At the same time, it seems that the in-plane mechanism of the SC has no or little relations to the magnetic interactions along the c axis. We also analyze data measured in heavy fermions UPt$_3$, UPd$_2$Al$_3$ and CeIrIn$_5$, and in some layered non-SC compounds with FM correlations.
II. IN-PLANE AND C-AXIS TUNNELING IN BI2212

Tunneling spectroscopy is an unique probe of SC state in that it can, in principle, reveal the quasiparticle density of states directly with high energy resolution. Figure 1 shows the temperature dependence of in-plane tunneling quasiparticle peaks, measured in slightly underdoped Bi2212 single crystals [14-17]. Tunneling measurements performed on slightly underdoped Bi2212 single crystals show similar temperature dependence [18]. So, the temperature dependence of in-plane quasiparticle peaks shown in fig. 1 can be considered as a typical one. In fig. 1, we present also the temperature dependence of resistivity along the ab planes and along the c axis. The authors conclude that the long-range magnetic order in BSCoO develops at TC along the c axis [22]. In layered manganite La1.4Sr1.6Mn2O7 (LSMO) which is composed of the MnO2 bilayers becomes FM at TC = 90 K [24]. The resistivity data show that, at TC, there are drastic changes in ρc (a few orders of magnitude), but very small changes in ρab. They conclude that, in LSMO, the long-range magnetic order develops at TC = 90 K along the c axis [22].

Neutron-scattering measurements performed on the heavy fermion URu2Si2 (Tc = 1.2 K) show that the AF order develops at TN = 17.5 K along the c axis [23]. So, it seems that, in all layered compounds, the long-range AF or FM order develops at TN or TC along the c axis (the in-plane magnetic correlations exist above TN and TC [24]).

We now return to the analysis of the phase diagram of non-SLSCO. The SC phase of pure LSCO is replaced by the second AF phase [24]. The conclusion made in the previous paragraph signifies that either the main AF phase of Eu-doped LSCO or the second AF phase develops along the c axis. Thus, the SC phase of pure LSCO is replaced in Eu-doped LSCO by the AF phase which develops along the c axis. Consequently, the SC in LSCO intimately relates to the establishment of the long-range AF order along the c axis.

III. LSCO

In LSCO, there is an evidence that the SC intimately relates to the establishment of AF order along the c axis. Recent µSR measurements performed on non-SC Eu-doped LSCO having different hole concentrations show that the SC phase of pure LSCO is replaced in Eu-doped LSCO by the second AF phase (see fig. 4 in Ref. [22]). Thus, the data show that it is possible to switch the entire hole concentration dependent phase diagram from SC to AF. It is a clear hallmark that the SC in LSCO intimately relates to the formation of AF order. We return to this important result later.

We turn now to the analysis of resistivity data measured in non-SC 2D layered compounds with AF or FM correlations. The data clearly show that, in all these layered compounds, the out-of-plane resistivity, ρc, has drastic changes either at Neel temperature, TN, or Curie temperature, TC, whereas the in-plane resistivity, ρab, passes through TN or TC smoothly.

We start with YBCO. In AF undoped YBCO (x = 0.35; 0.33; and 0.32) having TN ≃ 80 K, 160 K, and 210 K, respectively, ρc shows sharp increase, by about 2 orders of magnitude, upon cooling through TN [22]. At the same time, ρab changes at TN smoothly. The same effect has been observed in LnBCO (x = 0.34) [23]. So, the Neel ordering in undoped YBCO has remarkably different impact on the electron transport within CuO2 planes and between them. The authors conclude [23]: “The Neel temperature actually corresponds to the establishment of AF order along c axis.”
The low energy magnetic excitations in LSCO cuprate have been extensively studied, and the observed spin fluctuations are characterized by wave vector which is commensurate with the lattice \[37,38,39\]. These modulated spin fluctuations in LSCO persist in both normal and SC states. The spin dynamics in YBCO and Bi2212 studied by INS exhibit below \(T_c\) a sharp commensurate resonance peak which appears at well defined energy \(E_r\) \[28,29,30,31,32,33,34,35,36,37,38\]. Incommensurability in YBCO has been also reported \[35\], and it is consistent with that in LSCO of the same hole doping, but, in YBCO, it occurs in the SC state. Now it is clear that the incommensurability and the commensurate resonance are inseparable parts of the general features of the spin dynamics in YBCO at all doping levels \[39\]. Thus, there is a clear evidence of coexistence of AF order and SC below \(T_c\), at least, in LSCO and YBCO.

We now compare coherence SC and magnetic characteristics of the cuprates. Figure 2(a) shows the temperature dependences of the superfluid density in near optimally doped single crystals of Bi2212 \(T_c = 93\) K \[40\] and YBCO \(T_c = 93\) K \[41\], and in an overdoped LSCO \((x = 0.2)\) single crystal \(T_c = 36\) K \[42\]. The superfluid density is proportional to \(1/\lambda^2(T)\), where \(\lambda(T)\) is the magnetic penetration depth. Inset: temperature dependence of the superfluid density in heavy fermion CeIrIn\(_5\) \(T_c = 0.4\) K \[3\] (axis parameters as main plot). (b) Temperature dependence of Andreev-reflection gap, \(\Delta(T)/\Delta(T_{min})\), in an overdoped Bi2212 thin film \((T_c = 80\) K) \[43\], and in overdoped single crystals of Bi2201 \((T_c = 29\) K) \[44\] and LSCO \((x = 0.2)\) \(T_c = 28\) K \[45\]. Inset: temperature dependence of the Andreev gap in heavy fermion UPt\(_3\) \((T_c \sim 440\) mK) \[48\] (axis parameters as main plot). (c) Temperature dependence of the peak intensity of the incommensurate elastic scattering in LSCO \((x = 0)\) \(T_c = 42\) K \[27\] and the intensity of the magnetic resonance peak measured by INS in near optimally doped Bi2212 \((T_c = 91\) K) \[28\] and YBCO \((T_c = 92.5\) K) \[33\]. The neutron-scattering data are average, the real data have the vertical error of the order of \(\pm 10\%\) \[27,28,33\]. The BCS temperature dependence is shown by the thick solid line. The dashed lines are guides to the eye.

**IV. YBCO, Bi2212 AND LSCO**

We now compare coherence SC and magnetic characteristics of YBCO, Bi2212 and LSCO. The comparison shows that the magnetic and coherence SC characteristics have similar temperature dependencies, and, at different dopings, their magnitudes are proportional to each other (and proportional to \(T_c\)). Thus, the coherence SC and magnetic properties of cuprates intimately relate to each other.

First, we describe the magnetic properties of cuprates. The low energy magnetic excitations in LSCO cuprate have been extensively studied, and the observed spin fluctuations are characterized by wave vector which is incommensurate with the lattice \[27\]. These modulated spin fluctuations in LSCO persist in both normal and SC states. The spin dynamics in YBCO and Bi2212 studied by INS exhibit below \(T_c\) a sharp commensurate resonance peak which appears at well defined energy \(E_r\) \[28,29,30,31,32,33,34,35,36,37,38\]. Incommensurability in YBCO has been also reported \[35\], and it is consistent with that in LSCO of the same hole doping, but, in YBCO, it occurs in the SC state. Now it is clear that the incommensurability and the commensurate resonance are inseparable parts of the general features of the spin dynamics in YBCO at all doping levels \[39\]. Thus, there is a clear evidence of coexistence of AF order and SC below \(T_c\), at least, in LSCO and YBCO.

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Figure 2(c) shows the temperature dependences of the peak intensity of the incommensurate elastic scattering in LSCO \((x = 0)\) \[24\] and the intensity of the commensurate resonance peak measured by INS in near optimally doped Bi2212 \[28\] and YBCO \[23\].

In fig. 2, all temperature dependences of coherence SC and magnetic characteristics exhibit below \(T_c\) a striking similarity. Since all temperature dependences shown in fig. 2 are similar to the temperature dependence of \(c\)-axis quasiparticle peaks in Bi2212, shown in fig. 1, and
FIG. 3. The phase diagram of cuprates (lines) [10] and the energy position of the magnetic resonance peak, $E_r$, in Bi2212 [28,29] and in YBCO [30–38] at different doping levels. The strength of the superfluid density in heavy fermion CeIrIn$_2$, measured by $\mu$SR [3], and to the temperature dependence of the Andreev-reflection gap in heavy fermion UPt$_3$ [8], which are shown in the insets of figs 2(a) and 2(b), respectively. Spin fluctuations are believed to mediate the electron pairing in CeIrIn$_2$ and UPt$_3$, and hence, the magnetic resonance peak has not yet been detected in CeIrIn$_2$ or UPt$_3$, however, the magnetic resonance peak has been observed by INS in another heavy fermion UPd$_2$Al$_3$ [19] where spin fluctuations mediate the SC which coexists with the long-range AF order [8]. The latter fact also points to the presence of spin-fluctuation coupling mechanism in cuprates.

**V. DISCUSSION**

In spite of the unmistakable similarities among the magnetic and SC properties of YBCO, Bi2212 and LSCO (and some heavy fermions for which there is an indirect evidence for spin-fluctuation mechanism of SC), clearly, there is a difference between magnetic properties of LSCO and YBCO, which is shown in the insets of figs 2(a) and 2(b). The magnetic resonance peak has not yet been detected in CeIrIn$_2$ or UPt$_3$, however, the magnetic resonance peak has been observed by INS in another heavy fermion UPd$_2$Al$_3$ [19] where spin fluctuations mediate the SC which coexists with the long-range AF order [8]. The latter fact also points to the presence of spin-fluctuation coupling mechanism in cuprates.

The behavior of all temperature dependences shown in fig. 2 can be easily understood in terms of the spin-fluctuation mechanism of SC (electron-electron interactions): crudely speaking, they exhibit the squared BCS temperature dependence.
between the magnetic and SC properties of LSCO and YBCO can be understood in frameworks of one picture with different initial parameters.

VI. SUMMARY

The analysis of the data obtained by different techniques in YBCO, Bi2212 and LSCO shows that the long-range phase coherence intimately relates to AF interactions along the c axis. At the same time, it seems that the in-plane mechanism of the SC has no or little relations to the magnetic interactions, at least, along the c axis. Apparently, in cuprates, the magnetic and SC order parameters are coupled to each other, and the phase-coherence scale, $\Delta_c$, has the magnetic origin (see fig. 3).

There are common features in the SC state of the heavy fermions CeIrIn5, UPt3 and UPd2Al3, on the one hand, and the cuprates, on the other hand. It is possible that, in all heavy-fermion and organic SCs, the long-range phase coherence is also established due to spin fluctuations (the pairing mechanism may be different).

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