Common energy scale for magnetism and superconductivity in cuprates

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Many compounds based on CuO_2 planes (cuprates) superconduct below a critical temperature T_c. Some of them show a second phase where a spontaneous static magnetic field appears below a critical temperature T_g, which is lower than T_c. By comparing T_c and T_g in numerous superconducting families, each with its own maximum T_c, we find that the same energy scale determines both critical temperatures. This clearly indicates that the origin of superconductivity in the cuprates is magnetic.

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One of the most challenging tasks of solid-state physics today is to understand the mechanism for superconductivity in cuprates. These materials, which have a relatively high critical temperature T_c, are based on doped CuO_2 planes. Since at zero doping they are antiferromagnets, several theories ascribe their superconductivity to holes interacting via a magnetic medium.[1,2] Yet the phenomenon of superconductivity begins at doping levels in which magnetism almost disappears, and therefore there is no clear evidence relating the two. Fortunately, there is a narrow doping range in which superconductivity and magnetism, in the form of randomly oriented static spins (a spin glass), coexist below a critical temperature $T_g < T_c$. We thus focus on this doping range and examine T_g and T_c in numerous superconducting families, which are distinct in the sense that each one has its own maximum T_c $[T_c^{max}]$. We find that in all cases a common energy scale controls both critical temperatures. Therefore, magnetism and superconductivity in the cuprates are different facets of the same Hamiltonian.

The families for which both T_g and T_c data exist are $(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_{6+y}$ (CLBLCO),[3] $La_{2-y}Sr_yCuO_4$ (LSCO),[4,5] $Y_{1-y}Ca_yBa_2Cu_3O_6$ (YCBCO),[4] $Bi_{2.1}Sr_{1.9}Ca_{1-x}Y_xCu_2O_{8+y}$ (Bi-2212),[5] and $YBa_2Cu_3O_{6+y}$ (YBCO).[6] Several groups including ours gathered the data, and the determination of T_g was done using the μSR technique. In this technique one implants fully polarized positive muons in a sample and measures the time dependence of their polarization $P_z(t)$. This polarization changes dramatically when static magnetic fields appear. This is demonstrated for a superconducting compound from the CLBLCO family with $T_c = 33.1$ K in Fig. 1, which is taken from Ref. 3 for completion. Between $T = 40$ and 8 K, $P_z(t)$ is typical for muon polarization in an environment where the magnetic field emanates from nuclear moments. We denote this polarization by $P_z^{\infty}(t)$. At about $T = 7.4$ K a fast relaxation component appears, which is due to some additional strong magnetic field. As the temperature is lowered the fast relaxing component grows at the expense of the slow one, and at a temperature of 0.37 K, no slow relaxing component is observed. In addition, at this temperature the polarization saturates at long times at one-third of its initial value. This is typical for randomly frozen magnetic fields where one-third of the fields happen to point in the direction of the muon spin.

In order to determine T_g quantitatively all authors effectively fit their data to

$$P_z(t) = A_m \exp[-(\lambda t)^{\beta}] + A_n P_z^{\infty}(t), \tag{1}$$

where λ is a relaxation rate, and the amplitudes A_m and A_n represent muons in magnetic and normal environments. However, different authors use different parameters in the fit function for the determination of T_g. We will show below that this has no bearing on our final conclusion. In particular, we fit Eq. (1) to the data in Fig. 1 with $\beta = 1/2$ and $A_m + A_n$ common to all temperatures. In Fig. 2 we present A_m as a function of temperature for three different samples of the CLBLCO family with $x = 0.3$. As expected A_m grows as the temperature decreases and saturates. Our criterion for T_g is the temperature at which A_m is half of its saturation value as demonstrated by the vertical lines. This figure demonstrates the sensitivity of T_g to doping.

In order to quantify the relation between T_g and T_c, we distinguish between two kinds of holes. The first kind we call *mobile* holes, and their doping level is p_m. The second kind is the usual *chemical* holes, and their doping level is denoted by p. The reason for this distinction is that the only experimental known value is that of the chemical formula of the compounds, namely, the x and y values. Theoretical arguments relate x and y to p,[7–9] but the accuracy of these relations is debatable.[9] By introducing p_m we allow for an additional scaling parameter, which could be determined

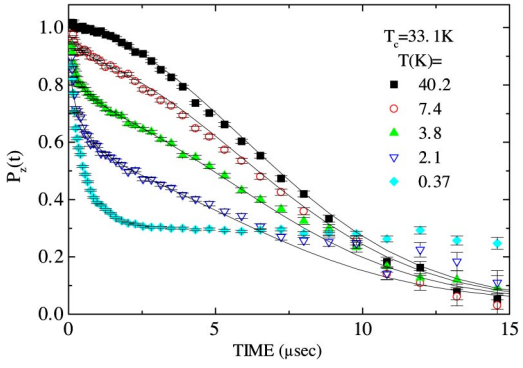

FIG. 1. (Color online) μSR spectra obtained in a $x = 0.1$, $y = 7.012$ CLBLCO sample at various temperatures. The solid lines are fits using Eq. (1). Taken from Ref. 3.

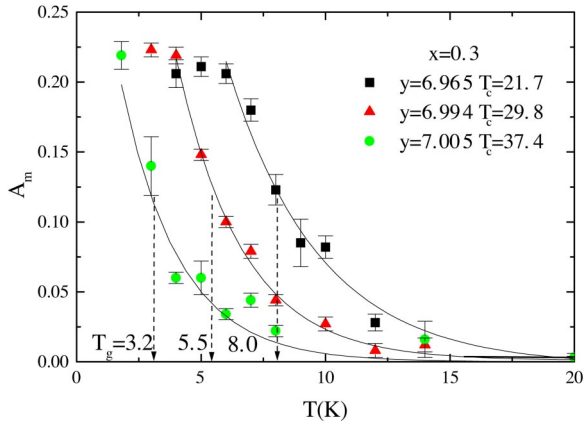

FIG. 2. (Color online) The magnetic amplitude A_m as a function of temperature for different $(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$ samples. The solid lines are guides to the eye. T_g is the temperature at which A_m is half of its saturation value, as demonstrated by the dashed lines. Taken from Ref. 3.

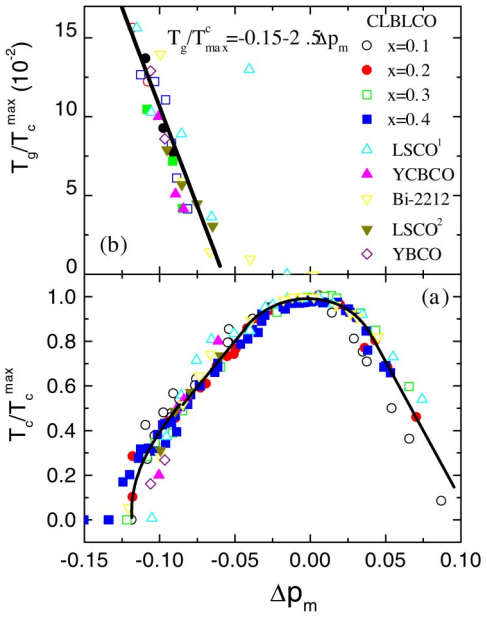

FIG. 3. (Color online) (a) T_c/T_c^{max} and (b) T_g/T_c^{max} as a function of $\Delta p_m = K_f \Delta p$ [see Eq. (2)]. K_f is chosen so that T_c/T_c^{max} vs Δp_m domes of various cuprate families collapse into a single curve. As a consequence T_g/T_c^{max} vs Δp_m also collapses into a single line.

experimentally, and could lead to a comparison between different compounds. An equally good name for p_m could have been ''corrected hole doping.'' The scaling parameter is determined as follows. First, we convert the T_g and T_c values of all material to be functions of p. The case of LSCO, YCBCO, and Bi-2212 is immediate since the authors of Refs. 4 and 5 present their data in this way. For CLBLCO, however, T_g and T_c are given as a function of y.[3] We assume the relation $p=-0.205+y/3$ obtained from simple valance counting. In the case of YBCO, the y to p conversion is taken from Presland *et al.*[10] Second, we define p^{opt} as chemical hole doping at optimum, where optimum means $T_c^{\max}$, and introduce $\Delta p = p - p^{opt}$. Finally, we write

$$\Delta p_m = K_f \Delta p, \tag{2}$$

where K_f is the scaling parameter that is different for the various cuprate families. We interpret Δp_m as $p_m - p_m^{opt}$ where p_m^{opt} is the number of mobile holes at optimum. This point requires extra attention; the scaling we perform between chemical and mobile holes is done by counting them from optimum, and not from $p=0$. We determine K_f from experimental data by making T_c/T_c^{max}, for all the families, collapse onto one curve, resembling the curve of $La_{2-y}Sr_yCuO_4$, since in this case it is believed that $p_m = p$. This is demonstrated in Fig. 3(a). It should be pointed out that LSCO serves only as a reference, and whether $p_m = p$ for this compound or not has no bearing on our conclusions. A summary of p^{opt}, K_f, and $T_c^{\max}$ is given in Table I. In Fig. 3(b) we also plot T_g/T_c^{max} as a function of Δp_m (using the previously determined values of K_f). Magically, T_g/T_c^{max} also collapse onto one line for all the cuprates we have examined. The line, depicted in Fig. 3(b), is described by

$$T_g/T_c^{max} = -2.5\Delta p_m - 0.15. \tag{3}$$

Up to date this type of scaling was demonstrated only for the CLBLCO family.[3]

It is important to mention that Eq. (3) is independent of the criteria used to determine T_g. In the case of LSCO, for example, T_g was determined from Eq. (1) by two different methods. (1) the temperature at which $\beta = 1/2$, a behavior typical of spin glasses at T_g[5]. (2) the temperature where λ, obtained only from fit to the long time data with $\beta = 1$, has a peak—a common feature of all magnets upon freezing.[4] Both methods agree with each other.[5]

We interpret the scaling of Fig. 3 as follows. The Uemura relations[12] and recent theories of hole pair boson motion in

TABLE I. Showing the optimal chemical doping, the scaling factor used in Eq. (2) to produce Δp_m, and the maximum T_c for the varius compounds presented in Fig. 3. The $T_c^{\max}$ (and p^{opt}) of YCBCO is not known, and the values given in the table are assumed. Only two samples of YBCO, for which both T_g and T_c have been measured, are shown.

HTSC Familiy	P_{opt}	K_f	$T_c^{\max}$
CLBLCO $x=0.1$	0.18	2.0	58
CLBLCO $x=0.2$	0.18	1.9	69
CLBLCO $x=0.3$	0.18	1.8	77
CLBLCO $x=0.4$	0.18	1.5	80
LSCO	0.16	1.0	38
YCBCO	0.16	1.1	65
Bi-2212	0.16	1.1	44
YBCO	0.16	1.0	93
LSCZO $x=0.01$	0.16	1.5	26
LSCZO $x=0.01$	0.18	2	17

an antiferromagnetic background[2] suggest that T_c is proportional to n_s with a proportionality constant J_f, where the subscript f stands for family, namely,

$$T_c = J_f n_s(\Delta p_m). \tag{4}$$

The reason different families have different $T_c^{\max} = J_f n_s(0)$ is because J_f varies from one family to the next, but $n_s(\Delta p_m)$ does not. Therefore,

$$T_c/T_c^{\max} = n_s(\Delta p_m)/n_s(0) \tag{5}$$

is a function of Δp_m for all cuprate families. Using Eq. (3) this gives

$$T_g = J_f n_s(0)(-2.5\Delta p_m - 0.15).$$

Thus, the successes of the simultaneous scaling of T_c and T_g for all the compounds discussed here suggests that the same energy scale J_f controls both the superconducting and magnetic transitions in all cuprates.

At first this result seems surprising, since it is believed that in the antiferromagnetic phase of the cuprates, there are three magnetic energy scales. The isotropic in-plane Heisenberg coupling J, and the in-plane and out-of-plane anisotropy energies $J\alpha_{xy}$ and $J\alpha_{\perp}$, respectively. However, Keimer *et al.* showed that the Néel temperature T_N depends only logaritmically on both anisotropies α_{xy} and $\alpha_{\perp}$.[11] It is conceivable that this is also the situation in the glassy phase. In that case the energy scale of T_g will be set only by J. Another two-dimensional theory that appears to support the existence of glassy freezing is given in Ref. 13.

Further insight could be achieved by assuming a linear relation between n_s and Δp_m, namely,

$$n_s(\Delta p_m) = \alpha(p_m^{opt} + \Delta p_m). \tag{6}$$

If all the mobile holes had turned into the Cooper pairs we would have $\alpha = 1/2$. Taking $p_m^{opt} = 0.16$, we find from Eqs. (3) and (6)

$$T_g/T_c^{\max} = 0.3[1 - c_g \times n_s(\Delta p_m)], \tag{7}$$

where $c_g = 8/\alpha$. This equation could be used to predict T_g for compounds in which the magnetic transition is not found yet.

Finally, it is important to demonstrate that the simultaneous scaling of T_g and T_c is a property of clean superconductors and does not work in all cases. A perfect example for a scaling failure is given by $La_{2-y}Sr_yCu_{1-x}Zn_xO_4$.[5] Here samples with the same amount of Zn are considered to be one family of HTSC with its own $T_c^{\max}$. The reduction of $T_c^{\max}$ with increasing Zn concentration is a result of the increasing impurity scattering rates, since the Zn reside in the CuO_2 plane. As demonstrated in Fig. 4, the scaling transformation that makes all T_c vs Δp_m domes collapse into one function does not apply for T_g vs Δp_m. The parameters used to generate this plot are also given in Table I. The failure of the scaling suggests that a mechanism with a different energy scale is involved in the reduction of T_c when impurities are present. Interestingly, the two data sets of $T_g/T_c^{\max}$ vs Δp_m for the impure cases do full on the same line.

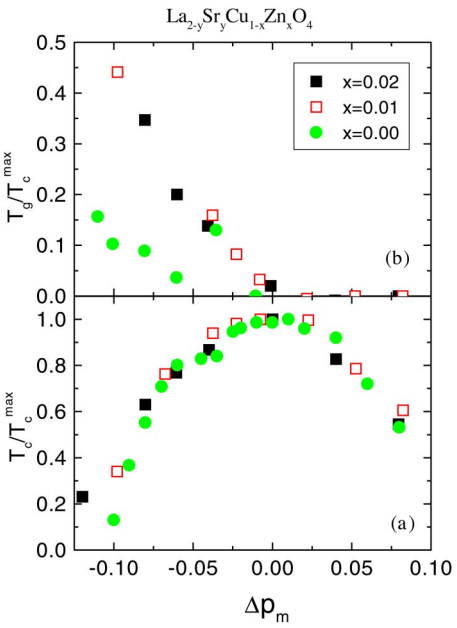

FIG. 4. (Color online) (a) T_c/T_c^{max} and (b) T_g/T_c^{max} as a function of $\Delta p_m = K_f \Delta p$ [see Eq. (2)]. K_f is chosen so that T_c/T_c^{max} vs Δp_m domes for various $La_{2-y}Sr_yCu_{1-x}Zn_xO_4$ compounds, representing impure cases, collapse into a single curve. The same scaling does not apply to T_g.

We conclude that the variation of T_c between different superconducting families, based on CuO_2 planes, is a consequence of variations in the strength of the magnetic interactions.

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