The Condensation Energy and Pseudogap Energy Scale of $La_{2-x}Sr_xCuO_4$ from the Electronic Specific Heat and Entropy

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Abstract

From the analysis of the electronic specific heat C_{es} and the entropy S_s of the superconducting phase of nine samples of high temperature superconductor (HTS) $La_{2-x}Sr_xCuO_4$ (La:214) of Sr doping rates ($0.03 \leq x \leq 0.24$), it is shown that the normal state pseudogap opens abruptly in the weakly overdoped region at the critical doping pcrit (Where x=0.20 and the hole concentration in CuO_2 planes is 0.19 holes/CuO_2) and increases as $Eg(p) \sim 1500(1-p/p_{crit.})(K)$ at lower doping . The condensation energy Ec(0) peaks strongly at the optimal doping dopt (where x=0.17 and the hole concentration in CuO_2 planes is 0.16 holes/CuO_2), exhibiting strong BSC like superconductivity ($Ec(0)/\gamma_n T_c^2 \sim 0.52$ for $p > p_{opt}$) and weak superconductivity below p_{dopt} . It can be concluded that the pseudogap is a property of the normal state NS density of state DOS and is not related to precursor superconducting fluctuations.

Keywords: HTS, Electronic Specific Heat, Entropy, Superconducting Condensation Energy and Pseudogap

حساب طاقةِ التكثيفِ ومقياس طاقة الفجوة الوهمية لنظام $La_{2-x}Sr_xCuO_4$ فائق التوصيل باستخدام السعة الحرارية والانتروبي

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الملخص

مِنْ حساب السعة الحراريةِ الإلكترونيةِ C_{es} والانتروبي S_s لطور التوصيل المفرط لتسعة من عينات $La_{2-x}Sr_xCuO_4$ (La:214) ذي درجةِ حرارة انتقال عالية (HTS) والمشوبة بنسب من Sr تتراوح بين($0.03<x<0.24$)، نلاحظ إن الفجوة الوهمية pseudogap لهذه العينات تبدأ بالظهور في منطقة فوق التشويب overdoped للطور الاعتيادي للتشويب القليل عند نقطة التشويب الحرج critical doped (عندماً $x=0.20$ وتركيز الفجوات في المستوي CuO_2 هو $p_{crit} \sim 0.19$ holes/CuO_2) وتزداد طاقة الفجوة الوهمية حسب العلاقة $Eg(p) \sim 1500(1-p/p_{crit.})(K)$ عند التشويب القليل.

تم حساب طاقة التكثيف $E_c(0)$ حيث تّبلغُ قيمتها العظمى عند التشويب الامثل optimal doped (عندماً $x=0.17$ وتركيز الفجوات في المستوي CuO_2 هو $p_{opt} \sim 0.16$ holes/CuO_2)، وتبدي امتثالا قويا لنظرية BCS وتساوي قيمة النسبة ($E_c(0)/\gamma_n T_c^2 \sim 0.52$) في منطقة $p>p_{crit}$ وتوصيلية مفرطة ضعيفة تحت نقطة التشويب الأمثل p_{opt} . يمكن إلآستنتاج بأن الفجوة الوهمية هي خاصية لكثافةِ الحالة في الطور الاعتيادي (NS)، وان لا علاقة لها بترجرجات التوصيلة المفرطة (Superconducting fluctuations).

Introduction:

Despite the enormous amount of effort spent in the last decades in resolving the fundamental physics behind high temperature superconductivity (HTS) the mechanism is still puzzling (J.E.Hirsch, 2002). It is more or less generally accepted now that the conventional electron-phonon pairing mechanism cannot explain cuprate superconductivity, because as high a transition temperature as 164 K (the record T_c up to now (Q.Xiong, et al., 1994)) cannot be explained by energy scale of lattice vibrations without leading to lattice instability (J.E.Hirsch, 2002). It has also been shown recently that the c-axis transport of the hole-content to the doping site in the charge reservoir in the normal state (NS) of cuprate may be important in understanding HTS (S.Sachdev and J.Ye, 2000). HTS exhibits a common generic phase diagram in which the superconducting transition temperature T_c rises to a maximum at an optimal doping of approximately 0.16 holes per planar copper atom and then falls to zero on the overdoped side. In addition the underdoped normal state exhibits correlation, which introduces a gap in the density of states that strongly affects all physical properties. There is no phase transition associated with the opening of this gap and so it is called a pseudogap. Analysis of specific heat data, for example, suggests that the pseudogap energy decreases with doping and falls to zero at a critical doping of pcrit~0.19 holes/CuO_2, just beyond optimal doping (J.W.Loram, et al., 1998 and J.L.Tallon , et al. 2001), a behavior rather analogous to the quantum- critical heavy- fermions materials (N.D.Mathur, et al., 1998).

Many fundamental physical quantities such as the superconducting condensation energy (J.W.Loram, et al., 1998 and J.L.Tallon, et al. 2001), the superfludity density (C.Panagopoulos, et al., 1999 and J.L.Tallon, et al., 2003a), and the quasiparticle weight (J.L.Tallon , et al. 2001), show abrupt changes as $p \rightarrow p_{crit}$.

The highly anomalous properties HTS cuprates are attributable in part to the presence of a normal state (NS) pesudogap extending across the underdoped region of the phase diagram (P.A.Lee, et al., 2004). The onset of the pesudogap opens up a gap in the density of states (DOS) which profoundly affects all physical properties in both the normal and superconducting (SC) states (J.L.Tallon , et al. 2003b). We believe that the evidence is firmly in support of the latter scenario and present here further supporting evidence, and the SC ground state is strongly perturbed by the pesudogap and major changes taken place at the critical doping state pcrit at which the pesudogap first appears.

To examine the so-called small pseudogap and the superconducting condensation energy Ec(0), the electronic specific heat Ce was calculated from 4-160K for nine samples of $La_{2-x}Sr_xCuO_4$ with planar hole density

$0.06<p<0.24 \equiv 0.03<x<0.24$, where p was determined from the T_c values by using the approximate parabolic phase curve$p=0.16\pm[(1-T_c/T_{c,max})/82.6]^{½}$ (Hai-Hu Wen, et al., 2005). The used γ was reported by Larom and et al (1998). The condensation energy Ec(T) was calculated for these samples from the calculated electronic specific heat C_{es} and the entropy S_s of the superconducting phase for each doping rate using the relation (S.J.Fakher, 2005).

$$E_C(T) = \frac{1}{2}\int_0^{T_C}[C_{es}(T) - S_s(T)]dT \qquad (1)$$

Results and Discussion:

Figure (1) shows the electronic specific heat C_e for a series of (La:214) samples of different Sr doping rates ($0.03\leq x\leq 0.24$) versus temperature T, the relations which were used to calculate the superconducting and normal C_e phase is to be found in (S.J.Fakher, 2005 and S.J.Fakher, 2007). It is clear that C_e reaches a maximum peak at T_c . The maximum value of T_c ~38K is at p_{opt}~0.16(holes/CuO_2). The dotted curve in the figures denotes the optimal doping where x=0.17 and p_{opt}~0.16(holes/CuO_2), the bold curve denote the critical doping where x=0.20 and p_{crit}~0.19 (holes/CuO_2).

Low temperature plot γ^{tot} vs T^2 shows the doping independent value of the electronic specific heat coefficient γ(0)~0 [mJ/gat.K^2] for all samples (see Figure 2), which shows also an initial phonon term that at the underdoped region (where x<0.17) decreases with increasing the Sr doping rate, whereas at the overdoped region (where $x\geq 0.17$) γ_s value start to increases.

The magnitude $\Delta\gamma(T_c)$ of the specific heat jumps is presented in Figure(3). $\Delta\gamma(T_c)$ increases with the increasing of the hole doping, whereas the value of T_c reaches it's maximum value at p_{opt} and at $p>p_{opt}$ begin to decrease. This behavior matches with the T_c values in Literature, but differs for $\Delta\gamma(T_c)$ values for BSCCO (J.W.Loram, et al., 2000), TlPb:1212 (C.Panagopoulos, et al., 1999) and YBCO [0,10,20% Ca) (T.Timusk and B.Statt, 1999), which stays almost independent of the doping in more heavily overdoped samples, and this is not the case for the studied samples where at p= p_{opt} there is a jump in $\Delta\gamma(T_c)$ ~5 mJ/gat.K^2, and increases in the more heavily overdoped samples.

Plots of the entropy S(T) and S/T versus temperature T are presented in Fig.(4) for the samples, the following relation was used to calculate S(T) (T.Timusk and B.Statt, 1999):

$$S(T) = \int_0^T \gamma(T')dT' \qquad (2)$$

The normal state (NS) entropy $S_n(T)$ extrapolates to zero or positive values at T=0K, see Fig. (4a), as for a conventional metal with a constant NS DOS. Below pcrit and coincident with the increase of the specific heat jump, S_n extrapolates also to zero or positive values at T=0K. S/T develops a shoulder at $Ts^*(p)$, see Fig. (4b), revealing the presence of a pesudogap at EF. Since Sn and its temperature derivative γn are featureless above Tc, it is clear that Ts^* reflects the energy scale $Eg\sim 3Ts^*$ of the pseudogap and not the onset of pseudogap correlations. The entropy curves do not converge at high temperature because of the permanent removal of the missing spectral weight at EF from the room temperature Fermi Window EF±100 meV, a property which is not compatible with a conventional states-conserving Fermi surface instability (J.W.Loram, et al., 2000).

Figure (5) include of accounts, it presents the energy gap Eg(p) which decreases linearly with p as $Eg(p)\sim 1500(1-p/p_{crit})(K)$ (N.D.Mathur, et al., 1998) with pcrit=0.19 holes/CuO_2. Eg values are close to those found for LSCO and doped YBCO (N.D.Mathur, et al., 1998), and Bi:2212 (S.J.Fakher, 2007). This universal behavior of the pseudogap energy Eg(p) contrasts sharply with the wide variation in Tc,max (P.A.Lee, et al., 2004), which is shown in Fig.(3).

Values of the condensation energy for zero temperature Ec(0) obtained by integrating specific heat and entropy data for superconductivity phase for each doping rate using equation (1) are plotted also in Figure (6), which shows that Ec(0) peaks sharply at Popt rather than pcrit, and it is due to the approximate vanishing of the energy gap Eg at this region and the reaching of the transition temperature T_c reaches its maximum value ($T_{c,max}$). The fact that Ec(0) passes through a sharp peak at $p_{opt}\sim 0.16$ rather than pcrit further underscores the unique and sudden character of this optimal doping point. For $p>p_{opt}$ the decrease in Ec(0) satisfies the relation $Ec(0)/\gamma_n T_c^2\sim 0.52$ (see Fig. 6) expected for a BCS SC with a flat DOS. The figure shows that Ec(0) decrease rapidly at underdoped region, where $p<p_{opt}$, and could be explained on a BCS model when account is taken of the reduced spectral weight in the region EF±Δ(0) available for pairing (J.W.Loram, et al., 1994). The strongly reduced number of normal excitations below T_c and the associated weakening of the T-dependence of the free energy difference Fn-Fs explain the much weaker effect of the pseudogap on T_c.

For the underdoped region, where $p<p_{opt}$ and $x<0.17$, the Ec(0) values decreases because of the decrease of values of T_c and γ (where the Ec(0) depends on the T_c and γ values, pursuant to the equation (S.J.Fakher, 2005):

$$E_C = \frac{1}{2}\gamma T_C - \int_0^{T_C} S_S(T)dT \quad . \qquad (3)$$

This decrease of Ec(0) values indicates that there is loss in energy resulting from the existence of the energy gap in this region, this is in agreement with (J.L.Luo, et al., 2003, P.A.Lee, et al., 2004 and S.J.Fakher, 2007) . Note that the Eg values are obtained from normal state data, but the Ec(0) values are T=0K properties reflecting the change in free energy in transforming from the normal state to the superconducting ground state, both identify the same critical doping point. Taken together, there is remarkable concurrence between normal state properties and the ground state superconducting properties, which indicates the existence a unique critical doping point in the phase diagram, where the properties changes suddenly and the pseudogap energy falls to zero and the superconductivity is almost robust. The effect of the pseudogap appears, when the values of Eg begin to increase in this region and the values of doping x% Sr decreases in the sample which leads to decrease the hole concentration in CuO_2 planes (p), which effects directly and grievous the condensation energy (measure for condensate couples).

Figure (6) shows the calculated ratio $Ec(0)/\gamma_n T_c^2$ against the hole concentration p holes/CuO_2 plane , which is constant for $p>p_{crit}$ but anomalous behavior for p<pcrit, further illustrating the abrupt change from conventional metallic to pesudogap behavior $p<p_{crit}$, this behavior is similar to studies of the Bi:2212 samples (S.J.Fakher, 2007). This confirms that the pseudogap (loss of low energy NS spectral weight) persists to $T<<T_c$, suppressing Ec(0) and weakening the condensate, and is strong evidence against a precursor fluctuation interpretation of the pseudogap above T_c.

Comparing the results of this work for (La:214) with results of YBCO:123 (0, 20%Ca) (J.W.Loram, et al., 2000) and Bi:2212 (S.J.Fakher, 2007) with same techniques of the pseudogap temperature scale, the results of this study is much higher than for $YB_2Cu_3O_{6+x}$, $Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{6+x}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ and the pseudogap state extends well into the overdoped region, and this results are in agreement with other techniques results published by T. Timusk and B. Statt (1999) and C. Panagopoulos and et al. (2003).

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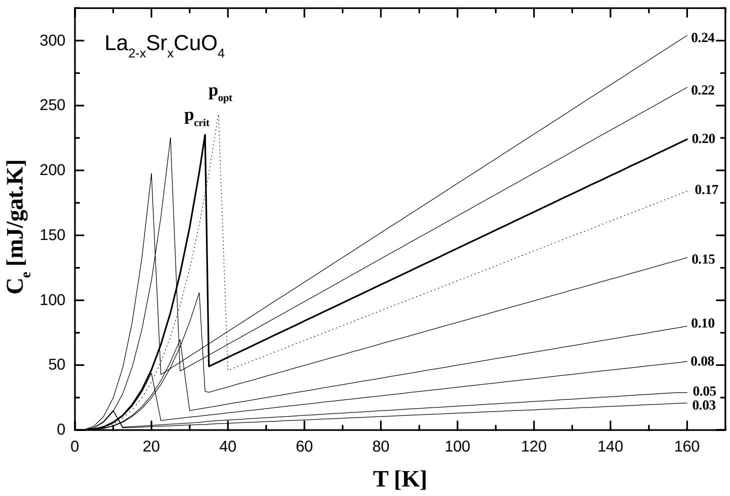


Figure 1: The electronic specific heat C_e versus temperature for a series of La:214 samples of different Sr doping rates ($0.03 \leq x \leq 0.24$). Dotted line represents the optimal doping, bold line the critical doping.

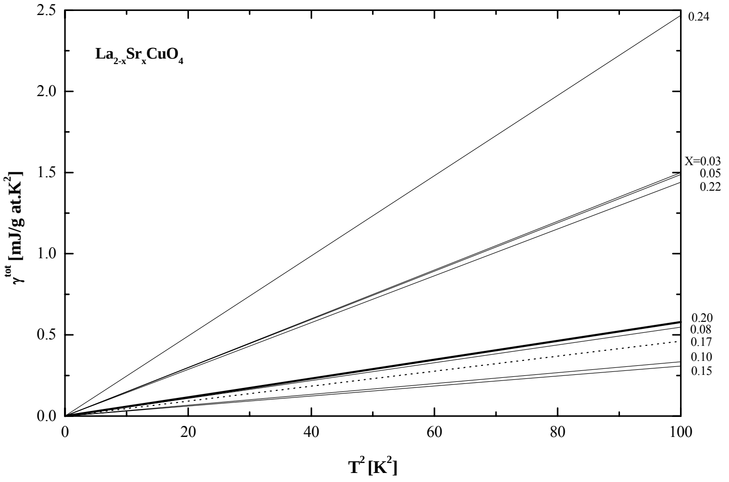


Figure 2: γ^{tot} vs T^2 at low temperature for La:214 samples.

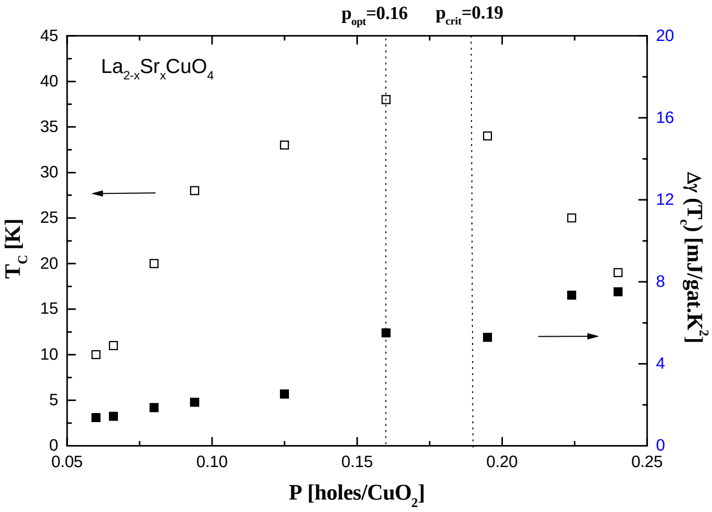
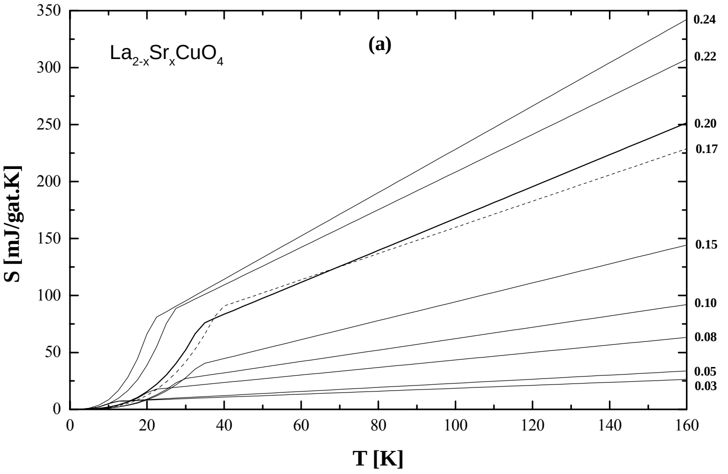


Figure 3: T_c (□) and the anomaly step height $\Delta\gamma(T_c)$ (■) dependence on doping.



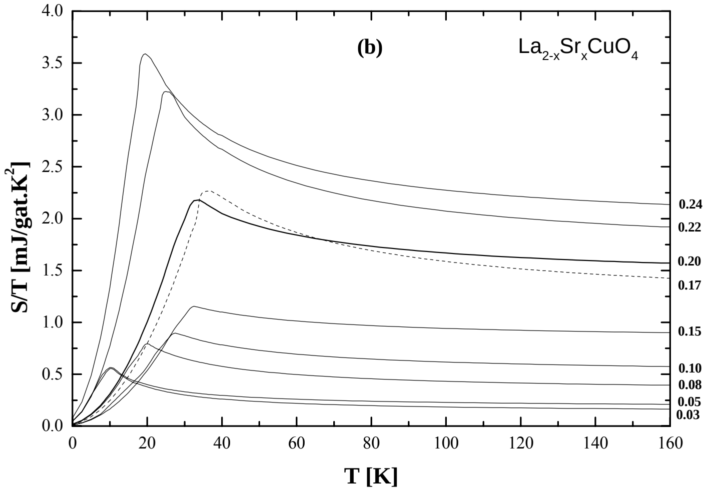


Figure 4: Entropy S (a) and S/T (b) for the La:214 Samples.

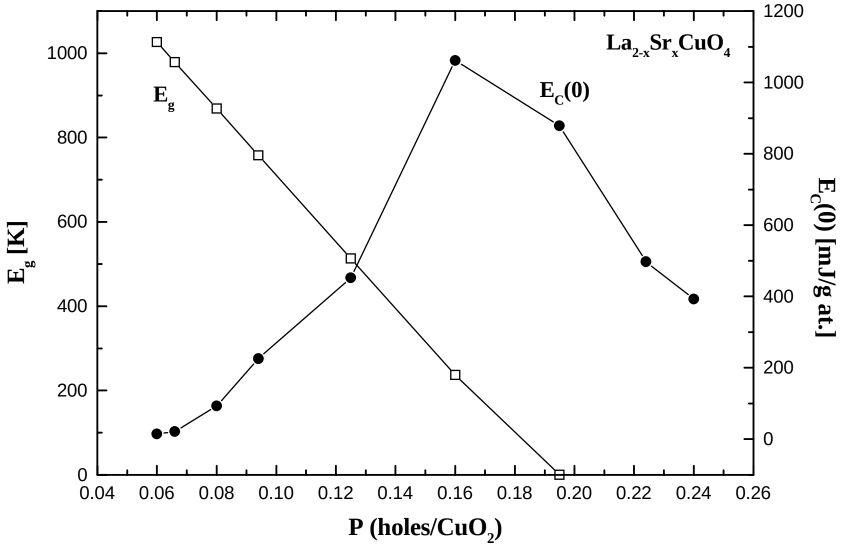


Figure 5: E_g and $E_c(0)$ values vs hole concentration p for La:214 samples.

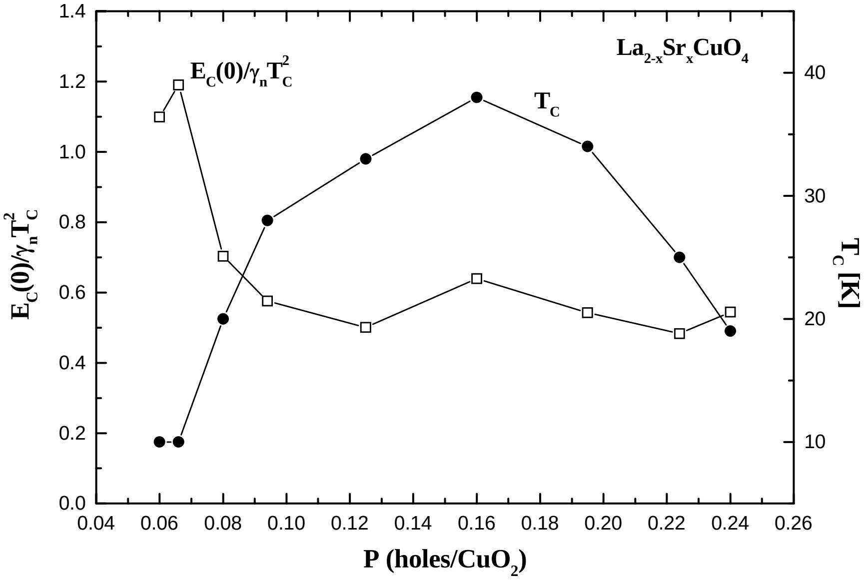


Figure 6: The T_c [6] and $E_c(0)/\gamma_n T_c^2$ values vs hole concentration p for La:214 samples.