# Superconducting condensation energy in the pseudogap region of $La_{2-x}Sr_xCuO_4$

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**Abstract**

The superconducting condensation energy at $T=0$, $U_0$, was examined from the measurements of the electronic specific heat $C_{el}$ on $La_{2-x}Sr_xCuO_4$. We reconfirmed that $U_0$ is markedly reduced in the pseudogap regime ($x \lesssim 0.2$). The doping-level ($p$) dependence of $U_0$ as well as $T_c$ can be explained in the pseudogap regime by introducing an effective energy gap $\Delta_{eff} = \beta p \Delta_0 (\beta = 4.5)$ instead of the maximum gap $\Delta_0$ at $T \ll T_c$.

*Key words:* condensation energy; pseudogap; $La_{2-x}Sr_xCuO_4$; specific heat

## 1. Introduction

The superconducting (SC) condensation energy at $T=0$, $U_0$, is exceedingly reduced even in slightly underdoped samples though their $T_c$'s are still high enough. This issue has been discussed in terms of a pseudogap, the evolution of an inter-plane phase coherence or the appearance of magnetic resonance in neutron scattering below $T_c$. [1,?,?] Another puzzling issue is an eccentric relationship between $T_c$ and the maximum gap $\Delta_0$ at $T \ll T_c$ in the underdoped region; that is, $\Delta_0$ continues to increase with the decrease of doping-level ($p$) whereas $T_c$ decreases there. [4,?] Recently it has been pointed out for $Bi_2Sr_2CaCu_2O_{8+\delta}$(Bi2212) and $La_{2-x}Sr_xCuO_4$ (La214) that $T_c$ roughly scales with $\kappa p \Delta_0 (\kappa \sim 1.7)$ instead of $\Delta_0$, as was first predicted by Lee and Wen theoretically, over a wide $p$-range including a slightly overdoped region. [6,?] The relation $T_c \sim \kappa p \Delta_0$, which is in sharp contrast to the BCS result, implies that the effective SC gap will be not $\Delta_0$ but $\beta p \Delta_0 (\beta = const.)$ there.

In the present study, we evaluated $U_0$ from the electronic specific heat $C_{el}$ measured on La214, and reconfirmed that $U_0$ is markedly reduced in the pseudogap regime ($x \lesssim 0.2$). It is demonstrated here that the $p$ dependence of $U_0$ can be well reproduced by introducing the effective SC gap $\Delta_{eff} = \beta p \Delta_0 (\beta = 4.5)$ instead of $\Delta_0$ in the pseudogap regime.

## 2. Experimental

The electronic specific heat $C_{el}$ was obtained by subtracting the phonon term $C_{ph}$, which was obtained on Ni-substituted non-superconducting samples, from the observed specific heat of superconducting ceramic samples. The partial substitution of Ni for Cu, which has little effect on the phonon system, enables us to determine the precise $C_{ph}$. [8]

## 3. Results and Discussion

We evaluated the SC condensation energy $U_0$ by integrating the entropy difference $S_n - S_s$ between $T = 0$ and $T_c$,

$$U_0 = \int_0^{T_c} (S_n - S_s)\, dT, \tag{1}$$

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where the subscripts $s$ and $n$ represent the SC and the normal state, respectively. Given both $\gamma_s = (C_{el}/T)_s$ and $\gamma_n = (C_{el}/T)_n$, we can obtain the entropy $S_s$ and $S_n$ by executing the integration $S_{s,n}(T) = \int_0^T (C_{el}/T)_{s,n}\, dT = \int_0^T \gamma_{s,n}\, dT$. In the present study, to obtain $\gamma_n(T < T_c)$ we extrapolated the data of $\gamma_n(T > T_c)$ down to below $T_c$ using a declining straight line (Fig. 1). The extrapolation was made on condition

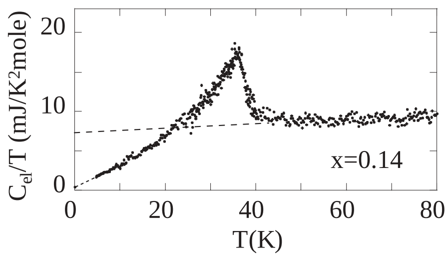


Fig. 1. T dependence of $\gamma = C_{el}/T$ of superconducting La214 (x=0.14). The broken line represents $\gamma_n(T < T_c)$ obtained by extrapolating $\gamma(T > T_c)$ down to below $T_c$.

that the extrapolated $\gamma_n$ should satisfy the constraint on the second order phase transition $S_n(T_c) = S_s(T_c)$, i.e., the so-called "entropy balance ". The SC condensation energy $U_0$ was calculated using $\gamma_s$ and $\gamma_n(T<T_c)$ thus obtained, and is plotted against $x(=p)$ in Fig. 2. The present results are consistent with those reported

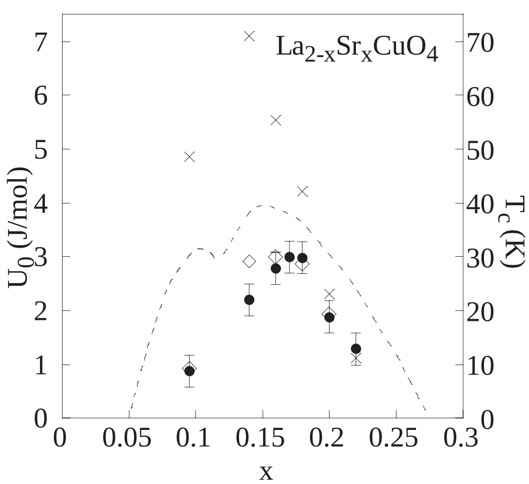


Fig. 2. SC condensation energy $U_0$ for La214. Experimental Data(•) are shown, together with both calculated values given by eq. (2) for $\Delta_0$(×) and $\Delta_{eff}(= \beta p \Delta_0)$ with $\beta = 4.5$(◇).

by Loram *et al.* for $x \lesssim 0.2$, but larger by about 40 % for $x < 0.2$. [1]

The SC condensation energy $U_0$(eV) for a flat DOS can be given by

$$U_0 \sim 2.1 \times 10^{-5} \alpha \gamma_n(T{=}0)\Delta_0^2 \qquad (2)$$

for $d$-wave BCS superconductors ($\alpha \sim 0.4$). [9] The condensation energy given by eq. (2) for $\gamma_n(T = 0)$(J/K$^2$mole) estimated above and $\Delta_0$(eV) determined in tunneling experiments on La214 [5] is shown in Fig. 2. The calculated values of $U_0$ are $2 \sim 4$ times larger than experimental values for $x < 0.2$. The serious disagreement between experimental and calculated values of $U_0$ at $x < 0.2$ seems to originate in the modification of the SC gap caused by the formation of the pseudogap. In fact, it has been pointed out that in the pseudogap regions of Bi2212 and La214, the effective SC gap $\Delta_{eff}$ will be not $\Delta_0$ but $\beta p \Delta_0 (\beta = const.)$ because $T_c$ scales with $p\Delta_0$ instead of $\Delta_0$, as mentioned above. Then we calculate $U_0$ again by substituting $\Delta_{eff} = \beta p \Delta_0$ for $\Delta_0$ in eq. (2) and treating $\beta$ as fitting parameter. In Fig. 2, the calculated value of $U_0$ for $\beta = 4.5$ is plotted against $x(= p)$. The new results can reproduce the experimental values very well over the whole $p$-range examined, as expected.

In summary- we evaluated the SC condensation energy $U_0$ from $C_{el}$, and reconfirmed that the $U_0$ is markedly suppressed in the pseudogap regime ($x \lesssim 0.2$) as well as $N(0)$. [10] The reduction of $U_0$ is too large to be explained by taking into account the reduction of $N(0)$, i.e., $\gamma_n$ only. To explain the experimental values of $U_0$ in the pseudogap regime, we have to introduce a new SC energy scale $\beta p \Delta_0 (\beta = 4.5)$, which plays a role as the effective SC gap, $\Delta_{eff}$, instead of $\Delta_0$. The new SC energy scale has been discussed in terms of the shrinkage of the Fermi surface to the nordal arcs near $(\pi/2, \pi/2)$, which is caused by the formation of a pseudogap or spinon pairing in the normal state. [6,**?**,**?**]


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