

Aspects of d-Wave Superconductivity+

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We highlight here some of works on impurity scattering and on the vortex state in d-wave superconductor. The model with impurity scattering in the unitarity limit describes not only the rapid suppression of the superconducting transition temperature but also concomitant generation of the residual density of states when Cu in the Cu-O₂ plane is substituted by a small amount of Zn. In a magnetic field parallel to the c axis we predict a square vortex lattice tilted by 45° from the a axis is most stable except in the immediate vicinity of $T = T_c$. The tilted square lattice, though elongated in the b direction, has been seen by small angle neutron scattering experiment and STM imaging in monocrystals of YBCO recently.

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We are now witnessing a striking success of d-wave model in high T_c cuprates [1,2]. Here we shall review our recent works on impurity scattering [3,4] and on vortex state in d-wave superconductor [5,6]. In particular the generation of the residual density of states (i.e. the density of states on the Fermi surface) due to Zn-substitution in LSCO is established by specific heat measurement by Momono and Ido [7,8]. Also this large density of states gives rise to a thermal conductivity which increases with Zn-concentration [4], which should be readily accessible experimentally. In vortex state in $B \parallel c$ a square lattice tilted by 45° from a axis is found to be most stable except in the immediate vicinity of the transition temperature T_c . We interpret an oblique vortex lattice seen in the vortex state in YBCO by a small angle neutron scattering (SAX) experiment by Keimer et al. [9] and by STM imaging by Maggio-Aprile et al. [10] as a square lattice elongated in the b direction due to the anisotropy within the u-b plane in orthorhombic YBCO (e.g. $\xi_a/\xi_b = 0.74 \sim 0.80$).

In Fig. 1 we show T_c/T_{c0} versus $N(0)/N_0$ obtained assuming that the impurity scattering is in the unitarity limit. Here T_{c0} is the transition temperature of the pure system and $N(0)/N_0$ is the residual density of states normalized by the one in the normal state. Experimental data is taken from Zn-substituted LSCO by Momono and Ido [7,8].

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It is remarkable that most of data follows closely the weak-coupling theory [8]. If we put the Knight shift data by Ishida et al. [11] from Zn-doped YBCO in Fig. 1, these data are somewhat further insides of the curve implying a strong-coupling effect of about 30% in YBCO [12].

At low temperatures (say $T \leq 0.05T_c$) the thermal conductivity κ is linear in T . Further the Wiedemann-Frantz law between κ and the real part of the conductivity $\sigma_1(0)$ is established [4]:

$$\kappa/\sigma_1(0) = \frac{\pi^2}{3} T/e^2. \quad (1)$$

Both κ and $\sigma_1(0)$ increase with impurity concentration [4].

The fourfold symmetry inherent to d-wave superconductor becomes clearly visible in the vortex state [2,5,6,13]. In Fig. 2 we show the Abrikosov parameter β_A for a square lattice tilted by 45° from the a axis and the one for usual triangular lattice in the presence of the Coulomb potential μ in the s -channel [14]. In this analysis the order parameter is taken as

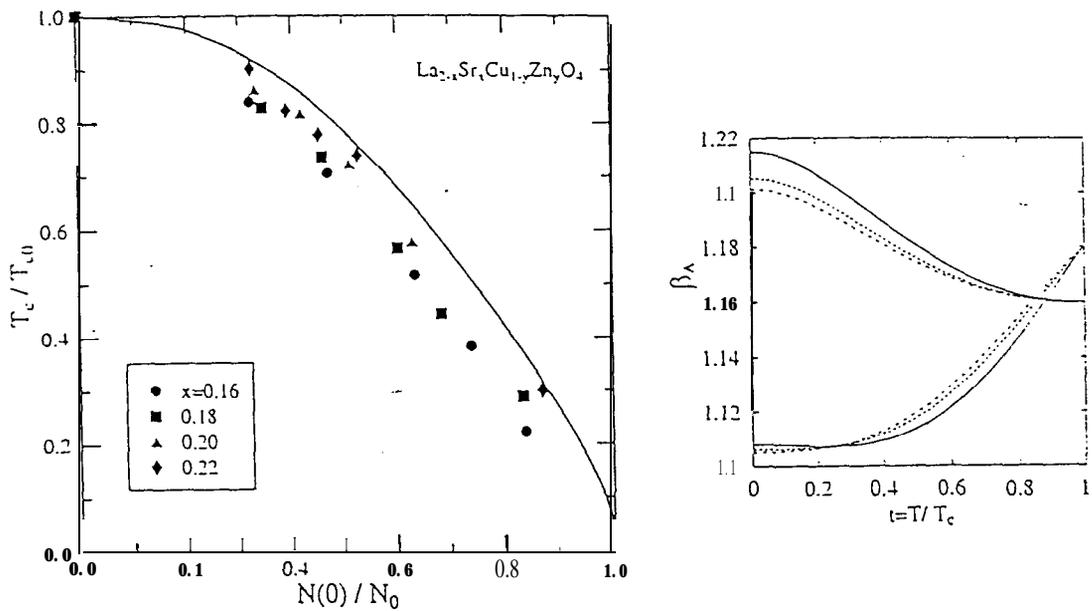


FIG. 1. T_c/T_{c0} versus $N(0)/N_0$ obtained from the specific heat data (Momono and Ido) [23] of $\text{La}_{2-x}\text{Sr}_x\text{Cu}_{1-y}\text{Zn}_y\text{O}_4$. The solid curve is the theoretical prediction [3]. It is remarkable that the data from $x=0.22$ are almost right on the theoretical curve.

FIG. 2. The Abrikosov parameter β_A for a triangular lattice (upper set of curves) and for a square lattice tilted by 45° from the a axis (lower set of curves) are shown for $\mu=0$ (solid line), 0.2 (dashed line), and 0.5 (dash-dotted line). Below around $0.8 T_c$, the square lattice becomes more stable independent of μ .

