Short Communication

High $T_c$ superconductivity by quantum confinement

A. Bianconi and M. Missori

Università di Roma, Dipartimento di Fisica, P.A. Moro 2, 00185 Roma, Italy

(Received 21 December 1993, accepted 4 January 1994)

Abstract. — We report the results of a careful experimental investigation of the Cu site configurations in the CuO$_2$ plane of Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212) showing that the quasi 2D Fermi liquid is confined in the stripes of width $L$ with a superlattice period $\lambda_p = 4.65\,\text{Å}$. The high $T_c$ superconductivity is stabilized at high temperature by tuning the Fermi energy of the 2D electron gas to the quantum resonance $k_Fy = 2\pi/L$. The confinement of a 3D electron gas in quantum wires can be realized by synthetizing Bi-Ca-Sr-Cu-O systems with some adjacent CuO$_2$ layers forming a metallic slab of thickness $H$. In this case the amplification of the critical temperature is assigned to quantization of the wavevectors along both the $y$ and $z$ directions satisfying the $k_{Fy} = 2\pi/L$ and $k_{Fz} = m\pi/H$ conditions.

The presence of polarons in the metallic phase of Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212) [1-3] has been investigated by measuring the Cu-O(apical) distance by Extended X-ray Absorption Fine Structure (EXAFS) experiments. In fact the local structure configurations associated with polarons can be described by two main configurational coordinates: 1) the shortening of the Cu-O(apical) distance due to Cu displacement from the CuO$_2$ plane and to the movement of the apical oxygen, and 2) the tilting of the apical oxygen from $(\pi, \pi)$ direction as in the low temperature orthorhombic (LTO) like structure to the $(0, \pi)$ direction in the low temperature tetragonal phase (LTT) like structure [4].

The idea of the present work is that by measuring the distribution of the long and short Cu-O(apical) bond lengths by EXAFS, and the modulation period $\lambda_p = 4.65\,\text{Å}$ by electron diffraction, it is possible to measure the width $L$ of the stripes of Cu sites of undistorted domains with LTO type structure confined between the stripes of polarons with the LTT structure. Experimental details have been reported elsewhere [5]. Two Cu-O(apical) distances 2.37 and 2.53 Å below $T_c$ have been found, in agreement with diffraction works [3] confirming the presence of domains with different Cu site configurations in the CuO$_2$ plane. The domains of the undistorted Cu sites, with the LTO type structure, are associated with the locus of the itinerant states giving a Fermi liquid. These domains form stripes of width $L$. In figure 1
we report the measure of \( L \) below \( T_c \), obtained by the measured values of \( N_{\text{long}}/N_{\text{tot}} \) in fact \( L/a = \lambda_p \left( N_{\text{long}}/N_{\text{tot}} \right) \).

This result allows us to describe the CuO\(_2\) plane as shown in figure 2 where polarons of area \( S_p = 4a^2 = 116 \text{ Å}^2 \) have condensed in a unidimensional charge density wave CDW, forming the polaronic stripes of width \( W = 2a \) with a LTT like structure. Therefore the CuO\(_2\) plane is decorated by two different Cu site structure configurations distributed in linear stripes.

This scenario shows that the Fermi liquid is confined in a superlattice of quantum stripes of width \( L \). The Bi2212 with two CuO\(_2\) layers form a quasi 2D electron gas. The anisotropic superconducting gap has been found to show a maximum in the \( \Gamma M \) direction with values of the components of the Fermi wavevector \( k_{Fx} = k_{Fy} = 0.37 \left( 2\pi/a \right) \) [6]. For a 2D-Fermi liquid confined in a quantum stripes of width \( L \) the \( k \)-vector is quantized in the \( y \) direction \( \left( k_{ny} = n\pi/L \right) \) and it is evident that \( k_{Fy} \) is very close to \( 2\pi/L = 1/2.7 \left( 2\pi/a \right) \), so the Fermi wavevector is tuned to the resonance \( n = 2 \).

The density of states of the superlattice of quantum stripes [7] is different from the density of states of the 2D square lattice, because it shows very intense and sharp peaks with maxima of the order of five-tens times the 2D density of states. If the Fermi energy is tuned at one of these maxima the superconducting critical temperature can be pushed up by a factor of the order of 5-10.

In fact for a standard superconducting metal following the BCS theory \( T_c \sim 2\omega_D \exp(-1/N_0V) \), where \( N_0 \) is the density of states at the Fermi energy and \( V \) is the electron-phonon coupling constant, therefore the increase of \( N_0 \) implies an increase of \( T_c \). Careful band structure calculations of the cuprates give the electron-phonon coupling constant \( V \sim 1.5 \) and the density of states \( N_0 \sim 0.15 \text{ states/eV-atom-spin} \) showing that \( N_0V \sim 0.2 \). Therefore by taking \( \omega_D \sim 500 \text{ K} \) as the Debye temperature we can calculate in first approximation, the critical temperature of a homogeneous CuO\(_2\) plane \( T_c \sim 7 \text{ K} \) predicted by the BCS theory. More refined calculations of \( T_c \) using the Allen-Dynes equation give \( T_c \sim 30 \text{ K} \) [8].

The enhancement of the critical temperature by forming metallic stripes of width \( L \) separated by stripes of width \( W \) can be calculated by following the solution of the gap equation of Thompson and Blatt [9] in a single film of a superconducting metal where the Fermi level is close and above the energy of the \( n \) resonance. The enhancement factor at the second resonance as found in the cuprates should be of the order of \( \exp(1/(3N_0V)) \sim 5 \) for a superlattice
in comparison with the homogeneous CuO$_2$ plane. Therefore the critical temperature can be enhanced by the confinement from the 7 (30) K range to the 35 (150) K range. The amplification factor depends on the resonance number $n$ and on the coupling term $N_0V$. In figure 3 we report the enhancement factor for the case of a superlattice of quantum wells as function of the resonance number for the case of $N_0V =$ 0.2 and 0.12, calculated by using the Thompson and Blatt approach. It is therefore clear that the largest amplification is obtained by tuning $E_F$ at the lowest resonances.

Fig. 3. — The ratio of the critical temperature $T_{cn}$ for a quantum well, with the Fermi energy tuned at the $n$ resonance normalized to the bulk critical temperature $T_{c\infty}$ for superconducting metals with different coupling constants $N_0V$, calculated by using the Thompson and Blatt approach.
The 3D superconducting state is stabilized by a superlattice where the distance between the wells or wires is less or of the order of the superconducting coherence length $\xi_0$ [10]. In fact in a superlattice is possible to rise $T_c$ by quantum confinement but in a single quantum well, as proposed by Thompson and Blatt, proximity effects and fluctuations will suppress the superconducting phase and $T_c$.

Recently Lagues et al. [11] reported high $T_c$ superconductivity in a Bi-Sr-Ca-Cu-O system with 8 CuO$_2$ layers. Following the present idea for the enhancement of $T_c$ by quantum confinement we propose that in the 8 layers compound a three dimensional (3D) Fermi liquid is confined in quantum wires as shown in figure 4. In fact by increasing the number of layers we expect to form a 3D Fermi liquid due to the hopping between the neighbor planes. Each quantum wire will have an effective thickness $H$ given by the slab of the 8 CuO$_2$ layers in the z direction and width $L$ in the y direction determined by the superstructure. For this quantum wire the $k$ vector will be quantized in two directions $y$ and $z$. The enhancement of $T_c$ in a superlattice of quantum wires is expected where $k_F$ is tuned to the quantized values $k_{yx} = m\pi/H$ and $k_{yz} = n\pi/L$, while in the quasi 2D electron gas in a single layer compound the quantization was only along the $y$ direction.

![Fig. 4. — Pictorial view of the superlattice of quantum wires that can be realized by tuning the Fermi level of a 3D electron gas to the resonance conditions $k_{Fy} = 2\pi/L$ and $k_{Fz} = 2\pi/H$.](image)

References


