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Charge Oscillations in Copper Oxide Superconductors

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ABSTRACT

The doped copper superconductors contain holes at a fraction of the oxygen sites in the copper-oxygen plane. The copper spins interact with the oxygen holes through the magnetic field which the motion of the holes produces at the neighboring copper sites. Integration over the degrees of freedom corresponding to the oxygen holes results in an effective magnetic interaction between the copper spins. Our calculation offers a basis for understanding the decrease of the spin wave stiffness of copper oxides with increased doping.

Keywords: Doped copper superconductors, Oxygen holes, vector potential, coherent charge oscillation, stripe phase, plaquette

INTRODUCTION

The mechanism of high temperature superconductivity in copper oxides e.g. $Y_1Ba_2Cu_3O_{6+x}$ and $La_{2-x}M_xCuO_4$ (where M is Ba, Sr or Ca and x is the fraction of doping between 0 and 1 still remains an open question [1]. However a number of important features have emerged. There appears to be consensus that superconductivity is confined to the CuO planes. The copper ions in these planes are in the valence state Cu^{++}, and the oxygen ions in the limit x = 0 are in the state O^{--}. As the doping fraction x is increased the valence state and the magnetic moment of the copper ions does not appear to change [2, 3].Increased doping causes an electron deficiency in the system resulting in some oxygen ions to exist in the O^- state, i.e. some oxygen ions have holes in the doped state in comparison to the reference state corresponding to zero doping. At zero as well as low doping the system is an insulator. In the doped state the charge carriers are oxygen holes. The motion of the holes involves the reversible transitions

$$O^{--} + h \rightarrow O^{-} \tag{1}$$

When these transitions occur at the same site we may think of it as a charge oscillation occurring at the same site. When transitions involve two different sites we may think of it as charge hopping between different sites. We shall confine ourselves to the doping limit where charge oscillation has been observed. Charge oscillation at the oxygen sites is also supported by µsr [4] experiments which show the signature of a dipolar magnetic field of electronic origin. In this paper we show that the magnetic field produced produces the stripe phase of superconductors (or spins which are alternately in opposite orientation. Further the coherent charge oscillations at the oxygen sites results in coherent radiation (in ThZ region) The calculated profile of this radiation agrees very well experimentally observed results [5].

2. Stripe Phase

Our model is illustrated in figure 1. Localized charge oscillations take place at the oxygen ions. These oscillations may be written as

$$p = p_z = p_0 \sin(wt) \tag{2}$$

The vector potential corresponding to this charge oscillation is [8]

$$A_z = \frac{1}{4\pi\varepsilon_0 c^2} \frac{wp_0 \cos(w(t - r/c))}{r} \tag{3}$$

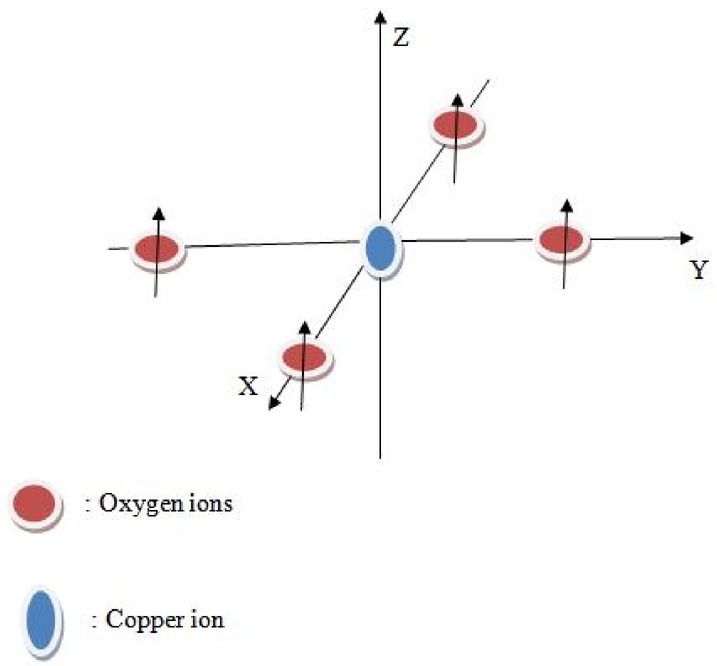

Figure . 1

The charges localized on the Oxygen ions undergo coherent oscillations along the z axis. These coherent oscillations give rise to the striped phase of High Tc super conductors and coherent radiation in the Tera Hertz region

We first note that the charge oscillations at the Oxygen sites are coherent. All the Oxygen sites will contribute the vector potential at a Copper site. The cosine term is replaced by

$$R = A[\cos(w(t - r/c)) + \cos(w(t - r/c) + \phi) + \cos(w(t - r/c) + 2\phi) + \dots + \cos(w(t - r/c) + (n-1)\phi) \quad (4)$$

where ϕ is the phase difference between one oscillator and the adjacent one. Performing the summation and substituting in (2) we obtain

$$A_z = \frac{1}{4\pi\varepsilon_0 c^2} \frac{wp_0 \cos(w(t - r/c))}{r} \frac{\sin(n\phi/2)}{\sin(\phi/2)} \quad (5)$$

The vector potential is zero when

$$\phi = \frac{2\pi}{n}, n = 1, 2, 3, 4.. \quad (6)$$

The vector potential is a maximum when

$$\phi = \frac{\pi}{n}, n = 1, 2, 3, 4... \quad (7)$$

The holes on Cu ions align themselves with the magnetic field when (6) is satisfied. In other words this is the condition for the occurrence of stripes in High T_c superconductors. Further the occurrence of the stripe phase is confirmation of the assumption made here that the charge oscillations are coherent.

3. Coherent Radiation from charge oscillations

Since the charge oscillations on the CuO plane are coherent, it stands to reason that the radiation from these oscillations will also be coherent. The time period of oscillations is in the range of pico seconds (the oscillation frequency is in the terahertz region). The power radiated by the oscillating charge is proportional to

$$\frac{dP}{d\Omega} \propto \sin^2(\theta) \quad (8)$$

Since charge oscillations are coherent each oxygen ion contributes to the radiated power with a differing phase as in (7). After taking into account the different contributions and squaring them we get

$$\frac{dP}{d\Omega} \propto \sin^2(\theta) \frac{\sin^2\left(\frac{n\phi}{2}\right)}{\sin^2\left(\frac{\phi}{2}\right)} \quad (9)$$

The radiated power is maximum when $\theta = \frac{\pi}{2}$ i.e. parallel to the CuO planes. Further the emitted coherent beam has both maxima, at positions given by (7) and minima given by (6). This profile has been confirmed experimentally [10].

IV. The RVB State

Anderson [14] has demonstrated that the RVB state is a natural ground state of the High Temperature Superconductors. However the mechanism via which RVB state is formed is still a subject of intense debate. The RVB are typically states singlets or plaquettes with no net magnetic moment. We know from section II that in striped superconductors adjacent spins are oppositely oriented. Further, in High T_c Solitons with spin are known to exist [11]. It has recently found that the superconducting state in high temperature superconductors is a superfluid state. The superconducting state, for high temperature superconductors displays zero viscosity. Goddard and Tahir-Kheli [15] have suggested that plaquettes are the natural ground states of high Tc superconductors. This agrees with our energy calculations. We note that double well potentials have been found in Cuprate superconductors with the minima at the Oxygen sites [16]. In a double well potential well the height of the potential well is given by $-\frac{A^2}{4B}$ [13]. K. H. Johnson, D. P. Clogherty and M. E. Mchenry [12] have found that delocalized Oxygen pπ bonds form shallow double wells. Electrons are trapped in these shallow double wells by the magnetic field generated by the charge oscillations. For 4 trapped electrons the trapping energy becomes $-\frac{A^2}{B}$. Since the Oxygen pπ bonds are delocalized the plaquette moves about in the lattice. The onset of superconductivity may be estimated from

$$k_B T_c = \left| \frac{A^2}{B} \right| \tag{10}$$

Here the height of a shallow double well is of the order of 10^{-3} ev. Since $k_B \approx 10^{-5}$ ev/T, $T_c \sim 10^2$ as observed.

IV. Conclusion

Based on the experimental results of charge oscillations in Cuprate superconductors, we have developed a model of coherent charge oscillations. These coherent charge oscillations result in the stripe phase and produce tera hertz radiation. Further, we suggest that electrons trapped in the shallow delocalized double well shaped pπ bonds form plaquettes which is the ground state of the high Tc superconductors.

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