The oxygen isotope effect on critical temperature in superconducting copper oxides

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The isotope effect provided a crucial key to the development of the BCS (Bardeen-Cooper-Schrieffer) microscopic theory of superconductivity for conventional superconductors. In superconducting copper oxides (cuprates) showing an unconventional type of superconductivity, the oxygen isotope effect is very peculiar: the exponential coefficient strongly depends on doping level. No consensus has been reached so far on the origin of the isotope effect in the cuprates. Here we show that the oxygen isotope effect in cuprates is in agreement with the bisoliton theory of superconductivity.

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FIG. 1. Oxygen isotope effect ($^{16}$O vs $^{18}$O) in LSCO, YBCO and Bi2212 (taken from Ref. [5]).

be much larger than the BCS value of 0.5 (according to the BCS theory, the isotope effect cannot be larger than 0.5). In the optimally doped region ($p \sim 0.16$), the oxygen-isotope effect is indeed small. With the exception of one point in LSCO, $p = 0.125$ (the so-called $1/8$ anomaly in LSCO), the doping dependence of the coefficient $\alpha_0$ is universal in these cuprates. The coefficient $\alpha_0$ has a maximum at $p \to 0.05$.

Even if a few attempts have been made in the literature to explain such a peculiar isotope effect in the cuprates [6], no consensus has been reached so far. The main purpose of this paper is to show that the isotope effect in cuprates can be well understood in the framework of the bisoliton theory of superconductivity for cuprates [7–11]. One of the chief results of the bisoliton model is that the potential energy of a static bisoliton, formed due to local deformation of the lattice, does not depend on the mass of the elementary lattice cell. This mass appears only in
the kinetic energy of bisolitons. It is a paradox: the effect of isotope substitution on the transition temperature manifests itself when the electron-phonon interaction is weak, and can disappear when the electron-phonon interaction becomes stronger!

The cuprates are materials with strongly correlated electrons. The Fermi-liquid approach is not applicable to this class of materials because the position and motion of each electron in these materials are correlated with those of all the others. If in metals, the electron-phonon coupling is weak and linear, in materials with strongly correlated electrons, it is moderately strong and nonlinear [11]. Therefore, phonons interact with charge carriers in conventional superconductors and in the cuprates in a different manner. For example, in BCS-type superconductors, $T_c$ increases with lattice softening, while in the cuprates, $T_c$ increases with lattice stiffening, as shown in Fig. 2. In the BCS model of superconductivity, only acoustic phonons participate in electron pairing, while tunnelling studies of the spectral function $\alpha^2 F(\omega)$ show that in cuprates, the charge carriers are coupled not only to acoustic phonons but also to optical ones [11]. The function $\alpha^2 F(\omega)$ is the parameter of the electron-phonon interaction in the Eliashberg equations, which characterizes the coupling strength between charge carriers and phonon vibrations. The energy of these optical phonons is about 73 meV. In the cuprates, the 73 meV branch is associated with half-breathing-like oxygen phonon modes that propagate in the CuO$_2$ plane.

The bisoliton model of superconductivity developed by Davydov for organic and high-$T_c$ superconductors [7–9] is based on the presence of one dimensionality in the system. So, in the bisoliton theory, the electron transport is considered along one-dimensional chain (when the bisoliton model was created there was no knowledge about charge stripes in the cuprates). Excess quasiparticles present on the chain can be paired in a singlet state due to the interaction with local chain deformation created by them. The potential well formed by a short-range deformation interaction of one quasiparticle attracts another quasiparticle which, in turn, deepens the well. The energy of a pair of quasiparticles moving in the field of local deformation of the lattice with a velocity $v$, called a bisoliton, is given by

$$E(v) = E_p(0) + \frac{m_{bs}v^2}{2},$$

where $E_p(0)$ characterizes the position of the energy level of a static pair of quasiparticles beneath their Fermi level $E_F$, and $m_{bs}$ is the effective mass of the bisoliton. The potential energy of a static bisoliton $E_p(0)$ is independent of the mass of the elementary cell $M$. At a small density of doped charge carriers, the effective mass of a static bisoliton can be represented as

$$m_{bs} \simeq 2m + \frac{8M\Delta_p}{ka^2},$$

where $m$ is the effective mass of quasiparticles; $\Delta_p$ is the pairing energy gap; $k$ is the coefficient of longitudinal elasticity, and $a$ is the distance between atoms on the chain. The mass of a bisoliton exceeds two effective masses of quasiparticles forming a bisoliton. It is worth noting that the weakest point of the bisoliton model of superconductivity is that the Coulomb repulsion of electrons is not taking into account. In spite of this fact, the bisoliton theory gives pretty accurate values of the Cooper-pair size in hole- and electron-doped cuprates [11].

Substituting the expression for $m_{bs}$ into Eq.(1), one obtains

$$E(v) = E_p(0) + mv^2 + \frac{4M\Delta_p v^2}{ka^2}.$$  

In this expression, only the last term contains the mass of the elementary lattice cell $M$. Therefore, in the framework of the bisoliton model, the isotope effect is determined by the product $\frac{\Delta_p v^2}{ka^2}$. Let us analyze its doping dependence. The divisor $ka^2$ is a weak function of $p$. The doping dependence of the pairing energy gap $\Delta_p$ in hole-doped cuprates is shown in Fig. 3. Figure 4 depicts the doping dependence of the velocity of nodal quasiparticles, determined by angle-resolved photoemission measurements. In Fig. 4(b), one can observe that the nodal high-energy quasiparticles in hole-doped cuprates move quicker in the underdoped region than in the overdoped region. Assuming that nodal quasiparticles with high

FIG. 2. Critical temperature as a function of Debye temperature for different cuprates [12].
energy play an important role in the occurrence of superconductivity in the cuprates, we obtain that, in the framework of the bisoliton model, the product \( \Delta_p v_{HE}^2 \) which determines the isotope effect has a doping dependence similar to that of \( \alpha_0 \) shown in Fig. 1. Thus, in the framework of the bisoliton theory, the doping dependence of \( \alpha_0 \) in Fig. 1 is natural. We are not going to discuss here the \( \tau \) point in LSCO, as well as the weak uprise of \( \alpha_0(p) \) in the overdoped region which can be due to several effects.

To conclude, we showed here that the isotope effect in the cuprates can be qualitatively understood in the framework of the bisoliton theory of superconductivity [7-11,5]. It follows from the fact that the potential energy of a static bisoliton, formed due to local deformation of the lattice, does not depend on the mass of the elementary lattice cell. In the framework of the bisoliton model, this mass appears only in the kinetic energy of bisolitons.

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