Jahn–Teller physics and high-T_c superconductivity

The discovery of high-temperature superconductivity in copper oxides was not accidental, but was based on the knowledge that the divalent copper ion, Cu^{2+}, is one of the strongest Jahn–Teller ions. The Jahn–Teller effect is a consequence of the interplay between electronic degeneracy and coupling to the lattice, i.e. unconventional local electron–lattice interactions. The search for superconductivity in copper oxides was motivated by the idea that Jahn–Teller polaron formation could be a novel and much stronger glue for electron pairing than conventional Bardeen–Cooper–Schrieffer electron–phonon coupling. The consequences of these ideas are unconventional isotope effects and complex pairing symmetries related to multiband superconductivity, which are reviewed here.

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The search for room-temperature superconductivity was motivated not only by the desire for resistance-free current in order to reduce energy costs, but was also an academic challenge, since until the mid-1970s, 30 K seemed to be the temperature limit for superconductivity. It should be recalled that superconductivity was discovered in 1911; it took nearly 60 years to achieve 25 K superconductivity. Only in 1957 were Bardeen, Cooper, and Schrieffer[1] (BCS) able to explain this phenomenon in terms of the interaction of electrons with lattice vibrations (phonons), which gives rise to an attractive channel for electron pairing. Since the phonon-mediated pairing mechanism imposes constraints on the maximum superconducting transition temperature, T_c, via the Eliashberg theory[2], novel mechanisms for the pairing have been proposed in terms of, for example, excitonic pairing, electronic mechanisms, and spin fluctuations, in order to achieve higher values of the transition temperature. A different approach was followed by Bednorz and Müller[3] who considered lattice-mediated pairing, not by incorporating classical lattice vibrations, but rather in terms of the Jahn–Teller polaron mechanism[4], which does not entail limits on T_c.

The Jahn–Teller effect[5] is based on the fact that degenerate electronic states can experience a lowering of their ground state energy by lifting this degeneracy through a lattice distortion. That these combined electron–lattice coupled objects can become mobile has been shown by Höck *et al.*[4], who introduced the concept of Jahn–Teller polarons. Since Cu^{2+} is one of the strongest Jahn–Teller ions[6], it was natural for Bednorz and Müller to concentrate on cuprates in their search for superconductivity. In addition, perovskite-type oxides are

ISSN:1369 7021 © Elsevier Ltd 2008

ideal candidates since the cubic lattice structure favors electronic degeneracy of the central transition metal ion, which can in turn be lifted via a lattice distortion. In addition, strong anharmonicity is present in these materials, and this is an important ingredient for polaron formation. That these ideas were indeed correct was proven in 1986 when high-temperature superconductivity was discovered in $La_{2-x}Ba_xCuO_4$[3], leading to an avalanche of efforts to discover further cuprate superconductors with even higher transition temperatures.

The microscopic origin of the pairing in cuprate high-temperature superconductors (HTSs) has still not been elucidated due to the fact that all undoped parent compounds are antiferromagnetic (AF) insulators with half-filled bands. Upon doping, the AF order is rapidly destroyed and a spin glass (SG) phase forms; this phase persists for a limited doping range, even in the superconducting phase, indicating phase separation (Fig. 1a). By increasing doping further, the SG phase is destroyed and superconductivity alone persists with high values of T_c. This already demanding phase diagram gains additional complexity due to the fact that a so-called pseudo-gap phase appears at high temperatures, T^*, over a large part of the phase diagram (Fig. 1a, b). While poor metallic properties are observed in the undoped and underdoped regime, this behavior changes smoothly to a strange metal followed by a conventional Fermi liquid on the overdoped side. The central issue in understanding the physics of HTSs is thus the description not only of the superconducting state, but of the full diversity of all phases observed.

An additional complication in the theoretical modeling of HTSs arises from the fact that the isotope effect at the optimum superconducting transition temperature (T_c^m)[8] almost vanishes, which has been taken as evidence that the lattice cannot be the glue to electron (hole) pairing. The AF properties of HTSs are mostly explained in terms of Mott–Hubbard physics, where a strong on-site Coulombic repulsion at the Cu ion prevents double occupancy and causes insulating behavior. Such a strong repulsion can be cast into rather simplistic t-J physics to which antiferromagnetism can be related[9]. As a consequence, there has been a huge theoretical focus on explaining HTS in terms of purely electronic models where the pairing mechanism was often explained in terms of spin fluctuations[9]. That these ideas are unrelated to the real physics of HTSs will be shown in the following, which focuses on various unconventional isotope effects, multicomponent superconductivity and polaron formation.

This article updates a recent summary written by one of the present authors in which the emphasis was on the intersite Jahn–Teller bipolaron[10]. These objects have been shown to be the generic quasiparticles of cuprates which are responsible for the formation of metallic clusters or stripes. They coexist with the regular lattice in regions where doped holes are located. In this way charge-rich and charge-poor regimes are spatially separated. However, as a consequence, huge strain fields are present which force the system into a dynamically ordered pattern. This dynamic aspect is, in turn, important since it induces substantial interactions between the two coexisting components.

The bipolaron ordering temperature can thus be considered as the energy scale for the onset of stripe formation, and is directly related to the pseudo-gap temperature T^* (Fig. 1a, b). At T_c, phase coherence sets in in both subsystems, and the interaction between them leads to pairwise exchange and high-temperature superconductivity.

Here we review important new developments in the field since Müller's[10] article appeared. These are related to unconventional isotope effects and multiband superconductivity.

Isotope effects

Comprehensive studies of the isotope effect on T_c started soon after the discovery of HTSs[11]. This effect shows an interesting

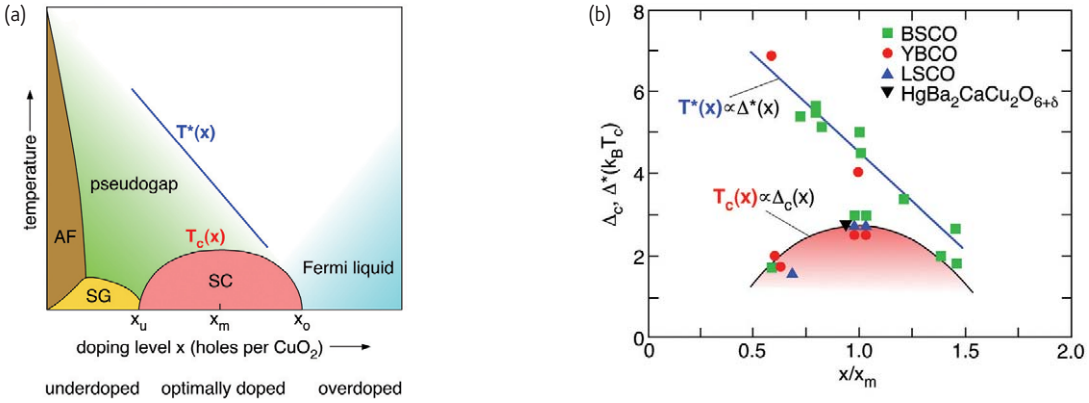

Fig. 1 (a) The generic phase diagram of cuprate superconductors as a function of doping x (AF, antiferromagnetic phase; SG, spin glass phase; SC, superconducting phase). (b) The experimental phase diagram as obtained by Andreev reflection for a number of cuprates is shown as a function of the reduced doping level x/x_m (x_m corresponds to the doping level where T_c is maximum within a given family). The appearance of the single-particle energy gap Δ^* coincides with T^* and the coherence energy range Δ_c corresponds to T_c. The gap values Δ^* and Δ_c are normalized to k_BT_c. (Reproduced with permission from[7]. © 2005 American Physical Society.)