12 Superconductivity and Magnetism

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We report on research projects in the field of high-temperature superconductors (HTS's) and materials with novel electronic properties. Our studies involve a number of complementary techniques, such as muon-spin rotation (μSR), neutron diffraction, X-ray absorption spectroscopy (XAS), and various standard magnetometry techniques.

12.1 Oxygen isotope effect on the static spin stripe order in $La_{2-x}Ba_xCuO_4$ ($x = 1/8$)

After the discovery of high-temperature superconductivity in $La_{2-x}Ba_xCuO_4$ (LBCO) numerous comprehensive studies have revealed a complex interplay between charge, spin, orbital, and lattice degrees of freedom [1]. In LBCO the superconducting (SC) transition temperature T_c shows a pronounced minimum at $x \simeq 1/8$ [2], known as the 1/8 anomaly. Here a structural transition from a low-temperature orthorhombic (LTO) to a low-temperature tetragonal (LTT) phase was observed [3]. Neutron diffraction experiments revealed two-dimensional charge and spin order in $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ [4]. It was proposed [4] that the dopant induced charge carriers, showing a periodically modulated spatial distribution forming a self-organized alternating array of charge and spin stripes, are pinned by the lattice modulation in the LTT phase, and T_c is suppressed. Later experimental studies indicate that uni-directional stripe-like ordering is in fact common to cuprates [5]. Despite of various attempts [6, 7], no consensus on the microscopic mechanism of stripe formation and the relevance of stripe correlations for high-temperature superconductivity in cuprates has been achieved. Exploring the mechanism of stripe formation may help to clarify the situation. The stripe phase may be caused by a purely electronic and/or electron-lattice interaction. There is increasing experimental evidence that a strong electron-lattice interaction is essential in cuprates (see, e.g., [8]) which may, however, not play a role in the formation of the stripe phase.

Isotope-effect experiments played a crucial role for understanding superconductivity. For conventional superconductors they clearly demonstrated that the electron-phonon interaction is responsible for the electron pairing. In the cuprate HTS's unconventional oxygen isotope ($^{16}O/^{18}O$) effects (OIE's) on various fundamental quantities were observed [8]. However, no OIE investigation on the charge and spin order in the stripe phase of cuprates has been reported.

We combined magnetization, zero-field as well as transverse-field μSR experiments in order to study the

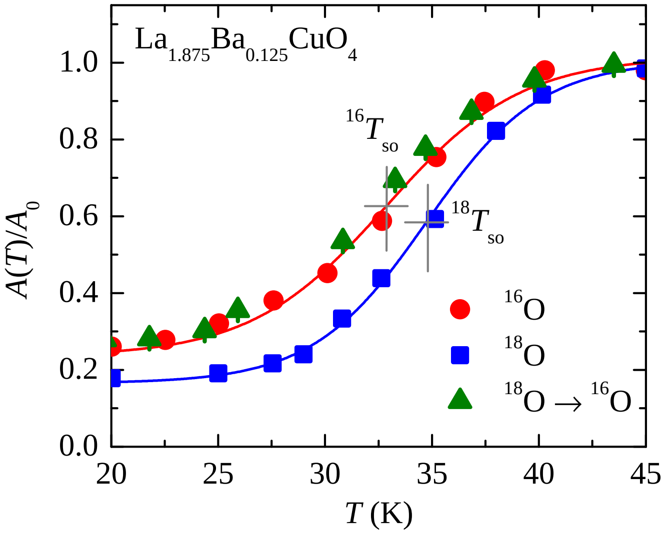

FIG. 12.1 – Normalized transverse-field μSR asymmetry A/A_0 versus temperature for ^{16}O, ^{18}O, and back-exchanged ($^{18}O \rightarrow {}^{16}O$) samples of LBCO-1/8.
The crosses mark the spin-stripe order temperatures T_{so}, of both ^{16}O and ^{18}O (from [9]).

OIE's on magnetic and SC quantities related to the static stripe phase of LBCO-1/8 [9]. μSR allows to determine separately the magnetic volume fraction and the order parameter in magnetically ordered materials. We found that the static spin-stripe order temperature $T_{\rm so}$ (see Figs. 12.1 and the magnetic volume fraction $V_{\rm m}(0)$ (see Fig. 12.2b) exhibit a large negative OIE which is novel and unexpected. This indicates that the electron-lattice interaction plays an essential role for the stripe formation in cuprate HTS's. Furthermore, the observed oxygen-isotope shifts of the superconducting transition temperature $T_{\rm c}$ (see Fig. 12.2) and the spin-ordering temperature $T_{\rm so}$ have almost the same magnitude, but opposite signs [9]. This provides clear evidence that bulk superconductivity and static spin-order are competitive phenomena in the stripe phase of LBCO-1/8, and that the electron-lattice interaction is a crucial factor controlling this competition. The present results may contribute to a better understanding of the complex microscopic mechanism of stripe formation and of high-temperature superconductivity in the cuprates in general.

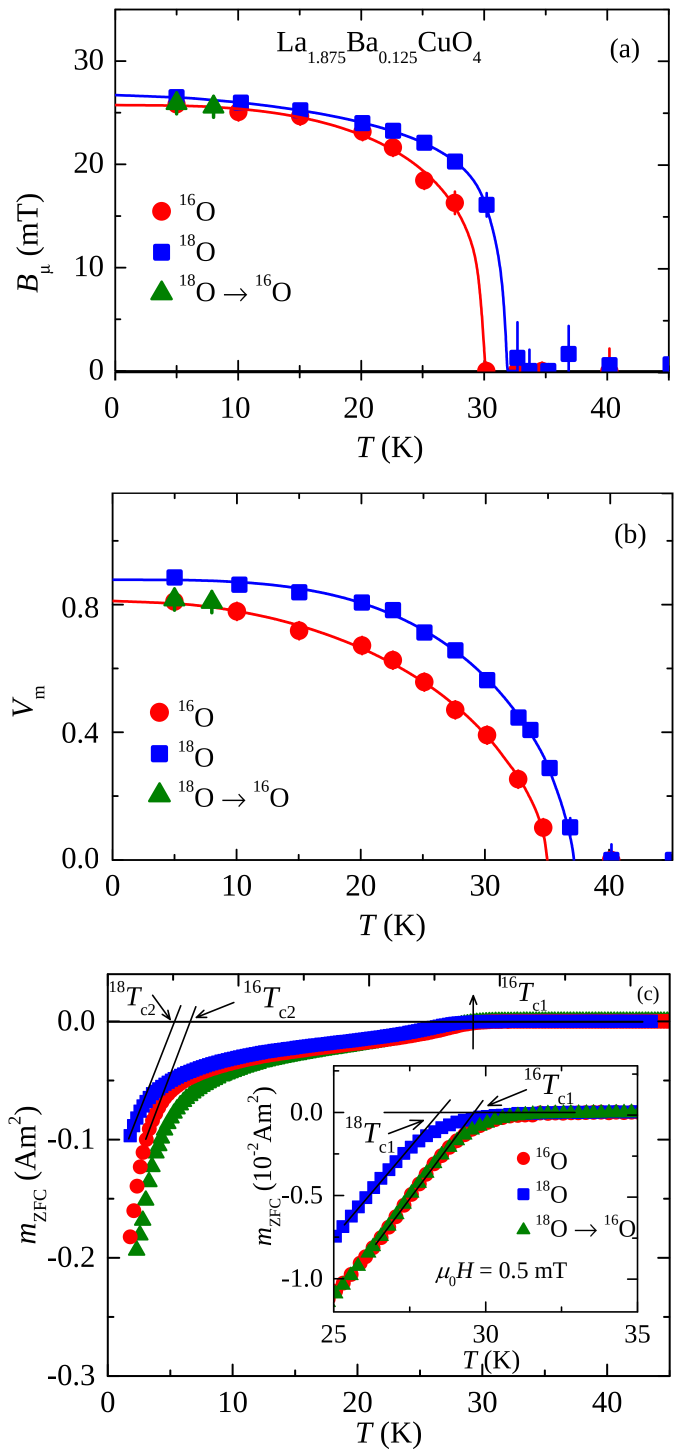

FIG. 12.2 – Comparative studies of ^{16}O, ^{18}O, and back-exchanged (^{18}O → ^{16}O) samples of LBCO-1/8 (from [9]). Shown are the temperature dependences of various observables.

Panels (a) and (b) show the average internal magnetic field B_μ at the muon site and the magnetic volume fraction $V_{\rm m}$, respectively. Solid lines represent empirical power-law fits. Panel (c) shows the diamagnetic moment $m_{\rm ZFC}$. The superconducting transition temperatures $T_{\rm c1}$ and $T_{\rm c2}$ are indicated. The inset gives a closer view of the SC transition near $T_{\rm c1}$.

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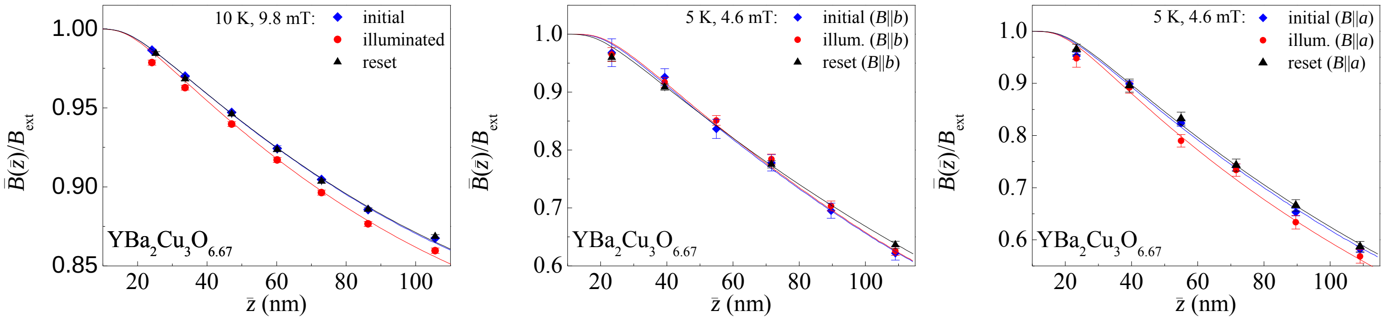

FIG. 12.3 – Magnetic penetration profiles $\bar{B}(\bar{z})$ normalized to the applied magnetic field B_{ext} for the thin-film set (left) and the detwinned ortho-VIII single crystal mosaic (other panels) of YBaCuO$_{6.67}$. B_{ext} is oriented parallel to either the crystallographic c axis (left), b axis (center), or a axis (right). The profiles correspond to the states before and after illumination and to the recovered state after one day at room temperature (from [5]).

12.2 Photo-induced effects on YBa$_2$Cu$_3$O$_{6+x}$ studied by low-energy μSR

Irradiation with light weakens the superconducting ground state in classical superconductors. Remarkably, studies on YBa$_2$Cu$_3$O$_{6+x}$ (YBCO) with reduced oxygen content ($x < 1$) show a persistent increase in the electrical conductivity after continuous illumination with visible light, both in thin films [1, 2] and in single crystals [3]. The critical temperature T_c increases for $0.4 \leq x \leq 0.9$ by up to 15 K [4].

We investigated the changes in the superfluid density n_s using the low-energy μSR technique. Muons were implanted at four different depths in a set thin-film samples ($x = 0.67$) for a determination of the magnetic screening profile $\bar{B}(\bar{z})$ in the Meissner state (see Fig. 12.3, left) [5]. Initially $\bar{B}(\bar{z})$ behaves as expected for a thin film in the Meissner state. After illumination $\bar{B}(\bar{z})$ shows a pronounced change in shape, shifted to lower values. After thermal reset the original screening profile is recovered so the photo persistent changes are fully reversible. Careful analysis of these data revealed that the changes of n_s appear on a length scale of only $50 - 60$ nm, corresponding to the light penetration depth determined in ellipsometry measurements [5].

Studies of single crystals reveal the role of disorder in the photo-induced effects. The investigated YBCO ortho-VIII single crystals consist of alternating Cu-O chains which are either empty or full, forming a superstructure. Therefore, the amount of disorder is greatly reduced compared to the thin-film sample set with equal doping level ($x = 0.67$). Moreover, the single crystals are detwinned which allows us to investigate the anisotropy of the photo-induced effects. In the ortho-VIII single crystal mosaic, the superfluid density at the vacuum interface is only increased if the magnetic field is applied along the crystallographic a axis (shielding currents flow along the Cu-O chains). Thus the magnetic screening profile is shifted to lower values for $B||a$-axis, but not for $B||b$-axis (see Fig. 12.3 center and right).

This anisotropic photo persistent behavior can be related to the in-plane anisotropy (different penetration depths λ_a and λ_b) present in YBCO. The large in-plane anisotropy is discussed in the context of multi-band effects. This picture suggests a contribution of the Cu-O chains to the superfluid screening current along the chain direction, leading to a lower λ_b. Since it is assumed that the illumination rearranges the Cu-O chains, the additional charge carriers may modify the contribution of the Cu-O chains to the superfluid density. Therefore, the photo-persistent effect would be clearly observed when the shielding currents flow along the chains ($B||a$), but would be virtually absent for $B||b$, as observed.

In conclusion we observed an anisotropic photo persistent effect in under-doped YBCO. The superfluid density is enhanced mainly close to the sample surface. These results can be explained by a self-organization of the Cu-O chains.

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