Spin Fluctuations in $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ (x = 0.25, y = 0.02)

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Neutron scattering studies of both elastic and dynamic spin ordering across the phase diagram of the prototypical, monolayer cuprate $La_{2-x}Sr_xCuO_4$ (LSCO) have shown a clear coupling between the existence of incommensurate, stripe-like, spin density wave (SDW) states and the presence of the high-T_c superconducting phase [1]. Undoped, LSCO (along with all other cuprates) is a long-range ordered, antiferromagnetic (AF) insulator. Upon doping however, the long range AF order is rapidly suppressed in favor of an incommensurate SDW state. In superconducting concentrations, this SDW phase manifests itself through an incommensurate quartet of magnetic peaks about the $\mathbf{Q}_{inplane}$ = (0.5, 0.5±δ), (0.5±δ, 0.5) wave vectors similar to those observed in systems exhibiting a known stripe ordered phase such as $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (with x = 0.12) [3]. Near optimal doping in LSCO (x ~ 0.15), the static SDW order breaks down and a well defined spin gap opens; however at low energies strong spin fluctuations remain distributed along the incommensurate SDW wave vectors $\mathbf{Q}_{inplane}$ = (0.5, 0.5±δ), (0.5±δ, 0.5). Upon continued Sr doping into the overdoped regime, this magnetic response becomes overdamped and spin excitations are suppressed concomitantly with superconductivity [4]. At 30% Sr doping, no discernable magnetic response remains – simultaneous to the disappearance of T_c. An effective route to study this microscopic coupling between SC and the incommensurate SDW states in LSCO further was realized by perturbing the superconducting state through the introduction of non-magnetic impurities (such as Zn) into the CuO planes and characterizing the resulting modification to the system's spin behavior.

The substitution of only a small amount of nonmagnetic Zn^{2+} impurities onto the Cu-sites in the $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ compound (LSCZO) results in a dramatic suppression of the superconducting phase [5]. Early transport measurements theorized that this Zn-substitution in fact stabilized stripe order at the expense of superconductivity; however neutron work subsequently uncovered that the Zn effect is to localize magnetic states within the spin gap of nearly optimally doped LSCO rather than merely closing the spin gap, as would be naively expected for stabilizing a dynamic stripe phase [6]. These subgap states have since been theorized to originate from a "Swiss cheese" picture of non-superconducting islands consisting of localized Cu moments induced in a halo about the Zn impurities within the superconducting planes [7]. Further experiments, however, have suggested that instead islands of superconducting regions form in which AF correlations coexist (and support electron pair formation), and these islands are intermixed within regions of Fermi-liquid, non-superconducting electronic states (about the Zn sites) [8]. This latter interpretation was introduced in order to explain experiments on Zn substituted, highly overdoped LSZCO (x = 0.25, y = 0.01) samples. These experiments demonstrated that the effect of Zn doping into LSZCO (x = 0.25, y = 0.01) was to surprisingly enhance the severely damped incommensurate magnetic scattering observed in overdoped LSCO [4]. The characteristic energy scale in the local susceptibility of Zn-free LSCO (x = 0.25) and Zn-doped LSZCO (x = 0.25, y = 0.01) remained identical in strong contrast to the subgap behavior reported for Zn doping into the LSZCO (x = 0.15, y = 0.01) system [6].

In order to understand the spin behavior in the overdoped regime further, we conducted experiments on the LSCZO (x = 0.25, y = 0.02) system in which we mapped out the spin fluctuations about the incommensurate SDW wave vectors at energies from ΔE = 3 meV to 12 meV on the C5 spectrometer. For this experiment, we coaligned 3 large single crystals LSCZO (x = 0.25, y = 0.02) within the [H,K,0] plane and mounted them in a closed cycle cooling cryostat. A fixed final energy of E_f = 14.7 meV was used and one PG filter was placed before the analyzer. Both monochromter (vertically focusing) and analyzer (flat) crystals were PG, and two different collimation settings were used: 33'-35'-40'-120' (tight) and 33'-48'-51'-120' (loose). To determine the spin excitation dispersion relation, we performed constant energy Q-scans around the (0.5, 0.5, 0) point in reciprocal space at different energy transfers. Figure 1 shows a typical Q-scan through (H, 0.5, 0) at 2 THz energy transfer and 6 K.

Our results reveal a surprising dispersion in the spin excitations about (0.5, 0.5), which is modified from the nearly dispersionless Zn-free LSCO (x = 0.25) response at these energies. Figure 2 shows this dispersion which strikingly resembles a renormalized version of the hour-glass type dispersion reported in optimally doped LSCO (x = 0.15); albeit the dispersion in this Zn-doped sample never truly reaches the commensurate position at $E_R \sim 7$ meV. The energy, E_R, with the minimum δQ from the commensurate in-plane (0.5, 0.5) position however corresponds to the renormalized energy scale of superconductivity in this system with $T_c \sim 11$ K, which would obey the linear relationship between E_R and T_c observed within other classes of cuprates ($E_R \sim 6k_B T_c$). The magnetic spectral weight for excitations below 12 meV also seems to retain its peak around 8 meV, similar to the reported results of more lightly Zn-doped samples of LSCZO (x = 0.25, y = 0.01).

The precise temperature dependence of this anomalous dispersion and the possible existence of inelastic spin signal at higher energies are the next natural step in this study and will be the focus of future experiments.

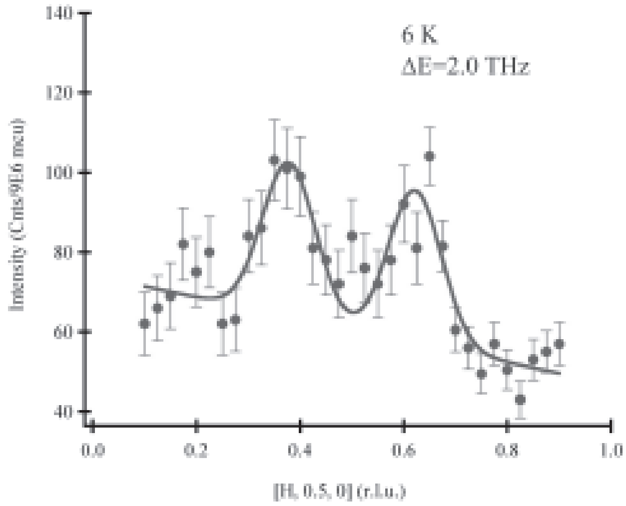

Fig. 1 *Q-scan through (H, 0.5, 0) at 2 THz energy transfer and at 6 K showing a typical fit utilized to determine the dispersion in LSCZO (x = 0.25, y = 0.02).*

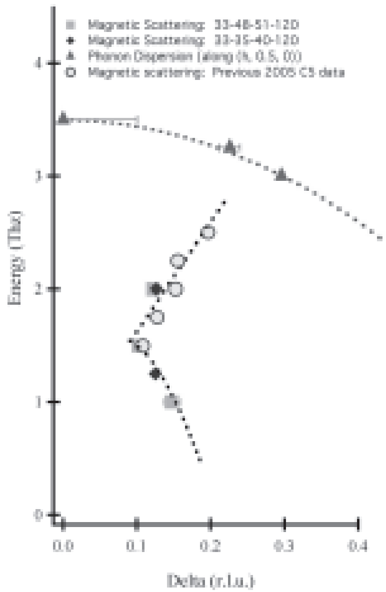

Fig. 2 *Dispersion of spin excitations and interfering phonon through (0.5± δ, 0.5) and equivalent positions. δ values represent the average displacement of the four incommensurate spin excitations from the (0.5, 0.5) position using the tetragonal unit cell.*

References

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