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Spin dynamics and sliding density wave in $Sr_{14}Cu_{24}O_{41}$ ladders

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Abstract

We use transport and Raman scattering measurements to identify the insulating state of self-doped spin 1/2 two-leg ladders of $Sr_{14}Cu_{24}O_{41}$ as a weakly pinned, sliding density wave with non-linear conductivity and a giant dielectric response that persists to remarkably high temperatures.

Keywords: Spin ladders; Charge density waves; Superconductivity; Raman spectroscopy

$Sr_{14}Cu_{24}O_{41}$ ladder compounds contain linear fragments of copper oxide planes. In contrast to the two-dimensional antiferromagnetic cuprates the spin 1/2 two-leg ladders have short-range magnetic order and a spin gap. Holes doped into these ladders pair and superconduct at high doping concentrations, while insulators are known to result from low hole concentrations. The competition between insulating states and superconductive pairing has emerged as a key feature of the high-T_c problem, but the character of the insulating states has remained elusive. Here, using transport and Raman scattering data, we identify the insulating state of self-doped two-leg spin ladders of $Sr_{14}Cu_{24}O_{41}$ as a weakly pinned, sliding density wave. This collective density-wave state exhibits a giant dielectric response, non-linear conductivity, and persists to well above room temperature [1].

In Fig. 1 we present the temperature dependence of the low-frequency Raman response function between 40 and 450 GHz measured for the (*cc*) geometry where the polarization of the incident and scattered photons are parallel to the legs of the ladders. A broad overdamped excitation is seen for high temperature scattering data below 1 meV (∼250 GHz). This quasi-elastic scattering peak (QEP) rapidly shifts to lower frequencies with cooling. In the figure we show a fit of these data by a relaxational form of the Raman response function

$$\chi''(\omega,T) = A(T)\frac{\omega\Gamma(T)}{\omega^2+\Gamma(T)^2}. \quad (1)$$

The fit reveals a decrease in the QEP intensity, $A(T)$, with heating and an Arrhenius temperature dependence with an activation gap $\Delta \simeq 2072$ K for the scattering rate $\Gamma(T)$. These observations at temperatures much higher than the QEP energy imply that the low frequency quasi-elastic Raman scattering reflects *collective* charge dynamics in the doped spin ladders and motivated us to perform a low-temperature transport study at low frequencies.

In Fig. 2 we display the complex dielectric constant $\epsilon = \epsilon_1 + i\epsilon_2$ as a function of frequency for temperatures between 85 and 150 K. The low-frequency response of ϵ_2 shows overdamped, inhomogeneously broadened peaks at characteristic frequencies $\nu_0(T)$ determined by damping parameters $\Gamma(T) = 2\pi\nu_0(T) = \tau^{-1}$ ($\tau(T)$ is relaxation time). These strong relaxational peaks lead to a giant real part of the dielectric response ϵ_1 below $\nu_0(T)$ observed up to room temperature and even above. Such behavior is incompatible with any single-particle theory since it would imply

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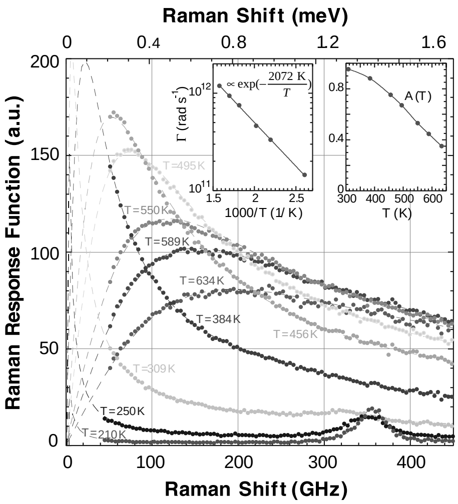

Fig. 1. The temperature dependence of the Raman response function in (cc) polarization: the data (circles) and the fit with Eq. (1) (dashed lines). The resonance at about 356 GHz at low temperatures is a phonon. Insets show the Arrhenius temperature dependence of the scattering rate $\Gamma(T)$ (left) and the slowly diminishing with heating quasi-elastic scattering intensity, $A(T)$ (right).

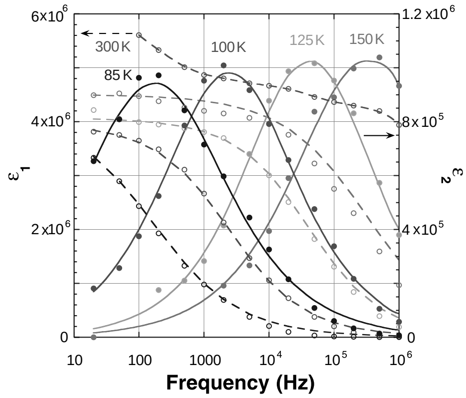

Fig. 2. Temperature dependence of the real (open circles) and imaginary (filled circles) parts of the complex dielectric function between 85 and 150 K. The dashed and solid lines are guides for the eye.

energy gaps more than six orders of magnitude smaller than the thermal energy. The figure illustrates the increase of the characteristic frequency $v_0(T)$ with heating.

We could scale all the measured complex dielectric functions between 80 and 160 K on one universal generalized Debye relaxational curve

$$\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_0 - \epsilon_\infty}{1 + [i\omega\tau(T)]^{0.58}} \tag{2}$$

where ϵ_0 and ϵ_∞ are low- and high-frequency dielectric constants [1]. The temperature dependence of the scattering rates $\Gamma(T) = \tau^{-1}$ from ac transport and Raman

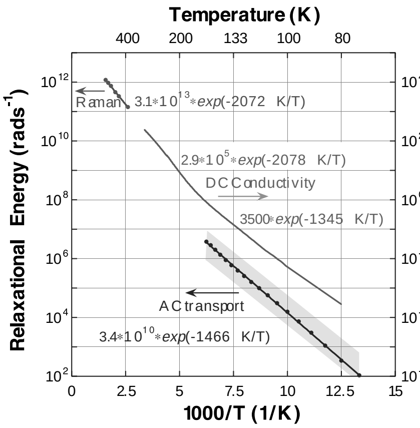

Fig. 3. The temperature dependence of the scattering rates $\Gamma(T) = \tau^{-1}$ from scaling of the ac dielectric (Fig. 2) and Raman (Fig. 1) response. The scattering rate (left scale) follows the activated behavior of dc conductivity (right scale) over 10 decades of frequencies.

measurements are plotted in Fig. 3 along with the dc conductivity. The figure emphasizes that the scattering rate $\Gamma(T)$ follows activated behavior of dc conductivity over 10 decades of frequency.

The Raman response function is proportional to $\Im\epsilon_L$. Although $\Gamma(T)$ extracted from the Raman data exhibits activated behavior with a gap consistent with dc conductivity, the values for $\Gamma(T)$ are about 50 times larger than the predicted relaxational energies [1]. The lowering of the peak intensity with increasing temperature (see Fig. 1 inset) suggests that there is a reduction of the density-wave amplitude which would produce a concomitant increase in Γ.

All our results have clear quantitative parallels with sliding density wave transport phenomena observed in established charge/spin density-wave materials, yet there must be a number of important microscopic differences from conventional weak-amplitude charge- and spin-density waves. The density-wave correlation in $Sr_{14}Cu_{24}O_{41}$ is a high-temperature phenomena that we observe up to the highest measured temperature, above 630 K. Such high temperature correlations cannot be supported by phonons and suggest that the charge/spin correlations arise from strong spin exchange interactions with characteristic energy scale $J \simeq 1300$ K [2]. Theoretical calculations for a doped two-leg spin ladder suggest that the holes are paired in a state of approximate d-wave symmetry with a few lattice spacings in size. The superconducting condensation of bound pairs is competing with a crystalline order of these pairs in a density-wave state.

References

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