LA-UR-98- - 4472

Title:

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AUG 18 1999
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Submitted to:

Ultrafast Phenomena XI

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Form No. 836 R5
ST 2629 10/91

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Nonequilibrium Superconductivity and Quasiparticle Dynamics in $\text{YBa}_2\text{Cu}_3\text{O}_7$

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Abstract. We use optical pump, coherent terahertz probe spectroscopy to transiently excite nonequilibrium populations of quasiparticles in $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$ and monitor, with picosecond resolution, the superfluid and quasiparticle dynamics.

We use an optical (1.5 eV, 150 fs) pump to transiently excite nonequilibrium populations of quasiparticles in superconducting $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$ (YBCO) and coherent terahertz spectroscopy [1] to monitor, with picosecond resolution, the subsequent interplay between the superfluid and the quasiparticle dynamics with the ultimate goal of understanding the character of the excited quasiparticles, their decay channels and relaxation times.

Previously, quasiparticle dynamics in YBCO have been studied using optical pump, optical probe spectroscopy.[2] However, the coherent detection of a terahertz probe permits a more direct picture of both the superfluid and the quasiparticle dynamics, yielding the real, $\sigma_R(\omega)$, and imaginary, $\sigma_I(\omega)$, parts of the conductivity over the frequency range from 0.2 to 0.8 THz, as a function of pump-probe delay. Using a two-fluid model,[3] the conductivity below T_c consists of a Drude-like component proportional to the number of quasiparticles and an imaginary component proportional to the superfluid population with an ω^{-1} dependence. Figure 1 reveals such transient spectra, $\sigma_R(\omega)$ and $\sigma_I(\omega)$, for $\text{YBa}_2\text{Cu}_3\text{O}_7$ at 4 K with an initially photoexcited quasiparticle density of $5 \times 10^{19} \text{ cm}^{-3}$. Before the pump arrives, $\sigma_R(\omega)$ is very small, indicating the

Figure 1: σ_R and σ_I are plotted for different pump delays at 4 K for $\text{YBa}_2\text{Cu}_3\text{O}_7$ and n is $5 \times 10^{19} \text{ cm}^{-3}$

presence of very few quasiparticles and $\sigma_i(\omega)$ is large and exhibits a ω^{-1} dependence due to the superfluid, consistent with a two-fluid picture. Immediately after excitation (0 ps) $\sigma_R(\omega)$ becomes large due to the creation of quasiparticles, while $\sigma_i(\omega)$ decreases and becomes roughly constant in ω because of both destruction of the superfluid component and a significant increase in a Drude component with a relaxation time of 0.2-0.4 ps.

Figure 2: σ_R and σ_I are plotted for $f=0.50$ THz versus pump delay for $\text{YBa}_2\text{Cu}_3\text{O}_7$ at 4 K for three different excitation densities.

To reveal the dynamics of the conductivity more clearly, we plot, in Figures 2 and 3, σ_R and σ_I at 0.5 THz and 4 K, as a function of pump delay for $\text{YBa}_2\text{Cu}_3\text{O}_7$ ($T_c = 85$ K) and $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ ($T_c = 55$ K) for three different excitation densities. For $\text{YBa}_2\text{Cu}_3\text{O}_7$ below T_c , the 1.5 eV pump pulse creates a highly excited quasiparticle distribution by absorbing $5 \times 10^{19} \text{ cm}^{-3}$ photons. The resulting large decrease in σ_i corresponds to nearly total destruction of the condensate ($> 10^{21} \text{ cm}^{-3}$ Cooper pairs), whereby, given a superconducting gap, Δ , of 0.03 eV, a 1.5 eV quasiparticle destroys $1.5 \text{ eV} / 0.030 \text{ eV} = 50$ superfluid carriers, creating as many quasiparticles. This destruction of the superfluid occurs in 1-2 ps. A temperature depend-

Figure 3: σ_R and σ_I are plotted for $f = 0.50$ THz versus pump delay for $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ at 4 K for three different excitation densities.

ent bottleneck in the condensate recovery occurs around 2-5 ps, resulting from an excess population of high energy (2Δ) phonons released during the quasiparticle recombination process which become locally trapped and can rebreak Cooper pairs. The initial recovery dynamics of the superfluid is both temperature and density dependent, occurring in 5-10 ps (10-20 ps) for $\text{YBa}_2\text{Cu}_3\text{O}_7$ ($\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$). As the excitation density is increased the number of phonons increases, and, as can be seen in Figures 2 and 3, delays the total recovery of the superfluid. In Figure 2, the rapid decrease in σ_R at high excitation densities, without the complementary increase in σ_I indicates that the quasiparticles are relaxing in such a way that they no longer contribute to the conductivity but are not yet reforming Cooper pairs. This behavior may be caused either by Anderson localization of the quasiparticles as they relax to the gap or an increase in mass due to a dressing of the quasiparticles by phonons. This relaxation mechanism is not seen in $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ (Figure 3).

In Figure 4, σ_R and σ_I for $\text{YBa}_2\text{Cu}_3\text{O}_7$ at a moderate excitation density of $2.5 \times 10^{19} \text{ cm}^{-3}$, are plotted for three temperatures near T_c (85K). In all cases a significant fraction ($> 20\%$) of the superfluid has not recovered after 20 ps indicative of a critical slowing down of the order parameter near a second order phase transition. Above T_c , for $\text{YBa}_2\text{Cu}_3\text{O}_7$, σ_R decreases by about 16%, corresponding to an increase in the scattering time, τ , which does not recover within 20 ps.

Figure 4: σ_R and σ_I are plotted for $f=0.50$ THz versus pump delay for $\text{YBa}_2\text{Cu}_3\text{O}_7$ for three temperatures near T_c (85 K). The excitation density, n , is $2.5 \times 10^{19} \text{ cm}^{-3}$.

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