Non-equilibrium quasiparticle dynamics in single crystals of YBCO ortho II

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Abstract

We report measurements of the photoinduced change in reflectivity of untwinned single crystals of YBa$_2$Cu$_3$O$_6.5$. The decay rate of the transient change in reflectivity was found to depend on the laser intensity and temperature strongly. By studying the intensity dependence at low temperatures we obtained the quasiparticle scattering coefficient from which we estimate the electron–phonon coupling constant.

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1. Introduction

Understanding low-energy excitations of cuprate superconductors is crucial for the theory of high-$T_c$ superconductivity. Studying non-equilibrium quasiparticle dynamics is one approach to achieve this. Pump probe spectroscopy is widely used to generate and measure non-equilibrium quasiparticles [1–3]. In this technique, a femtosecond laser pulse incident on the sample creates non-equilibrium quasiparticles which change the reflectivity of the sample. This change in reflectivity is measured by monitoring the change in the reflectivity of a weaker probe pulse. One can observe the relaxation of this non-equilibrium state as a function of time by changing the time delay between pump and probe pulses.

2. Experimental

Transient changes in reflectivity ($\Delta R/R$) of untwinned single crystals of YBa$_2$Cu$_3$O$_6.5$ ($T_c = 45$ K) are measured using degenerate optical pump probe spectroscopy at a photon energy of 1.5 eV. The optical pulses, produced by a mode-locked Ti:Sapphire laser, have duration of 100 fs, repetition rate 90 MHz, and center wavelength 800 nm. Pump and probe were focused onto the sample with a 20 cm focal length lens, yielding a spot size of 75 $\mu$m diameter. A photoelastic modulator varied the pump intensity at 100 kHz and a vibrating mirror oscillating at 40 Hz varied the time delay between pump and probe. This double modulation provides sensitivity to the fractional change in reflectivity $\Delta R/R$ of $10^{-7}$. This sensitivity is achieved by using phase sensitive detection with a 100 kHz reference signal from the photoelastic modulator.

3. Results

We begin by presenting the temperature and intensity dependence of the photoinduced reflectivity change. In Fig. 1a, the laser intensity is fixed at 2.5 mW and the temperature is varied between 5 and 70 K. All the curves are normalized to their value at zero time delay. One can see very clearly that the decay rate is increasing with increasing temperature. In Fig. 1b, temperature is fixed at 9 K and laser intensity is varied between 1.5 and
25 mW. Similarly the decay gets faster with increasing intensity.

In this paper, we focus on the intensity dependence of the decay at low temperatures. It is apparent that the curves in Fig. 1b are nonexponential. To characterize these curves, we plot the initial decay rate as a function of their unnormalized amplitudes in Fig. 2a. This reveals that the decay rate of these non-equilibrium quasiparticles is linear in their excitation density \[ b \]. Motivated by this, one can solve the bimolecular decay equation and obtain a time dependent expression for the amplitude.

To be able to fit the time traces, one also needs to account for the fact that the laser intensity decays with increasing depth below the sample surface. After correcting for this effect, we fit the time traces to the bimolecular decay equation. In Fig. 2b, the lines are the fits and the symbols are the data taken at 9 K for various laser intensities. This shows that these decays can be effectively described by a single coefficient \( b \), where \( b \) is the quasiparticle scattering coefficient and \( c = \frac{1}{C_0(1 - \frac{n}{n_0})} \frac{dn}{dt} = bn \). Since \( b \) is the proportionality constant between the decay rate \( \gamma \) and the excitation density \( n \), the value of \( b \) can be obtained from the slope of the line in Fig. 2a. After converting the reflectivity change \( (\Delta R/R)_{\text{norm}} \) to the excitation density \( n \), the value of \( b \) is determined to be 0.1 cm\(^2\)/s. The details of this analysis will be published elsewhere [4].

Kaplan et al. [5] obtained an analytical expression for \( b \) for a dirty s-wave superconductor in three dimensions. This model assumes that recombination is mediated by the electron–phonon interaction, which is not necessarily the case in the cuprates. According to their model \[ b = 4\pi x^2 F(2A)/N(0) \], where \( x^2 F(2A) \) is the electron–phonon coupling constant and \( N(0) \) is the density of states at the Fermi level. If we use this model for d-wave and substitute the expression for density of states in two dimensions for \( N(0) \), we obtain a very simple expression for the quasiparticle scattering coefficient: \( \beta \sim \frac{\hbar}{m^*} x^2 F(2A) \). If we use the previously estimated value for \( b \), we obtain \( x^2 F(2A) \approx 0.3 \).

In summary, we have presented optical pump probe measurements of quasiparticle dynamics in \( \text{YBa}_2\text{Cu}_3\text{O}_6 \). The quasiparticle decay rate is found to depend strongly on temperature and intensity. At low temperatures, the decay rate is linear in excitation density. From the linear dependence, we estimated the quasiparticle scattering coefficient \( \beta \) to be 0.1 cm\(^2\)/s. If quasiparticle recombination occurs with emission of a phonon, the electron–phonon coupling constant \( x^2 F(2A) \) is estimated to be around 0.3.

References