The Pairing Mechanism in HTSC investigated by Electronic Raman Scattering

A. Hoffmann, P. Lemmens, L. Winkeler, and G. Güntherodt

2. Physikalisches Institut der RWTH-Aachen, 52056 Aachen, Germany

By means of electronic Raman scattering we investigated the symmetry of the energy gap $2\Delta(\vec{k})$, its temperature dependence and its variation with doping of well characterized $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ single crystals. The oxygen content $\delta$ was varied between the under- and the overdoped regime by subsequently annealing the same single crystal in Ar and in $\text{O}_2$, respectively. The symmetry analysis of the polarized electronic Raman scattering is consistent with a $d_{x^2-y^2}$-wave symmetry of the energy gap in both regimes. The gap ratio $2\Delta_{\max}/k_B T_c$ and its temperature dependence changes with doping similar to predictions of theories based on paramagnon coupling.

1. INTRODUCTION

The symmetry of the superconducting order parameter or energy gap $2\Delta(\vec{k})$ gives an important clue to the mechanism of high $T_c$ superconductivity. Experiments which probe a possible phase shift in the order parameter with Josephson tunneling are in favor of a $d_{x^2-y^2}$-wave pairing. Moreover, various experiments, including electronic Raman scattering, are indicating the existence of nodes in the energy gap. A $d_{x^2-y^2}$-symmetry of the order parameter is predicted for a pairing mechanism based on spin fluctuations. Furthermore, there are theoretical predictions for the magnitude of the energy gap and its temperature dependence.

Electronic Raman scattering of free carriers occurs due to mass fluctuations about the Fermi surface. A continuous scattering background up to high frequencies is observed in all investigated high $T_c$ superconductors. At temperatures below $T_c$ this scattering background becomes renormalized for different frequencies below the energy gap $2\Delta(\vec{k})$, depending on the scattering geometry.

2. RESULTS AND DISCUSSION

We investigated the temperature dependence of the electronic Raman scattering in single crystals of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ and its variation with the oxygen content $\delta$. The crystals were characterized by magnetic measurements in a SQUID magnetometer, by X-ray diffraction, $c$-axis resistivity, and by Raman scattering. In order to change the oxygen content $\delta$, we annealed the same single crystal subsequently
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Fig. 1. Normalized intensities of the $A_{1g}$, $B_{1g}$, and $B_{2g}$ symmetry component of the electronic Raman scattering for (a) $\delta=0.17$ and (b) $\delta=0.29$.

| Oxygen content $\delta$ (K) | $T_c$ (K) | $A_{1g}$ $\text{max. (cm}^{-1}\text{)}$ | $B_{1g}$ $\text{max. (cm}^{-1}\text{)}$ | $B_{2g}$ $\text{max. (cm}^{-1}\text{)}$ | $2\Delta_{\text{max}}/k_B T_c$ |
|-----------------------------|----------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 0.17                        | 86       | 330±20                          | 370±30                          | 520±20                          | 8.7±0.3                         |
| 0.29                        | 81       | 280±20                          | 340±40                          | 460±20                          | 8.2±0.4                         |

Table 1. Positions of the maximum for different symmetry components. The maximum energy gap is determined by the $B_{1g}$ maximum.

In Ar and in $O_2$. After each annealing step $\delta$ was determined by comparing $T_c$ and the $c$-axis parameter to $T_c(\delta)$ and $c(\delta)$ known from iodometric titration of polycrystalline samples. For the Raman measurements we used the 488nm excitation line of an Ar$^+$-laser in quasi-backscattering geometry and power levels below 15 W/cm$^2$.

In order to suppress phonon peaks, and to emphasize the redistribution of the electronic Raman scattering intensity below $T_c$, spectra at $T=10$K are divided by spectra at $T=90$K, see fig. 1. In the underdoped ($\delta=0.17$, $\partial T_c/\partial \delta > 0$) and in the overdoped regime ($\delta=0.29$, $\partial T_c/\partial \delta < 0$) the frequency behaviors for the different symmetry components are consistent with a $d_{x^2-y^2}$-symmetry of the energy gap according to ref. 2, i.e. the low frequency behaviors and the maximum positions are different for the $A_{1g}$, $B_{2g}$, and $B_{1g}$ symmetry, see tab. 1. In the case of an energy gap with $d_{x^2-y^2}$-wave symmetry, $2\Delta(\vec{k})$ has a different weight in a particular direction of $\vec{k}$ for each symmetry component of the electronic Raman scattering. This leads to the different frequency behaviors. Regardless of the symmetry of the energy gap, the structure in $B_{1g}$-symmetry can be identified with the maximum energy gap $2\Delta_{\text{max}}$, see tab. 1. With doping the change of $2\Delta_{\text{max}}$ is stronger than the change in $T_c$, indicating non-BCS behavior ($2\Delta_{\text{max}}/k_B T_c \neq \text{const.}$).

In fig. 2a we show the temperature dependence of the $A_{1g}$- and $B_{1g}$-peak of an overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystal with $\delta=0.27$, $T_c=83$K. Both peaks show the same $T$ dependence up to $T/T_c=0.73$. This indicates that both peaks are due to the opening of the superconducting energy gap. In fig. 2b the temperature dependence of the $B_{1g}$-peak is shown for different oxygen contents $\delta$. Upon cooling below $T_c$ the energy gap opens more rapidly in the underdoped crystal ($\delta=0.17$).

The results shown here are in good agreement with earlier measurements on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals with different oxygen concentrations explained.
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Fig. 2. Temperature dependence of (a) the $A_{1g}$ and $B_{1g}$ peak for $\delta=0.27$, $T_c=83$K and (b) the $B_{1g}$ peak for $\delta=0.17$ and $\delta=0.29$ in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$.

by a change in anisotropy or dimensionality, i.e coupling between $\text{CuO}_2$ planes with doping. However, similar behavior is seen in the less anisotropic $\text{YBa}_2\text{Cu}_3\text{O}_7$.\[3\] For this reason we emphasize the similarity of this behavior with predictions based on paramagnon coupling. Within this model spin fluctuations have a pair-breaking and pair-binding effect. The opening of the superconducting energy gap leads to a decrease of low frequency spin fluctuations and thus to less pair-breaking. This feedback effect leads in underdoped samples to a more abrupt temperature dependence of $\Delta(T)/\Delta_{\text{max}}$ and to a higher magnitude of $2\Delta_{\text{max}}$ compared to BCS theory, and is in good agreement with our results. Since with increased oxygen content $\delta$ the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ single crystals are farther away from the antiferromagnetic insulator, this feedback effect should become reduced. This explains the smaller $2\Delta_{\text{max}}/k_BT_c$ and its weaker temperature dependence for the overdoped crystals compared with the underdoped ones.

In conclusion, the frequency dependencies of the different symmetry components of the electronic Raman scattering are consistent with a $d_{x^2-r^2}$-wave energy gap. Furthermore the measured magnitude of the energy gap, its temperature dependence and its variation with the oxygen content $\delta$ is consistent with a pairing mechanism due to antiferromagnetic spin fluctuations, i.e. paramagnon coupling.

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