Electronic Raman response in electron-doped cuprate superconductors

Zhihao Geng\textsuperscript{a} and Shiping Feng\textsuperscript{b}

\textsuperscript{a}Department of Physics, Beijing University of Chemical Technology, Beijing 100029, China
\textsuperscript{b}Department of Physics, Beijing Normal University, Beijing 100875, China

E-mail: zhhgeng@mail.bnu.edu.cn

Abstract. The electronic Raman response in the electron-doped cuprate superconductors is studied based on the $t$-$t'$-$J$ model. It is shown that although the domelike shape of the doping dependent peak energy in the $B_{2g}$ symmetry is a common feature for both electron-doped and hole-doped cuprate superconductors, there are pronounced deviations from a cubic response in the $B_{1g}$ channel and a linear response in the $B_{2g}$ channel for the electron-doped case in the low energy limit. It is also shown that these pronounced deviations are mainly caused by a nonmonotonic d-wave gap in the electron-doped cuprate superconductors.

For the $p$-doped cuprate superconductors, the results of Raman scattering measurements show that the electronic Raman response (ERR) depends linearly on energy in the $B_{2g}$ channel in the low energy limit, and depends cubically on energy in the $B_{1g}$ channel\cite{2, 3, 4}. However, in the $n$-doped counterparts \cite{1}, where although the low-energy behaviors of the $B_{1g}$ and $B_{2g}$ channels approach very specific power laws consistent with the presence of lines nodes in the superconducting (SC) gap, the pair-breaking peak energy values in the $B_{1g}$ and $B_{2g}$ channels can be different in some instances, while in some others they are virtually identical \cite{5, 6, 7, 8, 9}. The investigating similarities and differences of ERR between the $p$-doped and $n$-doped cuprate superconductors would be crucial to understanding physics of superconductivity in doped cuprates.

It has been shown that the essential physics of the $n$-doped cuprate superconductors is contained in the $t$-$t'$-$J$ model on a square lattice,

$$H = t \sum_{\sigma} PC_{i\sigma} P_{i+\gamma} + t' \sum_{\sigma} P C_{i\sigma} P_{i+\gamma} + \mu \sum_{\sigma} PC_{i\sigma} C_{i\sigma} + J \sum_{i\gamma} S_i \cdot S_{i+\gamma}, \quad (1)$$

The nontrivial part of the $t$-$t'$-$J$ model \textsuperscript{(1)} resides in the projection operator $P$ which restricts the Hilbert space to exclude the zero occupancy, i.e., $\sum_{\sigma} C_{i\sigma} C_{i\sigma} \geq 1$. We have developed a charge-spin separation (CSS) fermion-spin theory to incorporate the single occupancy constraint\textsuperscript{[10]}.

We have made a series of calculations for the ERR function. The results of (a) the $B_{1g}$ and (b) $B_{2g}$ spectra at the overdoping $p = 0.17$ in temperature $T = 3K$ are plotted in Fig. 1. We have also fitted the low-energy tails to an $\omega^3$ power law in the $B_{1g}$ response and linearly with $\omega$ in the $B_{2g}$ response, there are pronounced deviations from a cubic response in the $B_{1g}$ channel and a linear response in the $B_{2g}$ channel. Our present results show that these pronounced deviations in the $n$-doped counterparts are mainly caused by the nonmonotonic d-wave gap. For
the temperature dependence, the $B_{2g}$ spectrum as a function of energy with $T = 5.2\text{K}$ (solid line), $T = 8.2\text{K}$ (dotted line), and $T = 10.5\text{K}$ (dashed line) for $p = 0.17$ are plotted in Fig. 2. For the doping dependence, the (a) $B_{1g}$ and (b) $B_{2g}$ spectra as a function of energy with $p = 0.165$ (solid line) and $p = 0.17$ (dashed line) at $T = 3\text{K}$ are plotted in Fig. 3. We employ the shift of the leading-edge mid-point as a measurement of the magnitude of the gap at each doping concentration. The results for the extracted (a) $B_{1g}$ and (b) $B_{2g}$ peak energies as a function of doping with $T = 3\text{K}$ are plotted in Fig. 4. It is shown the maximum values of the peak energy for the $B_{2g}$ channel throughout the SC dome are very similar to the single particle spectroscopy gap values [1], and therefore continuously follows the SC transition temperature as $\omega_{\text{peak}}^{B_{2g}} \propto T_c$. Furthermore, incorporating with our previous results of ERR for the $p$-doped case [11], our present results also show that the domelike shape of the doping dependent peak energy in the $B_{2g}$ symmetry is a common feature for both electron-doped and hole-doped cuprate superconductors.

In summary, we have studied the doping and temperature dependence of ERR in the $n$-doped cuprate superconductors. Our results show that the pair-breaking peak energy in the $B_{2g}$ symmetry continuously follows the SC transition temperature $T_c$ throughout the SC dome as $\omega_{\text{peak}}^{B_{2g}} \propto T_c$, and therefore is a common feature for both $n$-doped and $p$-doped cuprate superconductors. Our results also show that these pronounced deviations from a cubic response in the $B_{1g}$ channel and a linear response in the $B_{2g}$ channel in the low energy limit are mainly caused by a nonmonotonic d-wave gap in the $n$-doped cuprate superconductors.
Figure 3. (a) $B_{1g}$ and (b) $B_{2g}$ spectra as a function of energy at $p = 0.165$ (solid line) and $p = 0.17$ (dashed line) for $T = 3K$. Inset: the corresponding experimental results of Pr$_{2-x}$Ce$_x$CuO$_{4-\delta}$ taken from Ref. [9].

Figure 4. (a) $B_{1g}$ and (b) $B_{2g}$ peaks as a function of doping for $T = 3K$. Inset: the corresponding experimental results of Pr$_{2-x}$Ce$_x$CuO$_{4-\delta}$ taken from Ref. [9].

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