Pseudogap and conservation of states in electron doped high-temperature superconductors

B. Welter [a,1], Y. Krockenberger [a], D. Einzel [a] M. Naito [b] R. Gross [a] L. Alff [a]

[a] *Walther-Meissner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany*
[b] *NTT Basic Research Laboratories, 3-1 Morinosato, Atsugi, Kanagawa 243, Japan*

Abstract

We report on tunneling spectroscopy measurements in underdoped $Pr_{2-x}Ce_xCuO_4$ (PCCO) in the temperature range between 2 K and 26 K and in magnetic fields up to 15 T. Our data show a pronounced depletion in the density of states near E_F in the normal state above B_{c2}. Furthermore, we find that the spectra in the superconducting state at 0 T do not follow the conservation of states rule. Yet the conservation of states is recovered after normalizing these spectra with that of the normal state in high fields, implying a coexistence of the superconducting gap and the pseudogap.

Key words: electron doped high-temperature superconductors ; tunneling spectroscopy; pseudogap

Recently, renewed interest in electron-doped high temperature superconductors (HTS) has arisen from the question whether the phase diagram is symmetric with respect to electron/hole doping. One of the main questions with respect to this symmetry concerns the existence of a pseudogap [1–3] on the electron doped side of the phase diagram. Very recently, considerable experimental evidence for a pseudogap in electron doped materials has been found. As in hole doped systems, a depletion in the density of states can be observed at two energy scales, one at the order of 100 meV [4–6], the other one at the energy scale of the superconducting gap [7,8]. As tunneling spectra mainly reflect the density of states (DOS) of the superconducting electrodes, tunneling spectroscopy is a useful tool to study changes in the DOS with an energy resolution of a few meV or below.

We carried out tunneling spectroscopy measurements on superconductor-insulator-superconductor (SIS) junctions based on bicrystal grain boundary junctions (GBJ). 300 nm thick c-axis oriented PCCO-films have been deposited by molecular beam epitaxy on [001] tilt bicrystal $SrTiO_3$ substrates with a misorientation angle of 36°. The sample preparation has been described in detail elsewhere [9]. Here, we will focus on data obtained from an underdoped PCCO sample ($x = 0.134, T_c = 20\,\mathrm{K}, B_{c2}(2\,\mathrm{K}) \approx 8\,\mathrm{T}$). A detailed analysis of the doping dependence is in progress and will be published elsewhere [10]. Fig. 1 shows the temperature dependence of unnormalized tunneling spectra in the superconducting state (a) and in the normal state (b), where superconductivity is quenched by a magnetic field of 15T perpendicular to the ab-planes. As reported before [7], no excitation gap is observed in the tunneling spectra above the transition temperature T_c, whereas a clear gap at the Fermi level is found in the normal state ($B > B_{c2}$) at low temperatures. This gap is of comparable magnitude to the superconducting gap and is filled with increasing temperature. Assuming a constant tunneling probability, the tunneling current is mainly given by the convolution of the DOS in both electrodes. As a consequence of the conservation of states rule ($\int N_S(E)dE = \int N_N(E)dE$) the integrated conductance $\int G(U)dU$ has to be the same in the superconducting and the normal phases. Passing from the

[1] Corresponding author. E-mail: bettina.welter@wmi.badw.de

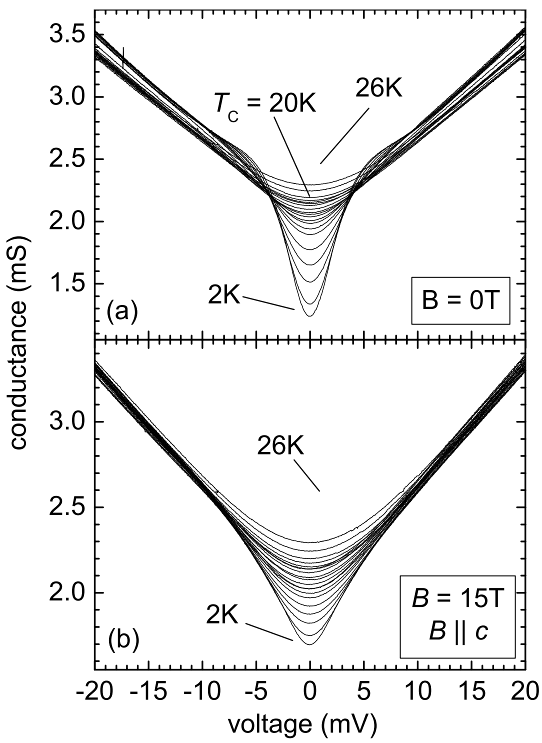

Fig. 1. Differential conductance spectra of a $Pr_{2-x}Ce_xCuO_4$-GBJ for temperatures ranging between 2 K and 40 K (a) in zero field and (b) in a field of 15 T perpendicular to the *ab*-planes

normal to the superconducting state, spectral weight is removed from the region within the gap to higher energies in such a way that the areas above and below the $G = G_N$-line cancel out. Fig. 2 shows a normalized tunneling spectrum at 2 K and 15 T (i). In order to remove background conductance effects, we normalized each conductance curve by a function of the form $f(U) = a + b \cdot \ln(\cosh(c \cdot U))$ which was fitted to the high energy range of the spectra. Looking at this normalized spectrum at 2 K and 15 T, it is evident that the area A is larger than $B_1 + B_2$. This means that there is a considerable loss of states near E_F. Yet, the conservation of states is recovered, if the tunneling curve at 2 K and 0 T is normalized by the spectrum taken at the same temperature but in a field of 15 T which suppresses superconductivity. To analyze this behavior more closely, both methods of normalization were applied to the spectra shown in Fig. 1(a) and the resulting normalized curves were integrated between 0 and 15 mV. If the conservation of states rule is satisfied, the integral should be constant. The deviation D of these integrals from the value expected for the normal state are shown in the inset of Fig. 2 as a function of temperature. The deviation of the field normalized curves at low T are about one order of magnitude smaller than those obtained from the corresponding

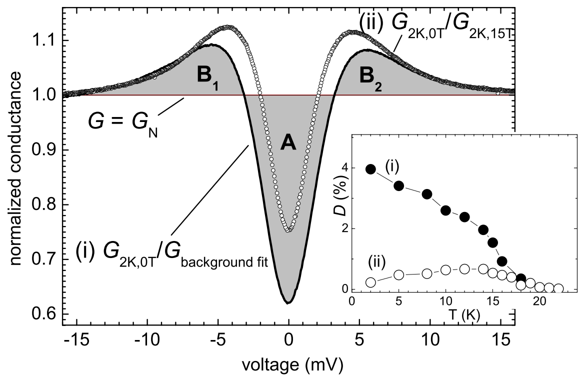

Fig. 2. Spectra at 2 K and 0 T, normalized by a background fit (i) and by the spectrum taken at 2 K and 15 T (ii). The inset shows the deviation D of the integrated conductance curves from the normal state value for both normalization methods.

curves normalized by a curve fitted to the background conductance. This strongly suggests the coexistence of the superconducting gap with the pseudogap below T_c, thus ruling out the possibility of preformed pairs as origin of the pseudogap. Very similar results were found in underdoped $Bi_2Sr_2CaCu_2O_y$ [11], indicating a possible common origin of the pseudogap in electron and hole-doped cuprates.

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