Comment on "Pseudogap Precursor of the Superconducting Gap in Under- and Overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$"

In a recent Letter Renner et al. [1] reported scanning tunneling spectroscopy on $Bi_2Sr_2CaCu_2O_{8+\delta}$ claiming several new results: The order parameter symmetry is doping independent, the pseudogap persists into the strongly overdoped region, and the pseudogap evolves continuously into the superconducting gap. They conclude that "the pseudogap is directly related to superconductivity and shows either the presence of important superconducting fluctuations or preformed pairs above T_c."

With their first point we concur: μSR studies of impurity scattering show d-wave symmetry to be preserved across the under- and overdoped regions [2]. We do not have a consensus, however, on their principal conclusion. NMR and heat capacity [3–5] both show the pseudogap and superconductivity to be *independent* and *competing.* Their respective gap energies E_g and Δ_0 have different magnitudes and doping dependences, with the former falling to zero in the lightly overdoped region [4]; there is an isotope effect in the latter but not in the former [5]; and the shear magnitude of E_g exceeding 1000 K at low doping must surely preclude precursor pairing. We wish to argue here that the smooth evolution of tunneling spectra from the pseudogap into superconductivity does not necessarily imply the pseudogap is a short-range pairing state with the same mean-field gap energy as superconductivity.

We adopt the Fermi liquid model of Loram *et al.* [3] referring the reader to justification elsewhere [6], particularly in the light of the issue of incoherent states near the zone boundary. In this model the total anisotropic gap, $\Delta(T, \mathbf{k})$, is expressed as

$$[\Delta(T, \mathbf{k})]^2 = [\Delta'(T)\cos(2\theta)]^2 + [E_g|\cos(2\theta)|]^2,$$

where Δ' is the order parameter, and E_g is found to be essentially T independent and assumed thus. The BCS gap equation is solved within this model and the density of states (DOS) is expressed as a tunneling conductance at different temperatures in Fig. 1, where the DOS has been thermally broadened. The adopted values: $\Delta_0 = 44$ meV is taken from Renner *et al.* [1] for the underdoped sample with $T_c = 83$ K, and $E_g = 34$ meV is a reasonable estimate based on other cuprates. The key result is that the simulated spectra evolve smoothly with no perceptible change at T_c but in no way imply that the pseudogap is precursor superconductivity. The small displacement of the peak to lower energy near T_c is due to the fact that $E_g < \Delta_0$, while the outward movement at higher T is due to thermal broadening. These effects may be too small to discern in the more broadened spectra of Renner *et al.* [1] but the inward movement of the peaks near T_c should be visible in the spectra for the optimally doped sample, where E_g should be substantially less than Δ_0.

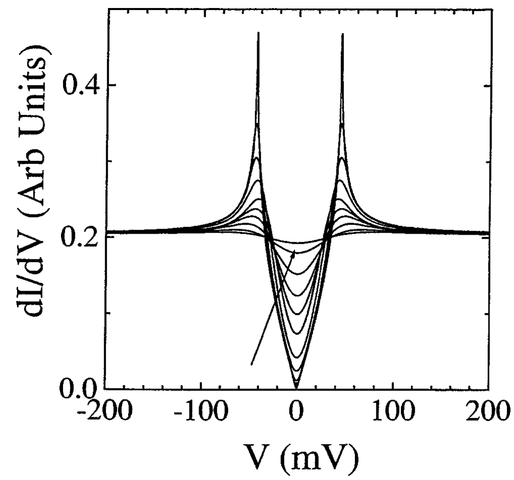

FIG. 1. Calculated tunneling spectra for underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ within the competing pseudogap model for $T = 0$, 21, 43, 64, 84, 104, 124, 154, 204, and 254 K. Arrow indicates increasing temperature.

As a highly local and surface probe, STM is probably not fully representative of the bulk and affected by either inhomogeneity or the fact that the probed area is comparable to a pair size and separation. The STM gap is found to be the same ($\approx$40 meV) on the underdoped and overdoped sides (Figs. 2 and 4 of [1]) and the fact that the overdoped normal-state gap extends only as high as 90 K (the maximum T_c) would suggest that this is just the superconducting gap exposed below $T_{c,\max}$ by inhomogeneity or averaging of the surface and bulk. In contrast, in underdoped, optimal [7], and *lightly* overdoped [7] samples the pseudogap spectra extend to 300 K or more. We are not convinced that, contrary to bulk NMR and heat capacity results, the pseudogap persists deep into overdoping and scales with the superconducting gap. Indeed in Fig. 2 of Renner *et al.* the pseudogap features move out from 40 to 100 meV at high T. The underdoped data certainly show pseudogap features, but the overdoped STM features may well be superconducting contributions below $T_{c,\max}$ in an inhomogeneous system.

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