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DENSITY OF STATES AND TUNNELING CHARACTERISTICS OF LAYERED SUPERCONDUCTORS*

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DENSITY OF STATES AND TUNNELING CHARACTERISTICS OF LAYERED SUPERCONDUCTORS

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We have studied the structure of the density-of-states (DOS) curves and tunneling characteristics of layered superconductors with two distinct layers in a unit cell. In general, the peaks of the DOS curves do not correspond to energy gaps of each layer, but depend on the gaps and the interlayer hopping strengths in a complex manner. This makes the interpretation of tunneling data of layered superconductors much less straightforward than isotropic superconductors. Our simulated tunneling characteristics bear certain resemblance to experimental results.

Electron tunneling is a powerful technique for studying the energy gap structure of superconductors. While details of experimental results on high- T_c superconductors are under debate, it is generally accepted that the main peaks in the tunneling characteristics are not BCS-like, and there may be structures both inside and outside the main peaks. In recent years a number of authors have analyzed the DOS and tunneling characteristics of layered superconductors with more than one distinct layers per unit cell, in both the weak hopping [1,2] and the strong hopping limits [3]. In this paper we report our investigation of a two-layer model in the intermediate hopping regime, i.e. the interlayer hopping strengths are comparable to the critical temperature. We show that the theoretical results of both weak hopping and strong hopping limits are incomplete. The peaks in DOS do not correspond to the gaps of either layer, but are determined by the gaps and the hopping strengths in a complex manner. We conclude that the tunneling curves must be interpreted with caution.

The model consists of two layers in a unit cell, with identical quasiparticle band structures within the layers and hopping strengths J_1, J_2 between adjacent layers. In the intralayer pairing model the quasiparticle pairs are assumed to be in the same layer. The pair coupling strengths are designated λ_{01} and λ_{02} , and the order parameters of the layers are Δ_1 and Δ_2 respectively. The standard formulation gives two gap equations such that each Δ_n is equal to λ_{0n} multiplied by a nonlinear expression involving both Δ 's. Due to space

limitations, we will not duplicate the derivation of these equations, but will refer interested readers to our earlier publications [4].

In the zero hopping limit, the two layers form two independent superconducting systems whose critical temperature T_{c0} is determined by the stronger of the two coupling strengths λ_{0n} . The DOS curve consists of two sets of BCS anomalies, each corresponding to a Δ_n . For nonvanishing but weak J 's, i.e., $J_n \ll T_{c0}$, T_c is reduced from T_{c0} , but the DOS can still be interpreted in terms of the zero hopping model [1,2]. In the opposite limit, $J_n \gg T_{c0}$, we find that the energy gaps are associated with the quasiparticle bands, not with the layers [3], and T_c is determined by the average coupling strength. The DOS has peaks which measure the gaps at the Fermi surface. In the intermediate hopping regime we solve the gap equations numerically, and the resulting $\Delta_n(T)$'s are plotted versus the reduced temperature T/T_c as shown in Fig. 1. These results allow us to calculate the DOS at finite temperatures, and then the tunneling characteristics by folding with the Fermi distribution functions [5]. A set of such curves is shown in Fig. 2.

The zero temperature tunneling curve, which is identical to DOS, has peaks nearly halfway between Δ_1 and Δ_2 . The peaks are not as sharp as that in the BCS theory, for reasons to be discussed in a future publication. There is an additional structure outside of Δ_1 , which is the larger of the two gaps. The position of this feature is insensitive to the temperature, and is determined mainly by the hopping strengths

Figure 1. Temperature dependence of layer energy gaps.

Figure 2. Tunneling characteristics of two-layer intralayer pairing model.

J_n . We trace its origin back to Cooper pairs in different bands, called interband pairs by the present authors [3,4]. With increasing hopping strengths the feature weakens and moves outward. The theoretical curves resemble those observed in BCSO [6].

In the interlayer pairing model the Cooper pairs are assumed to reside in adjacent layers, with pair coupling strengths λ_1, λ_2 . These produce two order parameters Δ_1, Δ_2 , which depend on T similar to Fig. 1. The tunneling characteristics, shown in Fig. 3, exhibit additional features inside the main

Figure 3. Tunneling characteristics of two-layer interlayer pairing model.

peaks. The origin of these features is the c-axis versus ab-plane gap anisotropy discussed earlier by the present authors [3]. The peak structures outside the main peaks are again the result of interband pairing. The theoretical curves resemble those observed in YBCO [7].

We conclude from this study that the tunneling data of layered superconductors must be interpreted with caution. Conversely, a detailed analysis of the data may reveal the nature of the pairing mechanism.

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