On the nature of superconductor pseudogaps

N. Kristoffel
Institute of Physics, University of Tartu, Riia 142, 51014 Tartu, Estonia
Institute of Theoretical Physics, University of Tartu, Tähe 4, 51010 Tartu, Estonia

Abstract

The physical origin of cuprate high-temperature superconductor pseudogaps remains debatable. We point out that the indication of such excitation is hidden in the usual expression for the quasiparticle energy. It can be realized on a suitable multiband spectrum with an interband pairing channel. The band components bearing the chemical potential manifest superconducting gaps. A band with the Fermi energy outside creates a pseudogap type excitation. The latter does not characterize the pairing strength. On a doping-driven spectral arrangement the nature of low-energy excitations changes with doping. The pseudogap appears as a precursor of the corresponding superconducting gap on the doping scale. The corresponding critical points on the phase diagram are determined by the doping-driven overlap dynamics of the bare gapped electron spectrum.

The pseudogap conception is connected with a peculiarity in the excitation spectrum of cuprate high-temperature superconductors. A depletion of low-energy excitation density around the Fermi level is observed in both the superconducting and the normal state. Since this gap feature survives in a remarkable extent at $T > T_c$ it has been designated as a pseudogap [1-4].

The pseudogap energy scale markedly exceeds the condensation energy, especially in the underdoped region. With an extended doping the pseudogap decreases and is quenched at a slight overdoping. Further, the spectrum remains determined by the superconducting gap(s). A magnetic counterpart of
the charge-channel pseudogap is also known in the spin-excitation spectrum. The physical origin of the pseudogap remains a widely debated problem with no consensus reached. Two major approaches to the nature of the pseudogap have been elaborated: (i) the internal, and (ii) the extrinsic one.

The internal approach relates the pseudogap immediately with the pairing strength, i.e. considers it as a precursor of the superconducting gap on the energetic scale. Here belong the approaches with preformed pairs (without any phase coherence at $T > T_c$), or the ones based on superconducting order fluctuations [1-6]. Recent experimental data seem to prefer the extrinsic scenario [2, 4]. Here the pseudogap source is reduced to bare normal-state gaps of various origins [1-3,7-10].

In the extrinsic mechanisms a gapped (at least a two-band) system must show the superconductivity besides the pseudogap. The two-gap behaviour of cuprates has been revealed by recent spectroscopy data [11-13]. As a minimum, it means the presence of a pseudogap plus a superconducting gap, or two pseudogaps and a superconducting gap [14-16], on the same doping. Indeed, in a gapped two-band system a spontaneous appearance of the superconductivity is possible [17], if the condensation energy prevails the bare gap. However, another highly-effective pairing channel can be operative [17-19]. It consists in the pair-transfer between band components. This mechanism, known already for a considerable time [20, 21], provides the simplest way to reach high transition temperatures in a multiband system. Here the pairing can arise by repulsive interband interaction, which operates in a considerable volume of the momentum space. There has been a number of multiband approaches to cuprate superconductivity (e.g. for review [18,22-26]). However the nature of coupled band components has often remained unspecified or without justification.

In this letter, I emphasize that the pseudogap can appear naturally as a minimal quasiparticle excitation energy in a multiband system with the interband pairing. The simplest representative system will include two gapped bands coupled by the pair transfer channel with the chemical potential ($\mu$) intersecting only one of them.

In a two-band model of superconductivity the usual expression for the quasiparticle energies

$$E_\sigma = [(\epsilon_\alpha - \mu)^2 + \Delta_\alpha^2]^{1/2}$$

holds [21]. Here $\epsilon_\alpha$ are the band energies and $\Delta_\alpha$ the superconducting gaps.
For a band bearing the chemical potential $E_\sigma$ is minimized at $\epsilon_\alpha = \mu$ and the low-energy excitations manifest the superconducting gap. In the opposite case
\[ E_\tau(\text{min}) = \left[ (\epsilon_\tau(e) - \mu)^2 + \Delta^2_\tau \right]^{1/2}. \] (2)

In this expression the minimal value $(\epsilon_\tau(e) - \mu)^2_m$, with $\epsilon_\tau(e)$ being the $\tau$-band edge, reflects the presence of a normal state $\sigma-\tau$ gap ($\mu$ out of $\epsilon_\tau$). In the normal state $E_\tau(\text{min})$ survives and the excitations of this band correspond to the pseudogap $\Delta_p = E_\tau(\text{min})$. The changes in the band structure and $\mu$ by doping can quench the pseudogap. Then the system will be characterized by two superconducting gaps. The bare gap contribution to the pseudogap energy can markedly exceed the superconducting contribution.

Spectrally the smaller of the gaps, also in the presence of $\Delta_p$, becomes manifested as an additive density inside the larger one. Our approach to the pseudogap formation exposes it as a precursor of the superconducting gap on the doping scale. It cannot be considered as a measure of the condensation energy.

The following illustration concerns the cuprate superconductors. However, the justification of the used model and a discussion of the results of its application remain out of the scope of the present letter. We use this model only to illustrate the natural appearance of the pseudogap on a nonrigid bare gapped spectrum of a doped charge – transfer insulator with the interband pairing channel.

Cuprate superconductivity as such is stimulated by doping and the associated characteristics depend strongly on doping. The structure of doped cuprates has been found to be inhomogeneous on the nanoscale (stripes, tweed patterns, granularity) with the associated electronic phase separation in the CuO$_2$ planes. A new distribution of doping-induced states appears in the charge-transfer gap near the Fermi energy [26-28]. Various data indicate the functioning of itinerant and "defect"-type carriers in the basic physics of cuprate superconductivity [29]. Correspondingly in Refs. [18,19,30] a simple model has been developed to describe such two-component scenario. An idea that the hole doping creates not only the carriers but prepares also the whole background with a new pairing channel for the cuprate superconductivity has been elaborated. The hole-poor material can be considered as remaining the source for the itinerant type band (of mainly oxygen origin between the Cu dominated Hubbard components) and the part of distorted material bear-
ing the doped holes as creating defect bands. The bare gaps between these subsystems, quenched by a progressive doping, have been supposed to be the origin for the pseudogap behaviour. The interband pairing between the itinerant and defect subsystem is postulated to be the leading pairing mechanism. The corresponding theoretical formulation can be followed by Refs. [19,30].

The band arrangements of the model [30] are schematized in Fig.1. The case a) corresponds to a heavily underdoped region. The $\alpha$ and $\beta$ bands represent the "hot" $(\pi, 0)$ and "cold" $(\frac{\pi}{2}, \frac{\pi}{2})$ regions of the momentum space and they belong to the defect subsystem. Experimentally it is well known that doping brings the defect states to merge with the basic itinerant band. An extended doping shifts correspondingly the bottoms of these bands down in energy, leading to the bands overlap. At moderate dopings the cold quasi-particles are metallic while the hot ones remain insulating. In the case b) the bare $\beta-\gamma$ gap ($\gamma$ designates the itinerant band) is quenched and $T_c$ grows until the optimal doping is reached, as shown on Fig.1c. The optimal doping corresponds to the overlap of all the band components being intersected by $\mu$. Further doping deteriorates the conditions for the leading $(\alpha, \beta) - \gamma$ pairing. The nongapped mixed spectrum reflects the restoring of the normal Fermi liquid behaviour on overdoping.

The calculated gaps of the model are illustrated on the whole hole doping scale ($p$) in Fig.2. The model contains two superconducting gaps $\Delta_\gamma$ and $\Delta_\alpha = \Delta_\beta$ (taken for simplicity) and two pseudogaps $\Delta_{p\alpha}$ (the larger one) and $\Delta_{p\gamma}$. For the visual purpose only the gap complex connected to the "$\Delta_{p\alpha}$ driven phase" is shown together with $T_c$. In the case a) one expects the observing of two pseudogaps (like in [14-16]). The smaller pseudogap $\Delta_{p\gamma}$ is lost when the $\beta-\gamma$ overlap is reached. In the case of missing $\beta-\gamma$ bare gap there will be only one pseudogap. However, the participation of $\beta$ subsystem is essential for increasing $T_c$ as the partner in the interband pairing. In the case of larger dopings $\Delta_{p\alpha}$ and $\Delta_\gamma$ reside until the large pseudogap is quenched for the bands arrangement in Fig.1c. The overdoped region is represented by two superconducting gaps $\Delta_{p\alpha, \gamma}$. The itinerant and $\alpha$ band excitations represent the "hot" spectrum. The "cold" part of the defect subsystem spectrum becomes empty for the d-wave ordering.

The crossing of the large pseudogap $\Delta_{p\alpha}$, corresponding to the spectral "hump" [31, 32], and of the larger superconducting gap $\Delta_\gamma$ occurs close to the optimal doping (cf. the experiment in [31]). These gaps belong to different
subsystems with noncompeting order parameters vanishing at $T_c$ simultaneously. The manifestation of a superconducting gap at a given doping can be substituted by the appearance [32] of the normal state gap for $T > T_c$. It means that at low temperatures a pseudogap may not manifest itself on dopings, where it will be found in the normal state (cf. [33]). The experimental data cannot be interpreted [32] as a transformation of a pseudogap into a superconducting gap of the same subsystem on the energetic (pairing strength [5]) scale. The pseudogaps transform smoothly into superconducting gaps with an extended doping on the doping-scale, as illustrated in Fig.2 and as known experimentally [14-16,33,34]. Note that the nature of the low-energy quasiparticle excitations changes with doping. The doping-driven spectral overlap appears this way as a novel source of critical doping concentrations on the phase diagram. In the normal state insulator to metal transitions are expected at these points, cf. [35].

The transition temperature (Fig.2) and the superfluid density [36] show the usual bell-like behaviour with doping. The bare normal state gaps do not manifest themselves as fermionic gaps in the superfluid density because of the interband nature of the doping. An argument against the "extrinsic" nature of the pseudogap [9] falls out. Various observed relations between the pseudo-, superconducting and normal state gaps on the cuprate phase diagram can be explained in the described way.

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Figure captions

Figure 1. The band arrangements evolution with hole doping ($p$): a) heavy underdoping; b) extended doping; c) optimal doping. $\alpha$ and $\beta$ designate the defect system subbands (normalized to $p/2$); the itinerant band $\gamma$ (only its upper part is shown) is normalized to $1 - p$. The horizontal sections of the bands reflect the densities of states.

Figure 2. Gaps and the transition temperature of a "typical" cuprate on the hole doping scale. Curve 1 – the large pseudogap $\Delta_{pa}$; curve 2 – the itinerant subsystem superconducting gap; curve 3 – the defect subsystem superconducting gap; curve 4 – $T_c$. 
