Physics of the pseudogap in high temperature superconductors

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Abstract

Recent experiments have shown the existence of a residual energy gap, the pseudogap, in the normal phase of the underdoped high-T_C cuprate superconductors that may be related to the superconducting energy gap. We present a brief introduction to the physics of the pseudogap in the cuprate superconductors and the relation of the normal state pseudogap to the superconducting gap. Some of the experimental evidence indicating that the superconducting gap emerges from the normal state pseudogap is presented along with a brief survey of some theoretical scenarios for the relationship between the two.

1 Introduction

The discovery of superconductivity in 1911 by H. Kamerlingh Onnes led to a revolution in solid state physics [1]. These superconductors have transition temperatures of several degrees Kelvin, and are now known as conventional superconductors. The physics of the conventional superconductors remained a mystery until 1957, when the BCS theory was put forth by Bardeen, Cooper, and Schrieffer [2, 3]. In the BCS theory, the mechanism for superconductivity is explained by a phonon-mediated coupling of two electrons with opposite spin and momenta into Cooper pairs. These Cooper pairs condense into a ground state with a single macroscopically coherent phase. The formation of Cooper pairs leads to an energy gap $\Delta(\mathbf{k}, T)$ between the ground state of the superconductor and the quasiparticle excited states. Roughly, Δ can be considered as the binding energy between the electrons in the Cooper pair. By definition, it is the energy gap that exists between the superconducting ground state and quasiparticle excited states of the superconductor. It discourages quasiparticle excitations so that the superconductor tends to remain in the superconducting ground state. Hence, the energy gap is considered one of the defining properties of superconductivity, as it dominates the low-temperature electronic transport and optical properties of the conventional superconductors.

A second revolution occurred with the discovery of high-temperature superconductivity in 1986 by Bednorz and Müller [4]. Previously, the highest superconducting transition temperature was 23.4 K for Nb_3Ge, but the discovery of the La-Ba-Cu-O superconductor by Bednorz and Müller raised the critical temperature to 30 K. Soon after, others extended their approach to create cuprate superconductors with transition temperatures as high as 125 K. These new high temperature cuprate superconductors are highly anisotropic layered structures all of which contain CuO_2 planes. They have many amazing properties that cannot be explained by existing theories. Most obvious of these new properties is the fact that they are superconductors with such high transition temperatures; this cannot be explained by "conventional" superconductivity theory. Other properties include the coexistence of superconductivity and a low density of carriers, a departure from Fermi-liquid behavior in the normal state, and the necessity of crystalline order for superconductivity. But even more, our current solid state theory is inadequate in predicting its normal state properties. According to the band theory approximation, the undoped cuprates contain copper in the d^9 state, so that the normal state should be an ungapped half-filled band state and hence a metal. But these undoped cuprates are in fact antiferromagnetic Mott insulators, and only with doping do the CuO_2 planes conduct. In fact, the approach from the insulating phase to the superconducting phase traverses a region that is now seen as a precursor to the superconducting phase, the pseudogapped phase.

This doped normal phase is characterized by a *pseudogap* at the Fermi surface. By a pseudogap we mean a significant suppression of the low frequency spectral weight, as opposed to a "hard" gap where the spectral weight strictly vanishes. In order words, the pseudogap can be considered as a partial gap, where an energy gap forms at the Fermi surface between occupied states and the next available state, but other parts of the Fermi surface remain ungapped. The behavior of these superconductors are especially dependent on the amount of doping, and as the dopant level increases, the gapped portions of the Fermi surface begin to close until a superconducting phase emerges. Thus, the pseudogap normal state exists universally among the underdoped cuprates. [1]

The phase diagram of a generic cuprate superconductor as a function of doping is shown in Figure 1. Near zero doping, the cuprate is in the antiferromagnetic Mott insulator (AFI) phase. As the amount of doping is increased, the magnetic phase is gradually destroyed until it completely vanishes at about 0.03 carriers per Cu ion. An spin glass state then exists at low temperature. At about 0.055 carriers per Cu ion, the material undergoes an insulator-metal transition to the pseudogap metal state, with weak superconductivity at low temperatures. The superconductivity in this weak stage has very small condensation energy and has a very low critical current, especially in the presence of a magnetic field. As doping is further increased, the temperature reaches a maximum at the optimal doping, and in the overdoped regime, no superconductivity has been observed.

As mentioned above, the superconducting energy gap is considered a defining property of the conventional superconductors, and early attempts to find the energy gap in the cuprate superconductors failed. For example, the frequency-dependent conductivity, the Raman efficiency or the tunneling conductance did not show the signatures of an energy gap, such as the

[1] An optimally doped cuprate superconductor is one with the amount of doping that gives the highest value of T_C. Thus the cuprates can be classified as underdoped, optimally doped, and overdoped.

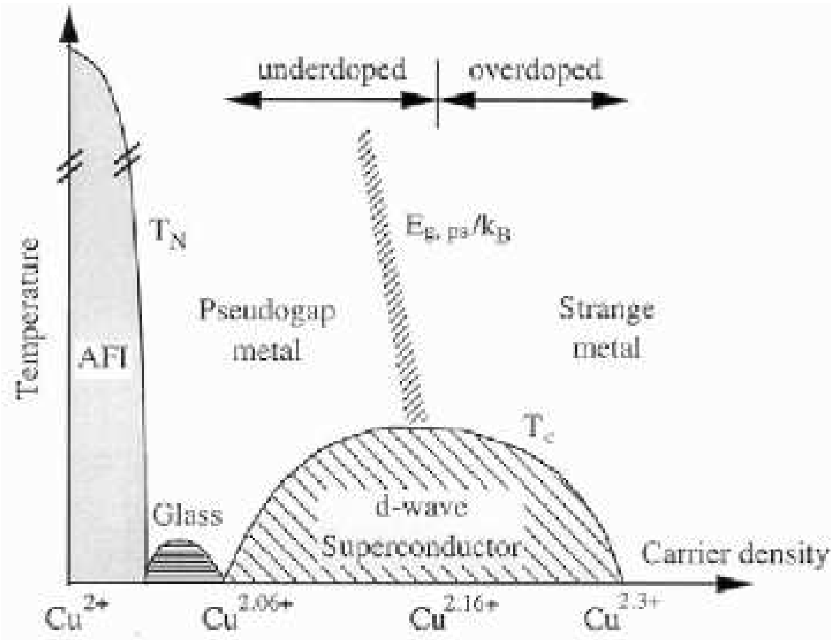

Figure 1: Phase diagram for generic cuprate superconductor

A generic critical-temperature-carrier-density phase diagram of high-T_C cuprate superconductors: zero carrier density corresponds to a Cu valence of 2+ in the CuO_2 layers. (From Liang[5]) sudden appearance of a zero density of excitations below an energy 2Δ at the superconducting transition. Instead, the excitations did not vanish completely, and often the decrease in excitations started well above T_C. At first these results were attributed to poor experimental technique or sample quality, but it has now been convincingly shown that they arise from the d-wave nature of the superconducting gap and the persistence of this gap into the normal state as the pseudogap. To date, the mechanism for high temperature superconductivity is not known; it is hoped that by understanding the normal state pseudogap and its relation to the superconducting gap, we can gain a glimpse into the mechanism for this new type of superconductivity. We present in this paper a brief introduction to the physics of the pseudogap in these cuprate superconductors. Some experimental techniques for the pseudogap and its evolution into the superconducting gap is presented along with a brief survey of some theoretical pseudogap scenarios.

2 Pseudogap experiments

Many experimental techniques have been used to probe the pseudogap, and by now there are some characteristics that the different techniques agree upon. Because of the stringent demands placed on sample quality, some techniques have been used with success on only certain families of the high temperature superconductors (HTS's) for which samples with suitable qualities can be fabricated. For example, magnetic neutron scattering requires large single crystals, and has been used only on YBCO123 and LaSr 214. Tunnelling and angle-resolved photoemission spectroscopy techniques are extremely sensitive to surface quality, and have been used extensively on $Bi_2Sr_2CaCu_2O_8$ which cleaves easily in ultra-high vacuum to provide a clean virgin surface. We present a brief overview to two of the experimental techniques used to probe the pseudogap regime of the underdoped cuprates: angle-resolved photoemission and tunnelling spectroscopy. Other techniques include dc probe techniques, nuclear magnetic resonance, and specific heat measurements. The various pseudogap experiments have been reviewed in depth by Timusk and Statt [6]. Liang also reviews the specific heat measurements along with some of the general properties of the HTS's [5]. Randeria provides a brief review of the various experimental techniques along with an overview of the various pseudogap theories; it provides an excellent perspective of the physics of the pseudogap [7].

2.1 Angle-resolved photoemission spectroscopy

Angle-resolved photoemission spectroscopy (ARPES) is a probe sensitive to the energy and momentum of the filled electron energy states below the Fermi surface, and has been used recently to great effect in the understanding of the pseudogap phenomena. It provides insight into questions about the **k**-dependence of the pseudogap, its evolution across T_C, and its affect on the spin and charge degrees of freedom.

ARPES is an advancement of the classic photoelectric experiment. A high-energy photon from a synchrotron source, usually about 20 eV in energy, is shot at the surface of a crystal cleaved in high vacuum. A photoelectron is emitted and its angle (θ, ϕ) relative to the surface normal is measured with an aperture or by position on a fluorescent screen. Its kinetic energy is measured with an electron spectrometer to an energy resolution of 20 meV or better. As a zero of energy, the sample is electrically connected to a reference metal, e.g., platinum, so that in thermodynamic equilibrium their Fermi levels are equal. The gap Δ can then be measured as shown in Figure 2.1. Because the planar surface of the sample has translational symmetry, the momentum of the electron parallel to the surface has to be offset by the momentum of the excitations inside the sample. Thus by sweeping through the angles (θ, ϕ) it is possible to map out the k dependence of the filled states below the Fermi surface.

The ARPES results show a highly anisotropic suppression of the spectral weight that remains far above T_C. The pseudogap opens up with d-wave symmetry in the normal state at a temperature $T^* > T_C$, and is seen to develop into the d-wave superconducting gap [8, 9]. The pseudogap is largest near the $(\pi, 0)$ point and the gap closes only at a much higher temperature that corresponds well to the crossover temperature from other measurements. Both the pseudogap and the superconducting gap have the same magnitude (scale) at all points in k-space, and the development of the pseudogap into the superconducting gap across T_C is smooth, with essentially the same **k**-dependence as we approach the transition temperature from either side. This scaling of the pseudogap with the superconducting gap is also seen in other measurements.

ARPES measurements have been reviewed exhaustively by Shen and Dessau [10] and more recently by Randeria and Campuzano [11].

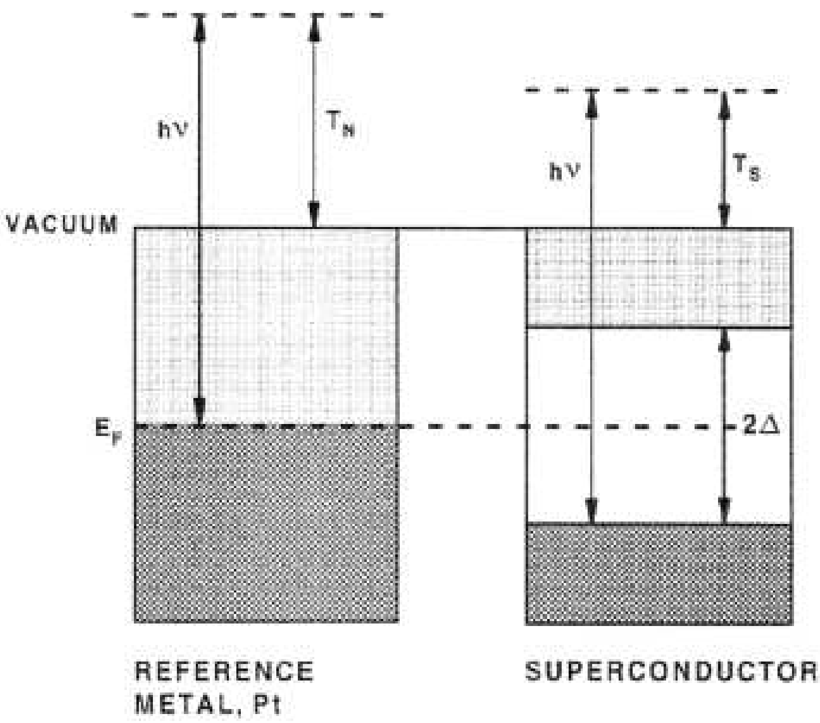

Figure 2: ARPES measurement of the gap energy

The kinetic energies T_N of the photoelectrons emerging from the normal metal will be higher in energy than the superconductor kinetic energies T_S by an amount Δ, the gap energy. The two systems are electrically connected and charge will flow until the Fermi surfaces are equal. (From Timusk *et al.*[5])

2.2 Tunnelling spectroscopy

Tunnelling spectroscopy measurements were most successful in probing the electronic density of states near the Fermi surface in the conventional BCS superconductors.[2] In a superconductor-insulator-normal metal (SIN) tunnelling experiment, an oxide layer is deposited over a superconductor and then covered by a normal metal. In thermodynamic equilibrium at zero temperature, the Fermi levels of the the two systems are equal and no current flows through an external circuit connected across the junction. If an external voltage of Δ/e is applied, the electrons in the metal have enough energy to tunnel through the insulator and reach the unoccupied states of the superconductor across the energy gap. In the conventional BCS superconductors, there is a peak in the density of states above the gap edges which shows as a large peak in the tunnelling conductance as the applied bias voltage approaches the gap value. The difficulty in doing tunnelling experiments with the cuprate superconductors is that because their short coherence length compared to the separation of the atomic layers, the experiments are extremely sensitive to surface quality, just as for the ARPES measurements.

The tunnelling results illustrate simply that a gap-like suppression in the conductance persists even after the temperature is above the transition temperature. Figure 3 shows data from Renner *et al.* of the conductance of a Bi2212 sample as a function of bias voltage for temperatures ranging from liquid helium to room temperature [13]. Note the conductance peaks and the gap in between. While the transition temperature is 83.0 K, the trace of a suppression persists well above the transition temperature, to as high as 175 K. The authors identify the conductance suppression with the pseudogap. Note that the magnitude of the pseudo- and superconducting gap as measured by the separation between the peaks does not change with temperature.

Tunnelling experiments have shown that unlike the case for BCS superconductors, where the energy gap disappears above the transition temperature, the cuprate gap is independent of temperature. Consequently, it is claimed that the suppression is not a band structure effect but arises from the superconductivity. Both the pseudo- and the superconducting gap are centered about zero bias at the Fermi surface, their energy scales are similar and temperature independent, and both gaps change in the same way as a function of doping.

[2]See Tinkham's book for an introduction [12].

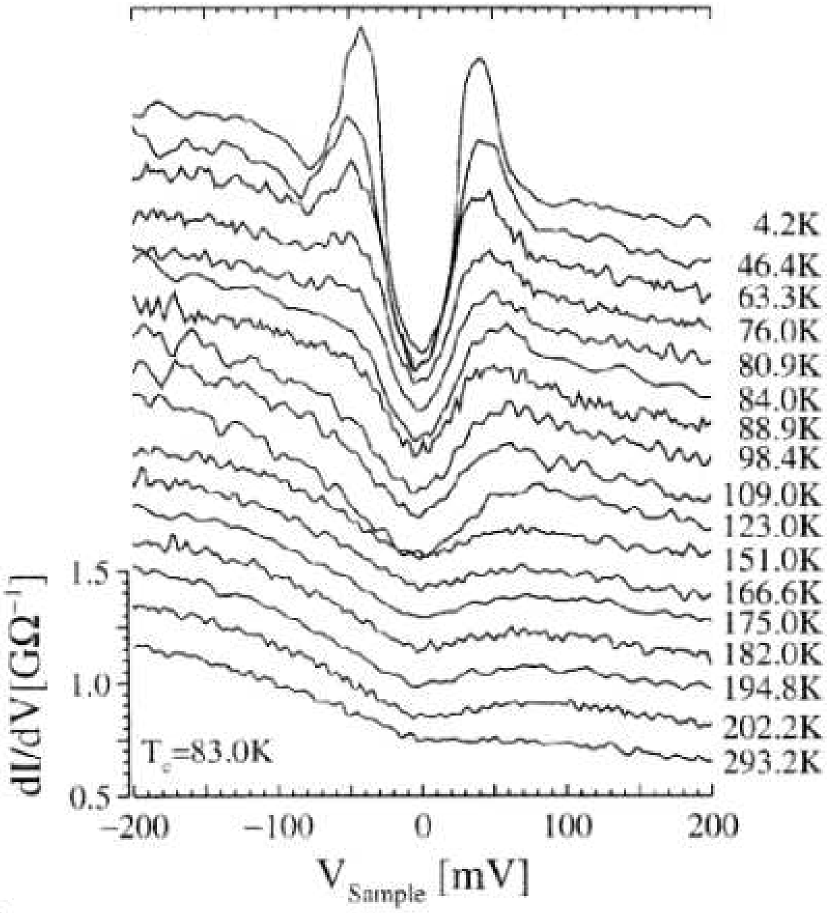

Figure 3: Tunnelling conductance for underdoped Bi2212

Tunnelling conductance for underdoped Bi2122. A gap-like feature at zero bias is the suppression in the conductance between the two conductance peaks. The feature persists above the transition temperature, and is evidence of the existence of the pseudogap. The gap size does not seem to be temperature dependent. (From Timusk [6].)

2.3 Experimental results

While it is difficult to compare the results of the different experimental techniques, there are some properties of the pseudogap that the experimental evidence all support. The pseudogap opens up in the normal state of the underdoped cuprates at a temperature T^* above T_C. Both the pseudogap and the superconducting gap have d-wave symmetry. The pseudogap smoothly evolves into the superconducting gap across T_C and. Thus, unlike the BCS superconductors, the superconducting gap does not vanish as T approaches T_C. The pseudogap magnitude is temperature independent. As the doping level approaches optimal, the pseudogap weakens until T^* approaches T_C just slightly above optimal doping. While there is some agreement between the different techniques for the above results, it should be kept in mind that each technique measures slightly different properties of the pseudogap, and without a microscopic theory, comparisons between the different techniques are difficult.

As an example, Figure 4 shows a graph compiled by Timusk plotting the pseudogap width of Bi 2122 measured by different labs. The curve shown is an empirical formula for T_C as a function of doping, given by

$$\frac{T_C}{T_{C,\max}} = 1 - 82.6(\delta - 0.16)^2,$$

where δ is the doping level. As can be seen, while there is order "close" agreement, the comparison is still not perfect, especially, as the author warns, there are variations between samples and an uncertainty in Bi 2122 about whether a sample is overdoped or underdoped near optimal doping.

3 Theoretical Models

There is by now amassed convincing experimental evidence that the superconducting transition of the cuprate superconductors is very different from the BCS mean field transition, and that the normal state above T_C has a pseudogap and looks quite different from an ordinary Fermi liquid. The current thrust of research in this area is to understand this pseudogapped precursor state to superconductivity, with the hope that by understanding the pseudogap mechanism and its evolution into the superconducting gap, one can hopefully unlock the secret to the mechanism for superconductivity

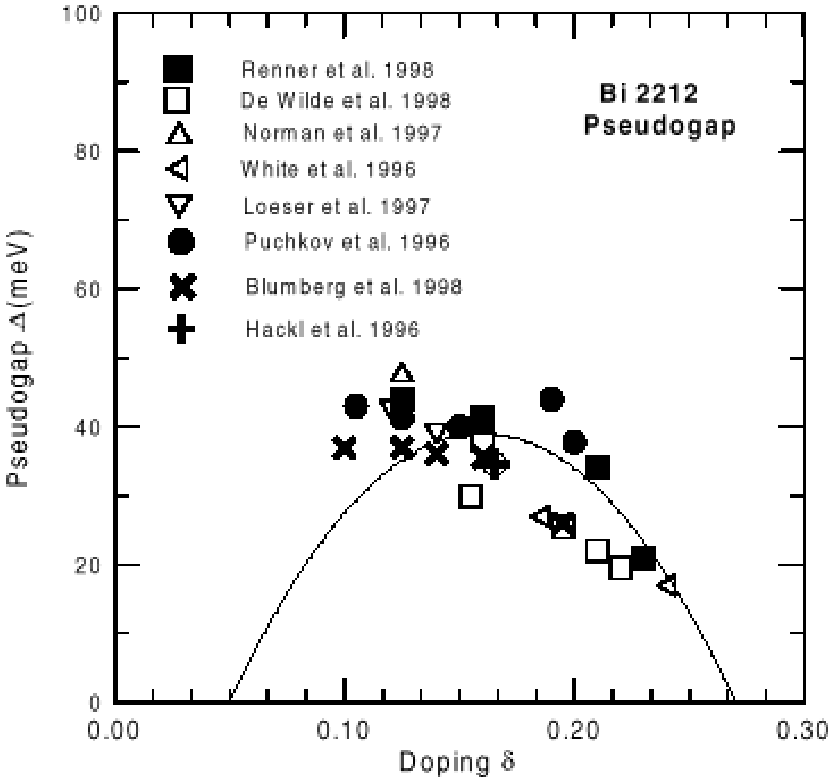

Figure 4: Pseudogap width for Bi 2212

Measured width Δ of the pseudogap in Bi 2212 from different experimental techniques. The curve is an empirical formula for T_C assuming $2\Delta = 9.5 k_B T_C$. The triangles are photoemission data; squares, tunneling; filled circles, ab-plane optical conductivity; open circles, Raman scattering. (From Timusk [6].)

in the HTS's. Many theoretical scenarios exist; a brief review is provided by Randeria [7].

In one scenario, the pseudogap is considered as the precursor to the superconducting gap. The aim is to understand the non-Fermi liquid state in order to understand the superconducting instability in that state. The pseudogap anomalous behavior is attributed to pairing correlations between fermions similar to those in the superconducting state. For example, Kosztin et al. investigate the nature of the "residual" pseudogap below T_C and show that there is a distinction between the superconducting order parameter Δ, the pseudogap Δ_{pg} and the superconductor excitation energy Δ_{sc} given by $\Delta^2 = \Delta_{pg}^2 + \Delta_{sc}^2$ [14].

Alternative scenarios include the non-pairing scenarios where the pseudogap has no connection with the superconducting gap, but, nevertheless, the pseudogap has the same scale and d-wave anisotropy as the superconducting gap. The difficulty here is to explain this coincidence.

There is also the spin-charge separation scenario, where the pseudogap comes from pairing of hypothetical spin 1/2 neutral spinons and from the pairing of real electrons. The approach is originates from resonating valence bond (RVB) theories. The aim is to understand to entire phase diagram from the Mott AFI, to the pseudogap, to the superconducting and the overdoped regime.

4 Outlook

The experimental probes of the pseudogapped state show conclusively that there is a pseudogap normal phase in the underdoped cuprates. Further, there is strong experimental evidence showing that the pseudogap and superconducting gap are strongly related: both have d-wave symmetry, similar energy scales, and smoothly evolve into one another as one crosses the transition temperature.

On the theoretical front, the need is to develop scenarios that incorporate more realistic features of the material while keeping the theories simple enough to handle. Transport in the pseudogap regime is one of the open questions, as well as the effects of magnetic fields in the pseudogap phase. A key question is why the underdoped cuprates have such a small superfluid density but a large effective pairing interaction.

Clearly, understanding the pseudogap normal state is crucial to understanding the cuprates. Hopefully, since the pseudogap and superconducting gap are so closely related, understanding the pseudogap normal state will lead to an understanding of the superconducting state.

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