Chapter 8
Nanoscale Structures and Pseudogap in Under-doped High-Tc Superconductors

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Abstract  We show that superconductor–insulator transitions in oxides and FeAs-based high Tc superconducting multilayers may arise due to a charge density wave instability induced by charged impurities and the over-screening of the long-ranged part of the Coulomb interaction, which is enhanced due to decreasing carrier density [1]. When the carrier density is low enough, impurities begin to trap particles and form bound states of clusters of charge carriers, which we call Coulomb bubbles. These bubbles are embedded inside the superconductor and form nuclei of the new insulating state. The growth of a bubble is terminated by the Coulomb force and each of them has a quantized charge and a fluctuating phase. When clusters first appear, they are covered by superfluid liquid due to the proximity effect and invisible. However, when the carrier density decreases the size of bubbles increases and the superconducting proximity inside them vanishes. The insulating state arises via a percolation of these insulating islands, which form a giant percolating cluster that prevents the flow of the electrical supercurrent through the system. We also show the formation of two groups of charge carriers in these compounds associated with free and localized states. The localized component arises due to the Coulomb bubbles. Our results are consistent with the two-component picture for cuprates deducted earlier by Gorkov and Teitelbaum [2] from the analysis of the Hall effect data and ARPES spectra. The Coulomb clusters induce nanoscale superstructures observed in scanning tunneling microscope (STM) experiments [3] and are responsible for the pseudogap [4].

8.1 Introduction

The discovery of high transition temperature superconductors in cuprates and more recently, for instance, in pnictides has created a long standing excitement in the study of superconductors, because new electronic devices have become feasible, and also because these materials show unconventional behavior as superconductors. In the conventional BCS theory of superconductivity [5], electrons are paired in momentum space, forming Cooper pairs. Cooper pairs are bosons and can occupy
a coherent, macroscopic Bose-condensate state. At sufficiently low temperatures, the system becomes superfluid and the superconductivity may then be described as the superfluid flow of the charged condensed liquid. Yet, the conventional Cooper pairing corresponds to momentum space correlations between the motion of two electrons, and in this sense, they are not point-like bosons at all. In the system of charged boson particles, the superconducting state arises in a similar way when a macroscopic number of bosons is condensed on the lowest possible energy level and becomes superfluid below a critical temperature. According to the Landau theory [6], the flow will be superfluid when its velocity is lower than the critical velocity associated with the lowest energy elementary excitation.

The size of Cooper pairs is assumed to be inversely proportional to the square root of the superconducting gap. At optimal doping, the coherence length and therefore the size of Cooper pairs in high $T_c$ cuprates is of the order of interparticle distances. This is in contrast to low temperature superconductors where the size of Cooper pairs is usually of hundreds or even thousands of interatomic distances. In over-doped cuprates, the value of superconducting gap decreases, and therefore, the “size” of Cooper pairs increases and becomes of the order of dozens of interparticle spacings, but the under-doped case is much more complicated because of the large pseudogap. The superconducting phase is very inhomogeneous and the coherence length is small, i.e., of the order of the Bohr radius. There are many experimental indications that pairs of electrons (or, more precisely, holes) are bound in the coordinate space, although the nature of the pairing in high $T_c$ superconductors at any doping is not yet established and many debates are still going on. However, a very appealing possibility is that in the under-doped region the size of pairs decreases with decreasing doping and therefore the type of pairing has crossed from the BCS regime to the BEC regime, where molecular-like pairs form the Bose-Einstein condensed state. In such a case, the charge carriers could be treated as charged bosons in the homogeneous fluid unless the temperature is so high that pairs break, and then we need to take into account the Fermi kinetic energy $E_F$, which in that strongly correlated regime is significantly smaller than the characteristic energy of the Coulomb interaction $E_c$. This ratio determines the parameter $r_s = E_c/E_F$. Our studies here concentrate to the physics in the under-doped region of cuprates where $r_s \gg 1$.

Increasing temperature or disorder destroys the superconducting state, but we will show that the superconducting state vanishes even at zero temperature when the charge carrier density decreases. The effect arises due to the presence of charged impurities and strong over-screening of the Coulomb interaction at low densities. As a result, superconducting charge carriers spontaneously form self-trapped clusters around each impurity, which we will call Coulomb bubbles (CB). The mechanism of formation of Coulomb bubbles and electronic phase separation described here for charged bosons is equally well applicable to charged fermions, because in both cases the dominating role is played by the Coulomb interaction and its nonlinear screening. However, it is also important to note that for fermionic Coulomb bubbles the internal, energetical, and spatial structure will be slightly different as well as the critical density when CBs first appear. For fermions bound inside the Coulomb bubble, the Pauli principle must be obeyed and thus lower density is required for the