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Pseudogap formation and quantum phase transition in strongly-correlated electron systems

Chyh-Hong Chern

Department of Physics, National Taiwan University, Taipei 10617, Taiwan

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ABSTRACT

Pseudogap formation is a ubiquitous phenomenon in strongly-correlated superconductors, for example cuprates, heavy-fermion superconductors, and iron pnictides. As the system is cooled, an energy gap opens in the excitation spectrum before entering the superconducting phase. The origin of formation and the relevancy to the superconductivity remain unclear, which is the most challenging problem in condensed matter physics. Here, using the cuprate as a model, we demonstrate that the formation of pseudogap is due to a massive gauge interaction between electrons, where the mass of the gauge boson, determining the interaction length scale, is the consequence of the remnant antiferromagnetic fluctuation inherited from the parent compounds. Extracting from experimental data, we predict that there is a quantum phase transition belonging to the 2D XY universality class at the critical doping where pseudogap transition vanishes.

1. Introduction

Correlation is a quantum-mechanical patent with non-perturbative nature, which gives rise to diverse quantum phenomena. Starting from the basic, the notion of exchange correlation states that two *independent* fermions (bosons) experience an effective exchange repulsive (attractive) force when their wave functions highly overlap. In the case of interacting particles, correlation often leads to versatile orderings, for example (anti-)ferromagnetism, superconductivity, and so on. However, there

E-mail address: chchern@ntu.edu.tw.

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remains insufficient understanding of what role the quantum correlation plays in the paramagnetic phase away from quantum criticality. This question began to attract attentions after the behaviours of many transition-metal oxides were found outside the box of the Fermi liquid theory. They were soon classified as *strongly-correlated* materials. The interest, with correlation still unknown, reaches its peak after the discovery of the Cu-based transition-metal oxides (cuprates), so-called the high-T_c superconductors [1,2].

The parent compounds of the high-T_c superconductors are insulating antiferromagnets (AFM) [3]. After chemical doping with charge carriers, the antiferromagnetic ordering disappears, followed by an enigmatic paramagnetic phase before the superconductivity emerges. The paramagnetic phase is now known as the pseudogap phase where a gap opens in the electronic spectrum without exhibiting any signature of conventional phase transition at $T = T^*$, higher than the superconducting transition temperature T_c [4]. Similar phenomenon is also seen in heavy-fermion superconductors [5] and iron pnictides [6], which share similar phase diagram to cuprates. This ambiguous transition is often regarded as a crossover. After almost three decades from its discovery, the central debates still focus on the formation of the pseudogap and its relevancy to the superconductivity in the lower temperature range.

Intensive studies have been done both experimentally and theoretically to identify whether or not the pseudogap phase belongs to a broken-symmetry state. Recently, experimental data in cuprates are accumulated to indicate that the pseudogap phase breaks time-reversal symmetry and preserves the translational symmetry [7–11]. However, in most of those data, the time-reversal symmetry begins to fluctuate precursory to the pseudogap transition. So far, the evidence is still vague that the pseudogap formation belongs to any symmetry-breaking scenario.

On the other hand, it is generally believed that the strong electron–electron repulsive interaction baptises the strong correlation. This naive belief was first challenged by Comanac et al. [12]. They found that a large Hubbard U value is not needed but the antiferromagnetic correlation is crucial to fit the experimental data of optical conductivity. A recent numerical calculation also indicates that Hubbard U value decreases as the system size increases [13]. Meanwhile, it has been advocated by Laughlin that the Coulomb interactions in the cuprates are simply the same as they are in elemental Si or Na metal [14]. However, to completely overrule the wrong belief, a mechanism responsible for pseudogap formation is needed in a framework of the *weak-coupling* theory.

In this article, we construct a weak-coupling theory for the pseudogap formation, where the gauge interaction weakly coupled to electrons acquires a mass leading to a gap-like structure in the electronic spectrum. The non-perturbative mass acquisition mechanism identifies the quantum correlation, where the remnant antiferromagnetic fluctuation becomes the longitudinal mode of the gauge field. Moreover, the pseudogap transition is identified as a BKT-*like* transition, and the transition temperature is computed. Most importantly, we provide a scheme for the pseudogap formation *without* breaking time-reversal and translational symmetry. Finally, a generalisation to the iron pnictides and heavy-fermion systems is briefly discussed.

2. The model

In cuprates, mobile charge carriers are introduced in the Mott insulator by chemical doping. As the electrons become more and more mobile, the electron scattering process becomes more and more important. The complete description of the scattering process should include the current–current (CC) interaction in the one-band Hubbard model

$$\mathscr{H} = -t \sum_{\langle ij\rangle,\sigma} (c^\dagger_{i,\sigma} c_{j,\sigma} + h.c.) + U_0 \sum_i n_{i\uparrow} n_{i\downarrow} + U_1 \sum_q \vec{J}_\uparrow(q) \cdot \vec{J}_\downarrow(-q), \tag{1}$$

where $c^\dagger_{i,\sigma}$ ($c_{i,\sigma}$) is the electron creation (annihilation) operator, $n_{i,\sigma} = c^\dagger_{i,\sigma} c_{i,\sigma}$, and $\vec{J}_\sigma(q)$ is the current operator

$$\vec{J}_\sigma(q) = \sum_p c^\dagger_{q,\sigma} c_{p+q,\sigma} \left(\vec{p} + \frac{\vec{q}}{2}\right). \tag{2}$$