Annals of Physics 360 (2015) 113–139

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Theory of quantum phase transition in iron-based superconductors with half-Dirac nodal electron Fermi surface

Imam Makhfudz *

Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA

Laboratoire de Physique Théorique–IRSAMC, CNRS and Université de Toulouse, UPS, F-31062 Toulouse, France

ARTICLE INFO

Article history:
Received 20 August 2014
Accepted 4 May 2015
Available online 12 May 2015

Keywords:
Quantum phase transition
Superconductivity

ABSTRACT

The quantum phase transition in iron-based superconductors with 'half-Dirac' node at the electron Fermi surface as a $T = 0$ structural phase transition described in terms of nematic order is discussed. An effective low energy theory that describes half-Dirac nodal fermions and their coupling to Ising nematic order that describes the phase transition is derived and analyzed using renormalization group (RG) study of the large-N_f version of the theory. The inherent absence of Lorentz invariance of the theory leads to RG flow structure where the velocities v_F and v_Δ at the paired half-Dirac nodes ($1\bar{1}$ and $2\bar{2}$) in general flow differently under RG, implying that the nodal electron gap is deformed and the C_4 symmetry is broken, explaining the structural (orthogonal to orthorhombic) phase transition at the quantum critical point (QCP). The theory is found to have Gaussian fixed point $\lambda^* = 0, (v_\Delta/v_F)^* = 0$ with stable flow lines toward it, suggesting a second order nematic phase transition. Interpreting the fermion–Ising nematic boson interaction as a decay process of nematic Ising order parameter scalar field fluctuations into half-Dirac nodal fermions, I find that the theory surprisingly behaves as systems with dynamical critical exponent $z = 1$, reflecting undamped quantum critical dynamics and emergent fully relativistic field theory arising from the non(fully)-relativistic field theory and is direct consequence of $(v_\Delta/v_F)^* = 0$ fixed point. The nematic critical fluctuations lead to remarkable change to the spectral function peak where at a critical point λ_c, directly related to nematic QCP, the central spectral peak collapses and splits into satellite spectral peaks around nodal point. The vanishing of the zero modes density of states leads to the undamped $z = 1$ quantum critical dynamics.

---

* Correspondence to: Laboratoire de Physique Théorique–IRSAMC, CNRS and Université de Toulouse, UPS, F-31062 Toulouse, France.

E-mail address: Imam.Makhfudz@irsamc.ups-tlse.fr.

http://dx.doi.org/10.1016/j.aop.2015.05.005
0003-4916/

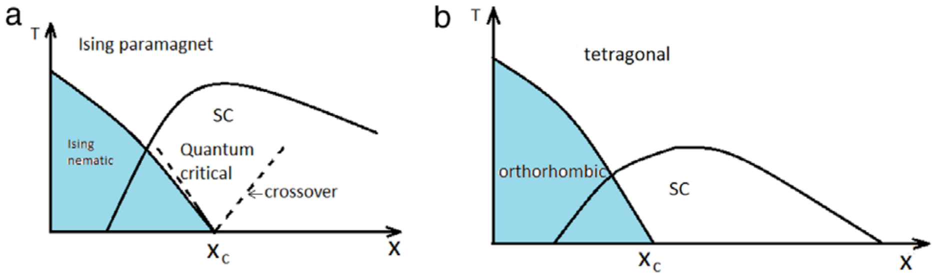

Fig. 1. (a) Quantum phase transition in cuprates with the quantum critical point and quantum critical region nearby. (b) Typical phase diagram of iron-based superconductors with similar quantum critical point. In both (a) and (b), the parameter x is defined as $x_c = -r$ and $x = -r(\lambda)$ as given in Eqs. (2) and (55). Physically, x may represent doping level, pressure, or other appropriate experimental quantities.

1. Introduction

Quantum phase transition in strongly correlated systems such as high T_c superconductors is one of the most active topics in condensed matter physics. In cuprates and several families of the recently discovered iron-based family of high T_c superconductors, there exists a quantum critical point at $T = 0$ deep inside the superconducting dome that represents such quantum phase transition (Fig. 1(a), (b)). This QCP also separates tetragonal and orthorhombic crystal structures and thus represents structural phase transition at zero temperature. It has been argued that the orthorhombic state is described by the so-called Ising nematic order [1–3] and such structural transition in cuprates [4,5] and iron-based superconductors [6–8] (where d-wave symmetry was assumed) is nematic transition.

The general phase diagram of several families of iron-based superconductors [9] illustrated in Fig. 1(b) shows that there is a tetragonal to orthorhombic structural phase transition at some finite temperature in the undoped case down to $T = 0$ at a critical doping x_c deep inside the dome where the Ising nematic order coexists with the superconducting state. At $T = 0$ this critical doping is a quantum critical point between Ising ordered state and Ising disordered state. The theory of quantum phase transition at this quantum critical point is the focus of this work.

The quantum phase transition in cuprates that relates structural phase transition with nematic order was first studied using renormalization group approach [10,11] which showed using perturbative RG calculation at fixed N_f with ϵ expansion around $3+1$ dimensions that the velocity anisotropy in the nodal fermion action and the anisotropic coupling between nodal fermion and Ising nematic order leads to a fluctuation-induced first order phase transition, as indicated by the runaway RG flows.

A large-N_f study of the same system but in $2+1$ dimensions [4] however found a second order quantum phase transition and has finite renormalized velocity anisotropy as compared to Dirac-like theory such as QED_3 which found velocity anisotropy to be irrelevant. Another RG study on the same system in $2+1$ dimensions [5] found vanishing velocity ratio $(v_\Delta/v_F)^* = 0$ as the fixed point.

The coupling between nodal quasiparticles to the nematic order was argued to be the most effective driving force of the structural transition. The presence of nodes and the resulting nodal quasiparticles in d-wave cuprates is therefore of crucial importance here. On the other hand, from the aspect of gap symmetry, iron-based family was originally thought to have isotropic $s_\pm$ wave symmetry, thus ruling out the presence of nodes. However it was found later that the electron Fermi pocket in iron-based superconductors admits anisotropic gap and thus permits existence of nodes.

In a related development, it has been shown recently that iron-based superconductors can have the so-called accidental (‘zero’) node (Fig. 2) at the electron pocket [12,13] due to the gap anisotropy where the gap just touches the Fermi surface, that is, it is right at the onset of being gapless. In the simplest model, we can represent it by $\Delta(\theta) = \Delta_0(1 - \cos 4\theta)$ (Fig. 2). Such accidental zero has anisotropic dispersion which in linear in p_x direction and quadratic in p_y direction or vice versa. One can therefore interpret such zero as “half-Dirac” node, because it has Dirac spectrum in one direction but has parabolic dispersion in the perpendicular direction as that for free particle.