Quantum Griffiths Effects and Smeared Phase Transitions in Metals: Theory and Experiment

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Abstract In this paper, we review theoretical and experimental research on rare region effects at quantum phase transitions in disordered itinerant electron systems. After summarizing a few basic concepts about phase transitions in the presence of quenched randomness, we introduce the idea of rare regions and discuss their importance. We then analyze in detail the different phenomena that can arise at magnetic quantum phase transitions in disordered metals, including quantum Griffiths singularities, smeared phase transitions, and cluster-glass formation. For each scenario, we discuss the resulting phase diagram and summarize the behavior of various observables. We then review several recent experiments that provide examples of these rare region phenomena. We conclude by discussing limitations of current approaches and open questions.

Keywords Quantum phase transition · Quenched disorder · Griffiths singularities

1 Introduction

Systems of itinerant electrons can undergo phase transitions upon variations of a control parameter such as temperature, pressure, magnetic field, and chemical composition. In recent years, considerable attention has been focused on a special class of phase transitions that occur at the absolute zero of temperature as a function of some non-thermal parameter [1–4]. In the vicinity of such quantum phase transitions, itinerant electron systems often display unconventional finite-temperature phenomena including deviations from Fermi-liquid behavior and novel phases [5].

Real materials always contain a certain amount of quenched (i.e., time-independent or frozen-in) disorder. This randomness can take the form of vacancies or
impurity atoms in a crystal lattice, or it can consist of extended defects such as dislocations or grain boundaries. The question of how quenched disorder affects phase transitions is therefore both of conceptual interest and of experimental importance. Over the last fifteen years, it has become clear that the influence of disorder is generically much stronger at zero-temperature quantum phase transitions than at thermal (classical) phase transitions, and often leads to unconventional behavior. The effects of quenched disorder on various classical, quantum and non-equilibrium phase transitions were recently reviewed in Ref. [6], paying particular attention to rare strong disorder fluctuations, and the spatial regions that support them.

In the field of quantum phase transitions in disordered metallic systems, important new results have been obtained since Ref. [6] has appeared. On the theoretical side, the application of the strong-disorder renormalization group to systems with dissipation has put a firmer ground under the phenomenological rare-region theories and also produced many additional results. Moreover, several recent experiments have found strong evidence for the unconventional disorder physics predicted by these theories.

The present mini-review thus focuses on quantum phase transitions of disordered itinerant electrons and incorporates these new developments. It is organized as follows: Some basic concepts of phase transitions and criticality are collected in Sect. 2. Section 3 gives an introduction to disorder, rare regions, and Griffiths singularities. In Sect. 4, we present and compare the different scenarios that can arise at magnetic quantum phase transitions in disordered metals. Section 5 is devoted to experiments. We conclude in Sect. 6.

2 Classical and Quantum Phase Transitions

Phase transition can be divided into first-order and continuous ones. At first-order transitions, the two phases coexist at the transition point, and usually a finite amount of heat (the latent heat) is released when going from one phase to the other. Transitions that do not involve phase coexistence and latent heat are called continuous transitions or critical points. In this paper, we focus on continuous transitions which are particularly interesting because they are accompanied by strong spatial and temporal fluctuations.

Most continuous phase transitions can be characterized by an order parameter, which is a thermodynamic quantity that is zero in one phase (the disordered phase) and non-zero and generally non-unique in the other phase (the ordered phase). Landau [7–10] assumed that the free energy $F$ close to a critical point is an analytical function of the order parameter $m$ and can thus be expanded in a power series

$$ F = F_L(m) = F_0 + rm^2 + vm^3 + um^4 + \cdots - hm. $$

Here, $h$ is the external field conjugate the order parameter, and the coefficients $r$, $v$, and $u$ are functions of external parameters such as temperature, pressure, chemical

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1In recent years, continuous transitions without conventional order parameters have attracted attention. As disorder effects at these exotic transitions have not been studied systematically, we shall not consider them in this paper.

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