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Disorder-induced quantum-Griffiths-like features from a non-conventional renormalization group analysis near four dimensions

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ABSTRACT

We investigate the role played by symmetry conserving quenched disorder on quantum criticality of a variety of d-dimensional systems with a continuous symmetry order parameter. We employ a non-standard procedure which combines a preliminary reduction to an effective classical random problem and a successive conventional renormalization group treatment. Solving the effective flow equations to first order in $\varepsilon = 4 - d$ and then restoring the original coupling parameters, for $d < 4$ we find a quantum critical point scenario exhibiting unusual features, which remind us of some predictions of the quantum Griffiths phase model.

1. Introduction

In recent years intensive theoretical [1–5] and experimental [6–8] effort has been devoted to clarify the role played by quenched disorder on the behavior of a variety of systems close to their quantum critical point (QCP). This is especially motivated by unexpected anomalies observed in many strongly correlated electron compounds [6–9]. Nevertheless, several crucial questions still remain to be explained and a fully satisfactory theory is lacking at the present time.

Shortly, the main features relevant for our purposes sound as follows.

For classical second order phase transitions the scenario induced by quenched randomness is sufficiently developed [1,10,11] although some relevant questions remain to be still clarified [11–14], as the role played by the so-called extended or totally correlated disorder along some directions (linear and planar defects, etc.) [15–24]. In contrast, for quantum phase transitions (QPTs) [25], which take place at zero temperature by variation of a non-thermal control parameter (pressure, applied magnetic field, doping, chemical potential, etc.), the effects of weak quenched disorder still constitute one of the less clear problems in condensed matter physics. However, in the last decade, new important methods and ideas have been acquired which open promising perspectives towards clarifying this hard problem when quantum fluctuations become relevant and may come into competition with thermal and static random ones. A recent clear discussion about quenched disorder effects on clean quantum and classical phase transitions can be found in Ref. [1]. The main trouble for case of QPTs, arises from the presence of the imaginary-time direction in the quantum Ginzburg–Landau–Wilson (GLW) actions [25]. The crucial point is that the frozen in (only space-dependent) disorder appears totally correlated at least in the time-like direction so that, also for spatial short-range correlated disorder, one is technically in the presence of a sort of extended

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randomness from the QPT point view. Below, we refer only to so-called symmetry-conserving randomness which does not break the symmetry seen by the local ordering parameter.

As concerning classical criticality, almost four decades ago, Harris [26] summarized the effect of short-range correlated disorder on the critical behavior by his famous criterion in establishing the stability condition of a clean sharp second order phase transition against weak randomness. The Harris criterion states that in the presence of weak short-range correlated quenched disorder the d-dimensional pure criticality is stable if the related correlation length exponent ν_p fulfills the inequality $d\nu_p > 2$ or the pure specific heat exponent α_p is negative, under condition of validity of the hyperscaling relation $d\nu_p = 2 - \alpha_p$. When this criterion is violated, i.e. when it happens that $d\nu_p < 2$ or $\alpha_p > 0$, the randomness destabilizes the pure critical behavior resulting, possibly, in a disorder-induced criticality with new critical exponents (however, other possibilities cannot be excluded "a priori" [1]). Extensions of the Harris criterion were next proposed to include power-law long-range correlated disorder [27], extended impurities [19] and weak quenched disorder effects on clean QPTs [19,28]. In this last case, the "quantum Harris criterion" for the irrelevance of short-range frozen in disorder can be expressed as $d\nu_{p,(d+z)} > 2$ where z denotes the appropriate dynamical critical exponent and $\nu_{p,(d+z)}$ represents the pure classical correlation length critical exponent in $d + z$ dimensions [25]. For cases of interest to us, the quantum Harris criterion is violated for $d < 4$ and a new zero-temperature disorder-induced scenario (to be determined) is expected.

From a theoretical point of view, the conventional renormalization group (RG) approach to quantum GLW actions [19,25] appears inadequate to give reliable information about the quenched disorder effects around a QPT for dimensionalities $d < 4$. An alternative double expansion RG framework has been suggested [16,29] in strict analogy to the extended disorder scenario for classical systems [15]. Here, in addition to $\varepsilon = 4 - d$, also the dimensionality ε_τ of a fictitious imaginary-time space, involved in properly continued quantum GLW actions, is assumed as a further small expansion parameter. Within this scheme the physical predictions should be then derived by extrapolation to $\varepsilon_\tau = 1$ of the small-ε_τ results, implying a sharp second order QPT with new critical exponents and oscillatory corrections to the power-law scaling [16]. Nevertheless, there are rather convincing indications [17,30–35] that also the double-expansion RG predictions are at least questionable.

More interestingly, using the real-space RG approach developed by Ma–Dasgupta–Hu [36], now called the strong-disorder RG [37], Fisher [38] showed that the one-dimensional transverse-field Ising model (TIM) in the presence of quenched disorder exhibits an unconventional infinite randomness QCP characterized by ultraslow activated rather than power-law dynamical scaling. Moreover, Motrunich et al. [39] proved that a similar scenario occurs for the same model in two and three dimensions. Quite recently, Vojta et al. [5] have developed a strong-disorder RG also to explore the QPT of a d-dimensional quantum GLW action with a continuous symmetry $O(n)$ order parameter in the presence of both quenched disorder and Ohmic dissipation. This action is suitable to describe the antiferromagnetic QPT of itinerant electron systems [25] and the superconductor-metal one in nanowires [40]. The central result is a quantum criticality (QC) governed by an exotic infinite-randomness fixed point (FP) in the universality class of the dissipationless random TIM [38,39].

Finally, great interest has been addressed to the so-called quantum Griffiths (QG) phase model [3]. Taking properly into account rare but large clean regions in a random system, this phenomenological model predicts possibly observable temperature-driven sample-dependent singularities (the QG singularities) in thermodynamic quantities as susceptibility and specific heat.

On the other hand, most of the recent experiments predict new modified scaling relations and power-law singularities in the disordered phase which for susceptibility are parameterized as $\chi(T) \sim T^{-1+\lambda}$ with a non-universal exponent λ ranging in (0, 1), in qualitatively agreement with the QG model results [1,2]. Nevertheless, other reliable measurements on random magnets [8] provide some evidence of a quantitative inadequacy of the genuine QG scenario. In any case, it has become clear that new ideas must be employed to suitably describe the intriguing disorder world at very low temperatures.

In the present paper we reexamine more deeply our recent suggestion [41] to describe the effects of weak quenched disorder on clean quantum criticality by eliminating from the problem the imaginary-time direction through a procedure already used in absence of randomness [42,43]. The basic idea can be summarized as follows. (i) One first performs, at a given disorder configuration, an averaging over the dynamic modes [25,42,43] to generate an effective classic GLW action with short-range correlated disorder for which the known perturbative scenario is applicable, consistently with the classical Harris criterion. Here the temperature and the quantum nature of a system are hidden in the effective coupling parameters. (ii) The next step consists of applying the usual RG approach [10] to this classical random action. (iii) Finally, the role of temperature and quantum information are extracted from the solution of the effective flow equations through the explicit expressions of the initial effective coupling parameters.

In Ref. [41], this last crucial step was achieved after linearization around the random FP of the effective classical action, which is stable for $d < 4$ and $1 < n < 4$ [10]. However, this procedure yields correct results only sufficiently close to the phase boundary so that eventual relevant low-temperature features are completely missed.

We will show here that, on the ground of the full flow solution for $n > 1$ to leading order in $\varepsilon = 4 - d > 0$, a peculiar low-temperature scenario takes place which reminds us of the QG phase model findings.

The rest of the paper is organized as follows. Section 2 introduces the general quantum random action of interest for us together with the related effective classical random one emerging from the one-loop averaging over the dynamical modes. Here, we also present the one-loop flow equations for the effective random problem and their solution to first order in $\varepsilon = 4 - d$. Moreover, focusing on dimensionalities $d < 4$, we derive a critical line ending in a QCP and a set of self-consistent equations to determine the correlation length, the susceptibility and other thermodynamic quantities within the disordered phase. In Section 3 we obtain the asymptotic behaviors of susceptibility close to the QCP for models with symmetry index