Journal of Magnetism and Magnetic Materials 453 (2018) 17–29

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Research articles

Crossover phenomena in the critical range near magnetic ordering transition

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ARTICLE INFO

Article history:
Received 4 August 2017
Received in revised form 23 November 2017
Accepted 26 December 2017
Available online 27 December 2017

Keywords:
Critical spin dynamics
Crossover events
Universality
Boson fields

ABSTRACT

Among the most important issues of Renormalization Group (RG) theory are crossover events and relevant (or non-relevant) interactions. These terms are unknown to atomistic theories but they will be decisive for future field theories of magnetism. In this experimental study the importance of these terms for the critical dynamics above and below magnetic ordering transition is demonstrated on account of new analyses of published data. When crossover events are overlooked and critical data are fitted by a single power function of temperature over a temperature range including a crossover event, imprecise critical exponents result. The rather unsystematic and floating critical exponents reported in literature seem largely to be due to this problem. It is shown that for appropriate data analyses critical exponents are obtained that are to a good approximation rational numbers. In fact, rational critical exponents can be expected when spin dynamics is controlled by the bosons of the continuous magnetic medium (Goldstone bosons). The bosons are essentially magnetic dipole radiation generated by the precessing spins. As a result of the here performed data analyses, critical exponents for the magnetic order parameter of $\beta = 1/2, 1/3, 1/4$ and $1/6$ are obtained. For the critical paramagnetic susceptibility the exponents are $\gamma = 1$ and $\gamma = 4/3$.

1. Introduction

Identification of crossover events in the temperature dependence of the thermodynamic observables of magnetic materials is extremely important for a correct analysis and interpretation of experimental data. A crossover means a functional change in temperature dependence. Often, however, the crossover appears as a distinguished event only if susceptibility or magnetization data are raised to a suitable power and are plotted as a function of linear temperature. Well known is the functional change from Curie-Weiss susceptibility to critical susceptibility in the paramagnetic phase. The two susceptibilities follow different functions of temperature. In particular, the critical susceptibility holds up to crossover to Curie-Weiss susceptibility at a clearly defined crossover temperature, T_{CO}. In other words, the width of the critical range is precisely defined by T_{CO}-T_C. Note that in the atomistic models of the critical behavior, crossover events do not occur because the critical power functions hold asymptotically for $T \rightarrow T_c$ only. The width of the critical range is, so to say, zero. Nevertheless it is common practice (and an experimental necessity) to extend the fit range for the critical exponents up to a finite distance from critical temperature. This procedure is justified because critical spin dynamics is not controlled by exchange interactions between spins but by a boson field. In fact, the finite and clearly limited width of the critical range indicates that critical spin dynamics is controlled by a boson field. As a result, accurate fits of the critical exponents require that the limits of the critical range are clearly identified.

The bosons controlling spin dynamics in ordered magnets are the excitations of the magnetic continuum. We will call all of them Goldstone bosons [1]. In [2] it could be rationalized that the Goldstone bosons are essentially magnetic dipole radiation generated by the precessing spins. The ballistic, that is, lattice structure independent propagation mode of the bosons can be termed universal. In fact, this propagation mode is the origin of universality of the boson controlled thermodynamic observables. Universality is the typical thermodynamic behavior of a field of freely propagating bosons. Since spin dynamics is controlled by the Goldstone boson field the spins merely are sensors to probe the dynamics of the field. The observed magnetic heat capacity is the heat capacity of the Goldstone boson field.

It is intuitively clear that the crossover at T_{CO} results from the competition between two excitation spectra. The two excitation spectra in question are generated by the continuous translational

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https://doi.org/10.1016/j.jmmm.2017.12.089
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symmetry of the infinite magnetic material and by the discrete translational symmetry of the atomic lattice. While the excitation spectra generated by the atomic structure (magnons and phonons) are well known, the excitation spectra of the Goldstone bosons are less explored [3,4]. This is mainly because mass less-bosons are invisible to neutrons. Practically, the heat capacity (or energy density) is the only thermodynamic observable of a boson field. It is not by chance that thermal decrease of the magnetic order parameter scales with the temperature dependence of the heat capacity of the boson field [2].

According to RG theory, a crossover results because atomistic excitations and boson field become alternatively relevant [5,6]. Relevance can be considered as a thermodynamic symmetry selection principle. The non-relevant system does not accumulate thermal energy, and its heat capacity is negligible [7]. In this way the non-relevant system becomes thermodynamically insignificant. Relevance has the severe consequence that all available energy states of field and atomistic system cannot be populated according to the Boltzmann factor. Detailed balance holds only in the relevant excitation system. At the crossover at T_{CO} thermal energy is transferred from the localized exchange interactions to the field of freely propagating bosons. Only above T_{CO} spin dynamics is controlled by exchange interactions between individual pairs of spins. For all temperatures below T_{CO} the Goldstone boson field is the relevant excitation spectrum to control spin dynamics. Since in the atomistic models, boson fields do not occur, crossover events are also unknown. Not recognized crossover events in the critical range frequently have led to incorrect data analyses. Moreover considerable systematic fit errors can result when the limits of the critical range are not clearly respected. In fact, there is no clear systematic recognizable in the reported critical exponents [8–14]. Without precise knowledge of the width of the critical range a safe data analysis is possible restricting data analysis to the asymptotic range for $T \rightarrow T_c$. However, neglect of useful data more away from T_c considerably increases the fit error for the critical exponents.

Another problem concerns the correct interpretation of the obtained critical exponents. Since RG theory we know that exchange interactions are not relevant for the critical spin dynamics. As a consequence, classification of the critical behavior in terms of atomistic categories such as dimensionality of the spin and dimensionality of the exchange interactions is inappropriate. Note that exchange interactions rarely have perfect dimensionality. For the boson controlled critical spin dynamics the energy degrees of freedom of the field have to be considered exclusively. Atomistic quantities can completely be neglected. This implies that order parameter and dimensionality of the ordering transition are properties of the boson field. Surprisingly, in the magnetically ordered state, the Goldstone boson fields have perfect dimensionalities. This allows for a clear symmetry classification of the critical behavior. Since magnetic dipole radiation is generated by stimulated emission, the basic field is perfectly one-dimensional and resembles the radiation field of a LASER. The one-dimensional boson field aligns all magnetic moments perfectly collinear, in spite of local exchange anisotropies. In terms of RG theory: exchange interactions and local exchange anisotropies are not relevant. In fact, perfectly collinear spin structures within each magnetic domain are puzzling for the atomistic models. Two-dimensional and three-dimensional boson fields result by some vector coupling of the one-dimensional basis fields. In other words, the dimensionality of the relevant boson field can be recognized from the number of differently oriented domains. The dynamic dimensionality is a property on the length scale of the linear dimension of the magnetic domains. On the other hand, generation of magnetic dipole radiation requires a three-dimensional spin. For instance, Ising spins do not precess and therefore are unable to generate magnetic dipole radiation [2]. As a consequence, in Ising magnets the boson field gets not populated by field quanta and the dynamics is atomistic. This means that spin dynamics in Ising magnets is, in fact, determined by the exchange interactions between spins. Under this condition atomistic theories can give correct description of spin dynamics. In fact, for the genuine 2D-Ising antiferromagnets K_2CoF_4 [15] and Rb_2CoF_4 [16] it could be shown experimentally that the temperature dependence of the magnetic order parameter exactly follows Onsager's analytical solution of the atomistic 2D Ising model [17,18]. Typical for Onsager's atomistic theory is that the critical power function with exponent $\beta = 1/8$ is the first term of a power series expansion at $T = T_N$. In other words, in contrast to boson dynamics the width of the critical range of the atomistic models is, so to say, zero. Moreover, Onsager's solution is -as spin wave theory- independent of spin quantum number.

2. Crossover events above ordering transition

In cubic magnets with isotropic boson field and half-integer spin the standard critical behavior is of mean field type (Fig. 1) [19]. In plots of the reciprocal susceptibility as a function of temperature the crossover from critical susceptibility to Curie-Weiss susceptibility is at intersection of critical susceptibility and Curie-Weiss susceptibility at T_{CO}. In the ferromagnet GdMg with simple cubic Gd lattice the spin is undisputedly half-integer (S = 7/2). It is evident that the analytical change at crossover temperature T_{CO} cannot be simulated by high-temperature series expansions [20]. A crossover means a non-monotonous functional change. Quite generally, the crossover from exchange controlled to boson controlled spin dynamics shifts the ordering transition to a lower temperature compared to exchange controlled spin dynamics. In other words, the critical temperature is always lower than Curie-Weiss temperature Θ. In contrast to the gluons of quantum chromodynamics, the Goldstone bosons have, so to say, anti-binding function and destabilize magnetic order. Since continuous dynamic symmetry (boson dynamics) holds above and below ordering temperature it follows that the ordering transition is executed by the boson field. This process is not yet understood but it resembles onset of stimulated emission of a LASER. The two indications of the boson controlled critical spin dynamics are the finite

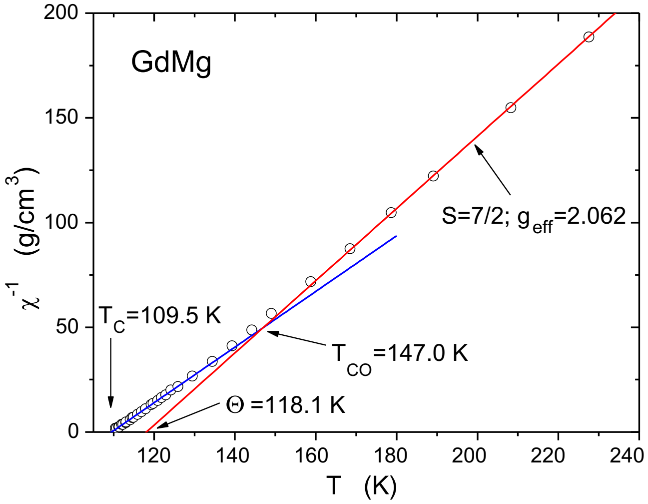

Fig. 1. Paramagnetic susceptibility of the cubic ferromagnet GdMg (S = 7/2) measured on a small spherical single crystal using conventional magnetization methods [28]. Crossover from Curie-Weiss susceptibility to critical susceptibility is at T_{CO} = 147 K. The finite width of the critical range, (T_{CO}-T_C), is characteristic for boson controlled spin dynamics. Crossover to boson dynamics shifts the transition temperature to a smaller value compared to Curie-Weiss temperature of Θ = 118.1 K.