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Shape Anisotropy and Magnetization of Ferromagnetic Nanostructures

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The temperature dependence of the spontaneous magnetization in rectangular ferromagnetic nanostructures is derived in the framework of a quantum microscopic approach taking into account discreetness of excitation spectrum. The results are discussed in connection to the existing phenomenological description of experimental data to suggest another general form of the temperature dependence of magnetization in nanostructures.

Keywords: Nanomagnets, Magnetization, Bloch Law, Magnons.

1. INTRODUCTION

Understanding the properties of magnetic nanomaterials is at the origin of their applications in a growing range of areas and of the progress in technological development,[1] and is generally proceeding from a phenomenological description towards the microscopic mechanisms of the observed phenomena. Our aim is to analyze the effects of varying size and shape anisotropy of a ferromagnetic nanocluster or nanoparticle on the temperature dependence of its magnetization $M(T)$ from the perspective of the Bloch theory, i.e., its microscopic generalization to a finite ferromagnet. More precisely, we do not include the shape effects due to demagnetization field as its role decreases with decreasing the particle size[2] and investigate a single domain particle with magnetization due to magnon excitations in samples of rectangular shape assuming a homogeneous ground state. As it has been shown before the homogenous magnetization is indeed achievable in such systems.[3]

Presently the results of numerical cluster simulations or experimental measurements of nanoparticle magnetization are usually cast into the form of a phenomenological (ph) expression meant to be an extension of Bloch $T^{3/2}$ law to nanomagnets[4–7]

$$M_{ph}(T) = M_0(1 - \gamma T^{\alpha}) \tag{1}$$

This expression is flexible enough to fit accurately the observed behavior of a large number of nanometric systems and seems to be in a plausible continuity relation with the bulk limit where $\alpha = 3/2$ and γ is determined by the magnon stiffness D (i.e., $\gamma \sim D^{-3/2}$). Equation (1) has been proposed some time ago[4] to account for the temperature dependence of ferromagnetic clusters obtained in numerical simulations. However, unlike its macroscopic limit, the microscopic origin of the parameters remains unclear and as well as the physical justification of the functional form of this expression. The reason for that is the absence of a microscopic generalization of the Bloch theory to systems of finite size. Indeed, it is easy to see that arbitrary values of α are inconsistent with the spin-wave theory which generates multiples of $1/2$. Another obvious inconsistency of (1) is that measurement units of γ depend on the value of the other parameter, α. It then becomes difficult to interpret the physical meaning of γ, compare its values for different samples, e.g., argue that the measured values are "much larger" in nanoparticles than in the bulk material "because of magnon softening" (e.g., Ch. 6.9 of the review Ref. [8]). Moreover, the observed dependence of α on particle size is found to be very irregular and its values can be above, below or even coincide with the bulk "benchmark." Moreover, the Bloch exponent has been reported even for epitaxial ultrathin films although "the $T^{3/2}$ dependence is not theoretically founded for two-dimensional systems."[9]

To address these issues we have devised a controllable approach allowing to investigate this problem analytically

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