NANOPARTICLE ASSEMBLY DYNAMICS APPLIED TO THE EXPLORATION OF MAGNETIC NOISE AMPLITUDE CORRELATION

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Abstract

Ferromagnetically linked nanoparticle assembly is studied, taking into consideration inter- and intra-particle electrical structures, inside the randomly hopping interactive moment's model that also includes quantum fluctuations caused by discrete levels and disorder. In order to support the existence of spinal regions and crucial sites at the magnetic jump anomalies caused by quantization, the magnetic state equation and phase diagram are found. It is anticipated that arrays of magnetized nanoparticles will exhibit a certain set of features. Such arrays exhibit well-separated instability regions around the anomalous locations when weak coupling is present. When the link gets stronger, we observe more structural change, which might indicate bifurcation-type alteration. While the stable zone appears as a limited island at low coupling, the dynamical instability region grows with high coupling. Exploring magnetic noise amplitude correlations is demonstrated to be a useful analytical tool for the quantitative definition, description, and research of super magnetism, as well as self-organized criticality.

Introduction

The assemblages of magnetic nano-particles offer a chance to create novel materials with properties that go beyond those of conventional solids and that have potential uses in modern technology and medicine. In particular, a single nano-magnet assembly, or "lab on a chip" system, may be used to perform several laboratory operations, including as injection, sample preparation, manipulation, reaction control, detection, and separation, among others. See [1, 2] and references therein for further information. In this article, we look at the analytical techniques used to define, characterize, and evaluate such devices in relation to magneto dynamics.

At sufficiently high density of nano-magnets the assembly structure changes from super Para- (SPM) to super ferro-magnetism (SFM) [1-4] inducing, thereby, jerky magneto dynamics with sharp discontinuities in the array magnetization process. The electronic spatial quantization is well-known to represent specific nano-particle feature bringing the sharp step-like discontinuities of the magnetic response in varying fields due to the Zeeman splitting [4, 5]. Familiar examples are related to the singlet-triplet transitions (cf., e.g., [4] and refs. therein) in semiconductor quantum dots and carbon nanotubes in magnetic field. We compare in this contribution different cases and demonstrate that this particular feature makes the system of nano-particles significantly different from traditional ensemble of magnetic elements with constant spins. In particular, we demonstrate that an effect of multiple discontinuity anomalies can bring in SFM structure some new phases related to self-organized (SO) criticality.

Super ferromagnetism with disorder

Recent theoretical studies [3, 4] of realistic super crystalline objects show, that the relationship between inter-particle magnetic interaction and the disorder substantially determines the magnetic structure and dynamics. Then an occurrence of SO criticality represents, perhaps, one of the most interesting phenomena. At such a regime magnetic induction of nano-particle arrays displays erratic stochastic discontinuities with rather wide distribution of jump amplitudes.

Mean-field approach to ensemble of interacting discrete moments at a disorder

At a modeling of the nano-particle assembly magnetism we employ very general form

$$m = \mu \sum_n v_n \theta(b - b_n)$$ μ

for namo- particle magneticmoment with moment unit and step $\theta(x)$ functiondepending on local magnetic field *b*. $\{v, b\}_n \equiv \{v_n, b_n\}$ The set of quantities determines the value of

magnetic moment directed along the field vector (for more details see [4] and refs.

therein).The conditions simulate the discrete anomalies of moment jumps. The field independent

$v_n \neq 0$ $v_n = 0$ at $n \neq 0,1$

with the g-factor *g* and.

The particles with a singlet-triplet

$\{v,b\}_{-1} = \{-g, -\infty\}$; $\{v,b\}_0 = \{g, -B_{st}\}$; $\{v,b\}_1 = \{g, B_{st}\}$. In addition, we consider the particle array with 5 such jumps.

The magnetic jump anomalies induced by quantization result in discontinuities in MSE. At increasing disorder such stepwise behaviour is smeared out.

It is worthy to notice here, that each particle jump anomaly brings two MSE discontinuities, see Fig. 1B. Therefore, Fig. 1C shows part of 6 jumps from the total 10 discontinuities on magnetization curve.

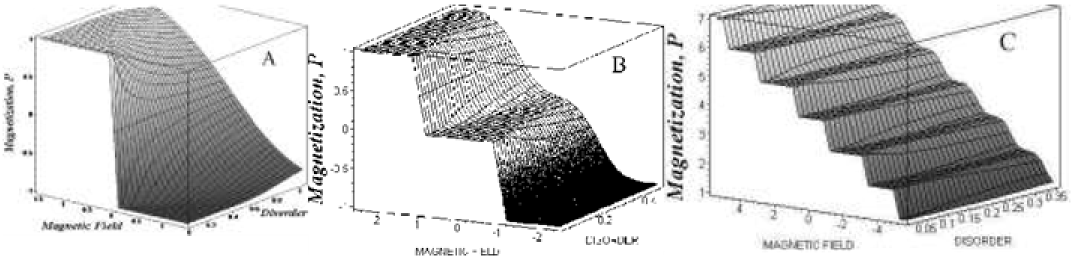

Figure 1. Magnetic state equation, MSE, of an assembly of nano-particles with constant spin (panel A), singlet-triplet transition (panel B) and 5 jump anomalies (panel C).

2.2. Magnetic phase diagram of SFM

Ferromagnetic inter-particle coupling brings the hysteresis loops in magnetization curves at the external field strengths corresponding to discontinuity anomalies. Such a behaviour can be understood in terms of avalanche propargation. When the local field b_i of some i-th lattice element passes through the value b_n the moment changes step-wise. Due to the ferromagnetic interaction a jumping moment can cause some of the nearest neighbors to jump, which may in turn trigger some of their neighbors, and so on, generating, thereby, magnetic avalanche, cf., [3, 4]. As a consequence some sharp stepwise discontinuity arises on magnetization curves. Within the mean-field approach MSE is given by the solution of an equation $P=P[H+JP]$, cf., Eq. (2). Therefore, the value J NI represents an average

$$b_i = H(t) + JV_D \sum_{j \subset nn} P_j + h_i,\ \mathrm{H} = -\sum_i m_i b_i \tag{1}$$

$$P = \int dh W(h) m(H + JP + h) \tag{2}$$

number of induced jumps per single jumping moment and the negatively defined susceptibility yields adiabatic spinodal region for SFM, cf. Eq. (2). Since the number of induced moment jumps exceeds 1 the system favours to evolve in an avalanche spanning almost entire sample with a macro- magnetization discontinuity. Evidently, the relation corresponds to the instability condition.

Such spinodal regions are located insight of contour lines on $\{B,R\}$-plane as is indicated in Fig. 2. The upper and lower field-lines meet at the critical point. As is seen in Fig. 2B and Fig. 2C for the case of multiple jumps in particle magnetization the array with weak coupling experience well isolated spinodal regions. The respective magneto dynamics is, therefore, quite similar to the case of a single jump. However, for strong coupling the region of instability is very spread so that we observe a confined isolated stability domain at small disorders.

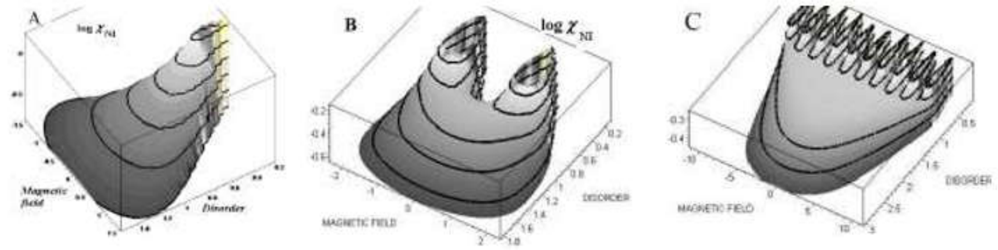

Figure 2. The magnetic susceptibility for an array of non-interacting nano-magnets with constant spin (panel A), singlet-triplet transition at B_{st}=1 (Panel B) and 5 jump anomalies (Panel C) at disorder R.

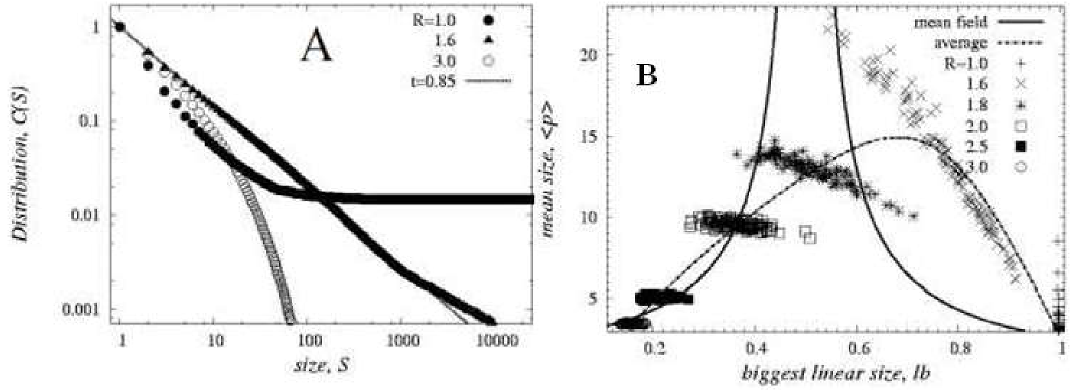

Figure 3. Panel A - Cumulative avalanche size distributions are compared to the power law with an exponent. Results of the RJIM model for $(30)^3$ simple cubic lattice are shown for disorders R=1 - solid circles, 1.6 - solid triangles, 3 - open circles. Panel B - Mean avalanche size versus the linear size of the biggest avalanche in units of array length. Results of RJIM model at various disorders are shown by particles while dashed-dotted line joins respective average values for each disorder. Solid line displays the prediction of the mean-field approximation in the thermodynamic limit.

Making use of the analytical form Eq. (3) we analyze some analytical tools which might be employed in order to specify and analyze SFM systems. Similarly to methods of high energy physics (cf, e.g., [7,8] and refs. therein) the correlations of avalanche size distribution might provide the criticality signals and a tool specifying and quantifying magnetic structure. For certain *i*th (re)magnetization event we define the mean noise signal

$$<p>=SS\ S\ D(S)/\ S\ D(S) =(\Pi-S_b)/(N_{tot} - 1) \quad (4)$$

where the sum runs over the avalanche sizes S excluding the biggest one, the quantity N_{tot} gives the total number of noisy jumps, i.e. avalanches. Substituting Eq. (3) into Eq. (4) the mean avalanche size, i.e. mean value for magnetic emission signals, is evaluated to be $<p>_{mf}\sim|d|^{-1}$ + *const(d)*, and diverges at critical conditions, i.e. d 0 , in the thermodynamic limit.

If the system undergoes a critical behaviour being a precursor of SO criticality in some particular (re)magnetization events, strong correlations will appear in magnetic noise. For instance, in case of magneto dynamics we can study correlations between the strongest signal. numerical model or experimental data. These correlations are similar to the Campi scatter plots [7,8]. In Fig. 3B we plot the mean avalanche size versus the length of largest avalanche for certain event. The data in Fig. 3B were obtained from RJIM simulations assuming various disorders as partially presented in Fig. 3A. In Fig. 3B we can clearly distinguish two branches corresponding to under- critical, i.e., large size of the biggest jump amplitude and small mean value, and overcritical, i.e. small size of the biggest avalanche and small average values. The right branch consists mainly of events with small disorders, while the left branch originates from events having large *R*. The set of two branches meet in the critical region. The results of the mean field approximation in the thermodynamic limit are in a reasonable agreement with numerical data for overcritical disorders. At sub-critical conditions the mean field approach reproduces only qualitatively the RJIM model simulations.

Conclusions

While accounting for the inter- and intra-particle characteristics, we took the magnetic structure of nanoparticle assemblies into consideration. Sharp step-vise anomalies for magnetic moments in the external field are brought on by spatial quantization brought on by intra-particle confinement. Such moment jumps coupled with ferromagnetic inter-particle interaction result in jerky magneto dynamics with abrupt steps in the array (de)magnetization process, as demonstrated in [3,4]. We take into consideration quantum effects brought on by inter-particle interaction, disorder, and discrete particle levels using the RJIM model [3,4]. Such a system's MSE and phase diagram are shown to have spindle areas on the R, B-plane. These zones of instability are well spaced and surround the locations of the particle magnetic anomalies in a situation of weak coupling. With increasing coupling, we observe further structure modification, plausibly, of bifurcation type. At strong coupling the instability region become wide while the stable regimes are reduced to narrow islands at small disorders. We consider analytical tools exploring correlations of magnetic noise amplitudes and demonstrate an application for quantitative definition, description and study of SFM structure and origin, as well as self-organized criticality. Further analysis based on numerical simulations within RJIM model and implications of proposed tools will shed a light on the origin and properties of this transition.

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