Understanding dynamics of interacting magnetic nanoparticles: from the weak interaction regime to the collective superspin glass state

D. Fiorani* and D. Peddis
ISM-CNR, Area della Ricerca Roma 1, Via Salaria km 29.300, Monterotondo Scalo (RM), Italy
Email: dino.fiorani@ism.cnr.it

Abstract

A brief review of the investigations on interparticle interaction effects (weak and strong interactions regimes) is reported with a special emphasis on the critical behaviour in the static and dynamical properties and on the out of equilibrium dynamics of the collective superspin glass (SSG) state. The results of the investigation of aging and memory effects in two peculiar SSG systems are discussed: MnFe$_2$O$_4$ nanoparticles, in powder form, with very strong dipolar interactions, and a diluted system, consisting of a film of Co particles dispersed (5% volume fraction) in a Mn matrix, where interparticle interactions are mainly mediated by the matrix.

1. Introduction

Since the pioneering work of Louis Néel in the 1940s[1], nanoparticle magnetism has been representing one of the most attractive and challenging topics in both fundamental[2,3] and applied magnetism (magnetic recording, biomedicine, energy, sensors….)[4–7]. The topic, having an interdisciplinary character, has been evolving continuously and in particular the progress was enormous in the last two decades, with the discovery of new phenomena and the opening of new perspectives for applications in different fields. They come from the control of the interplay between intrinsic intraparticle properties (finite size and surface effects) and interparticle interaction effects. The latter is responsible for the existence of different types of collective magnetic states and has a dominant role in technological applications. Moreover, the capability of engineering, by advanced chemical and physical methods, organized arrays of nanoparticles and ordered structures of single domains nanodots[8,9], has been further expanding the applications in nanotechnology. This paper is aimed at briefly reviewing the progress, since the first International Conference on Fine Particle Magnetism (ICFPM – Rome, 1991)[10], in the understanding of interparticle interactions effects leading to the collective superspin glass (SSG) state. The results of the investigation of out of equilibrium dynamics in two peculiar SSG systems will be discussed: MnFe$_2$O$_4$ nanoparticles, in powder form, with very strong dipolar interactions, and a diluted system consisting of a film of Co...
particles embedded (5% volume fraction) in a Mn matrix, where the interactions are mainly mediated by the matrix.

2. Interparticle interactions effects

2.1 Weak interparticle interactions regime

Until the early 90s, the study of the effect of interparticle interactions was restricted to the weak interactions regime, defined as the regime of an assembly of magnetic nanoparticles where the interparticle dipolar interaction energy \( E_{\text{int}} \), contributing to the total effective anisotropy energy \( E_{\text{tot}} \), is much lower than the individual particle anisotropy energy \( E_a \). The superparamagnetic (SP) model basically still holds, provided that the actual contribution of interparticle interactions to the total anisotropy energy is taken into account \( E_{\text{tot}} = E_a + E_{\text{int}} \). In such conditions, the effect of interparticle interactions was considered just a perturbation to the SP state, leading to the so called “modified SP” regime, where the static and dynamical properties of individual particles are partially modified by the interaction with the neighbouring particles.

In the pure SP regime, where interparticle interactions are absent, the static properties of the particles are described by the Langevin function, like for paramagnets. Allia et al. [11] proposed a modified Langevin function to account for the presence of weak interparticle interactions:

\[
M = N\mu_n L \left( \frac{\mu_n H}{k_B (T - T^*)} \right)
\]  

(1)

Where \( \mu_n \) is the nanoparticle moment, \( N \) is the number of moments per unit volume, \( L \) is the Langevin function and \( T^* \) is fictive temperature (a positive definite quantity), which basically measures the magnitude of the dipolar interaction and depends on structural parameters, such as magnetic nanoparticles density, and on saturation magnetization. For a given nanoparticles system a \( T^* \) value is derived at each temperature (being \( T^* \) weakly dependent on temperature because it contains the sample's magnetization).

The model satisfactorily explains the main features of the \( M \) vs \( H \) curves. Such regime was defined by the authors as an “interacting superparamagnet”, i.e. a SP regime where the dipolar interactions are no longer negligible.

The dynamical properties for an assembly of non interacting nanoparticles with uniaxial symmetry were described by the Néel model\(^1\), which predicts a temperature and anisotropy energy dependence of the relaxation time \( \tau \) according to an Arrhenius law. This law implies a \( T \ln T/\tau \) scaling in the whole SP regime[12]. The effect of interparticle interactions on the dynamical properties was described modifying the Arrhenius law for SP systems and replacing it by the phenomenological Fulcher law:

\[
\tau = \tau_0 \exp \left( \frac{K_a V}{k_B (T - T_0)} \right)
\]  

(2)

where the effect of weak interparticle interactions is accounted by the temperature \( T_0 \), giving an estimation of their strength[13].

A more general description of the dynamical properties was given by Dormann et al[14] with a model describing the effect of magnetic dipolar interactions on the relaxation time of the particle moments. A disordered assembly of non-identical particles with volume distribution was considered. This implies a distribution of relaxation times and a distribution of energy barriers, which depends on the particle volume and on the dipolar interactions. Since the particle moments fluctuate with different \( \tau \), even the angle between two non identical particles fluctuates with time. Thus, it is not possible to calculate the effect of the dipolar interactions strength in static conditions. To model the effect of interparticle interactions in dynamical conditions, the Boltzmann statistics was used introducing a modified Langevin function containing the interparticle interactions dipolar energy,
which adds to the individual particle anisotropy energy. Considering the approximation $E_{\text{int}} \ll E_a$, the interaction energy can be written as:

$$E_{\text{int}} = \left( \frac{\mu}{V} \right) \sum_j b_j L \left( \frac{\mu^2 a_j}{V K_B T} \right) \quad (3)$$

$$a_j = V \frac{2 \cos 2\alpha_j}{d^3} \quad (3b)$$

Where $a_j$, $b_j$, $\alpha_j$ are parameters that define the spatial arrangement of nanoparticles. The frequency dependence of the blocking temperature ($T_b$) is well reproduced by the model in a very large time window. Interparticle interactions modify the energy barrier, leading to an increase of $T_b$, in agreement with experimental observations[15,16].

2.2 Strong interparticle interactions regime

In the “strong interactions” regime, the interparticle interaction energy is much larger than the individual particle anisotropy energy ($E_{\text{int}} \gg E_a$). Moving from the weak to strong interparticle interactions regime, a crossover occurs from the blocking of particle moments to a collective magnetic state where particle moments lose their individuality. This is observed in concentrated frozen ferrofluids [17,18] and in concentrated granular systems where single domain particles are dispersed in a non magnetic matrix[19]. Two sub-regimes are distinguished in the strong interactions regime, with increasing the particle concentration: the superspin glass (SSG) regime and the superferromagnetism (SFM) regime. The difference in the two sub-regimes is in the strength of interparticle interactions, which is moderate in SSG and stronger in SFM, and in the symmetry of interactions, leading to a disorder state or to an ordered one, in SSG and SFM, respectively. For large particle concentration, but prior to physical percolation, the interparticle interactions become much stronger than in SSG and finally they can lead to the SFM state, characterized by FM domains of supermoments of particles, i.e. domains where ferromagnetic correlations are between supermoments of individual particles, instead that between atomic moments[20].

2.2.1 Superspin glass

The investigation of similarities between a SG system and strongly interacting nanoparticle systems has been receiving a growing attention since the early 90s [16,17,21–29]. In a particle system with sufficiently narrow size distribution, sufficiently strong interparticle interactions, randomness in the distribution of particle positions and of anisotropy axes orientations, a SSG state can be observed, characterized by a collective random freezing of particle moments below a characteristic glass temperature ($T_g$). Both the required ingredients of the SG state are also present in the SSG one, i.e. randomness and frustration of interactions between particle moments. A SSG behaviour was recently observed in a random-close-packed (volume fraction 67%) ensemble of highly monodisperse nanoparticles ($\gamma$-Fe$_2$O$_3$)[30]. Being the collective freezing between particle moments rather then between atomic spins, the dynamics in SSG is much slower, as the microscopic flip time of one superspin (in the order of 10$^9$ s at room temperature; up to 10$^6$ s in the frozen state at low temperature) is much longer than an atomic spin flip time (in the order of 10$^{12}$ s). The growth of dynamical correlation length is slower in SSG and thus the slower dynamics of SSG is of particular interest because a much shorter time scale becomes experimental accessible. Nevertheless, theoretical models developed for atomic SG have so far succeeded in describing many aspects of the SSG static and dynamical properties. It was found, by frequency dependent ac susceptibility and ZFC relaxation measurements, that the growth of supermoments correlation length in a disordered SSG state of a frozen ferrofluid sample follows the same physical law as for Heisenberg SG [17].

SSG exhibits the same type of features of SG both in the static and dynamic properties. The temperature dependence of the low field susceptibility is characterized by a maximum of the zero-field-cooled (ZFC) susceptibility and small maximum of the field cooled (FC) susceptibility, followed by a plateau with decreasing temperature. Ageing and memory effects, typical of SG behaviour, are also observed in SSG. The basic analogy is the critical behaviour in both static and
dynamical properties, which represent the real proof of the existence of the special type of transition at $T_g$ to the SG and SSG state.

A critical behaviour in the temperature dependence of the non linear susceptibility $\chi_2$, diverging at $T_g$, was observed in SSG systems (e.g. Fe$_2$N[27], $\gamma$-Fe$_2$O$_3$[31] Fe-C[32] nanoparticles) A critical behaviour was also observed in the temperature dependence of the relaxation time with decreasing temperature, diverging at $T_g$, according to a power law, with critical exponents having values quite similar to those reported for SG ($z\nu = 8-10$) [31–33] ($z$ is the dynamical critical exponent; $\nu$ is the critical exponent driving the correlation length, $\xi$).

\[
\tau = \tau_0 \left( \frac{T}{T_g - 1} \right)^{-z\nu}
\]

(4)

The $z\nu$ value was found to be dependent on the anisotropy of the SG system, as shown for Ising ($\text{Fe}_0.5\text{Mn}_0.5\text{TiO}_3$; $z\nu = 10.5$) and Heisenberg like ($\text{CdCr}_{1.7}\text{In}_{0.3}$; $z = 7$) SG[34].Another evidence of SG like properties is the observed dynamic scaling, i.e. the collapse onto a master curve of the values of the imaginary component of the dynamic susceptibility ($\chi''$) measured at different frequencies and temperatures[31,32].

The dynamical properties below $T_g$ are characterized by ageing and memory effects, which are manifestation of an out of equilibrium state, associated to the onset of a random collective state of particle moments. As in SG, even in SSG it was observed a slowing down of the relaxation of the ZFC magnetization with increasing the time spent (waiting time, $t_w$) at a constant temperature below $T_g$, before the application of the magnetic field [21]. This reflects the slow evolution of the system towards an equilibrium configuration, during the aging, starting at the time of the quench below $T_g$. The aging effect was satisfactorily explained both by the model of hierarchical system of energy minima in the phase space, by Parisi[35] and the droplet model of Fisher and Huse[36]. Ageing is a manifestation of a slow growth of a dynamical correlation length, when the system is aged in the frozen state, developing in the same way as the correlations between the spins of an atomic spin glass. The ageing phenomenon is absent in the most diluted samples revealing that this phenomenon is a manifestation of a collective dynamical behaviour.

Memory effects were also observed in the ZFC magnetization curve, as in SG, following the so called “stop and wait” experimental protocol during the ZFC process: the ZFC cooling down is interrupted at a given temperature below $T_g$, the system is maintained at this temperature for a certain time and then the cooling continues down to the lowest temperature. When the magnetization is measured on warming up, lower values of the magnetization with respect the values of the reference curve, measured without interruption in the ZFC process, are observed in the temperature region where the previous ZFC cooling process was stopped. This phenomenon is another manifestation of ageing, which occurs during the stop time at the stop temperature before cooling down to the lowest $T$, and it reveals that the system remembers the stopping procedure[22,36].

3. Examples of SSG systems

3.1 MnFe$_2$O$_4$ nanoparticles

MnFe$_2$O$_4$ nanoparticles have been synthesized by coprecipitation of Fe$^{3+}$ and Mn$^{2+}$ from water-in-toluene reverse micelle system and subsequent thermal treatment at 320$^\circ$C. The mean crystallite size obtained by XRD analysis is ~2 nm, whereas the value obtained by powder specific area (278 m$^2$/g) is about 4 nm. This suggests that the particles consist of a few aggregated crystallites[38,39].

ZFC and FC magnetization measurements, recorded with an applied field of 100 Oe (figure 1a) show the typical SSG behaviour, with a sharp maximum of both curves at $T_g = 45$ K. A critical divergence of the relaxation time, according to a power law ($z\nu = 8.6$), was found by the analysis of the frequency dependence of $T_g$ by using ac susceptibility measurements. The non equilibrium dynamics below $T_g$ has been investigated by memory and rejuvenation experiments.
reference curve was recorded according to the usual procedure. The memory curves (Fig. 1b) were measured in the same way, but after maintaining the sample in zero field for 3 h at 20 K (T/T_g = 0.45) and 33 K (T/T_g = 0.45). A reduced magnetization was observed at the stop and wait temperatures, the effect being larger at the higher temperature.

Figure 1: (a) FC (empty circles) and ZFC (full circles) magnetization of MnFe_2O_4 nanoparticles in an applied field of H=100 Oe; (b) upper curves: ZFC-memory curves for a stop-and-wait of 10000 sec at 0.45 T/T_f (T= 20 K; empty circles) and at 0.75 T/T_f (T= 33 K; full circles); lower curves: difference, multiplied by a factor 10, between ZFC-reference and ZFC-memory curve (full circles in panel a) at 0.45 T/T_f and at 0.75 T/T_f.

3.2 Co nanoparticles embedded in antiferromagnetic Mn matrix

Co particles embedded in Mn matrix (Co@Mn) with ~5% volume fraction (VF) were prepared in thin film form by co-deposition using a gas aggregation cluster source and a molecular beam epitaxy (MBE) source[39]. The cluster source produces a log-normal distribution of particle sizes, with a mean size of 1.8 nm, as measured in situ by an axially mounted quadrupole filter. In order to clarify the role of the antiferromagnetic matrix, a reference sample of Co nanoparticle embedded in diamagnetic Ag matrix with the same volume fraction (Co@Ag) was prepared[40,41]. Figure 2a reports ZFC and FC susceptibility for Cobalt nanoparticles dispersed in Mn and Ag matrix. The comparison provides a clear evidence of an independent blocking of particle moments in Co@Ag and of a correlated freezing of particle moments, SSG type, in (Co@Mn). Indeed, in Co@Ag the continuous increase of $\chi_{FC}$ with decreasing temperature, indicates that interparticle interactions are very weak. On the other hand, in Co@Mn the FC susceptibility shows, with decreasing temperature, a sharp maximum at 70 K followed by a plateau below 30 K. This landscape is confirmed by AC susceptibility measurements. In Co@Ag, the frequency dependence of $T_{max}$ is well described by an Arrhenius law, whereas in Co@Mn by a power law ($z\nu=8.2$)[41]. The Co@Mn sample exhibits a non equilibrium glassy dynamics, as shown the by the stop and wait experiment using the ZFC protocol (inset figure 2a). In Fig. 2b, Monte Carlo (MC) simulation of ZFC curves for different waiting times $t_w = 300, 1000, 3000,$ and $10000$ s are reported on a normalized temperature scale. The differences between the reference and memory curves for different $t_w$ are reported in the inset of Fig. 2b. For a logarithmic spacing of waiting times as those used in the experiment, equally spaced depths in the measured memory dips were observed. In this dilute system, the interface exchange coupling
between Co ferromagnetic particles and the antiferromagnetic Mn matrix plays a very important role in transmitting long range interparticle interactions. Actually, due to a partial alloying (the existence of Co$_x$Mn$_{1-x}$ alloy was shown by EXAFS data) the interface coupling is between the ferromagnetic Co core and the surrounding antiferromagnetic Co$_x$Mn$_{1-x}$ shell, consistently with the very low Co moment measured by XMCD spectra [40]. MC Simulations were also performed for a 10% VF sample, larger memory effect were experimentally observed. This indicates that both dipolar interparticle interactions and the interface exchange coupling with the Mn matrix contribute to stabilize a SSG phase and its dynamical behaviour. Simulations including both contributions reproduce well the memory effect for different $t_w$. Simulations without including dipolar interactions still show the memory effect, although weaker, confirming the role played by the matrix. The interface exchange coupling between the FM and AFM phase is also responsible for the observed Exchange Bias (EB) effect below the temperature at which the FC susceptibility starts to become temperature independent, signalling a complete freezing of particle moments [42-44]. Due to the intrinsic energy structure of SSG, characterized, according to the Parisi’s model [35,44], by a hierarchical organization of many energy minima separated by energy barriers of different height, EB involving a SSG phase provides an even better possibility of tuning the coercivity, since it is dependent on the energy barrier distribution [41][45].

Figure 2: (a) ZFC (full circles/squares) and FC (empty circles/squares) susceptibility for Co@Ag (circles) and Co@Mn (squares) samples with Co VF 5%; Inset, upper curve: ZFC-reference curve (full circles) and ZFC-memory curve (empty circles squares): for a stop-and-wait of 10000 s at $T/T_f \approx 0.8$ ($T= 50$ K); lower curve: difference, multiplied by a factor 10, between ZFC-reference and ZFC-memory curve (empty triangles). (b) Monte Carlo simulation of ZFC-FC reference curve ($t_{ref} = 3 \times 10^3$ MCSS) and ZFC-memory curves after stop-and-wait for different waiting times at $T/T_f = 0.64$ for 5 % volume fraction and $H = 0.20$ JC/gµB; inset: difference between ZFC-reference and ZFC-memory curve as a function of temperature for different waiting times $t_w$.

4. Conclusions

Interparticle interaction effects have been reviewed with a special emphasis on the analogies between the static and dynamical properties of a collective frozen disordered state of particle
supermoments (SSG state) and those of atomic spins (SG state). Apart from the much slower
dynamics in SSG, the same phenomenology as in Heisenberg SG is observed: temperature
dependence of the ZFC/FC susceptibility curves, critical divergence at $T_c$ of the non linear
susceptibility and of the relaxation time with comparable critical exponents; dynamic scaling, ageing
and memory effects. The results of the investigation of out of equilibrium dynamics in two SSG
systems have been discussed: MnFe$_2$O$_4$ nanoparticles, in powder form, with very strong dipolar
interparticle interactions, and a diluted system, consisting of a film of Co particles dispersed (5% volume fraction) in a Mn matrix, where the antiferromagnetic matrix, interface coupled with the
ferromagnetic particles, plays an important role in transmitting long range interparticle interactions.

References

[1] L. Néel, Ann. Gèophysique 5 (1949) 99.

[2] J.L. Dormann, D. Fiorani, E. Tronc, in:, wiley (Ed.), Advances Chem. Phys., New York, 1997.

[3] S. Morup, M.F. Hansen, C. Frandsen, Magnetic Nanoparticle, 2011.

[4] D. Weller, a. Moser, IEEE Trans. Magn. 35 (1999) 4423.

[5] C.B.M. S. Sun D. Weller, L. Folks and A. Moser, Science (80-. ). 287 (2000) 1989.

[6] Q.A. Pankhurst, N. Thanh, S. Jones, J. Dobson, J. Phys. D. Appl. Phys. 42 (2009) 224001.

[7] L. Suber, D. Peddis, in:, Nanomater. Life Sci., Wiley, 2010, p. 431475.

[8] T.R. Albrecht, D. Bedau, E. Dobisz, H. Gao, M. Grobis, O. Hellwig, D. Kercher, J. Lille, E.
Marinero, K. Patel, R. Ruiz, M.E. Schabes, L. Wan, D. Weller, IEEE Trans. Magn. 49 (2013)
773.

[9] S. Sun, S. Anders, H.F. Hamann, J.-U. Thiele, J.E.E. Baglin, T. Thomson, E.E. Fullerton,
C.B. Murray, B.D. Terris, J. Am. Chem. Soc. 124 (2002) 2884.

[10] J.L. Dormann, D. Fiorani, in:, North-Holland (Ed.), Amsterdam, 1992.

[11] P. Allia, M. Coisson, P. Tiberto, F. Vinai, M. Knobel, M.A. Novak, W.C. Nunes, Phys. Rev.
B 64 (2001) 144420.

[12] A. Labarta, O. Iglesias, L. Balcells, F. Badia, Phys. Rev. B 48 (1993) 10240.

[13] S. Shtrikman, E.P. Wohlfarth, Phys. Lett. 85 (1981) 467.

[14] J.L. Dormann, L. Bessaist, D. Fiorani, J. Phys. C Solid State Phys. 21 (1988) 2015.

[15] D. Fiorani, J.L. Dormann, R. Cherkaoui, E. Tronc, F. Lucari, F. D’Orazio, L. Spinu, M.
Nogues, A. Garcia, A.M. Testa, J. Magn. Magn. Mater. 196-197 (1999) 143.
[16] J.L. Dormann, R. Cherkaoui, L. Spinu, M. Noguès, F. Lucari, F. D’Orazio, D. Fiorani, A. Garcia, E. Tronc, J.P. Jolivet, J. Magn. Magn. Mater. 187 (1998) L139.

[17] S. Nakamae, C. Crauste-Thibierge, D. L’Hôte, E. Vincent, E. Dubois, V. Dupuis, R. Perzynski, Appl. Phys. Lett. 101 (2012) 242409.

[18] S. Nakamae, C. Crauste-Thibierge, K. Komatsu, D. L’Hôte, E. Vincent, E. Dubois, V. Dupuis, R. Perzynski, J. Phys. D. Appl. Phys. 43 (2010) 474001.

[19] D. Peddis, C. Cannas, A. Musinu, Piccaluga.G., J. Phys. Chem. C 112 (2008) 5141.

[20] S. Bedanta, W. Kleemann, W. Kleeman, J. Phys. D. Appl. Phys. 42 (2009) 013001.

[21] T. Jonsson, J. Mattsson, C. Djurberg, F.A. Khan, P. Nordblad, P. Svedlindh, Phys. Rev. Lett. 75 (1995) 4138.

[22] S. Sahoo, O. Petracic, W. Kleemann, P. Nordblad, S. Cardoso, P.P. Freitas, J. Magn. Magn. Mater. 272-276 (2004) 1316.

[23] T. Jonsson, P. Nordblad, P. Svedlindh, Phys. Rev. B 57 (1998) 497.

[24] S. Nakamae, C. Crauste-Thibierge, K. Komatsu, D. L’Hôte, E. Vincent, E. Dubois, V. Dupuis, R. Perzynski, J. Phys. D. Appl. Phys. 43 (2010) 474001.

[25] D. Parker, V. Dupuis, F. Ladieu, J.P. Bouchaud, E. Dubois, R. Perzynski, E. Vincent, Phys. Rev. B 77 (2008) 104428.

[26] J.L. Dormann, D. Fiorani, E. Tronc, J. Magn. Magn. Mater. 202 (1999) 251.

[27] H. Mamiya, I. Nakatani, T. Furubayashi, Phys. Rev. Lett. 80 (1998) 177.

[28] M. Sasaki, H. Takayama, H. Mamiya, P.E. Jönsson, Phys. Rev. B 71 (2005) 104405.

[29] H. Mamiya, S. Nimori, M. Ohnuma, I. Nakatani, M. Demura, T. Furubayashi, J. Magn. Magn. Mater. 316 (2007) e535.

[30] J. a. De Toro, S.S. Lee, D. Salazar, J.L. Cheong, P.S. Normile, P. Muñiz, J.M. Riveiro, M. Hillenkamp, F. Tournus, a. Tamion, P. Nordblad, Appl. Phys. Lett. 102 (2013) 183104.

[31] P. Jönsson, T. Jonsson, J.L. Garcimh, P. Svedlindh, J. Magn. Magn. Mater. 222 (2000) 219.

[32] M.F. Hansen, P.E. Jonsson, P. Nordblad, P. Svedlindh, J. Phys. Condens. Matter 4901 (2002).

[33] D. Peddis, D. Rinaldi, G. Ennas, A. Scano, E. Agostinelli, D. Fiorani, Phys. Chem. Chem. Phys. 14 (2012) 3162.

[34] V. Dupuis, E. Vincent, J.-P. Bouchaud, J. Hammann, a. Ito, H. Katori, Phys. Rev. B 64 (2001) 174204.
[35] G. Parisi, Phys. Rev. Lett. 50 (1983) 1946.

[36] D.S. Fisher, D.A. Huse, Phys. Rev. B 38 (1988).

[37] S. Sahoo, O. Petracic, W. Kleemann, P. Nordblad, S. Cardoso, P. Freitas, Phys. Rev. B 67 (2003) 214422.

[38] M. Bellusci, B. Aurelio La, S. Luca, P. Franco, P. Antonella, V. Francesca, Polym. Int. 58 (2009) 1142.

[39] M. Bellusci, S. Canepari, G. Ennas, A. La Barbera, F. Padella, A. Santini, A. Scano, L. Seralessandri, F. Varsano, Mariangela Bellusci, A. La Barbera, J. Am. Ceram. Soc. 3983 (2007) 070922001308006.

[40] N. Domingo, A.M. Testa, D. Fiorani, C. Binns, S. Baker, J. Tejada, J. Magn. Magn. Mater. 316 (2007) 155.

[41] C. Binns, N. Domingo, a M. Testa, D. Fiorani, K.N. Trohidou, M. Vasilakaki, J.A. Balckman, A.M. Asaduzzaman, S. Baker, M. Roy, D. Peddis, J. a Blackman, J. Phys. Condens. Matter 22 (2010) 436005.

[42] N. Domingo, D. Fiorani, A.M. Testa, C. Binns, S. Baker, J. Tejada, J. Phys. D. Appl. Phys. 41 (2008) 134009.

[43] M. Vasilakaki, K.N. Trohidou, D. Peddis, D. Fiorani, R. Mathieu, M. Hudl, P. Nordblad, C. Binns, S. Baker, Phys. Rev. B 140402 (2013) 1.

[44] G. Parisi, Phys. Rev. Lett. 43 (1979) 1754.

[45] D. Fiorani, L. Del Bianco, a. Testa, K. Trohidou, Phys. Rev. B 73 (2006) 092403.