Kondo Effect and Spin Glass Behavior of Dilute Iron Clusters in Silver Films

W. T. Herrera[1],* Y. T. Xing[1], S. M. Ramos[1], E. M. Baggio-Saitovitch[1], and F. J. Litterst[1,2]
[1] *Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil and*
[2] *Technische Universität Braunschweig, Germany*

Thin films of silver containing $0.2 - 3at\ \%\ Fe$ have been prepared by vapor co-deposition under ultra-high vacuum conditions onto cooled Kapton substrates. Depending on substrate temperature and iron concentration we could systematically follow the formation of nanometer size clusters of iron from initially dilute iron monomers. Characterization of samples was performed via X-ray diffraction, resistivity, magnetization, susceptibility, and Mössbauer spectroscopic measurements. The silver matrices had typical grain sizes around $10 - 20\ nm$. Two well-defined types of iron clusters could be distinguished with hyperfine parameters indicating local atomic coordinations significantly deviating from *bcc* or fcc iron clusters.

The magnetic behavior derived from Mössbauer and magnetization data can be best described with an ensemble of ferromagnetic mono-domain particles with about 6 and 15 iron atoms for the two types of clusters, respectively, situated probably in grain boundaries.

The magnetic freezing observed at low temperatures, is clearly different from a blocking process of free small particles. It is controlled via the inter-particle interactions mediated via conduction electron polarization, i.e. $RKKY$ interaction. The interaction of the cluster magnetic moments with the conduction electron sea is best quantified by the electrical resistivity data. For all studied concentrations we find a non-monotonic variation with temperature which can be understood by competing shielding of the cluster moments by conduction electron spin scattering due to Kondo effect and the magnetic coupling. We will discuss the development of these competing mechanisms as a function of varying types of clusters and concentration. Notably the derived Kondo temperatures up to iron concentrations of 1% *at* are in keeping with earlier data on extremely dilute iron in silver. Deviations are met for higher concentrations and will be discussed especially under new aspects of magnetic inter-cluster coupling even via long distances.

Keywords: Mössbauer spectroscopy, Kondo effect, spin freezing, magnetic clusters

[1] William T. Herrera, Dissertação de Mestrado: *Propriedades Magnéticas de nanoclusters de Fe em filmes de Ag*, CBPF Brasil 2007.
[2] P. Munayco, J. Larrea J., Y. T. Xing, H. Michlitz, E.M. Baggio-Saitovitch, Phys. Rev. B **74**, 014423 (2006).
[3] M. G. Vavilov, L.I. Glazman, and A.I. Larkin, Phys. Rev. B **68**, 075119 (2003).
[4] M. A. Morales, E. C. Passamani, E. Baggio-Saitovitch, Phys. Rev. B **66**, 144422, (2002).
[5] S.N. Mishra, P. Taneja, P. Ayyub, A.A. Tulapurkar, Phys. B, **312-313**, 162-164 (2002).
[6] O. Diéguez, M.M.G. Alemany, C. Rey, P. Ordejón, L.J. Gallego, Phys. Rev. B **63**, 205407 (2001)
[7] A. Crépieux and C. Lacroix, Phyisica B **259-261**, 204-205 (1999).
[8] D. Riegel, L. Büermann, K. D. Gross, M. Luszik-Bhadra, and S. N. Mishra, Phys. Rev. Lett. **62**, 316 (1989).
[9] D. Riegel, L. Büermann, K. D. Gross, M. Luszik-Bhadra, and S. N. Mishra, Phys. Rev. Lett. **61**, 2129 - 2132 (1988).
[10] C. Lacroix and M. Cyrot, Phys. Rev. B **59**, 13824 (1979).
[11] U. Larsen, Phys. Rev. B14, 4356 (1976) M. Hanson, J. Phys. F: Met. Phys. 7, 2555 (1977)
[12] J.S. Schilling, P.J. Ford, U. Larsen, and J.A. Mydosh, Phys. Rev. B **14**, 4368 (1976)
[13] P. Steiner and s. Hüfner, Phys. Rev. B **12**, 842 (1975)

*Electronic address: william@cbpf.br