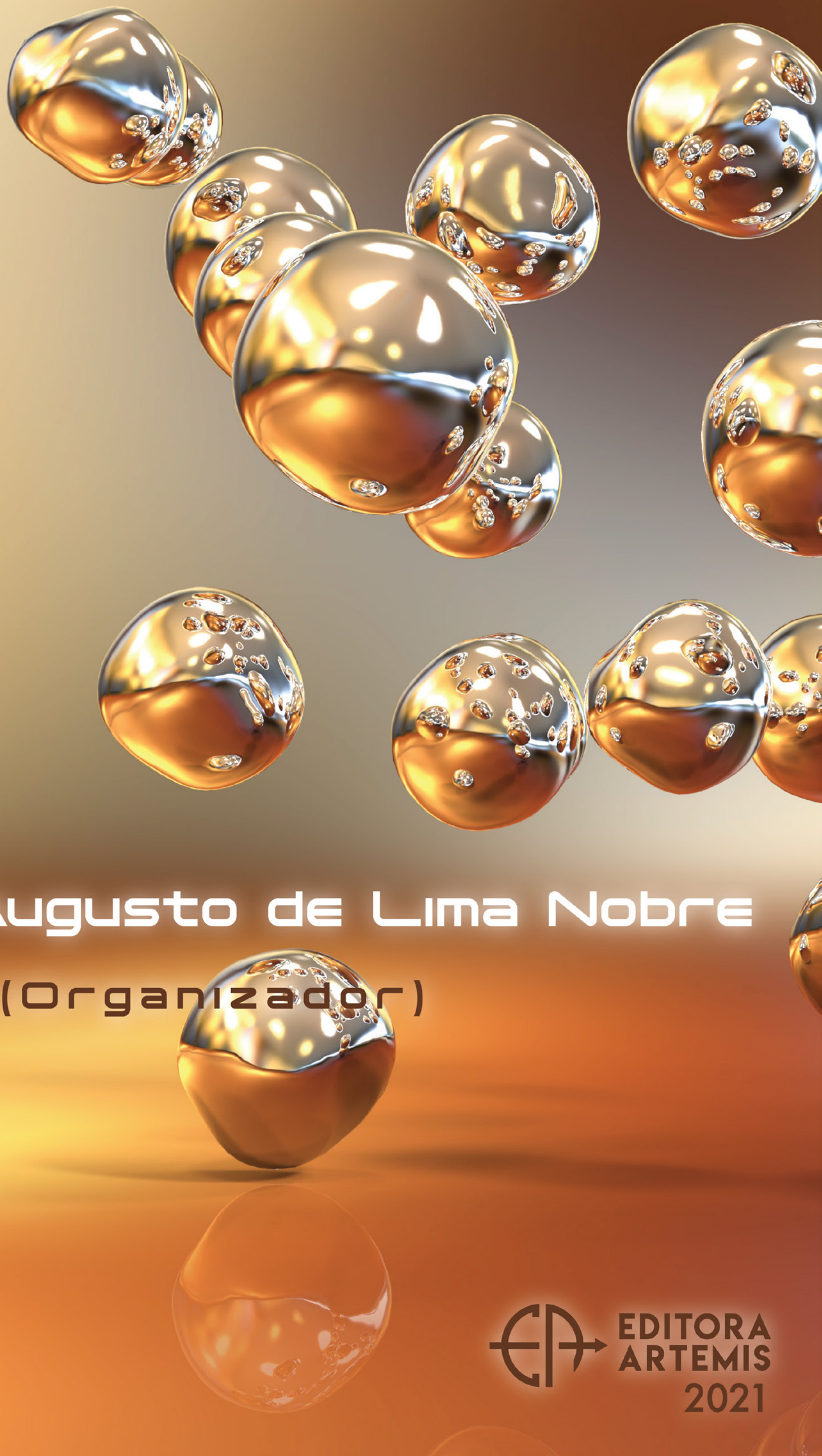
THE GREAT WORLD OF NANOTECHNOLOGY



Marcos Augusto de Lima Nobre

(Organizador)

VOL II

EDITORA ARTEMIS

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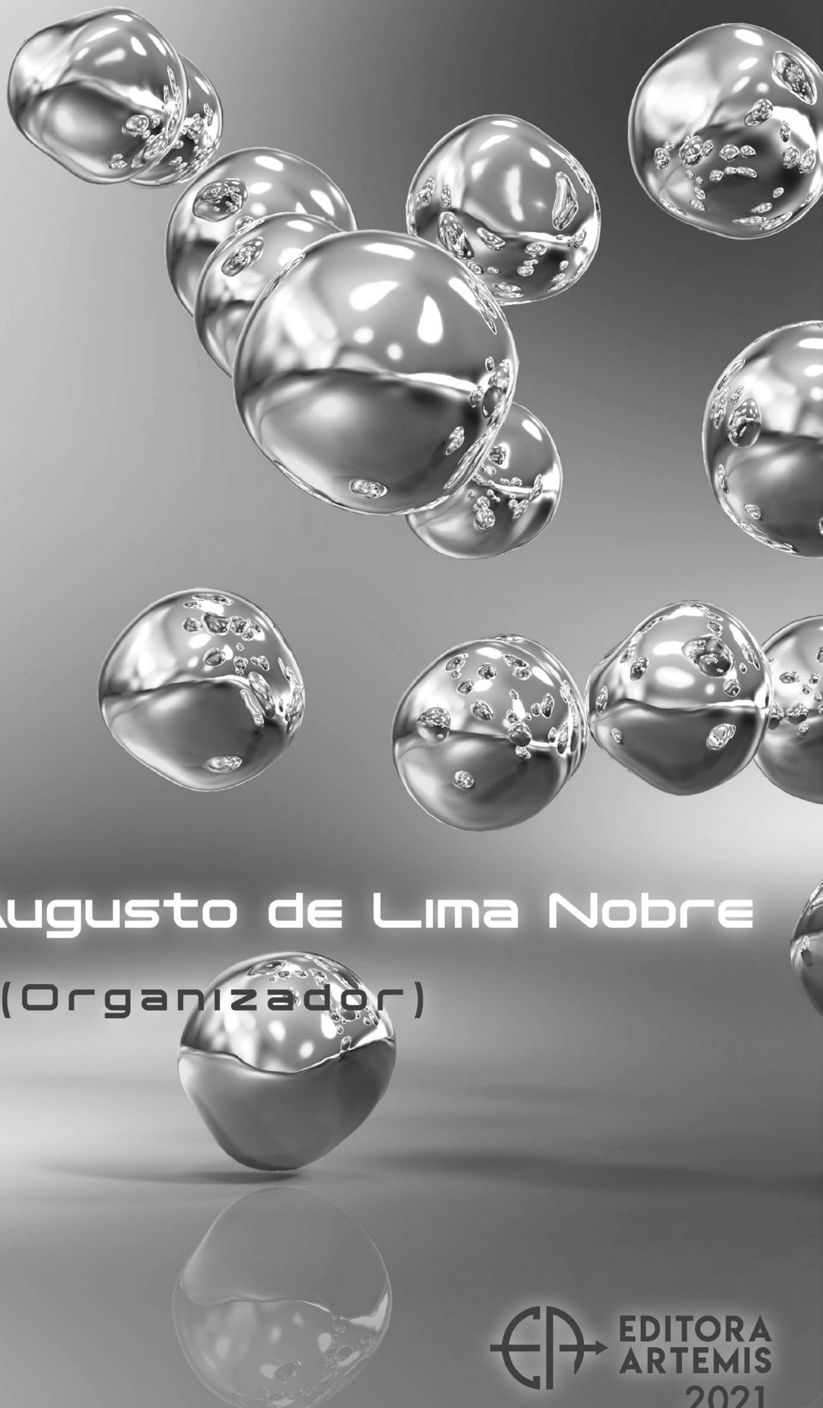

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PREFACE

The insertion of new and enhanced materials based on materials belonging to the Nano scale in the day-by-day has growth up in a silent way. In part, a number of works in the nanotechnology stemming of theoretical research using Density Functional Theory (DFT) and sophisticated simulation methods; another part is associated to the protected technologies associated to the military and patented nanomaterial and its process. In this sense, open access to recent aspects on the nanostructures application and properties can be reached in this book. Here, an interesting set of chapters gives opportunity of access texts that reach process and processing of nanostructures, applications of nanotechnology, advanced techniques to theoretical development. A broad set of nanostructures are here covered such as, nanocrystal, superficial nanograins, inner microstructures with nanograins, nanoaggregates, nanoshells, nanotubes, nanoflowers, nanoroad, nanosheets, Also, reveals new investigations areas as grainboundary of nanograins in ceramics and metals. A great number of software has been used as a tool of development of Science and Technologies for nanotechnology COMSOL Multiphysics 5.2. Phenomena and properties has been investigated by recent or classical techniques of materials characterization as Localized Surface Plasmon Resonance (LSPR), X-ray photoelectron spectroscopy (XPS), Field Emission Gun Scanning Electron Microscopy (FEG-SEM) with Energy Dispersive Spectroscopy (EDS), Raman Scattering Spectroscopy (RSS), X ray diffraction (XRD), ^{57}Fe Mössbauer spectroscopy, UV-vis spectroscopy, dynamic light scattering (DLS), Atomic Force Microscopy (AFM), and Field Emission Gun Scanning Electron Microscopy (FEG-SEM). In this sense, collections of spectra from Mössbauer spectroscopy, UV-vis spectroscopy and Infrared spectroscopy can be found. As a matter of fact, some chapter's item can be seemed as specific protocols for synthesis, preparations and measurements in the nanotechnology.

I hope you enjoy your reading.

Prof. Dr. Marcos Augusto Lima Nobre

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CHAPTER 11

ON SPIN HAMILTONIAN FITS TO MÖSSBAUER SPECTRA OF NIFE2O4 NANOPARTICLES SYNTHESIZED BY CO-PRECIPITATION[1]

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ABSTRACT: Nanocrystalline $NiFe_2O_4$ particles prepared by chemical co-precipitation method were studied using magnetic measurements, ^{57}Fe Mössbauer spectroscopy, X-ray diffraction, and transmission electron microscopy. Fits to Mössbauer spectra, in the range of 4.2 K – 300 K, were done using spin hamiltonians to describe both the electronic and nuclear interactions, a model of superparamagnetic relaxation of two levels (spin ½) and stochastic theory, a log-normal particle size distribution function as well as a dependency

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of the magnetic transition temperature and the anisotropy constant on particle diameter. We have used evolutionary strategies to fit the more complex Mössbauer spectra line shapes. The nanoparticles have an average size of 7 nm and exhibit superparamagnetism at room temperature. The saturation magnetization (Ms) at 4.2 K was determined from M vs. 1/H plots by extrapolating the value of magnetizations to infinite fields, to 24.21 emu/g and coercivity to 3.15 kOe. A magnetic anisotropy energy constant (K) 1.9´10^5 J/m^3, at 4.2 K, were calculated from magnetization measurements. The synthesis, characterization, and functionalization of magnetic nanoparticles is a highly active area of current research located at the interface between materials science, biotechnology, and medicine. Superparamagnetic iron oxides nanoparticles have unique physical properties and have emerged as a new class of diagnostic probes for multimodal tracking and as contrast agents for magnetic resonance imaging (MRI).
KEYWORDS: $NiFe_2O_4$ nanoparticles. Evolutionary strategies. Fits on Mössbauer spectra.

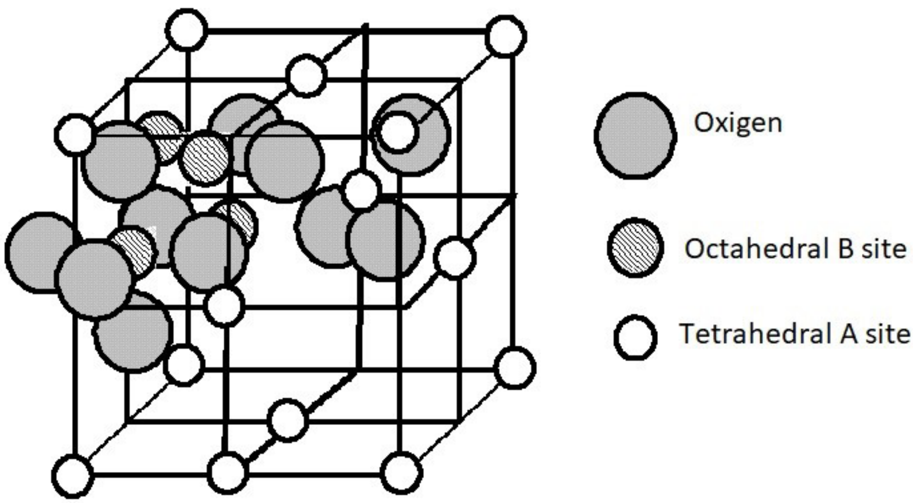
SOBRE AJUSTES POR HAMILTONIANO DE SPIN DE ESPECTROS MÖSSBAUER DE NANOPARTÍCULAS DE NIFE2O4 SINTETIZADAS POR CO-PRECIPITAÇÃO

RESUMO: Partículas nanocristalinas de $NiFe_2O_4$ preparadas pelo método de co-precipitação química foram estudadas usando-se medidas magnéticas, espectroscopia Mössbauer de ^{57}Fe, difração de raios-X e microscopia eletrônica de transmissão. Ajustes de espectro Mössbauer, na faixa de 4,2 K – 300 K, foram feitos utilizando-se hamiltonianos de spin para descrever as interações eletrônicas e nucleares, um modelo de relaxação superparamagnética de dois níveis (spin ½) e teoria estocástica, função distribuição de tamanho de partículas log-normal, bem como uma dependência da temperatura de transição magnética e da constante de anisotropia dependendo do diâmetro das partículas. Usamos estratégias evolutivas para ajustar as formas mais complexas das linhas de espectro Mössbauer. As nanopartículas têm um tamanho médio de 7 nm e exibem superparamagnetismo à temperatura ambiente. A magnetização de saturação (M_s) a 4,2 K foi determinada a partir de plotagens de M vs 1/H, extrapolando o valor das magnetizações para campos infinitos, para 24,21 emu/g e coercividade para 3,15 kOe. Uma constante de energia de anisotropia magnética (K) 1,9´10^5 J/m^3, a 4,2 K, foi calculada a partir de medidas de magnetização. A síntese, caracterização e funcionalização de nanopartículas magnéticas é uma área altamente ativa de pesquisa atual localizada na interface entre ciência dos materiais, biotecnologia e medicina. Nanopartículas de óxidos de ferro superparamagnéticos têm propriedades físicas únicas e emergiram como uma nova classe de sondas de diagnóstico para rastreamento multimodal e como agentes de contraste para ressonância magnética (RM).
PALAVRAS-CHAVE: Nanopartículas de $NiFe_2O_4$. Estratégias Evolucionárias. Ajustes de espectros Mössbauer.

1 INTRODUCTION

Nickel ferrite nanoparticles, $NiFe_2O_4$ prepared in different ways, have attracted considerable attention due to both their unusual properties compared to those of the bulk materials and their potential applications (J. L. López, 2001). Like other iron oxides, e.g., magnetite (Fe_3O_4), manganese ferrite ($MnFe_2O_4$), and cobalt ferrite ($CoFe_2O_4$), $NiFe_2O_4$ is a soft ferrite and presents easy magnetization and demagnetization. All of them have a *spinel* structure with octahedral and tetrahedral sites (Fig. 1). Sites A and B are antiferromagnetic and ferromagnetic regions, respectively. The synthesis, characterization, and functionalization of magnetic nanoparticles is a highly active area of current research located at the interface between materials science, biotechnology, and medicine.

Figure 1 – Spinel structure.



Source: Adapted from MARTINS (2008, p. 16).

For many years, it has been known that magnetic particles with a size smaller than few tens of nanometer can be considered as single domains and, hence, display properties markedly different from the bulk (MEDRANO et al., 2018). Another exciting feature of the nanoparticles is due to the surface spin disorder, which is induced by the broken exchange bonds at the surface. This is especially true for the case of ferrites where the (negative) superexchange interaction is mediated by an intervening oxygen ion, and it can be missing at the surface. As a result, the system should be considered a core-shell structure with ferromagnetically aligned core spins and a spin-glass like surface layer. With the reduction of the particle size at the nanoscale, the surface to volume ratio becomes very large, and surface effects may induce a spin-canted structure as well as an enhanced surface anisotropy (KODAMA, 1996).

Besides having unique physical properties, nanoparticles are a couple with size range commensurate with biomolecular and cellular systems. These properties make nanoparticles attractive for therapeutic and diagnostic applications (photothermal therapy, imaging, and delivery applications). However, application in biomedicine requires controlled interactions with molecules, like non-cytotoxicity, cellular internalization ability, and carrier ability (SAHA, 2011). For the effective utilization of these materials in biomedicine, nanoparticles have been functionalized with a variety of ligands such as surfactants, small molecules, polymers, dendrimers, and biomolecules. Nanoparticles interacting with organic compounds show different effects that depend on how the functionalization is performed (LÓPEZ, 2001) (TOURINHO, 1999). Oleic acid has proved to be useful as a surfactant to magnetic nanoparticles. On the other hand, vegetable oils have in their composition different fatty acids, including oleic acid, palmitic, linolenic, and others.

$NiFe_2O_4$ nanoparticles studied in this work were prepared by chemical co-precipitation method using an aqueous solution of $Ni(NO_3)_2.6H_2O$ and $Fe(NO_3)_3.9H_2O$ and the NaOH solution as the precipitating agent. They were studied using magnetic measurements, ^{57}Fe Mössbauer spectroscopy, X-ray diffraction, and transmission electron microscopy.

Mossbauer spectroscopy (ME) allows displaying the hyperfine structure of an ion in a solid. Due to the interactions of the ion with its environment, the electronic, magnetic moment, and the charge distribution of the ion can fluctuate. The times which characterize these fluctuations depend on the intensity of the interactions. Through the hyperfine coupling, the nucleus feels these effects. By means of ME one can observe fluctuations whose characteristic times are in the interval 10^{-6}-10^{-11} s (CIANCHI, 1986).

The paper is organized as follows. In section 2, the basic informations of sample preparation are presented, the basic features of the theoretical model and of the Mössbauer spectroscopy are introduced, and the characteristics of evolutionary algorithms used in the model parameterization are discussed. In section 3, the obtained results are presented and discussed. In section 4, we made conclusions and proposals for future works.

2 MATERIALS AND METHODS

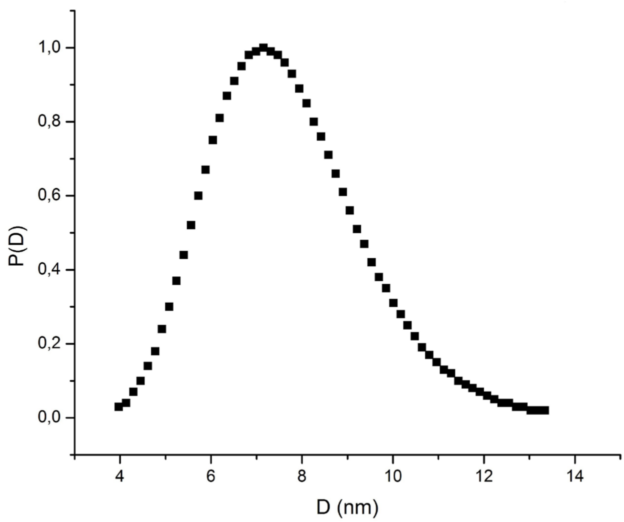
$NiFe_2O_4$ nanoparticles were prepared by the chemical co-precipitation method using an aqueous solution of $Ni(NO_3)_2.6H_2O$ and $Fe(NO_3)_3.9H_2O$ and the NaOH solution as the precipitating agent. The precipitate was calcined at 500 °C. (Albuquerque et al., 2001). They were studied using magnetic measurements, ^{57}Fe Mössbauer spectroscopy, X-ray diffraction, and transmission electron microscopy.

The nanoparticles have an average size of 7 nm (obtained from XRD pattern) and exhibit superparamagnetism at room temperature. The saturation magnetization (Ms) at 4.2 K was determined from M vs 1/H plots by extrapolating the value of magnetizations to infinite fields, to 24.21 emu/g and coercivity to 3.15 kOe. A magnetic anisotropy energy constant (K) 1.9×10^5 J/m3, at 4.2 K, were calculated from magnetization measurements.

Fits to Mössbauer spectra, in the range of 4.2 K – 300 K, were done using spin hamiltonians to describe both the electronic and nuclear interactions, a model of superparamagnetic relaxation of two levels (spin ½) and stochastic theory (CLAUSER, 1971) (JONES et al., 1989), a log-normal particle size distribution function P(D) (Eq. 1) (Fig. 2).

To fits on more complexes Mössbauer spectra lineshapes, it's necessary to consider a hyperfine magnetic field distribution (which is a purely statistical approach) or, as is done in the Pfannes-Higino model (PFANNES et al., 1998; PFANNES et al., 2001; FILHO, 2001), a dependency of the magnetic transition temperature and the anisotropy constant on particle diameter (Eqs. 2 and 3) (Fig. 3). The magnetic transition temperature dependency on particle diameter leads to a Brillouin function (Eq. 4), a relation between the reduced hyperfine internal field and the reduced temperature (Fig. 4).

Figure 2 – Log-Normal size distribution, P(D).



Source: The authors.

$$P(D) = \frac{1}{\sqrt{2\pi}\sigma D} e^{\left[-\frac{\ln(D/D_0)^2}{2\sigma^2}\right]} \quad (1)$$

where D is the particle diameter, σ is the standard deviation, D_0 is the average size.

$$T_N(D) = -A_1 \times e^{(-D/A_2)} + T_{bulk} \quad (2)$$

where T_{bulk} is the bulk magnetic transition temperature of the sample, and A_1 and A_2 are parameters to be found.

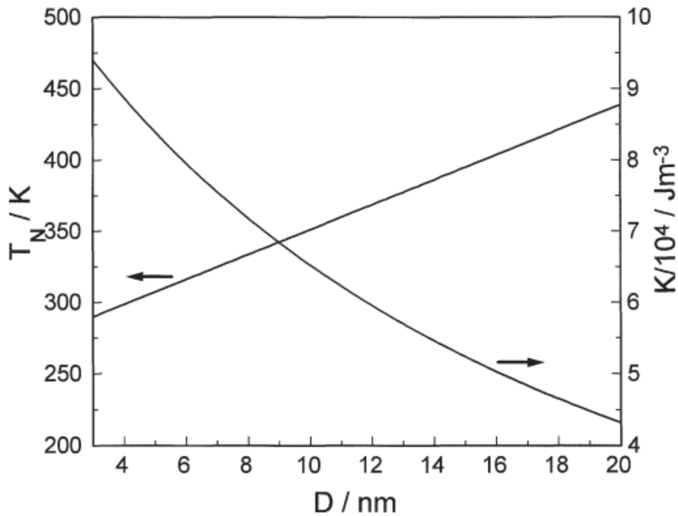
$$K(D) = AN01 + \frac{AN02}{(D \times AN03)} \quad (3)$$

where AN01, AN02 e AN03 are parameters to be found.

$$BR1(T/T_N) = BR11 \times [1.0 - BR12 \times (T/T_N)^{BR13}] \quad (4)$$

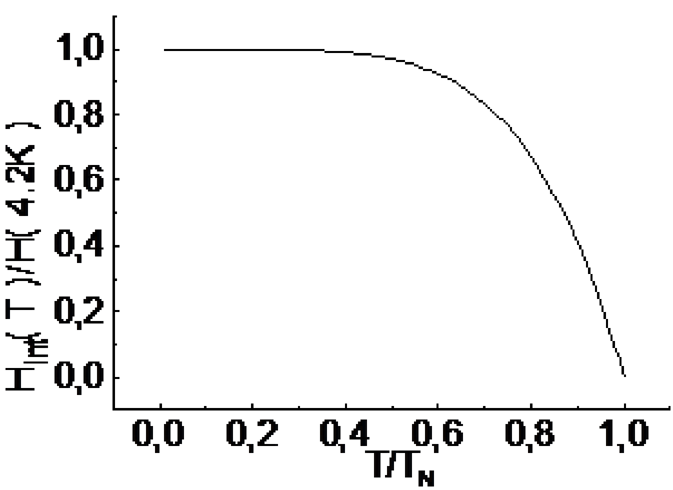
Where BR11, BR12 e BR13 are parameters to be found.

Figure 3 – Transition temperature TN and anisotropy constant K vs. diameter.



Source: (PFANNES et al, 1998).

Figure 4 – Reduced Internal Field [Hint/H (4.2K)] vs. reduced temperature (T/TN).



Source: (PFANNES et al., 1998).

We have used evolutionary strategies and non-linear to fit the more complex Mössbauer spectra line shapes (BARBOSA, 2017; RECHENBERG, 1965; SCHWEFEL, 1975). The CHI2 parameter is a way of measure the differences between experimental and theoretical spectra, calculated by the theoretical model. CHI2 values in the range [1,6] indicate that experimental and theoretical spectra are in good agreement.

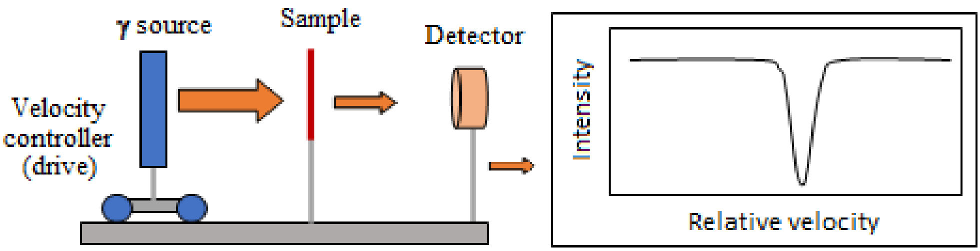
The evolutionary algorithms have been implemented using Python programming language. The parameterization problem is treated as a problem of minimizing the measure of the Root Mean Square Error, RMSE, of the points of the theoretical spectrum obtained by the model, compared to the experimental spectrum.

2.1 MÖSSBAUER SPECTROSCOPY

The Mössbauer effect is the nuclear recoil free emission and absorption of gamma photons (nuclear resonance fluorescence). This effect only occurs when the nucleus is embedded in a solid matrix (GOLDANSKII, 1968; YOSHIDA, 2013). The Mössbauer effect was discovered in 1958 by Rudolf L. Mössbauer, who, in order to correctly interpret and explain the effect, developed an experimental technique called Mössbauer spectroscopy (Fig. 5), which is applied in several areas of knowledge, such as the study of magnetism and magnetic materials (GÜTLICH et al., 2011). Mössbauer spectroscopy has high energy resolution that allows the study of electrical and magnetic hyperfine interactions arising from the interaction between electrical and magnetic moments of the nucleus and the fields created by the core electrons. It is widely used, for example, in the characterization of organometallic iron compounds (CHEN, 2007). Zeeman nuclear splitting for the fundamental and first excited states of the 57Fe and the respective Mössbauer spectra are shown in Figure 6 (allowed transitions between nuclear levels are labeled with the magnetic, m, and nuclear spin, I, quantum numbers).

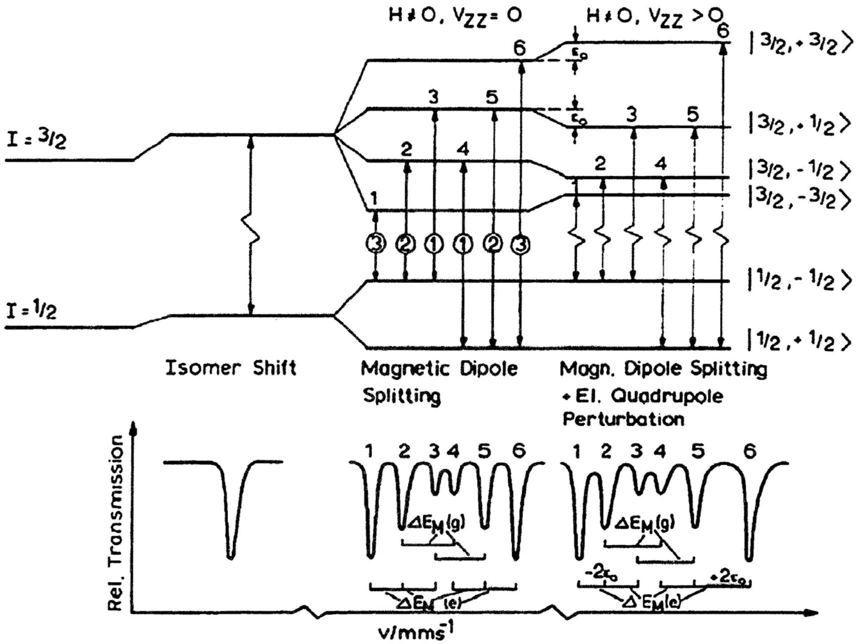
The Mössbauer theoretical lineshape used in the model is a complicated expression that calculates the Laplace transform of the correlation function for the nuclear transition operator. A detailed deduction of this expression can be found in (CIANCHI, 1986).

Figure 5 – Typical experimental arrangement for Mössbauer spectroscopy (scheme) and an outline of a transmission spectrum.



Source: Adapted from PIRES (2014, p. 11).

Figure 6 – Scheme of nuclear energy levels (57Fe) for electric monopole interaction (causing isomer shift, left), pure magnetic dipole interaction (causing magnetic splitting, middle), and combined electric quadrupole and magnetic dipole interactions.



Source: (YOSHIDA, 2013).

3 RESULTS AND DISCUSSION

With the aim to evaluate the algorithm's parameterization performance, we applied the Differential Evolution (DE) and Evolution Strategies (ES) algorithms (BARBOSA, 2017) in the fitting procedure of nickel ferrite powder Mössbauer spectra in several temperatures. All experiments involved in this work were carried out in the Physics Department, Federal University of Minas Gerais.

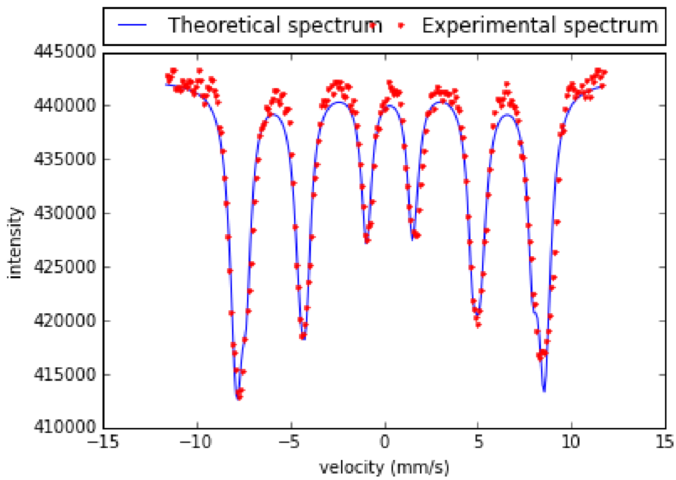
Experimental and theoretical Mössbauer spectra of the powder sample at temperatures in the range of 4.2 K – 300 K are shown in figures 7 to 10. The spectra collapse rapidly in the range of 140 K –300 K without showing a pronounced central peak (characteristic of superparamagnetic relaxation) initially. There should be another cause of internal field reduction besides increasing relaxation frequency. We adopted a dependence of T_N and the anisotropy on the particle diameter (cf. figure 3). For each diameter D, we obtain T_N, and from this and the actual temperature T, we get an internal magnetic field value corresponding to the variation of the internal field dependence shown in figure 4. A lot of parameters must be found during the fit process. Tables 1 and 2 show these parameters founded for the spectrum at 140 K. For comparison, the two algorithms obey the termination criterion of 6,000 evaluations of the objective function. Each algorithm has been executed 30 times.

Table 1 – Parameters founded during the fit on the spectrum at 140 K.

Parameters	Values found
AN01	4641.009
AN02	279736378.496
AN03	20.000
BR12	4.500
BR13	5.600
BR21	-0.200
BR22	5.499
BR23	2.224

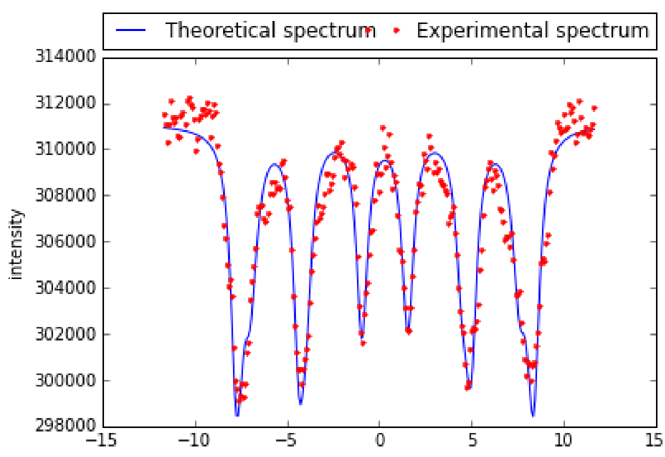
Source: The authors.

Figure 7 – Nickel ferrite Mössbauer spectrum at 4 K (CHI2 = 5.77).



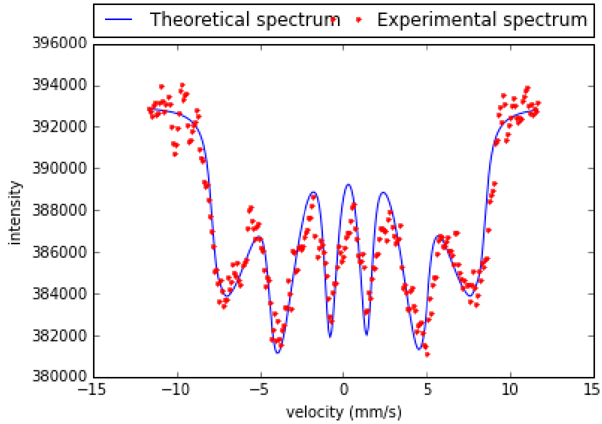
Source: The authors.

Figure 8 – Nickel ferrite Mössbauer spectrum at 100 K (CHI2 = 3.32).



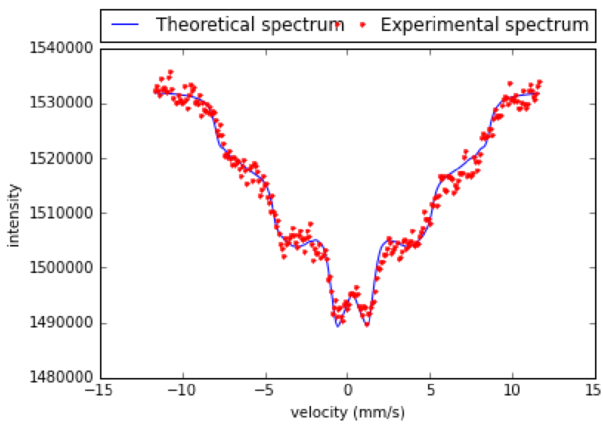
Source: The authors.

Figure 9 – Nickel ferrite Mössbauer spectrum at 140 K (CHI2 = 2.98).



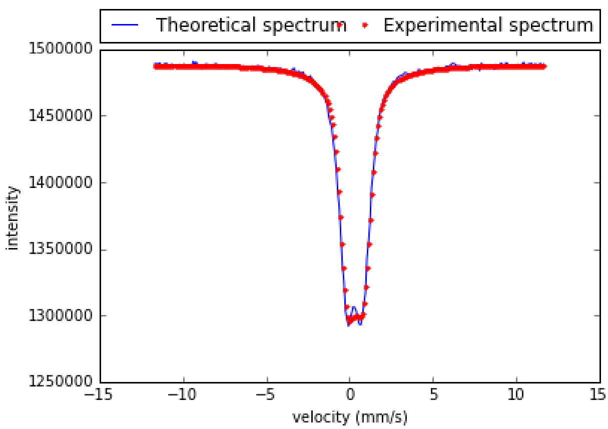
Source: The authors.

Figure 10 – Nickel ferrite Mössbauer spectrum at 180 K (CHI2 = 1.81).



Source: The authors.

Figure 11 – Nickel ferrite Mössbauer spectrum at 300 K (CHI2 = 2.51).



Source: The authors.

The values of CHI2 in the range [1.81 – 5.77] show that the model can reproduce the main features of the Mössbauer spectra, even in the situations when the thermally activated phenomena produce complexes lineshapes. A good agreement between the experimental and theoretical spectra occurs in all temperatures in the range 4.2 K to 300 K, and the model describes the collapse of the hyperfine field at high temperatures due to superparamagnetic relaxation or magnetic transition temperature dependency on the particle diameter.

4 CONCLUSIONS

Nickel ferrite nanoparticles were successfully synthesized by the co-precipitation method, and their magnetizations are affected by the thermally activated phenomena predicted in the Pfannes-Higino model.

Effects like particle size distribution as well as a dependency of the magnetic transition temperature on particle diameter are very important to the analysis of the Mössbauer spectra of nanoparticles, and these effects can substitute the hyperfine field distributions, a statistical approach commonly used in the Mössbauer fitting programs.

Evolutionary algorithms and a theoretical model based on superparamagnetic relaxation phenomena and particle size distribution, as well as a dependency of the magnetic transition temperature on particle diameter, can be successfully used on Mössbauer spectra fits. The values of CHI2 are in the range [1.81 – 5.77]. Future works include modifications in the theoretical model and application of evolutionary algorithms on the fits of more complex Mössbauer spectra, taking into account other physical phenomena, e.g., interparticle interactions and surface effects.

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