Adsorption of cobalt ferrite nanoparticles within layer-by-layer films: a kinetic study carried out using quartz crystal microbalance
Adsorption of cobalt ferrite nanoparticles within layer-by-layer films: a kinetic study carried out using quartz crystal microbalance†

Gustavo B. Alcantara,* Leonardo G. Paterno, André S. Afonso, Ronaldo C. Faria, Marcelo A. Pereira-da-Silva, Paulo C. Morais and Maria A. G. Soler*

Received 22nd August 2011, Accepted 4th October 2011
DOI: 10.1039/c1cp22693b

The paper reports on the successful use of the quartz crystal microbalance technique to assess accurate kinetics and equilibrium parameters regarding the investigation of in situ adsorption of nanosized cobalt ferrite particles \( \text{CoFe}_2\text{O}_4 \) (10.5 nm-diameter) onto two different surfaces. Firstly, a single layer of nanoparticles was deposited onto the surface provided by the gold-coated quartz resonator functionalized with sodium 3-mercapto propanesulfonate (3-MPS). Secondly, the layer-by-layer (LbL) technique was used to build multilayers in which the CoFe\(_2\)O\(_4\) nanoparticle-based layer alternates with the sodium sulfonated polystyrene (PSS) layer. The adsorption experiments were conducted by modulating the number of adsorbed CoFe\(_2\)O\(_4\)/PSS bilayers \( (n) \) and/or by changing the CoFe\(_2\)O\(_4\) nanoparticle concentration while suspended as a stable colloidal dispersion. Adsorption of CoFe\(_2\)O\(_4\) nanoparticles onto the 3-MPS-functionalized surface follows perfectly a first order kinetic process in a wide range (two orders of magnitude) of nanoparticle concentrations. These data were used to assess the equilibrium constant and the adsorption free energy. Alternatively, the Langmuir adsorption constant was obtained while analyzing the isotherm data at the equilibrium. Adsorption of CoFe\(_2\)O\(_4\) nanoparticles while growing multilayers of CoFe\(_2\)O\(_4\)/PSS was conducted using colloidal suspensions with CoFe\(_2\)O\(_4\) concentration in the range of \( 10^{-8} \) to \( 10^{-6} \) (moles of cobalt ferrite per litre) and for different numbers of cycles \( n = 1, 3, 5, \) and \( 10 \). We found the adsorption of CoFe\(_2\)O\(_4\) nanoparticles within the CoFe\(_2\)O\(_4\)/PSS bilayers perfectly following a first order kinetic process, with the characteristic rate constant growing with the increase of CoFe\(_2\)O\(_4\) nanoparticle concentration and decreasing with the rise of the number of LbL cycles \( (n) \). Additionally, atomic force microscopy was employed for assessing the LbL film roughness and thickness. We found the film thickness increasing from about 20 to 120 nm while shifting from 3 to 10 CoFe\(_2\)O\(_4\)/PSS bilayers, using the \( 8.9 \times 10^{-6} \) (moles of cobalt ferrite per litre) suspension.

Introduction

Adsorption of nanosized materials onto surfaces has been the focus of intensive research activity considering its impact on the investigation of the interaction of nanostructures with biological and non-biological templates, with emphasis ranging from cell labeling to coatings and films.\(^1\)\(^\text{–}^7\) Additionally, the increasing growth in the production of nanosized materials nowadays at both laboratory and industrial scales has called special attention to the potential hazardous effects caused by discarding them into the environment, and their binding to organic matter and living organisms.\(^8\) Therefore, investigation regarding the adsorption of nanoparticles onto surfaces, with as diverse composition and function as possible, has become critical to accomplish medical and industrial applications as well as to unveil the path of their dissemination into the environment and their possible damaging effects to living systems.

In this scenario, superparamagnetic iron oxide (SPIO) particles\(^9\) play an important role, since their high magnetization and biocompatibility make them potential nanomaterials for use in biomedicine, as for instance in drug delivery systems,\(^10\) biolabeling,\(^11\) magnetic hyperthermia,\(^12,13\) and magnetic...
resonance imaging contrast enhancers among others. Additionally, the use of SPIO particles may also have a profound impact on new industrial technologies as for instance while developing insulating magnetic oil for transformers, structures for spin electronics, bioelectrochemistry, catalysis, and chemical sensing. Specific applications include surface modification of SPIO particles to allow covalent attachment with biomolecules which are then used as molecular recognition sites for sensing. The large surface-to-volume ratio of SPIO particles enhances reaction activity and catalytic efficiency and, hence, improves chemical sensitivity. Indeed, it has been reported that SPIO particles have the capability to increase electron transfer between electrode and molecular recognition sites, such as enzymes.

SPIO particles, as for instance maghemite (γ-Fe₂O₃), magnetite (Fe₃O₄) and cobalt ferrite (CoFe₂O₄), display a typical cubic inverse spinel structure and form single domains of about 5–20 nm in diameter. Under wet chemical synthesis approaches SPIO particles can be prepared in large quantities with appreciable control over size, composition, crystallinity, and physical properties (e.g., magnetic properties). Furthermore, with proper surface functionalization SPIO particles can be readily dispersed into suitable solvents, thus producing homogeneous and highly stable magnetic fluid (MF) samples. Therefore, while using MF samples as a material platform for manipulation and encapsulation of SPIO particles, their adsorption energetics and kinetics on different surfaces, as for instance in metal electrode and polymeric matrix, need to be known in order to provide optimum parameters for their deposition and also to improve loading of recognition sites within the sensor structure.

The quartz crystal microbalance (QCM) technique has already been used to investigate tiny amounts of nanomaterials adsorbed as ultra-thin films. The multilayer assembly of nanoparticles (silica or magnetite) and glucose oxidase on charged latex particles was successfully investigated by the QCM technique. It was reported that a single monolayer of either nanoparticle or enzyme was adsorbed at each surface deposition cycle. Additionally, it was found that the introduction of magnetic nanoparticles enhances the effectiveness of the nanoreactor and also combines the benefits of magnetic properties with high surface area. Also, QCM measurements with energy dissipation have been employed to track the adsorption of TiO₂ nanoparticles onto silica in order to evaluate its contamination potential in natural water sub-surface environments. The authors found that water characteristics (e.g., pH and ionic strength) play a major role in TiO₂ surface adsorption, in particular adsorption rates are increased when conditions favor electrostatic interactions between nanoparticles and the surface.

Investigations performed on assembling nanoparticles onto the polymeric surface have been focused on the energetic and kinetic features of adsorption. For example, investigation of the adsorption of gold hydrosol (18 nm diameter) onto polystyrene and poly(2-vinylpyridine) films by means of a QCM technique suggested that the particle adsorption is irreversible. At the first stage of adsorption the authors found that the number of adsorbed particles increased linearly with the square root of adsorption time, which characterizes a diffusion-limited adsorption process. Adsorption kinetics and energetic parameters for CdSe-ZnS core–shell quantum dots (3.5 nm diameter) have been attained after treating QCM data using the Langmuir adsorption theory. Irreversible adsorption was identified with adsorption constants being much higher than desorption ones.

In previous investigations we have attained preliminary understanding of the adsorption of citrate-coated maghemite nanoparticles onto doped polyaniline, as well as positively charged bare maghemite onto sodium sulfonated polystyrene (PSS). We found that nanoparticles rapidly form a densely-packed layer regardless of the polyelectrolyte type. However, details regarding the adsorbed nanoparticles were limited. Firstly because iron oxide bands in the UV-Vis range are rather structureless, which imparts a significant measurement error. Secondly, no long-term, time-dependent experiment was carried out, including capability for in situ adsorption observation. In the present contribution, however, we employed the QCM technique to monitor in situ and in a long-term regime the adsorption of positively-charged CoFe₂O₄ nanoparticles onto bare gold-coated and surface-functionalized QCM resonators and also onto PSS deposited layers. The multilayer deposition was entirely performed inside the QCM cell itself, which allowed continuous monitoring of nanoparticle and polyelectrolyte mass uptake in situ. CoFe₂O₄ nanoparticles (10.5 nm in diameter) were supplied as ionic colloidal suspension at different nanoparticle concentrations and fixed low-pH value. Data obtained from the QCM measurements allow for robust determination of kinetics (adsorption and desorption constants) and thermodynamics (free energy of adsorption) parameters for adsorption at planar substrates and, additionally, to monitor multilayer film deposition. Further, the adsorption trend was interpreted within the framework of the Langmuir adsorption theory. Moreover, atomic force microscopy (AFM) images of deposited CoFe₂O₄/PSS films provided additional information about the CoFe₂O₄ nanoparticles adsorption.

CoFe₂O₄ nanoparticle was chosen as a model system because of its enhanced properties, such as high magnetocrystalline anisotropy, high coercivity, moderate saturation magnetization and high stability at higher temperatures and aggressive chemical media. The presence of surface cobalt atoms also improves catalytic efficiency of CoFe₂O₄ nanoparticles towards oxidation of some biochemical substrates, and thus opens up opportunities for applicability as a biosensor. Furthermore, cobalt ferrite nanoparticles have been investigated aiming biomedical applications. Toxicity studies indicated that while using appropriated protocols cobalt ferrite nanoparticles can be reported as biocompatible and could be used as a material platform for biomedical applications.
Experimental

Materials

Cobalt nitrate, iron chloride, iron nitrate, sodium sulfonated polystyrene (PSS, $M_w$ 70,000 g mol$^{-1}$), sodium 3-mercaptopropanesulfonate (3-MPS), and 3-mercaptopropionic acid (3-MPA) were purchased from Aldrich (USA) and used as received. Perchloric acid, hydrochloric acid, sulfuric acid, sodium hydroxide, and hydrogen peroxide were all analytical grade or better purchased from Merck (Germany) and Synth (Brazil). All water used for nanoparticle synthesis, solution preparations and substrate cleaning was provided by a purification system Milli-Q (water resistivity: 18 MΩ cm$^{-1}$). PSS solution (1.0 g L$^{-1}$, pH 1.85) was prepared by dissolving the polyelectrolyte in diluted HCl solution (pH 1.85) under magnetic stirring. Glass slides (BK7, 10 mm × 25 mm × 1 mm) used as substrates for AFM imaging were rendered negatively-charged prior to film deposition by a cleaning procedure, including sequentially a piranha solution ($H_2SO_4$/$H_2O_2$, 3 : 1 v/v) followed by RCA solution ($H_2O$/$H_2O_2$/$NH_4OH$, 5 : 1 : 1 v/v). QCM experiments were carried out using a 5 MHz AT-cut quartz crystal (QCM 200 STANFORD) with gold electrodes (5 mm in diameter) at both sides.

Synthesis of CoFe$_2$O$_4$ nanoparticles

Positively-charged CoFe$_2$O$_4$ nanoparticles were synthesized by co-precipitation of Co(II) and Fe(III) ions in aqueous alkaline medium according to the protocol previously reported$^{44}$ and described in short as follows. Concentrated nitric acid (40 mL) was added to previously prepared aqueous solutions of Co(NO$_3$)$_2$ (0.1 mol L$^{-1}$, 250 mL) and FeCl$_3$ (0.2 mol L$^{-1}$, 250 mL) and heated at boiling temperatures (~95 °C) under magnetic stirring. The pH was then raised to 12 with sodium hydroxide solution (3.0 mol L$^{-1}$), leading to immediate precipitation of CoFe$_2$O$_4$ nanoparticles. The reaction mixture was cooled down to room temperature and the black precipitate (CoFe$_2$O$_4$ nanoparticles) was isolated by centrifugation following extensive washing with ultrapure water until neutral pH was reached. The isolated nanoparticles underwent a step of surface passivation by suspending them into Fe(NO$_3$)$_3$ (0.5 mol L$^{-1}$) aqueous solution for 30 min, at boiling temperature. The reaction mixture was cooled down to room temperature and the pH was adjusted to 6 with diluted sodium hydroxide (0.1 mol L$^{-1}$). The precipitate composed of passivated CoFe$_2$O$_4$ nanoparticles was washed several times with ultrapure water until neutral pH was reached. A stock ionic colloidal suspension was then produced by peptization of nanoparticles using perchloric acid solution (0.25 mol L$^{-1}$). The acidic medium ensures protonation of nanoparticles’ surface sites. Soluble ions, left over in the aqueous phase, were extracted from the fresh MF sample by dialysis against pure water for several days. Hydrodynamic diameter and zeta potential of colloidal suspensions were determined by dynamic light scattering/zeta potential measurements using a Malvern Instrument Zeta Sizer Nano Series ZS90. The hydrodynamic diameter and the ζ-potential for cobalt ferrite nanoparticles suspended within the produced MF sample were found as 41.9 nm and +37.2 mV, respectively. For adsorption studies and film deposition, CoFe$_2$O$_4$ aqueous dispersions were prepared directly from dilution of the stock ionic MF sample. The concentrations of CoFe$_2$O$_4$ nanoparticles (expressed in moles of cobalt ferrite per litre) within the used MF samples were set at: S-A 8.9 × 10$^{-7}$ mol L$^{-1}$; S-B 8.9 × 10$^{-7}$ mol L$^{-1}$; S-C 3.0 × 10$^{-7}$ mol L$^{-1}$; S-D 1.3 × 10$^{-7}$ mol L$^{-1}$; and S-E 8.9 × 10$^{-8}$ mol L$^{-1}$.

The morphology and size distribution of CoFe$_2$O$_4$ nanoparticles were assessed by transmission electron microscopy (TEM) employing a JEOL 1011 microscope operating at 100 keV. Fig. 1 presents the particle size histogram (vertical bars) of the CoFe$_2$O$_4$ sample attained from TEM micrographs (the inset is a typical TEM micrograph of the sample). The average particle diameter $(D_{TEM})$ and standard diameter deviation $(σ)$ calculated from the curve fitting were 10.5 ± 0.1 nm and 0.15 ± 0.01, respectively. X-Ray diffraction patterns of the powder sample (not shown) referred to cobalt ferrite material in agreement with the JCPDS 22-1086.$^{46}$ The chemical composition of nanoparticles, expressed as the [Fe]/[Co] ratio, was determined by atomic absorption spectrometry using a Perkin-Elmer 5000 spectrometer. The ratio [Fe]/[Co] found was 3 : 1.

Quartz crystal microbalance measurements and in situ deposition

When homogeneous and rigid ultrathin layers are adsorbed onto the surface of an oscillating crystal the characteristic shift in frequency $(Δf)$ can be related to the increase in mass per unit area $(Δm)$ according to the Sauerbrey equation,$^{47}$

$$Δf = - \frac{1}{C_f} Δm,$$

where $C_f$ is the mass sensitivity constant (in our experiments, $C_f = 56.6$ Hz µg$^{-1}$ cm$^2$ at 5 MHz). Thus, frequency shifts $(Δf)$ could be converted into mass $(Δm)$ of adsorbed species (nanoparticle and/or polyelectrolyte). The main advantage of this method is the higher sensitivity (nanograms) it provides, which surpasses for instance detection limits imposed by UV-Vis spectroscopy. In the present study, all measurements were conducted at controlled temperature (25 °C) in a
QCM 200 STANFORD, with the aid of a peristaltic pump (ISMATEC IPC) which allowed the controlled flow of 60 μL min⁻¹. Prior to the experiments, the electrode surface was cleaned using a piranha solution, rinsed with water and left for drying in air. The clean electrodes were further functionalized with sulfonic groups by soaking overnight in an aqueous solution of 3-MPS (0.02 mol L⁻¹). The electrodes were then removed from the 3-MPS solution, rinsed with excess of ultrapure water and left for drying in air. For a control experiment, electrodes were functionalized with carboxylic acid groups using 3-MPA. The chemical structures of 3-MPA and 3-MPS functionalized in the gold electrodes are depicted in Scheme 1.

The as-functionalized electrodes were placed in the QCM cell with one side facing the liquid phase (cleaning solution, nanoparticle dispersion or polyelectrolyte solution) while the other side left exposed to air. At the beginning, the cell was filled with diluted HCl solution (pH 1.85) in order to set the baseline. Afterwards, in order to monitor nanoparticle adsorption on planar functionalized substrates, CoFe₂O₄ dispersion was introduced until the cell was completely filled (about 300 μL). The flow was stopped and the adsorption of the first layer of nanoparticles was observed by monitoring the frequency change (∆f) with time (t). The adsorption of CoFe₂O₄ nanoparticles at the PSS polymer surface was also in situ monitored. The CoFe₂O₄/PSS bilayers were deposited (LbL approach) inside the QCM cell, by simply introducing the nanoparticle dispersion and polyelectrolyte solution alternately, just like it is performed in a current LbL procedure. The mass uptake (∆m) was continuously monitored as a function of time (t). A rinsing step with diluted HCl solution (pH 1.85) was performed after every deposited layer (LbL cycle). Three concentrations of CoFe₂O₄ were employed to prepare three different multilayered films, comprising up to ten bilayers, labeled (CoFe₂O₄/PSS)QCM−A, (CoFe₂O₄/PSS)QCM−Bn and (CoFe₂O₄/PSS)QCM−En, where the subscripts stand for the ionic magnetic colloidal suspensions S-A, S-B or S-E whereas n means the number of bilayers.

Deposition of CoFe₂O₄/PSS films

In order to study the nanocomposite morphology CoFe₂O₄/PSS multilayered films were deposited onto glass slides using the LbL technique. Diluted ionic colloidal suspensions and the PSS polyelectrolyte solution were employed. Cleaned glass slides were firstly immersed into the MF samples (S-A, S-B, or S-E) for 3 min, then rinsed in a stirred HCl solution (pH 1.85) for 30 s and dried under a flow of N₂ gas. In a second step, the substrate containing a layer of positively surface charged nanoparticles was immersed into the anionic solution (PSS) for 3 min, then rinsed and dried as in the nanoparticle layer deposition to produce the first CoFe₂O₄/PSS bilayer. Films with up to 10 bilayers were produced by simply repeating the steps described above, originating samples (CoFe₂O₄/PSS)A, (CoFe₂O₄/PSS)Bn, and (CoFe₂O₄/PSS)En where the subscripts stand for the ionic magnetic colloidal suspensions S-A, S-B or S-E.

Results and discussion

CoFe₂O₄ nanoparticle adsorption onto QCM crystals modified with 3-MPS

Fig. 2a displays the time-dependence of ∆f during adsorption of CoFe₂O₄ nanoparticles onto QCM crystals surface-modified with 3-MPS. The adsorption process was investigated in the time window of 1150 seconds at different CoFe₂O₄ nanoparticle concentrations (MF samples S−A, S−B, and S−E).

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The morphological characterization of the as-produced multilayers was assessed by tapping AFM using a Digital MultiMode Nanoscope IIIa (silicon tips with a rectangular shaped and cantilever spring constant set at 70 N m⁻¹). Film surface roughness (root-mean-square roughness, Rₘₚₘ) was obtained using the software provided with the instrument. Values measured at three different spots on the sample surface were used to calculate the average Rₘₚₘ. Film thicknesses were also measured by AFM, following a procedure developed by Lobo et al.⁴⁸

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and fixed pH (1.85), as indicated. In the investigated time window the saturation of the QCM frequency shift was reached for all nanoparticle concentrations employed. Note that saturation for samples with higher nanoparticle concentration (MF samples S–A and S–B) is reached faster, around 660 seconds, whereas for the lower nanoparticle concentration employed (MF sample S–E) saturation was reached at longer times, around 1000 seconds. In addition, it was observed that the more concentrated the colloidal suspension is the greater the amount of adsorbed nanoparticles, reaching 6.4 µg cm⁻² while using MF sample S–A. The asymptotic behavior of the adsorbed mass of nanoparticles as a function of time suggests the occurrence of a first order kinetics process. To support this hypothesis we fitted the experimental data with a first order adsorption process equation described by

\[ \Gamma(t) = \Gamma(\infty) \left[ 1 - \exp(-k_{obs}t) \right], \]

where \( \Gamma(t) \) is the adsorbed amount in µg cm⁻² at time \( t \), \( \Gamma(\infty) \) is the adsorbed amount at infinite time and \( k_{obs} \) is the characteristic rate constant. The \( \Gamma(\infty) \) and \( k_{obs} \) values obtained from our fitting (see Fig. 2a) are collected in Table 1. Fig. 2a shows a very good agreement between the experimental data (colored symbols) and the fitting (solid black lines), thus supporting our hypothesis of a first order kinetics process for nanoparticle’s adsorption. Adsorption of CdSe/ZnS quantum dots⁵³ and gold nanoparticles⁵⁰ onto planar substrates also follows a first order kinetic process.

The observed rate constant \( k_{obs} \), included in eqn (2) can be expressed as:⁵⁰

\[ k_{obs} = k_a C + k_d, \]

where \( C \) is the nanoparticle concentration in the colloidal suspension (in moles of CoFe₂O₄ per litre) and \( k_a \) and \( k_d \) are adsorption and desorption constants, respectively. The linear relationship observed between \( k_{obs} \) and \( C \) was fitted by the red solid line shown in Fig. 2b. From that fitting it was possible to estimate adsorption and desorption constants, as collected in Table 2.

<table>
<thead>
<tr>
<th>MF sample</th>
<th>( k_{obs}/s^{-1} )</th>
<th>( \Gamma(\infty)/\text{Hz} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-A</td>
<td>((2123 \pm 40) \times 10^{-5})</td>
<td>(355.0 \pm 0.4)</td>
</tr>
<tr>
<td>S-B</td>
<td>((1091 \pm 10) \times 10^{-5})</td>
<td>(246.0 \pm 0.4)</td>
</tr>
<tr>
<td>S-C</td>
<td>((267 \pm 1) \times 10^{-5})</td>
<td>(204.0 \pm 0.6)</td>
</tr>
<tr>
<td>S-D</td>
<td>((287 \pm 2) \times 10^{-5})</td>
<td>(81.0 \pm 0.2)</td>
</tr>
<tr>
<td>S-E</td>
<td>((234 \pm 3) \times 10^{-5})</td>
<td>(43.0 \pm 0.2)</td>
</tr>
</tbody>
</table>

The adsorption of CoFe₂O₄ nanoparticles onto planar substrates occurs at a significantly higher rate than desorption, as we found \( k_a \) to be greater than \( k_d \) (see values collected in Table 2). The equilibrium constant for the process, as calculated from \( K = k_a/k_d \), is equal to \( 0.5 \times 10^6 \) (mol/L)⁻¹, which is within the range of values reported in the literature for CdSe/ZnS core–shell nanoparticles (3.5 nm) or Au nanoparticles (≈10 nm) assembled onto the amine-terminated surface.⁵⁷⁴⁹ This finding evidences a strong association between CoFe₂O₄ nanoparticles and the substrate surface. Considering a model picture for the system in which all surface sites are occupied, with adsorbed nanoparticles forming a monolayer composed of a hexagonal close-packed arrangement of spheres, a simple calculation gives \( 2.0 \times 10^{12} \) nanoparticles per cm². Note that narrow particle size distribution, as we found in the colloidal dispersion employed (\( \sigma = 0.15 \pm 0.01 \)), is a key point for spontaneous dimer formation in CoFe₂O₄ aqueous dispersions.⁵¹ Additionally, dimers are favorable units for organizing hexagonal close-packed arrangement of spheres on a hosting surface. Based on this model picture, the nanoparticle surface coverage of planar substrates could be estimated at 92%, 64%, 53%, 21% and 11% while using the MF samples S-A, S-B, S-C, S-D and S-E, respectively. The total coverage is a limiting case, even while using concentrated MF samples (S-A for instance), as all available sites at the hosting surface are fully occupied and less favorable adsorption sites may also appear at the surface. Moreover, some nanoparticle clustering is expected to occur at higher particle concentration as confirmed by the AFM analysis performed in this study (see below). The total surface coverage reported here far outweighs those reported for the adsorption of \( \gamma \)-Fe₂O₃ nanoparticles onto mica and gold flat substrates, which reached a maximum of 20%.²⁵ As already pointed out by Semmler et al.,⁵² smaller particles are capable of adsorbing within the voids inaccessible to the large ones and, consequently, the maximal surface coverage is increased with respect to the monodisperse case. In addition, the investigations regarding adsorption of magnetic nanoparticles rarely consider the inherent dipolar interactions, which are strong enough to overcome electrostatic repulsions and thus enhance the surface coverage. Since the adsorption kinetics of CoFe₂O₄ is of first order, the rate (and the amount adsorbed) increases as the adsorbate (nanoparticle) concentration increases. Thus, if the nanoparticle concentration in the deposition fluid is low, the amount of adsorbed nanoparticles is low as well. In more concentrated fluids, some nanoparticle aggregation is possible, but the estimative of substrate covering suggests for compact layers rather than aggregation. The partial surface coverage, however, is attributed to both the reduced number of nanoparticles available in more diluted magnetic colloidal dispersions (like S-D and S-E) and the repulsive interaction among the already adsorbed nanoparticle and the incoming ones.

Once \( K \) is known the standard free energy of the nanoparticle adsorption can be estimated from the fundamental equation of equilibrium, \( \Delta G_{ads} = -RT\ln K \). As quoted in Table 2 \( \Delta G_{ads} \) is negative, as expected for a spontaneous process. In most cases, where the electrostatic attraction occurs between oppositely charged species, adsorption is a spontaneous process.⁵³⁵⁴ The decrease in the free energy as the adsorption proceeds is favored by entropy variation, which
increases due to the release of water molecules and counterions by the hosting substrate and adsorbed nanoparticles, thus increasing the degree of disorder in the surroundings (e.g. the nanoparticle dispersion).

The equilibrium state of the adsorption process of CoFe₂O₄ nanoparticles onto planar substrates was additionally investigated taking into account the Langmuir adsorption theory, which relates the fractional coverage of the surface with the concentration (C) of the adsorbed species, at a particular temperature (isotherm). In the simplest case it is assumed that every adsorption site is equivalent and the probability of a particle to bind at the site is not influenced by occupied neighboring sites. The Langmuir isotherm equation is given by:

\[ \Gamma = \frac{\Gamma_{\text{max}} K_L C}{1 + K_L C}, \]

where \( \Gamma \) is the adsorbed amount in \( \mu g \text{ cm}^{-2} \) and \( \Gamma_{\text{max}} \) is the maximum amount of adsorbed nanoparticles (or maximum surface coverage). Rearranging the Langmuir equation (eqn (4)) one obtains its linear form:

\[ \frac{C}{\Gamma} = \frac{1}{\Gamma_{\text{max}} K_L} + \frac{C}{\Gamma_{\text{max}}}. \]

As the QCM frequency shift (\( \Delta f \)) scales with the adsorbed mass (\( \Delta m \)) Fig. 3a shows the nanoparticle concentration dependence of the equilibrium QCM frequency shift (after 20 min adsorption isotherm), as obtained from the data plotted in Fig. 2a. The red solid line in Fig. 3a represents the best curve fitting using eqn (4). From the curve fitting procedure shown in Fig. 3a we found \( \Gamma_{\text{max}} = 6.51 \mu g \text{ cm}^{-2} \). This value is equivalent to the calculated mass of a two-dimensional close-packed arrangement of 2.0 \( \times \) \( 10^{12} \) spherical CoFe₂O₄ particles, as described above. The linear form of the Langmuir equation was used to fit (solid line) the experimental data (symbols) of \( C/\Gamma \) versus \( C \), as shown in Fig. 3b. Note, from Fig. 3h, the good agreement between the experimental data (symbols) and the linear form of the Langmuir equation (red solid line).

The equilibrium constant \( K_L \) value estimated from the Langmuir isotherm shown in Fig. 3 is 2.1 \( \times \) \( 10^{13} \) (mol/L)⁻¹, whereas the value found from the kinetic study is 0.5 \( \times \) \( 10^{10} \) (mol/L)⁻¹. Despite the experimental error, the order of magnitude of both values is comparable and indicates a strong interaction between CoFe₂O₄ nanoparticles and the sulfonic groups used to functionalize the substrate surface. In a previous experiment we have conducted the adsorption of CoFe₂O₄ nanoparticles onto crystals surface-modified with 3-mpa, in which case we observed a less-pronounced surface adsorption.

We have attributed the less-pronounced adsorption to the reduced number of negatively-charged adsorption sites at the crystal surface, once under pH 1.85 the 3-mpa molecule remains protonated (–COOH pKₐ around 4.7). On the other hand, surface-functionalization of microbalance crystals with 3-mpa provided sulfonic groups which remain negatively charged over a broader pH range (–SO₃ pKₐ is about 0.7) and thus available (negatively charged) for nanoparticle adsorption. According to these findings it can be concluded that the adsorption of positively-charged CoFe₂O₄ nanoparticles is mainly driven by electrostatic attraction due to negatively-charged sites at the gold-plated and functionalized substrate surface.

**Multilayer deposition onto planar substrates**

The adsorption kinetics of CoFe₂O₄ nanoparticles within the multilayered LbL film was also investigated *in situ* by employing magnetic fluid samples at different nanoparticle concentrations (pH 1.85) and fixed polyelectrolyte concentration. Fig. 4 shows the entire adsorption cycles of CoFe₂O₄/PSS multilayered LbL films while monitored by QCM, with the inset in Fig. 4a indicating each separate adsorption step. This periodic behavior is ensured by the reversal of the net surface charge after complete adsorption of each layer. Note that the periodic adsorption behavior was observed for a time window larger than eleven hours while assembling (CoFe₂O₄/PSS)₁₀ (Fig. 4a) and (CoFe₂O₄/PSS)₁₀⁻¹₀ films (Fig. S1, ESI†). However, the more diluted suspension (S-E) imposed a less regular film growth (see Fig. 4b), which is interrupted after absorption of a few bilayers. Since the adsorption is driven by electrostatic interactions it is reasonable to conclude that the reduced concentration of CoFe₂O₄ nanoparticles in sample S-E responds to a continuous decrease in the number of positive substrate sites, which thus gradually reduces the adsorption until it stops completely.

Representative pictures of the multilayer deposition (CoFe₂O₄/PSS nanofilms) are shown in Fig. 5, which displays adsorption isotherms for the 1st, 3rd, 5th and 10th CoFe₂O₄ nanoparticle layers using the magnetic colloidal suspensions S-A.
It can be clearly seen that the Δf saturation values take longer to be reached the farther the CoFe₂O₄/PSS layers are from the substrate surface. While using sample S-A to grow the nanofilm we found that the amount of the CoFe₂O₄ nanoparticles at the very first layer is smaller (6.4 µg cm⁻²—1st) than the amount found at latter layers: 10.5 µg cm⁻²—3rd; 11.2 µg cm⁻²—5th; and 11.8 µg cm⁻²—10th. The same trend was observed while using the sample S-B (Fig. S2, ESI†), with 4.4 µg cm⁻² for the first layer; 6.3 µg cm⁻²—3rd; 6.4 µg cm⁻²—5th; and 6.5 µg cm⁻²—10th. The key difference between adsorption of a single layer of nanoparticles onto the substrate surface and a multilayer scenario is clear; the net amount of nanoparticles is greater at the top of already deposited bilayers, just because the number of charged sites and the available surface area is greater at the bilayers than it is at the bottom (plain substrate).

Table 3 collects the values of k_{obs} obtained by fitting the experimental data shown in Fig. 5 while using the first order kinetics process described by eqn (2), at different bilayer numbers (n). We found that the fitted k_{obs} values decrease monotonically as the number (n) of deposited bilayers increases or, alternatively, as the distance from the bottom (close to the substrate surface) to the top increases. Our observation is rationalized as follows. Once adsorbed onto the very first flat surface nanoparticles have little chance to move around for better accommodation or re-organization and that explains the fast initial deposition process. Note that the adsorption of the first nanoparticle layer takes place at the substrate surface and a multilayer scenario is clear; the net amount of nanoparticles is greater at the top of already deposited bilayers, just because the number of charged sites and the available surface area is greater at the bilayers than it is at the bottom (plain substrate).

Adsortion of (CoFe₂O₄/PSS) films onto glass slides

Fig. 6 shows AFM images (topography and amplitude) of the LbL (CoFe₂O₄/PSS)ₙ films with n = 1, 3, 5 and 10 bilayers deposited onto glass slides. Regardless of the layer number (n), the typical globular morphology involving CoFe₂O₄ nanoparticles predominates, which spread throughout the entire surface forming a densely-packed layer. Clustering has been also observed, especially in films with several bilayers, as in

<table>
<thead>
<tr>
<th>Sample (S-A)</th>
<th>k_{obs}/s⁻¹</th>
<th>Sample (S-B)</th>
<th>k_{obs}/s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st layer</td>
<td>(2123 ± 40) × 10⁻⁵</td>
<td>1st layer</td>
<td>(1091 ± 100) × 10⁻⁵</td>
</tr>
<tr>
<td>3rd layer</td>
<td>(1214 ± 8) × 10⁻⁵</td>
<td>3rd layer</td>
<td>(550 ± 5) × 10⁻²</td>
</tr>
<tr>
<td>5th layer</td>
<td>(1161 ± 7) × 10⁻⁵</td>
<td>5th layer</td>
<td>(508 ± 4) × 10⁻²</td>
</tr>
<tr>
<td>10th layer</td>
<td>(1155 ± 6) × 10⁻⁵</td>
<td>10th layer</td>
<td>(435 ± 2) × 10⁻²</td>
</tr>
</tbody>
</table>

Fig. 4 Deposition of multilayered films of (a) (CoFe₂O₄/PSS)QCM–A₁₀ and (b) (CoFe₂O₄/PSS)QCM–E₁₁₀ monitored by QCM for a time window larger than eleven hours. Magnetic dispersions (at different nanoparticle concentrations) and fixed polyelectrolyte concentration were introduced alternately into the QCM cell (in situ) procedure. The inset in Fig. 4a indicates individual adsorption steps.

Fig. 5 Adsorption isotherms for the 1st, 3rd, 5th, and 10th CoFe₂O₄ nanoparticle layers, assembled using colloidal dispersion samples S-A.
Fig. 6e and g. Surface roughness values of CoFe$_2$O$_4$/PSS films, with different $n$ numbers and fabricated using different magnetic fluid samples (S-A, S-B, and S-E) are collected in Table 4. Note from the data included in Table 4 that surface roughness increases as the number ($n$) of CoFe$_2$O$_4$/PSS bilayers increases, especially while using samples S-A and S-B with higher nanoparticle concentration. Films deposited using the MF sample S-E reveal only small changes in the surface roughness.

The roughness increase reported in this study is expected for this type of bottom-up construction simply because defects are naturally formed at the freshly formed surface and act as nuclei for film growth. For instance, agglomeration is usually driven by reduction of the high surface energy when nanoparticles adsorb onto themselves. Additionally, the polyelectrolyte also plays its role by coating individual and clustered nanoparticles and thus increasing the layer surface area. The top surface becomes more irregular or even fractal as more layers are being adsorbed and this new condition favors the adsorption of even more material, as we have observed in the QCM measurements. This effect is usually observed in LbL films made of polyelectrolytes only and has also been reported for films fabricated while alternating polyelectrolytes with nanoparticles of different chemical compositions, including iron oxides, Au, TiO$_2$, carbon, and graphene platelets. Note that the nearly constant surface roughness observed for the film fabricated using the most diluted (8.9 × 10$^{-8}$ mol L$^{-1}$) MF sample S-E (data in the last line of Table 4) we attribute to the low surface coverage at the very first layer (11%) and on the subsequent layers ($n = 3, 5, 10$), which limits the surface adsorption to very low amounts.

The AFM data show amplitude images (Fig. 6, right hand-side panels) in which the contour of nanoparticles is clearly seen though no contrast difference is observed among films with different numbers ($n$) of CoFe$_2$O$_4$/PSS bilayers. As typical of LbL films the deposited surface is composed of both cationic/anionic materials distributed homogeneously onto the surface. Moreover, the topmost layer in all samples is made of PSS, which ensures identical chemical composition and tribologic properties. However, one should expect differences when topmost layers of different compositions are compared. We have observed changes in the amplitude images of CoFe$_2$O$_4$/PEDOT:PSS LbL films when comparing samples with the topmost layer made of CoFe$_2$O$_4$ nanoparticles or PEDOT:PSS. Despite the homogenous distribution of each material when the topmost layer was composed of CoFe$_2$O$_4$ nanoparticles the contour of nanoparticles was clearly seen. On the other hand, when the topmost layer comprises PEDOT:PSS the contours were less evident because the polymeric material fills in the voids left over around nanoparticles. Damping forces experimented by the AFM tip were substantially different to generate distinct images for each terminated surface.

Estimation of the nanofilm thickness was independently performed by AFM evaluation. The AFM tip was used to scratch and peel out a small spot of the film deposited onto the glass slides and the thickness was measured using the AFM images. The dependence of the film thickness on the number of CoFe$_2$O$_4$/PSS bilayers is shown in Fig. 7. The thickness increases linearly with the number of bilayers, as expected for LbL films.

### Table 4

<table>
<thead>
<tr>
<th>Films</th>
<th>$n = 1$</th>
<th>$n = 3$</th>
<th>$n = 5$</th>
<th>$n = 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CoFe$<em>2$O$<em>4$/PSS)$</em>{A</em>{nr}}$</td>
<td>2.1</td>
<td>5.6</td>
<td>8.3</td>
<td>10.7</td>
</tr>
<tr>
<td>(CoFe$<em>2$O$<em>4$/PSS)$</em>{B</em>{nr}}$</td>
<td>6.9</td>
<td>9.2</td>
<td>11.0</td>
<td>14.7</td>
</tr>
<tr>
<td>(CoFe$<em>2$O$<em>4$/PSS)$</em>{E</em>{nr}}$</td>
<td>2.1</td>
<td>2.1</td>
<td>3.3</td>
<td>3.5</td>
</tr>
</tbody>
</table>
solid substrate in order to create a step (see, for instance, Fig. S3a and b, ESI†), allowing estimation of the film thickness. A linear dependence was found between the film thickness and the amount of adsorbed species is mainly regulated by the mass of nanoparticles is virtually the same on each bilayer, leading to the decrease of the nanoparticle surface is related to the increasing surface roughness at the top particles onto the surface-functionalized electrodes takes no within a multilayer structure consisting of alternated layers of CoFe₂O₄ nanoparticles and sodium sulfonated polyethylene (PSS), the multilayer structure being grown by the layer-by-layer (LbL) approach. All experiments were conducted in situ within the QCM and allowed the determination of the Langmuir constant (K₁) and the adsorption free energy (∆G° ads). The formation of densely-packed layers of CoFe₂O₄ nanoparticles onto the surface-functionalized electrodes takes no longer than 11 minutes, with magnetic colloidal dispersions containing at least 10⁻⁷ g of cobalt ferrite per litre. Using more diluted MF samples the surface coverage is incomplete and the saturation plateau cannot be reached at the time window of our investigation (up to 20 minutes). The huge kinetics adsorption and equilibrium constants found for the process indicate a strong electrostatic interaction between the nanoparticle’s positively-charged surface and the negative sulfonic groups at the functionalized QCM electrode. Under equilibrium conditions, the adsorption of CoFe₂O₄ nanoparticles can be described by the Langmuir adsorption theory. The maximum surface coverage determined by the Langmuir isotherm agrees quite well with the adsorbed mass predicted by the model picture proposed for a compact layer of nanoparticles, with spherical particles composing a two-dimensional hexagonal close-packed array. The free-energy of adsorption of CoFe₂O₄ nanoparticles is negative, as expected for a spontaneous process. Likewise, the absorption of CoFe₂O₄ nanoparticles within multilayers of CoFe₂O₄/PSS follows a first order kinetic process. However, the adsorption of nanoparticles takes longer at the top of already deposited CoFe₂O₄/PSS bilayers than it does at the plain QCM electrode. This finding we hypothesize is related to the increasing surface roughness at the top bilayers, leading to the decrease of the nanoparticle surface diffusivity and thus increasing the time the nanoparticle spends to find out equilibrium sites. Atomic force microscopy (AFM) pictures and morphology data confirm our hypothesis. However, the mass of nanoparticles is virtually the same on each bilayer, which thus leads to the conclusion that despite kinetics of the amount of adsorbed species is mainly regulated by the electrostatic attraction and charge compensation inside the multilayer structure. Indeed, our findings show that the combination of in situ QCM measurements and models of adsorption can provide fundamental information regarding the adsorption of nanoparticles onto planar surfaces. This information is extremely important as far as different aspects of nanoparticle science and technology are concerned, in particular to address issues related to nanotoxicology and remediation, biological risks, and biomedical applications.

Conclusions

In this paper the quartz crystal microbalance (QCM) technique was successfully employed to assess kinetic and equilibrium parameters related to the adsorption of nanosized cobalt ferrite particles (10.5 nm-diameter) onto two different surfaces, namely a single layer of cobalt ferrite (CoFe₂O₄) nanoparticles onto the surface of a gold-coated quartz resonator functionalized with sodium 3-mercapto propanesulfonate (3-MPS) and within a multilayer structure consisting of alternated layers of CoFe₂O₄ nanoparticles and sodium sulfonated polyethylene (PSS), the multilayer structure being grown by the layer-by-layer (LbL) approach. All experiments were conducted in situ within the QCM and allowed the determination of the Langmuir constant (K₁) and the adsorption free energy (∆G° ads). The formation of densely-packed layers of CoFe₂O₄ nanoparticles onto the surface-functionalized electrodes takes no longer than 11 minutes, with magnetic colloidal dispersions containing at least 10⁻⁷ g of cobalt ferrite per litre. Using more diluted MF samples the surface coverage is incomplete and the saturation plateau cannot be reached at the time window of our investigation (up to 20 minutes). The huge kinetics adsorption and equilibrium constants found for the process indicate a strong electrostatic interaction between the nanoparticle’s positively-charged surface and the negative sulfonic groups at the functionalized QCM electrode. Under equilibrium conditions, the adsorption of CoFe₂O₄ nanoparticles can be described by the Langmuir adsorption theory. The maximum surface coverage determined by the Langmuir isotherm agrees quite well with the adsorbed mass predicted by the model picture proposed for a compact layer of nanoparticles, with spherical particles composing a two-dimensional hexagonal close-packed array. The free-energy of adsorption of CoFe₂O₄ nanoparticles is negative, as expected for a spontaneous process. Likewise, the absorption of CoFe₂O₄ nanoparticles within multilayers of CoFe₂O₄/PSS follows a first order kinetic process. However, the adsorption of nanoparticles takes longer at the top of already deposited CoFe₂O₄/PSS bilayers than it does at the plain QCM electrode. This finding we hypothesize is related to the increasing surface roughness at the top bilayers, leading to the decrease of the nanoparticle surface diffusivity and thus increasing the time the nanoparticle spends to find out equilibrium sites. Atomic force microscopy (AFM) pictures and morphology data confirm our hypothesis. However, the mass of nanoparticles is virtually the same on each bilayer, which thus leads to the conclusion that despite kinetics of the amount of adsorbed species is mainly regulated by the electrostatic attraction and charge compensation inside the multilayer structure. Indeed, our findings show that the combination of in situ QCM measurements and models of adsorption can provide fundamental information regarding the adsorption of nanoparticles onto planar surfaces. This information is extremely important as far as different aspects of nanoparticle science and technology are concerned, in particular to address issues related to nanotoxicology and remediation, biological risks, and biomedical applications.

Acknowledgements

The financial support from the Brazilian agencies MCT/ CNPq, FINEP, CAPES, FUNAPE, and FINATEC is gratefully acknowledged. The authors acknowledge Dr Emilia C.D. Lima (Universidade Federal de Goiás, Brazil) for supplying the magnetic fluid samples, Dr Fernando J. Fonseca (Universidade de São Paulo, Brazil) for sample preparation facilities, and Dr Sonia Nair Bao (Universidade de Brasília, Brazil) for TEM facilities.

Notes and references

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