Accepted Manuscript

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PII: S0021-9797(08)01230-7
DOI: 10.1016/j.jcis.2008.09.071
Reference: YJCIS 14373

To appear in: Journal of Colloid and Interface Science

Received date: 25 July 2008
Revised date: 23 September 2008
Accepted date: 24 September 2008

Please cite this article as: C. Barrera, A.P. Herrera, C. Rinaldi, Colloidal Dispersions of Monodisperse Magnetite Nanoparticles Modified with Poly(ethylene glycol), Journal of Colloid and Interface Science (2008), doi: 10.1016/j.jcis.2008.09.071

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Colloidal Dispersions of Monodisperse Magnetite Nanoparticles Modified with Poly(ethylene glycol)

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ABSTRACT

Monodisperse magnetite nanoparticles modified with poly(ethylene glycol) (PEG) were synthesized using a silane functionalized PEG obtained by reacting 3-aminopropyl triethoxysilane with carboxylic acid-methoxy PEG (mPEG-COOH) using amide reactions. Transmission electron microscopy (TEM), dynamic light scattering (DLS), and zeta potential measurements show the particles are monodisperse (σ_{gv} ~ 0.2) and stable in water for pH of 3-9 and ionic strengths, up to 0.3M NaCl. Thermogravimetric analysis coupled with TEM and DLS indicates formation of a dense graft layer on the particle surface. An analysis of the interparticle interaction energy indicates that the particles are stabilized by strong steric repulsions between PEG chains on their surface.

Keywords: magnetite, thermal decomposition, PEG, PEG-Silane, APS, steric stabilization.
1. INTRODUCTION

The design of magnetic nanoparticles dispersible in aqueous media is under intense investigation due to increased interest in their potential applications such as cancer treatment [1-4], contrast and targeting agents [5-8], biosensors [9-12], and separations [13-19]. In many of these applications it is desirable to obtain stable aqueous colloidal dispersions consisting of particles of uniform size and properties. Polymers and natural polymer-like materials have been used as surfactants to stabilize the particles. Examples include dextran [20-22], chitosan [23], poly(vinyl alcohol) [24], poly(ε-caprolactone) [25,26], and poly(ethylene glycol) [27]. Among these polymers, poly(ethylene glycol) (PEG) is of great interest, specially in biological applications since it has been shown to enhance particle stability in water due to its high solubility. This reduces particle agglomeration that could lead to non-specific adsorption of plasma proteins and a rapid clearance of the particles by the immune system [28]. Other potential applications of PEG modified magnetic nanoparticles include nanocomposites such as magnetic nanofibers that can be used for protective clothing, magnetic filters, magnetic imaging, and magnetic storage [29].

Several techniques have been employed to obtain PEG modified magnetic nanoparticles using functional PEG’s [30] or engineered co-polymers of PEG [31] with functional groups such as -OH and -COOH that can interact with the surface of the particle. Most often, these groups are physisorbed on the surface of the particle limiting stability to certain time and pH ranges [32]. In situations were particle stability is of utmost importance, as in biomedical applications, silane chemistry is being explored as an alternative functionalization route because molecules can bind with the surface of the particle, enhancing particle stability in suspensions at physiological conditions [33-35]. The preparation of PEG modified magnetic nanoparticles synthesized by the well known co-precipitation technique has been reported using commercial PEG-Silanes that are either expensive or difficult to obtain [6,36-38]. The co-precipitation technique is suitable for the production of large quantities of magnetic nanoparticles but does not provide control over the nucleation and growth stages that govern the formation of the nanoparticles. This results in particles with a broad size distribution (e.g., between 5-30 nm in diameter) and that are usually agglomerated, even after surface modification with
surfactants or polymers. Polydispersity and agglomeration could potentially affect the uniformity and reproducibility of the magnetic and physico-chemical properties of these magnetic suspensions in different settings, which is undesirable in many applications.

An alternative to control particle size and size distribution is the use of the thermal decomposition technique where iron precursors decompose in the presence of a non-polar surfactant using high boiling point solvents [39,40]. This technique produces highly monodisperse magnetic nanoparticles with almost no agglomeration during synthesis. However, the resulting particles are hydrophobic, hence additional steps are needed after synthesis to make the particles water dispersible by replacing the non-polar surfactant on the surface of the particle with a hydrophilic molecule. There are a few reports on the synthesis of PEG-Silane modified magnetic nanoparticles using thermal decomposition, in which commercial PEG-Silanes are employed or several steps are required to obtain PEG-Silane modified magnetic nanoparticles [41,42].

PEG has been shown to enhance the stability of magnetic nanoparticles in suspension due to its high solubility in polar and non-polar solvents such as water and toluene. PEG grafted on the surface of the nanoparticles provides steric stabilization that competes with the destabilizing effects of van der Waals and magnetic attraction energies. This can be modeled using the DLVO theory which describes the interparticle forces affecting particle stability in suspensions [43]. This theory has not been widely applied to magnetic nanoparticles coated with polymer chains since most of the derived models apply for cases when the polymer layer on the surface of the particles is very thin compared to the particle radius of curvature (the Derjaguin approximation). This condition is often not the case experimentally, as the particle radii are ~5 nm and the coatings are 2-10 nm in thickness. Expressions are now available that can be used to describe the effective volume of overlap between two spheres with grafted polymer chains without resorting to the Derjaguin approximation, which tends to overestimate the steric interaction energy when particles come close to a distance equal to the polymer layer thickness. In this case, the interaction potential between particles is evaluated using the exact volume of overlap calculated analytically assuming the polymer layer on the surface of the particles is characterized by a fixed width of uniform distribution of polymer segments [44].
The present contribution describes the synthesis and stability of colloidal dispersions of monodisperse PEG-Silane modified magnetite nanoparticles. PEG-Silane was prepared in our lab using an affordable technique by reacting mPEG-COOH with 3-aminopropyl triethoxysilane (APS) as shown in Figure 1. Particle stability in aqueous media was studied through dynamic light scattering and zeta potential measurements. The DLVO theory was used to model the effect of PEG-silane on particle stability using analytical expressions derived for steric repulsion applicable to the case where the particle radius is comparable to the polymer layer thickness, as is the case in our PEG-Silane coated magnetite nanoparticles. Techniques developed as part of this work can be applied in the functionalization of other metal or silicon oxides where particle stability in water is of utmost importance.

2. EXPERIMENTAL SECTION

2.1 Materials

Iron (III) acetylacetonate (Fe(acac)₃), 1,2 hexadecanediol, oleic acid, oleylamine, benzyl ether, poly(ethylene glycol) methyl ether (mPEG, 2000 molecular weight), chromium trioxide, acetic acid, and sulfuric acid were purchased from Sigma Aldrich and used as received. Toluene and 3-aminopropyl triethoxysilane (APS) were purchased from TCI America and used as received.

2.2 Synthesis of PEG-Silane

The synthesis of PEG-Silane is divided into two steps as shown in Figure 1. First, mPEG-COOH was synthesized using a strong oxidizing agent that converts terminal hydroxyl groups in mPEG to carboxylic acids. This was done using Jone’s reagent prepared by adding 70 g of chromium trioxide to 500 mL of distilled water in an ice bath. To this solution 61 mL of concentrated sulfuric acid was added slowly [45]. To obtain mPEG-COOH, 40 g of mono-methoxy PEG (mPEG) were dissolved in 400 mL of acetone followed by the addition of 17 mL of Jone’s reagent. The mixture was stirred at room temperature for 24 hrs and quenched by addition of 5mL of isopropyl alcohol. The blue-green colored solution obtained at the end of the reaction indicates the successful oxidation of terminal hydroxyl groups to carboxylic acids, precipitating chromium salts
as by-products. To remove these chromium salts, the reaction mixture was filtered under vacuum until a clear acetone solution was obtained. This solution was then concentrated to a viscous liquid using a rotary-evaporator and then dried in air to obtain a powder. To estimate the amount of carboxylic acid present in mPEG after treatment, titration was performed using KOH and phenolphthalein as indicator.

Carboxyl groups now available in mPEG-COOH are reacted in a second step with -NH$_2$ in APS via amidation reaction to finally obtain PEG-Silane following a procedure similar to the one described by Darwin [46]. In a reaction vessel, mPEG-COOH was mixed with a stoichiometric amount of APS at 180°C for 2 hrs under a nitrogen atmosphere. After reaction, the mixture was cooled to room temperature and stored in a dessicator.

2.3 Synthesis of Magnetic Nanoparticles coated with Oleic acid (OA)

Magnetite nanoparticles were synthesized in 100 mL of benzyl ether where 12.92 g of 1,2 hexadecanediol and 3.22 g of Fe(acac)$_3$ were dissolved until a clear solution was obtained. To this solution 8.5 g of oleic acid and 8.0 g of oleylamine were added to control particle agglomeration during synthesis. The solution was heated first to 150 °C for 1 hr to promote nucleation and then to 300 °C for another hour under reflux to allow particles to grow. After cooling, particles were precipitated by adding ethanol in a 3:1 ethanol:solution proportion and using a permanent magnet. The precipitate was washed again with ethanol to remove free oleic acid, oleylamine, and benzyl ether.

2.4 Surface modification of magnetite-OA nanoparticles with PEG-Silane

Oleic acid on the surface of magnetite nanoparticles was exchanged for PEG-Silane by dissolving 3 g of PEG-Silane in 180 mL of toluene. To this solution 0.2 g of magnetite-OA nanoparticles were added and dispersed using a sonicator. To catalyze the hydrolysis and condensation of silane groups on the surface of the particle 25 μL of acetic acid were added and the solution was placed in a shaker for 72 hrs at room temperature. Particles were then precipitated by adding ethyl ether until a turbid solution was observed. The precipitate was then suspended in acetone and precipitated again using ethyl ether.
2.5 Characterization Techniques

Infrared spectroscopy using a Varian 800 Fourier Transform Infrared (FTIR) was used to study the synthesis of mPEG-COOH, PEG-Silane, and surface modification of magnetite nanoparticles. PEG-Silane was also analyzed using ¹H NMR spectra using a Bruker 500 Ultrashield. Particle size was measured using a Zeiss 922 TEM. A Brookhaven Instruments BI-90 Plus Particle Size Analyzer and Zeta Potential Analyzer was used to determine the hydrodynamic size and zeta potential of the particles. Magnetic properties of oleic acid and PEG-Silane coated magnetic nanoparticles were studied using a Quantum Design MPMS XL-7 SQUID Magnetometer. The amount of bound PEG-Silane was analyzed by thermogravimetric analysis using a TA-2950 Thermo Gravimetric Analyzer under an air atmosphere.

3. RESULTS AND DISCUSSION

3.1 Characterization of PEG-Silane magnetite nanoparticles

3.1.1 FT-IR Analysis

Oxidation of hydroxyl groups to carboxylic acids in mPEG was confirmed through FT-IR by the appearance of bands at 1722 cm⁻¹ and 3420 cm⁻¹, characteristic of the -C=O and -OH vibration of -COOH. These were not present in the FT-IR spectrum of mPEG (Figure 2). The -COC vibration at 1104 cm⁻¹, characteristic of PEG, can be observed in both spectra.

The amount of carboxylic groups obtained was estimated by titration against KOH and using phenolphthalein as indicator. One gram of mPEG-COOH was dissolved in 10 mL of distilled water and titrated against KOH 0.0168 M by adding two drops of phenolphthalein to the mPEG-COOH solution. An 80 to 90 % conversion of hydroxyl groups to carboxylic acids was obtained, compared to 0.5 mmol COOH/g mPEG-COOH calculated assuming all hydroxyl groups available in mPEG were converted to carboxylic acids and using a mean molecular weight of 2,000, as reported by the supplier.

The reaction of terminal -NH₂ groups in APS with terminal -COOH groups in mPEG-COOH was confirmed by FT-IR. Figure 3 shows that the band at 1584 cm⁻¹, characteristic of -NH₂ in APS, shifted to 1540 cm⁻¹ in PEG-Silane indicative of the
formation of an amide bond (-C(=O)-NHR) between APS and PEG. Also, the band at 1722 cm\(^{-1}\) characteristic of -C=O in oxidized mPEG disappeared after reaction with APS and a new band at 1655 cm\(^{-1}\) appeared characteristic of -C=O in -C(=O)-NH [35, 47, 48].

The FT-IR spectra of OA and PEG-Silane coated magnetite nanoparticles are shown in **Figure 4**. OA-coated nanoparticles show relevant vibrational bands at 1630 cm\(^{-1}\) and 1549 cm\(^{-1}\) characteristic of asymmetric and symmetric COO- vibration of the chelating bidentate interaction between oleic acid and Fe atoms on the surface of the particles [49]. Exchange of OA molecules for PEG-Silane chains is confirmed by the appearance of bands at 1105 cm\(^{-1}\) characteristic of -COC vibrations in mPEG. Also, bands at 1647 and 1557 cm\(^{-1}\) appeared, characteristic of the -C(=O)-NH vibration in mPEG-Silane. Other characteristic bands observed for the PEG-Silane magnetite nanoparticles, such as bands at 2943, 2880, 2821, 2804, 2704, 1466, 1359, 1342, 1279, 1241, 1060, 961, 949, and 842 cm\(^{-1}\), indicate that the PEG grafted onto the particle surface is crystalline [50].

**3.1.2 NMR Analysis**

\(^1\)H-NMR for PEG-Silane in DMSO shows relevant peaks at the following chemical shifts (δ): δ 7.15 (-CONHCH\(_2\)-), δ 3.48-3.5 (-CH\(_2\)CH\(_2\)O-), δ 1.31 (-NHCH\(_2\)CH\(_2\)-). This confirms the formation of an amide bond between APS and mPEG-COOH.

**3.1.3 TEM Micrographs**

Particle size was analyzed using TEM. OA and PEG-Silane coated nanoparticles were suspended in hexane and water, respectively, and deposited on copper grids. **Figure 5** shows TEM of magnetite nanoparticles coated initially with oleic acid and after ligand exchange with PEG-Silane. A volume mean diameter \(D_{pgv}\) of 10 nm and a geometric deviation \(\sigma_g\) of 0.24 were obtained by analyzing 250 particles. Particles have a narrow size distribution and are not agglomerated even after the exchange of OA to PEG-Silane.

**3.1.4 DLS measurements**
DLS measurements of particles coated with OA show a particle volume mean diameter of ~13 nm after suspension in hexane and filtering using a 0.22 μm PTFE filter. The increase in particle diameter of about 3 nm relative to TEM measurements is in good agreement with reported values of ~2 nm for the chain length of oleic acid [49].

For PEG-Silane coated nanoparticles suspended in water and filtered using a 0.22 μm Nylon filter, the volume mean diameter increased to ~35 nm which indicates that OA previously on the surface of the particles was exchanged for PEG-Silane chains. This value is close to the expected diameter of ~36 nm estimated using the particle diameter obtained by TEM and assuming a linear PEG-Silane chain length of ~13 nm, calculated for a molecular weight of 2,000 using GaussView 3.07.

3.1.5 TGA Analysis

To determine the amount of OA and PEG-Silane on the surface of the particles, TGA analysis was performed from 20 to 800 ºC at a heating rate of 10ºC/min under an air atmosphere. A mass loss of about 15 % at 250 ºC was found for OA-coated nanoparticles, attributed to the degradation of oleic acid. This weight loss indicates that the ratio of the mass of OA $w_s$ to the mass of magnetite $w_p$ is 0.18 which is close to the theoretical value of 0.21 calculated from

$$\frac{w_s}{w_p} = \rho_p \left( \frac{D_{DLS}^3 - D_{TEM}^3}{D_{TEM}^3} \right),$$

(1)

based on the hydrodynamic diameter $D_{DLS}$ of 13 nm measured by DLS, the core diameter $D_{TEM}$ of 10 nm determined by TEM, using a value of 0.895 g/mL for the OA density $\rho_s$, and a value of 5.2 g/mL for the magnetite density $\rho_p$.

The PEG-Silane coated nanoparticles showed a mass loss of 84% at 398 ºC indicative of a stronger interaction between PEG-Silane and the surface of the particles than with OA. This mass loss corresponds to a mass ratio of PEG-Silane to magnetite of ~ 5 which is in agreement with the value of ~ 8 obtained using Eq. (1), a hydrodynamic diameter of 35 nm from DLS, a core diameter of 10 nm from TEM, and an assumed polymer density of 1 g/mL. This and the DLS measurements indicate that the PEG-Silane coating on the particle surface is fairly dense.
3.1.6 Stability analysis of PEG-Silane magnetic nanoparticles at physiological conditions

The zeta potential of PEG-Silane magnetite nanoparticles suspended in 0.1M KNO₃ aqueous solution was studied from pH 3 to 9 by adding 0.1M KOH and HNO₃ to adjust pH. As seen in Figure 6, the particle surface is charged through most of the pH range except close to 7.5 where the isoelectric point, pI, of the particles is obtained. PEG-Silane does not have any ionizable groups, hence the surface charge is attributed to ions absorbed from solution to the PEG-Silane layer surrounding the particles [41]. The hydrodynamic diameter of the particles varies between 35 and 45 nm as the pH changes, with no visible precipitation.

Particle stability was also studied as a function of ionic strength by measuring zeta potential as a function of NaCl concentration at pH 7. The NaCl concentration was varied from 0.038 M to 0.32 M and, as seen in Figure 7, particles were stable in this range with no precipitation. Also, as salt concentration increased the zeta potential of the suspension decreased, as expected from the Debye-Hückel theory.

3.2.8 Magnetic measurements

The magnetic core size of the particles was estimated for samples of OA and PEG-Silane coated magnetite nanoparticles suspended in hexane and water respectively. For both cases, a magnetic core size of 10-12 nm with a volume mean diameter $D_{pgv}$ of 12 nm and a geometric standard deviation $\sigma_g$ of 0.19 was obtained using magnetization $M$ data shown in Figure 8 and the equations due to Chantrell et al. [51]

$$D_{pgv} = \left( \frac{18k_B^2T}{\pi M_d} \left[ \frac{\chi_i}{3\phi M_d H_0} \right]^{1/2} \right)^{1/3}, \quad (2)$$

$$\ln \sigma_g = \frac{1}{3} \left[ \ln \left( \frac{2\chi_i H_0}{\phi M_d} \right) \right]^2, \quad (3)$$

where $M_d$ is the domain magnetization (446 kA for magnetite), $\chi_i$ is the initial susceptibility of the suspension, $\phi$ is the particle volume fraction, and $H_0$ is the magnetic field extrapolated to zero $M$ when $M$ is plotted versus $1/H$ using data obtained at high fields. As seen in Figure 8, particles remain magnetic after functionalization with PEG-
Silane. The difference in $M_s$ is primarily due to differences in particle volume fraction in the two suspensions.

3.2 Stability analysis of PEG-Silane magnetic nanoparticles

The role of the PEG-Silane layer $\delta$ thickness on particle stability can be modeled by considering the total interaction energy between two polymer-coated nanoparticles of diameter $d$ suspended in water, as shown schematically in Figure 9. The total interaction energy may be expressed as the sum of van der Waals forces, magnetic dipole-dipole interactions, and electrostatic and steric repulsion as a function of surface-to-surface particle distance $h$.

The van der Waals attraction energy $U_{VDW}$ for coated particles can be calculated for two identical interacting particles of radius $R$ with a homogeneous layer of adsorbed polymer $\delta$ by [52]

$$U_{VDW} = -\frac{1}{12}[(A_m^{0.5} - A_s^{0.5})^2 H\left(\frac{h}{2R + 2\delta};1\right) + (A_s^{0.5} - A_p^{0.5})^2 H\left(\frac{h + 2\delta}{2R};1\right) + 2((A_m^{0.5} - A_s^{0.5})(A_s^{0.5} - A_p^{0.5})H\left(\frac{h + \delta, R + \delta}{2R};R\right)]$$

where $A_m$, $A_s$, and $A_p$ are the Hamaker constants for the medium (water, $4.15 \times 10^{-19}$ J [53]), surface coating (PEG, $7.20 \times 10^{-20}$ J [54]), and particles (magnetite, $5.09 \times 10^{-19}$ J [53]), respectively, and $H(x,y)$ is

$$H(x,y) = \frac{y}{x^2 + 2xy + x} + \frac{y}{x^2 + 2xy + x + y} + 2\ln\left(\frac{x^2 + 2xy + x}{x^2 + 2xy + x + y}\right).$$

To protect particles against the van der Waals attraction, the particle surface is modified with suitable polymers that provide steric repulsion against aggregation. Estimation of the total steric interaction between two approaching particles is commonly divided into osmotic and elastic contributions that depend on the distance between the approaching particles. When the particle-particle separation reaches a distance that is smaller than $2\delta$, polymer chains of opposing particles interpenetrate resulting in an
osmotic pressure leading to spontaneous flow of the solvent into the interpenetrated volume, pushing the particles apart. This osmotic repulsion can be calculated from [44]

\[ U_{\text{osmotic}} = \frac{4\pi k_B T}{3 V} \varphi^2 \left( \frac{1}{2} - \chi \right) \left( \frac{\delta - \frac{h}{2}}{2} \right)^2 (3\delta + 2\delta + \frac{h}{2}) \; ; \; \delta < h < 2\delta, \]  

(6)

where \( \varphi \) is the volume fraction occupied by PEG-Silane, \( V \) is the molecular volume of water (0.03 nm\(^3\)), \( k_B \) is Boltzman’s constant, \( T \) is the absolute temperature, and \( \chi \) is the Flory Huggins parameter. For PEG-Silane, a value of \( \chi = 0.4 \) was used, obtained for PEG with a molecular weight of 4000 in water [55]. A value of 0.89 was estimated for the volume fraction \( \varphi \) using the expression

\[ \varphi = \frac{6w_s}{\pi \rho_s N_p (D_{\text{DLS}}^3 - D_{\text{TEM}}^3)}, \]  

(7)

where \( N_p \) is the number of particles calculated by dividing the mass of magnetic nanoparticles obtained from TGA measurements by the mass of a 10 nm magnetic nanoparticle. When the distance between particles becomes less than \( \delta \), polymer chains attached to the particle surface compress each other restricting their movement towards the solvent. This results in a loss of configurational entropy that can be described by an elastic repulsion given by [44]

\[ U_{\text{elastic}} = \frac{2\pi k_B T}{V} \varphi^2 \left( \frac{1}{2} - \chi \right) \left( \frac{2V_a}{V} - V_a \right); \; \; 0 < h < \delta, \]  

(8)

\[ V_a = \frac{\pi \delta (-24R^2 h + 36\delta R^2 - 12Rh^2 + 28\delta^2 R - 6h^2 \delta + 3\delta^3 + 8h^2 \delta)}{12(2R + h)}, \]  

(9)

\[ V_c = \frac{\pi (24R^2 \delta^2 - 12R^2 h^2 + 24\delta^3 R - 8Rh^3 + 6\delta^4 - h^4)}{12(2R + h)}, \]  

(10)

where \( V_a \) and \( V_c \) are the effective volume of overlap between two approaching spheres in the region of osmotic and elastic repulsion respectively.

The magnetic attractive interactions between PEG-Silane magnetite nanoparticles can be estimated from [53]

\[ U_m = \frac{-2 (\mu_0 M_d \frac{\pi}{6} d^3)^4}{3 (4\pi\mu_0)^2 S^6 k_B T} \]  

(11)
where \( \mu_0 \) is the permittivity of free space (1.26x10^{-6} H/m), \( d \) is the particle diameter, and \( S \) is the center-to-center particle separation \((S=h+d)\). Magnetic attractive interactions were less than 1 \( k_BT \) at a particle-particle separation of 2\( \delta \) and were therefore not included in subsequent figures.

**Figure 10** shows the total steric and van der Waals interaction energy for the PEG-Silane magnetite nanoparticles with \( R = 5 \text{ nm} \) and \( \delta = 12.5 \text{ nm} \). The PEG-Silane layer on the surface of the particle at the given surface density and particle volume fraction provides sufficient repulsion to counteract the van der Waals attractive interaction.

The calculated total interaction energy for the PEG-Silane magnetite nanoparticles suspended in water is shown in **Figure 11**. Electrostatic repulsions are not considered since at physiological-like conditions (pH 7 and high salt concentrations) the zeta potential is small as seen in **Figures 8 and 9**. The interaction curve shows a minimum at a distance close to 2\( \delta \) followed by a rapid increase characteristic of sterically stabilized systems. Steric repulsion between overlapping polymer chains of approaching particles prevents particles from reaching a distance closer than 2\( \delta \), avoiding agglomeration and resulting in highly stable suspensions in water. The magnitude of the calculated minimum is much less than 1 \( k_BT \), indicating that aggregates formed at this distance break due to thermal agitation [56].

**4. SUMMARY**

Stable colloidal dispersions of monodisperse magnetic nanoparticles in water were obtained by synthesizing magnetite nanoparticles by the thermal decomposition method, and exchanging the OA molecules on the surface of the particles for PEG-Silane chains. The size of the particles and the chemical nature of the coating were determined by TEM and FTIR, respectively. TGA measurements show a mass loss of about 84\% at 398 °C indicative of strong interaction between silanol groups of PEG-Silane with the surface of the nanoparticles. The procedure produces highly stable suspensions of magnetite nanoparticles in water at pH of 3 to 9 and at salt concentrations as high as 0.32 M NaCl. The stability of the nanoparticles in suspension is further confirmed using DLVO theory and expressions for the steric repulsion between approaching hard particles coated with
thick polymer shells. The analysis shows particles are stabilized by steric repulsion between the PEG-Silane chains, preventing particle agglomeration in suspension.

PEG-Silane was obtained using a single step reaction between terminal amines in APS with carboxylic acid groups in mPEG-COOH by heating at 180°C for 2 hours, as confirmed by FT-IR and NMR. This allowed us to obtain large quantities of silane modified PEG using an inexpensive, straightforward technique, that can be used to covalently attach PEG to magnetic nanoparticles or other metal oxide surfaces. These particles could potentially be used in a wide range of applications such as biotechnology, MRI, magnetic fluid hyperthermia, nanocomposites, or smart/functional textiles. Additionally, because of their uniform size, polymer coating, and stability in aqueous media, these particles could be used as model colloids in studies of magnetic particle-particle interactions.

5. ACKNOWLEDGEMENTS

This work was supported by the US National Science Foundation Nanoscale Interdisciplinary Research Teams program (Grant No. CBET-0329374), the Partnerships for Research and Education in Materials program (Grant No. DMR-0351449), the Experimental Program to Stimulate Competitive Research (Grant No. OIA-0701525), and NASA (Grant No. NCC5-595). The authors are grateful to Victoria Calero for TEM measurements and Edwin de la Cruz for NMR measurements and analysis.

6. REFERENCES

Figure 1: Schematic representation of the synthesis of magnetite nanoparticles coated with PEG-Silane. 

I. mPEG-COOH obtained by oxidation of mPEG using Jone’s reagent. 

II. PEG-Silane obtained by reacting mPEG-COOH with APS. 

III. Exchange of OA molecules for PEG-Silane.
Figure 2: Oxidation of hydroxyl groups to carboxylic acids in mPEG using Jone’s reagent. Spectrum a) shows characteristic bands of mPEG before and b) after oxidation of –OH groups to –COOH.
Figure 3: Reaction of terminal –NH₂ groups in APS with –COOH groups in mPEG-COOH. Spectrum a) shows band at 1584 cm⁻¹, characteristic of –NH₂ in APS. Spectrum b) shows this band has shifted to 1540 cm⁻¹, characteristic of formation of an amide bond between APS and mPEG-COOH.
Figure 4: Comparison of FT-IR spectra a) OA coated magnetite nanoparticles and b) PEG-Silane coated magnetite nanoparticles.
Figure 5: Transmission electron microscopy images of (a) OA coated magnetite nanoparticles and (b) magnetite nanoparticles coated with PEG-Silane. In both cases particles appear to be spherical and separated by a shell which has no contrast against the amorphous carbon background.
Figure 6: Stability of PEG-Silane coated magnetite nanoparticles as a function of pH. (a) Zeta potential vs. pH for PEG-Silane magnetite nanoparticles suspended in water and (b) particle hydrodynamic diameter as a function of pH.
Figure 7: Stability of PEG-Silane coated magnetite nanoparticles as a function of ionic strength. (a) Zeta potential and (b) hydrodynamic diameter vs. NaCl concentration for PEG-Silane magnetite nanoparticles suspended in water at pH 7.
Figure 8: Magnetization curves for OA and PEG-Silane magnetite nanoparticles. Both suspensions are superparamagnetic, with different saturation magnetizations due to the different particle concentrations in each. The negative slope at high magnetic fields in the PEG-Silane sample is due to the diamagnetic background of the sample holder.
Figure 9: Schematic representation of the core-shell model used to study particle stability. Inorganic hard spheres of radius $R$ are coated with uniform polymer shells of thickness $\delta$ and separated by a distance $h$ measured from the surface of the inorganic cores.
Figure 10: Comparison of the steric and van der Waals contributions to the particle-particle interaction energy between two approaching PEG-Silane coated magnetite nanoparticles. The particle radius $R = 5 \, \mu m$ and the polymer thickness is $\delta = 12.5 \, nm$. 
Figure 11: Total interaction energy for PEG-Silane coated magnetite nanoparticles in water. The inset shows the prediction of a shallow energy minimum at contact between particles.
Monodisperse magnetic nanoparticles were coated with mPEG-silane molecules. The colloidal stability of these nanoparticles was studied from DLVO theory. Steric repulsion between PEG-Silane chains of approaching particles was responsible for nanoparticle stabilization, making these nanoparticles suitable for biological applications.