Aqueous Ferrofluid of Citric Acid Coated Magnetite Particles

A. Goodarzi[1], Y. Sahoo[2], M.T. Swihart[1], P.N. Prasad[2]

[1]Department of Chemical and Biological Engineering and Institute for Lasers, Photonics and Biophotonics, University at Buffalo (SUNY), Buffalo, NY, 14260

[2]Department of Chemistry and Institute for Lasers, Photonics and Biophotonics, University at Buffalo (SUNY), Buffalo, NY, 14260

ABSTRACT

Magnetic nanoparticles have found application in medical diagnostics such as magnetic resonance imaging and therapies such as cancer treatment. In these applications, it is imperative to have a biocompatible solvent such as water at optimum pH for possible bio-ingestion. In the present work, a synthetic methodology has been developed to get a well-dispersed and homogeneous aqueous suspension of Fe_3O_4 nanoparticles in the size range of 8-10 nm. The surface functionalization of the particles is provided by citric acid. The particles have been characterized using transmission electron microscopy, magnetization measurements with a superconducting quantum interference device, FTIR spectroscopy (for surfactant binding sites), thermogravimetric studies (for strength of surfactant binding), and x-ray photoelectron spectroscopy and x-ray diffraction (for composition and phase information). The carboxylate functionality on the surface provides an avenue for further surface modification with fluorescent dyes, hormone linkers etc for possible cell-binding, bioimaging, tracking, and targeting.

INTRODUCTION

Magnetic nanoparticles have drawn much scientific interest for a variety of studies on topics including superparamagnetism[1], magnetic dipolar interactions[2], single electron transfer[3], magnetoresistance[4] and so on.   One area that is particularly promising is the use of magnetic nanoparticle systems for probing and manipulating biological systems[5]. Magnetite (Fe_3O_4) nanoparticles have been widely studied, and their colloidal dispersion is a well-known ferrofluid that has many potential bio-medical applications. The particles, for this purpose, are subjected to suitable surface modifications by various coating agents such as dextran[6], dimercaptosuccinic acid [7,8], starch and methoxypoly(ethylene glycol)[9], protein[10], silica coating [11] etc.

It is a technological challenge to acquire control over the nanoparticles' sizes and dispersibility in desired solvents. Because of their large surface to volume ratio, nanoparticles possess high surface energies. The particles tend to aggregate to minimize total surface energy. In the case of metal oxide surfaces, such energies are in excess of 100 dyn/cm [12]. Because the particles are magnetic in nature, there is an additional contribution from inter-particle magnetic dipolar attraction that tends to destabilize the colloidal dispersion further. Suitable surface functionalization of the particles and choice of solvent are crucial to achieving sufficient repulsive interactions between particles to prevent aggregation and obtain a thermodynamically stable colloidal solution   For magnetite particles, oleic acid acts as an efficient surfactant that binds through the carboxyl end leaving aliphatic chains extending out from the surface[13]. This

makes the coated particles effectively hydrophobic and dispersible in non-polar solvents. Sahoo et al. [14] have shown that alkyl phosphonates and phosphates also bind to magnetite particles well and render the surfaces hydrophobic. There has been some work on the aqueous suspension of magnetic particles. For example, Fauconnier et al. have thiolated the particle surface[8] and Shen et al. [15] have created a bilayer structure of fatty acids to make the surface hydrophilic, enabling stable aqueous dispersion. In the present work, we have used citric acid (CA) as surfactant to form a stable aqueous dispersion of magnetite particles and simultaneously provide functional groups on the particle surface that can be used for further surface derivatization.

EXPERIMENTAL

Magnetite(Fe_3O_4) particles were prepared by co-precipitation of $FeCl_2$ and $FeCl_3$ (1:2 molar ratio) by the addition of NH_4OH. In a typical reaction, 0.86 g $FeCl_2$ and 2.35 g $FeCl_3$ were mixed in 40 ml water and heated to 80º C under argon in a three-necked flask. While vigorously stirring the reaction mixture, 5 ml of NH_4OH was introduced by syringe and the heating continued for thirty minutes. After that, 1g of citric acid (CA) in 2ml water was introduced, the temperature raised to 95º C and the stirring continued for an additional ninety minutes. A small aliquot of the reaction mixture was withdrawn, diluted to twice its volume and placed on a 0.5 Tesla magnet in a vial. At the point when the particles did not settle down under the influence of the magnet, the colloidal solution was stable. The as-formed reaction product contained an excess of citric acid. Therefore, the nanoparticle dispersion was subjected to dialysis against water in a 12-14 kD cut-off cellulose membrane (Spectrum Laboratories, Inc., USA) for 72 hours to remove the excess unbound CA. The citric acid coated magnetic particles are abbreviated as MP-CA.

The particles were characterized by Fourier transform infrared (FTIR) spectroscopy, X-ray photoelectron spectroscopy (XPS), thermogravimetric analysis (TGA), and transmission electron microscopy (TEM). FTIR spectra of neat citric acid and coated magnetic particles were taken in KBr pellets using a Perkin Elmer FTIR spectrometer model 1760X. XPS studies were performed on a Physical Electronics/PHI 5300 x-ray photoelectron spectrometer operated at 300W (15 kV and 20 mA) with a Mg K_α radiation (1253.6 eV) source. TGA was performed on a Perkin Elmer instrument model TGA7 on roughly 5mg samples heated to 800^0C. TEM images were obtained by employing a model JEOL 100 CX II microscope at an acceleration voltage of 80 kV in the bright field image mode. Magnetization measurements (DC) were made on aqueous samples hermetically sealed in non-magnetic ampoules, by using a superconducting quantum interference device (SQUID) MPMS C-151 magnetometer from Quantum Design.

RESULTS AND DISCUSSION

The formation of Fe_3O_4 particles by co-precipitation of Fe^{2+} and Fe^{3+} by an alkali is fairly well known and is widely used. XPS (Fig. 1(a)) and XRD (Fig. 1(b)) results are consistent with the expected composition of Fe_3O_4 particles. XPS shows a binding energy of the Fe $2p_{3/2}$ shell electron at slightly above 710 eV, which agrees with the oxidation state of Fe in Fe_3O_4 [16]. The XRD peaks can be indexed into the spinel cubic lattice type with a lattice parameter of 8.34 Å. It cannot be ascertained from the XRD whether the further oxidized Fe_2O_3 phase exists in the
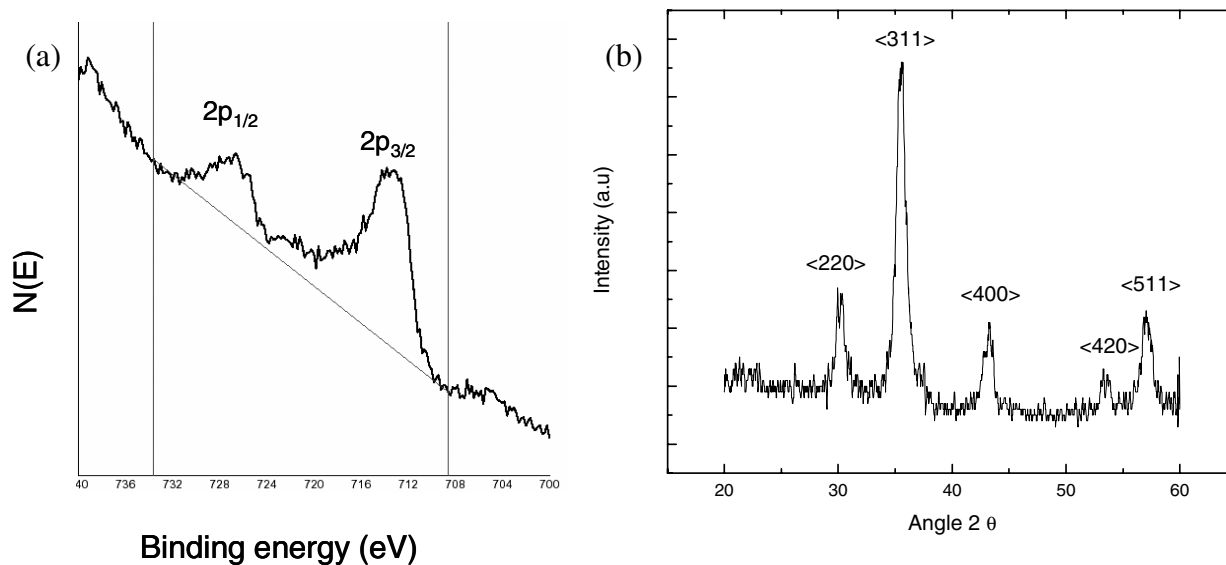
Figure 1. (a) XPS and (b) XRD of MP-CA show the composition and crystal structure of magnetite.

sample because of similar lattice type and lattice constant [11]. The TEM image of the citric acid coated magnetite particles without any size selection is shown in Fig. 2(a). The sizes range from 5 to 13 nm with a dominant population of 6-8 nm (44%) (Fig 2.b).   A size selection can be carried out by adding incremental volumes of acetonitrile as non-solvent and carrying out sequential centrifugation. However, for the present paper we have characterized and present results for the moderately polydisperse sample. XRD shows broadening of the diffraction peaks, and the particle size calculated using the Scherrer formula is ~10 nm.

FTIR spectroscopy shows that the surface passivation of the particles occurs via the –COOH group. Fig. 3 shows the FTIR spectra of the neat citric acid (CA) and magnetite particles coated
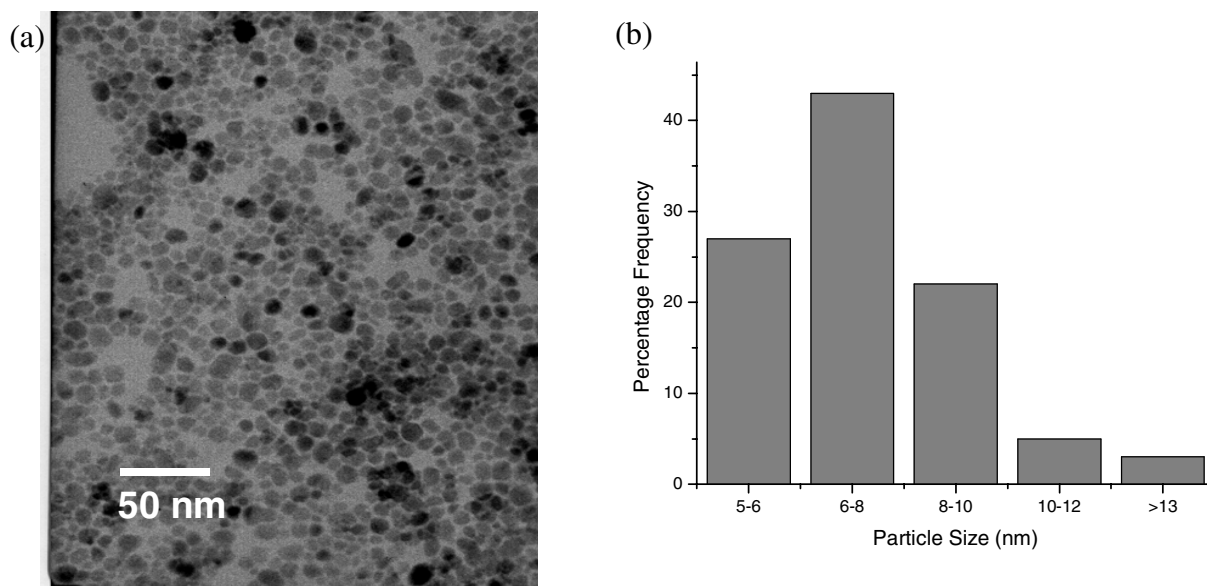

Figure 2. (a) TEM of MP-CA before any size sorting and (b) the corresponding size distribution.

with citric acid (MP-CA). The vibration bands for the CA are found to be rather broad, as expected due to the strong intra- and intermolecular hydrogen bonding. The 1715 cm^{-1} peak assignable to the C=O vibration in neat CA is present as a broad band. On binding of CA to the magnetite surface, this band shifts to 1618 cm^{-1} in MP-CA. The carboxylate end of CA may complex with the Fe of the magnetite surface and render the C=O bond partial single bond character. This observation is similar to the citrate complex in YFeO$_3$ studied by Todorovsky et al [17]. It is proposed that CA binds to the magnetite surface by chemisorption of the carboxylate i.e citrate ions. Earlier studies by Matijevic's group [18] have shown that oxalic acid and citric acid bind to the hematite surface through chemisorption that is highly pH dependent. The citric acid was inferred to be bound either as a bidentate or a tridentate ligand from their zeta potential measurement. TGA results (Fig.4) show a single step weight loss on the neat CA and MP-CA. The weight loss in the latter case starts at a higher temperature and occurs more gradually than for the neat CA. CA does not have a normal boiling point because it decomposes before boiling at atmospheric pressure. There is about 30ºC difference (195º and 225ºC for the neat and MP-CA respectively) in the weight loss onset temperatures. This is an indicator of the enthalpy of adsorption of CA molecules on the magnetite surface. Also, while the net weight loss in the neat sample is 100% as expected, the weight loss for MP-CA is 40%. We can attribute the weight loss to desorption of citric acid molecules from the surface of the magnetite particles. The mass of surfactant bound to the particle surface can be calculated as follows. If we assume a close-packed monolayer of the surfactant on the surface of a nanoparticle of diameter d_p then the total weight of the nanoparticle plus the monolayer is $(1/6)\pi d_p^3\rho + (\pi d_p^2/a)(M/N_0)$,

where d_p = the diameter of the particle, ρ = the density of the particle, a = the head area per molecule of the surfactant, M = the molecular weight of the surfactant, and N_0 = Avogadro's number. Assuming that the TGA heating causes weight loss of only the surface bound surfactant, the percentage weight loss from a particle of diameter d_p is $100 \times (\pi d_p^2/a)(M/N_0) / ((1/6)\pi d_p^3\rho + (\pi d_p^2/a)(M/N_0))$. For a polydisperse sample with discrete size distribution $f(d_p)$, the fractional weight loss is obtained by summing over the size distribution:
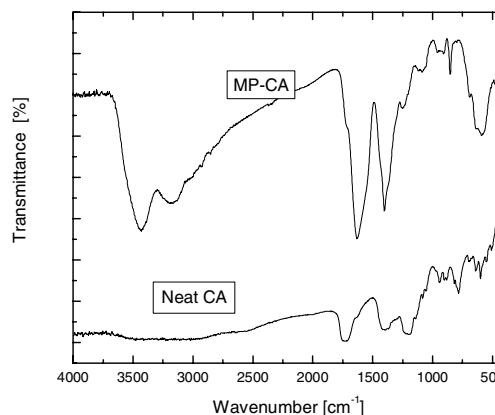

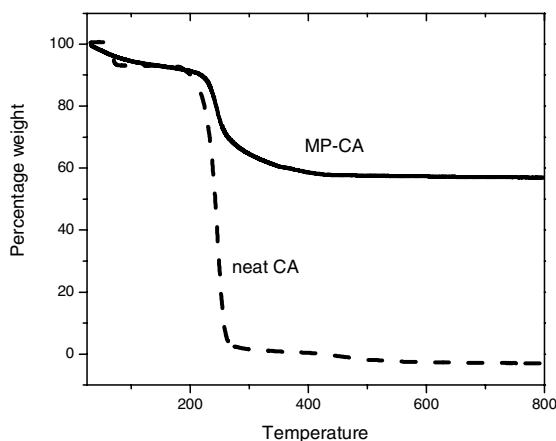**Figure 3.** FTIR of neat CA and MP-CA showing binding through a –COOH group.

Figure 4. TGA of neat CA and CA coated Fe$_3$O$_4$.

$$\text{weight loss} = \frac{\sum_i \left(\pi d_{p,i}^2 \Big/ a\right)\left(M \Big/ N_0\right) f\left(d_{p,i}\right)}{\sum_i \left[\frac{1}{6}\pi d_{p,i}^3 \rho + \left(\pi d_{p,i}^2 \Big/ a\right)\left(M \Big/ N_0\right)\right] f\left(d_{p,i}\right)}$$

Summing over the discrete nanoparticle size distribution fractions as in the size distribution plots of Fig 3.b, with $\rho = 5.18$ g/cm^3, $a = 21$ Å^2, and $M = 192.12$ amu gives the percentage weight loss for this particle size distribution as 18 %. This value is about half the value of the weight loss observed from TGA (Fig. 5). This discrepancy can be explained as follows. In the calculation, the head area of 21 Å^2 is appropriate for close packed monodentate ligands [13]. This suggests that in spite of repeated washing, substantially more than a monolayer of surfactant is present, possibly due to potentially strong hydrogen bonding among the citric acid molecules. Surfactant not bound to the particle surface, but held by interdigitation with the first monolayer should show an extra step in the TGA curve [15]. However, because of the strong hydrogen bonding in CA, the molecules might still remain bound and leave *en masse* on desorption giving rise to a single step weight loss feature.

The CA coated particles forming the ferrofluid in this study are in their superparamagnetic regime. At 300K, magnetization measured up to a dc magnetic field of 10000G shows saturation of magnetization (Fig. 5), but no hysteresis loop. However, on lowering the temperature to 5K, the hysteresis appears, with a coercive field of ~430 G. This suggests that the blocking temperature of the particles is above 5K.

In this study, we have stabilized the surface of magnetite nanoparticles by adsorption of citric acid. The citric acid may be adsorbed on the surface of the magnetite nanoparticles by co-ordinating via one or two of the carboxylate functionalities depending on the steric necessity and the curvature of the surface. Yet, there will be at least one carboxylic acid group exposed to the solvent, that should be responsible for making the surface charged. Further, the presence of a terminal carboxylic group provides an avenue to extended bond formation with fluorescent dyes, proteins, and hormone linkers so that specific targeting within biological systems can be facilitated.

ACKNOWLEDGEMENTS

REFERENCES

1. C. P. Bean and J. D. Livingstone, J. Appl. Phys. **30**, 120S (1959); Neel, L. *Rev. Mod. Phys.* **25**, 293 (1953).
2. G. A. Held, G. Grinstein, H. Doyle, S. Sun and C. B. Murray, *Phys. Rev.* B **64**, 012408 (2001).

3. S. N. Molotkov, S. S. Nazin, *Phys. Low-Dimens. Struct.* **10**, 85 (1997); R. Weisendanger, MRS Bull. **22**, 31 (1997).

4. P. Poddar, T. Fried and G. Markovich, *Phys. Rev*. B **65**, 172405 (2002); C. T. Black, C. B. Murray, R. L. Sandstrom and S. Sun, Science **290**, 1131 (2000).

5. K. Raj, B. Moskowitz, R. Casciari, *J. Magn. Magn. Mater*. **149**, 174 (1995); R. F. Ziolo, E. P. Giannelis, B. A. Weinstein, M. P. O'Horo, B. N. Ganguly, V. Mehrotra, M. W. Russell and D. R. Huffman, *Science* **257**, 219 (1992).

6. D. K. Kim, W. Voit, W. Zapka, B. Bjelke, M. Muhammed , K. V Rao , *MRS Symp. Proc*. 676, (2002).

7. C. Wilhelm, C. Billotey, J. Roger, J.N Pons, J. C. Bacri and F. Gazeau, *Biomaterials*, **24**, 1001 (2003).

8. N. Fauconnier, J.N. Pons, J. Roger, A. Bee, J. *Coll. Interfac. Sci*. **194**, 427(1997).

9   D. K Kim, K. Do ; M. Mikhaylova , Y. Zhang, M. Muhammed*,   Chem. Mater*. **15(8),** 1617 (2003).

10. K. Nishimura, M. Hasegawa, Y. Ogura, T. Nishi, K. Kataoka, H. Handa , M. Abe*, J. App. Phys*. **91(10, Pt. 3**), 8555 (2002).

11. L. Levy, Y. Sahoo, K. Kim, E. J. Bergey, and P. N. Prasad, *Chem. Mater*. **14**, 3715 (2002).

12. L. Vayssieres, C. Chaneac, E. Troc, J.P Jolivet, *J. Coll. Interfac. Sci*. **205**, 205 (1998).

13. T. Fried, G. Shemer, and G. Markovich, *Adv. Mater*. 13, 1158, (2001).

14. Y. Sahoo, H. Pizem, T. Fried, D. Golodnitsky, L. Burstein, C. N. Sukenik, and G. Markovich, *Langmuir*, **17**, 7907 (2001).

15. L. Shen, A. Stachowiak, S. K. Fateen, P. E. Laibinis, T. A. Hatton, *Langmuir*, **17**, 288 (2001).

16. C. D. Wagner, R. M. Riggs, L. E. Davis, J. F. Moulder, *Handbook of Electron Spectroscopy*, edited by G. E. Muilenberg (Perkin Elmer Corp., Physical Electronics, Eden Prairie, MN, 1979.)

17. D. S. Todorovsky, D. G. Dumanova, R. V. Todorovska, M. M.Getsova, *Croatica Chemica Acta,* **75(1)**, 155 (2002).

18. N. Kallay and E. Matijevic, *Langmuir*, **1**, 195 (1985).