

Probing Dynamic Phase Transformations of Hydrated Iron Oxide Nanoparticles with *in situ* Scanning Transmission Electron Microscopy

Ryan Hufschmid¹, Kannan M. Krishnan¹, and Nigel D. Browning^{1,2}

¹ Department of Materials Science and Engineering, University of Washington, Seattle, WA, USA

² Physical and Computational Sciences Directorate, Pacific Northwest National Laboratory, Richland, WA, USA

Dynamic processes at interfaces are fundamental to environmental, biological, and engineered systems. Iron oxides are ubiquitous in nature[1] and serve as a platform for a variety of engineered applications, including biomedical imaging and therapeutics[2], [3]. Interactions between minerals, organic molecules, and ions in aqueous environments are fundamental for both engineered nanoparticles that interface with complex biological media, and for naturally occurring particles in delicate environmental systems. In this work, we directly observe and quantify dynamic phase changes of iron oxide nanoparticles in solution. By altering surface chemistry with organic molecules, we can then systematically study colloidal stability at the nanoscale.

Recent advances in *in situ* transmission electron microscopy (TEM) techniques and instrumentation enable direct nanoscale imaging and spectroscopy in relevant environments[4]. For example, specialized holders encapsulate liquid samples, allowing direct observation of dynamic liquid phenomena under controlled electron dose conditions[5]. Here, to assemble liquid cells, 0.2 uL of each solution was drop cast on silicon chips with 50 nm thick silicon nitride membranes. Liquid cells were static; no solution flowed during the experiment. Samples were imaged in scanning (S)TEM mode. Contrast in STEM is proportional to atomic number at high scattering angles. Growth or dissolution of the high-contrast mineral phase can thus be quantified. Imaging can be complimented with other characterizations available in the TEM, for example electron energy loss spectroscopy (EELS) for chemical analysis. The intensity of the zero-loss peak also provides an estimate of sample thickness[6], an important consideration in liquid TEM.

Here we use *in situ* STEM techniques to directly observe the behavior of iron oxide nanoparticles with different surface chemistries in organic and aqueous solutions. By quantifying the kinetics of mineral phase transformations, we can determine the influence of different organic species. Aqueous magnetite (Fe₃O₄) nanoparticles terminated with poly-ethylene glycol (PEG) dissolve, as shown in **Figure 1a** and **b**, even under relatively low dose conditions of 1 e⁻/Å²s. The dissolution rate increases with electron dose rate delivered during imaging. However, certain surface functionalization, for example polycationic peptides, promotes growth at the Fe₃O₄ surface (**Figure 1c**). Under some conditions the growth and dissolution reactions are reversible. Similar phase transformations also occur in aqueous suspensions of α-FeOOH, where the addition of organic molecules influences aggregation and templates recrystallization of new phases[7].

Based on these observations we conclude that colloidal stability depends strongly upon surface chemistry and local solution conditions, while bulk indicators of stability such as zeta potential may not predict all behavior of individual nanoparticles. For systems that depend on dynamic nanoscale phenomena, characterization with *in situ* TEM is therefore an important complement to conventional

analyses. With increasingly widespread application, *in situ* methods will enable direct visualization at unprecedented length and time scales in materials science and beyond[8].

References:

- [1] G. A. Waychunas, C. S. Kim, and J. F. Banfield, “Nanoparticulate Iron Oxide Minerals in Soils and Sediments: Unique Properties and Contaminant Scavenging Mechanisms,” *J. Nanoparticle Res.*, vol. 7, no. 4–5, pp. 409–433, Oct. 2005.
- [2] K. M. Krishnan, “Biomedical Nanomagnetism: A Spin Through Possibilities in Imaging, Diagnostics, and Therapy,” *IEEE Trans. Magn.*, vol. 46, no. 7, pp. 2523–2558, Jul. 2010.
- [3] K. M. Krishnan, “Chapter 12: Magnetic Materials in Medicine and Biology,” in *Fundamentals and Applications of Magnetism*, Oxford University Press, Oxford, United Kingdom, 2016.
- [4] M. L. Taheri *et al.*, “Current status and future directions for *in situ* transmission electron microscopy,” *Ultramicroscopy*, Aug. 2016.
- [5] N. de Jonge and F. M. Ross, “Electron microscopy of specimens in liquid,” *Nat. Nanotechnol.*, vol. 6, no. 11, pp. 695–704, Oct. 2011.
- [6] T. Malis, S. C. Cheng, and R. F. Egerton, “EELS log-ratio technique for specimen-thickness measurement in the TEM,” *J. Electron Microsc. Tech.*, vol. 8, no. 2, pp. 193–200, 1988.
- [7] R. Hufschmid, C. J. Newcomb, J. W. Grate, J. J. De Yoreo, N. D. Browning, and N. P. Qafoku, “Direct Visualization of Aggregate Morphology and Dynamics in a Model Soil Organic-Mineral System,” *Prep.*, 2017.
- [8] This work was supported by the Chemical Imaging Initiative, a LDRD program at Pacific Northwest National Laboratory (PNNL). PNNL is operated by Battelle for DOE under Contract DE-AC05-76RL01830. A portion of the research was performed using the William R. Wiley Environmental Molecular Sciences Laboratory, a US DOE national scientific user facility sponsored by the DOE’s Office of Biological and Environmental Research and located at PNNL. The nanoparticle synthesis and functionalization was also supported NIH 1R01EB013689-01/NIBIB, 1R41EB013520-01, 1R42EB013520-01.

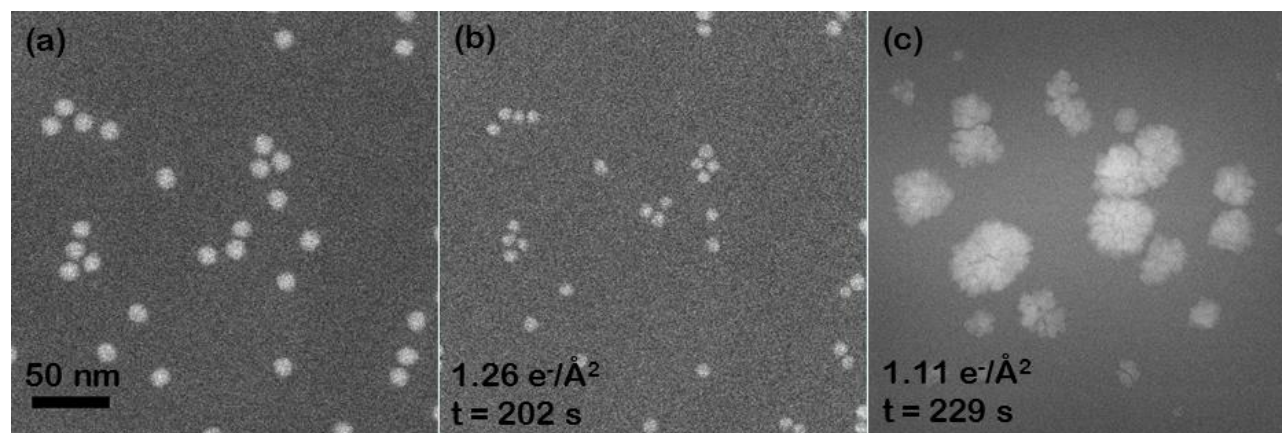


Figure 1 The surface chemistry of iron oxide (Fe_3O_4) nanoparticles mitigates interactions with solution in the TEM liquid cell. Aqueous Fe_3O_4 terminated with polyethylene glycol (PEG) (a) dissolve under prolonged exposure to the electron beam (b). However, PEG terminated particles functionalized with a poly-cationic cell-penetrating peptide grow and agglomerate (c). Scale bar is 50 nm for all images. Both (b), (c) were exposed to a total dose of $254 \text{ e}^-/\text{\AA}^2$.