Nonclassical Behaviors in Early-Stage Crystallizations

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Understanding the molecular and atomistic mechanisms underlying the synthesis, structure, and reactions of materials requires investigation at the nanoscale or below, a challenging task due to limited analytical methods capable of capturing in-situ structural information at such resolutions. Advanced in-situ transmission electron microscopy (TEM), including techniques like liquid-phase, electrochemical biasing, and cryo-TEM, offers unique opportunities to directly observe diverse chemical reactions at this scale.

In this talk, we present applications of in-situ TEM for studying nucleation, crystallization, and morphological transformations in various nanomaterials.[1] Our findings reveal multiple non-classical pathways in material formation and crystallization, including two-step nucleation, amorphous-to-crystalline transitions, and cluster coalescence.

We also introduce a novel method combining liquid-phase TEM with computational reconstruction, enabling direct 3D atomic-scale structure mapping of single particles in solution.[2] This approach allows us to link atomic structures with the functional properties of nanomaterials. Furthermore, we demonstrate how electrochemical liquid-phase TEM provides insights into key interfacial reactions between heterogeneous catalysts and electrolytes.[3] Real-time observations using liquid, gas, and cryo-TEM further extend these studies to electrode processes in various battery systems.

1) B. H. Kim *et. al.*, *Science* **2020**, *368*, 60. 2) S. Jeon *et. al. Science* **2021**, *371*, 498. 3) S. Kim *et. al. J. Am.*, *Chem. Soc.* **2025**, *147*, 7804.

