Editorial

Nonclassical Nucleation and Crystallization

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Nucleation and growth are of uttermost importance for crystallization since they determine the structure, shape, and properties of a crystal. It is therefore not surprising that these processes are already studied as long as crystallization is investigated. The first studies towards the understanding of nucleation as the relevant phase transition for the formation of a crystal were already reported by J.W. Gibbs in 1876 [1] and further developed by Volmer and Weber in 1926 [2]. In 1935, Becker and Döring derived the classical crystallization theory (CNT) for nucleation from supersaturated vapor using continuum thermodynamics [3]. This theory is based on the balance of the energy gain by formation of a new phase after nucleation and the energy loss by the formation of a new interface. CNT was further developed and improved in the following years [4,5]. Due to its simplicity and prediction power, CNT is still widely used nowadays although predictions of nucleation rates can be wrong by orders of magnitude. Crystal growth can continue after nucleation according to the classical Kossel and Stranski growth model through adsorption of growth units to the crystal surface and their subsequent migration over the crystal surface until they reach edges and kinks where their attachment is favorable [6]. That way, a layer by layer crystal growth is achieved. Burton, Cabrera, and Frank later developed the crystal growth theory through screw dislocations and spiral growth resulting in the BCF model of crystal growth [7].

However, in the last two decades an increasing number of examples were observed, which could not be explained by classical models. One example is the two step nucleation mechanism, which was observed for proteins but also organic molecules and other substances [8]. In this nonclassical mechanism, first a dense liquid phase is formed by phase separation in which a crystal grows in a second step [8]. Furthermore, the prenucleation cluster (PNC) pathway was discovered for the system $CaCO_3$ [9]. In this nucleation pathway, nucleation is not triggered by the energetic counter-play between bulk energy gain and surface energy loss such as in CNT but by a reduction in the dynamics of the involved species. In the PNC pathway, dynamic clusters form driven by entropy gain generated by hydration water loss of hydrated ions. These highly dynamic clusters are thermodynamically stable with respect to the initial ions and they are even present in undersaturated solutions where no thermodynamic driving force exists for nucleation within the classical view. The PNCs continue to lose water and reduce their dynamics thus leading to nucleation of a dense liquid phase. Further water loss eventually coupled to droplet coalescence/aggregation leads to the formation of an amorphous phase from which finally the crystal forms [10]. These nonclassical views on nucleation developed many decades later than CNT, which is not surprising since the detection of the involved very small and highly dynamic species in their native solution state is still a great analytical challenge. In addition, the role of water respectively solvent is crucial and this has often been neglected.

Not only nucleation can proceed along nonclassical pathways. Moreover, nonclassical crystallization respectively crystal growth pathways are known. For a long time, experimental observations already exist indicating that a crystal can not only grow by attachment of atoms/ions/molecules as in the classical models but also through the attachment of particles [11,12]. An important process is the formation of mesocrystals (an abbreviation of mesoscopically structured

crystals), which consist of individual nanocrystals showing crystalline short-range order together with a mutual orientation leading to very interesting materials. These can show single crystalline and nanocrystal properties at the same time and can profit from the mutual order of the nanocrystals, which can, for example, lead to the coupling of magnetic dipoles just as it is observed in the magnetite nanoparticle chains in magnetotactic bacteria [13].

Systematic and intensified research was triggered by the observation, that the formation of some crystals observed in biominerals could not be explained using the classical models of crystal growth. A mesocrystal structure was indeed found in sea urchin spines [14] or nacre [15] as two prominent examples. This shows that nature is using these advanced nanocrystal structures for mechanically strong biominerals.

However, mesocrystals were shown to be intermediates in the formation of single crystals [16,17]. They are not thermodynamically stable since they have a large internal surface so that the system can win a substantial amount of energy upon crystallographic fusion of the oriented nanoparticles through the process of oriented attachment. Oriented attachment leads to single crystals once the particles come together in an oriented way through oriented aggregation. This process could be observed in situ using high resolution liquid cell transmission electron microscopy [18]. Oriented attachment and mesocrystals offer great perspectives for future applications since they allow, for example, the bottom-up synthesis of single crystalline nanowires by oriented attachment. Mesocrystals themselves can combine the properties of nanoparticles with microscopic or macroscopic size resulting, for example, in very effective catalysts [19] or mechanically strong materials such as fracture resistant cement [20]. It is already now clear that nonclassical pathways will have an increasing importance in crystallization research, both in academia and industry, since they enable synthesizing crystalline materials with new properties and also offer powerful pathways for the structure and property control of crystalline materials such as, for example, polymorph control for pharmaceutical compounds. It will therefore be very exciting to observe this rapidly developing field with a great future potential.

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