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Insights into the Molecular Mechanism Underlying Polymorph Selection

Caroline Desgranges and Jerome Delhommelle*

Department of Chemical Engineering, 301 South Main Street, University of South Carolina,
Columbia, South Carolina 29201

Received September 30, 2006; E-mail: delhomm@engr.sc.edu

Controlling polymorphism, that is, in which structure a molecule crystallizes, still remains an unsolved problem.[1,2] Since polymorphs generally have different physical properties (e.g., solubility for a drug), understanding this phenomenon is crucial for many systems. In this work, we use molecular dynamics simulations to study the onset of crystallization in supercooled liquids of spherical particles and to shed light on the molecular mechanisms underlying polymorph selection. Our results show that we achieve polymorphism control in this simple system. By modifying the conditions of crystallization, we invert the stability of two polymorphs and form crystallites whose structure is predominantly that of the stable polymorph. However, our simulations reveal that kinetics plays a major role not only during the nucleation step but also in the growth mechanism. We show that the growth of the postcritical crystallites of the stable polymorph proceeds through a complex mechanism involving the heterogeneous nucleation of a third metastable polymorph followed by the conversion of this third polymorph into the stable structure. This mechanism is reminiscent of the phenomenon of cross-nucleation observed in experiments.[3,4] It also has significant consequences on the structure of the crystal eventually formed since the conversion of the third polymorph is not complete and remnants of the third polymorph get trapped in the crystallite.

Experiments on charge-stabilized colloidal suspensions have shown that adding a salt destabilizes the base centered cubic (bcc) structure and stabilizes the face centered cubic (fcc) structure. In simulations, we can reproduce this effect by changing the value of the dimensionless screening parameter λ for the Yukawa (screened-Coulomb) potential.[5] The expressions and system of units we use are given in the Supporting Information. We consider two systems. First, for $\lambda = 10$ and a temperature $T = 3.319 \times 10^{-3}$ (25% below the melting point), fcc is stable and bcc is metastable.[6,7] Second, for $\lambda = 5$ and $T = 2.594 \times 10^{-3}$ (25% below the melting point), we have the opposite: bcc is stable and fcc is metastable.[7] We add that for both values of λ, the hexagonal close packed (hcp) structure is metastable and that its free energy is only slightly larger to that of the fcc structure.[8]

We carry out two different types of molecular dynamics (MD) simulations, corresponding to the two mechanistic steps of nucleation and growth. We first induce the formation of a critical nucleus. We perform MD simulations together with an umbrella sampling bias potential on systems of 3200 particles. The bias potential[9] allows the system to overcome the free energy barrier of nucleation. It imposes a fixed value of the global order parameter Q_6 to the system[10] (this bias potential does not favor the formation of a specific polymorph since Q_6 takes similar values for the fcc, hcp, and bcc polymorphs). By gradually increasing the imposed value for Q_6, we are able to grow a crystal nucleus. Using local bond order parameters,[10] we analyze the structure of the nucleus. As expected from previous studies,[7,12] our simulations show that, regardless of the relative stability of bcc and fcc, nucleation proceeds into the bcc phase. This shows that kinetics predominates during the nucleation step. However, when fcc is stable ($\lambda = 10$), the fraction of fcc particles increases with the size of the precritical nucleus. We anticipate that, in this case, polymorph selection will take place during the growth step.

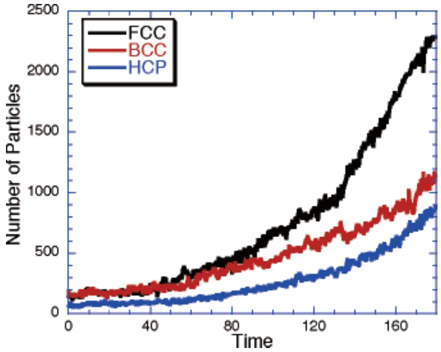

Figure 1. Evolution of the number of fcc, bcc, and hcp particles during the growth of the crystal nucleus for $\lambda = 10$ ($t = 0$ denotes the time at which the bias potential is switched off and the system starts to evolve freely).

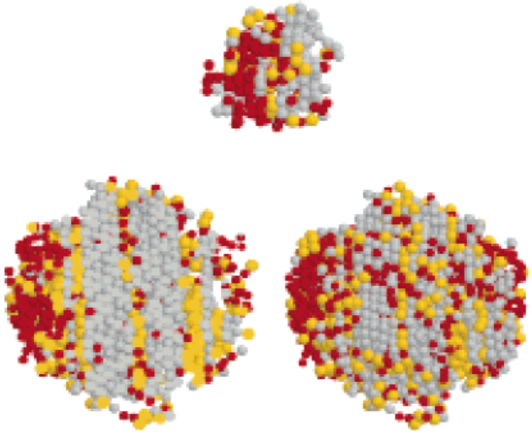

Figure 2. $\lambda = 10$: outside view of the critical nucleus ($t = 0$); cross section and outside view at $t = 160$ (gray, fcc; yellow, hcp; and red, bcc).

Once we have formed a critical nucleus, we can simulate the growth step. We proceed as in previous work.[11] The system of 3200 particles is embedded in a larger system of liquid to form a system containing 35 000 particles. After an equilibration run, we switch off the bias potential and monitor the free evolution of the crystal nucleus. We repeat this last operation 10 times and check that we have formed a genuine critical nucleus, that is, that the nucleus grows for half of the MD trajectories and dissolves into the liquid for the other MD trajectories.

We present in Figures 1 and 2 the results obtained for one of the MD trajectories for $\lambda = 10$ (all trajectories showed the same qualitative behavior). Our results demonstrate that polymorph selection takes place after the nucleation step: the structure of the

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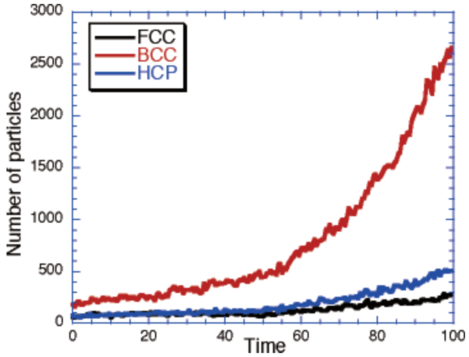

Figure 3. Evolution of the number of fcc, bcc, and hcp particles during the growth of the crystal nucleus for $\lambda = 5$ ($t = 0$ denotes the time at which the bias potential is switched off and the system starts to evolve freely).

crystallites only becomes predominantly that of the stable (fcc) structure well within the growth step. Our simulations also provide insight into the growth mechanism. Initially, the critical nucleus is composed of two blocks of different structure (fcc and bcc). At first ($t < 50$), the growth of the two blocks is sluggish and the number of fcc (N^{fcc}) and bcc (N^{bcc}) particles slowly increase (the number of hcp particles, N^{hcp}, remains constant). At $t = 50$, the growth mechanism for fcc changes: N^{fcc} starts to increase at a faster rate than N^{bcc}, and, at the same time, N^{hcp} starts to increase. For $t > 50$, fcc grows according to the following mechanism: (i) a hcp cluster nucleates on the structurally compatible (111) surface of the fcc block, (ii) fcc particles nucleate on the surface of the hcp cluster, and (iii) hcp particles gradually convert into fcc particles. The conversion is incomplete and lines of hcp particles get trapped within the cluster as shown in Figure 2. This mechanism is consistent with recent experimental evidence[3,4] of cross-nucleation, that is, of the heterogeneous nucleation of a metastable polymorph on the stable polymorph, and with simulations of the growth of a Lennard-Jones crystal.[11] On the other hand, N^{bcc} increases very slowly for $t > 50$. The bcc block, present in the critical nucleus, shows little growth (see Figure 2) and N^{bcc} mainly increases with the area of the nucleus since bcc particles are scattered on the surface of the crystallite.

The results obtained for $\lambda = 5$ are shown in Figures 3 and 4. In this case, nucleation proceeds directly into the stable bcc phase and the critical nucleus is mainly bcc. Polymorph selection already takes place during the nucleation step. Our results show that polymorph selection goes on during the growth step as the fraction of bcc particles in the nucleus keeps increasing. The growth mechanism is much simpler than for $\lambda = 10$ and remains the same throughout the growth. The core of the nucleus is almost entirely composed of the stable (bcc) particles while metastable (hcp and fcc) particles are scattered on the surface of the crystallite (see Figure 4).

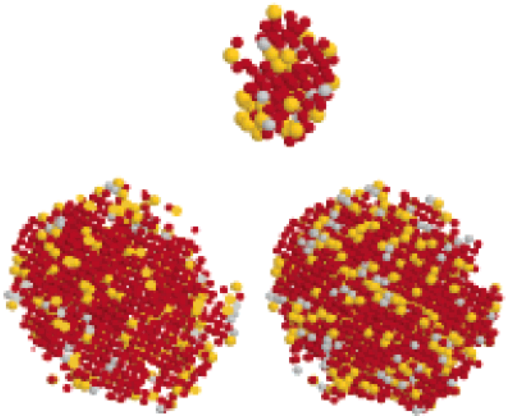

Figure 4. $\lambda = 5$: outside view of the critical nucleus ($t = 0$); cross section and outside view at $t = 100$ (gray, fcc; yellow, hcp; and red, bcc).

By modifying the thermodynamic conditions of crystallization, we have succeeded in controlling the polymorph formed during crystallization. In both cases, we form crystallites whose structure is predominantly that of the stable polymorph. However, the systems follow two very different pathways: polymorph selection takes place either during the nucleation step, when kinetics and thermodynamics favor the same polymorph, or well within the growth step in the opposite case. In the latter, we show that the growth mechanism is extremely complex. It involves the cross-nucleation of a third metastable polymorph and the subsequent conversion of this polymorph into the stable polymorph. This has important consequences on the structure and on the purity of the crystal formed since remnants of the third metastable polymorph are trapped within the crystal.

Supporting Information Available: The expressions for the Yukawa potential, the definitions for the local bond order parameters and how we use these parameters to analyze the structure of the crystal nuclei. This material is available free of charge via the Internet at http://pubs.acs.org.

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