

Collectivity and individuality of particle dispersion under gravity

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Collective motion of fine particles in liquid can be widely seen not only in engineering processes but also in natural phenomena such as water treatment [1], sediment transport [2], bio-convection [3] and lava convection [4]. It is well-known that the spatial variance of particle concentration brings about large-scale convection flow under gravity and sometimes it affects macroscopic motion of particles. In this study, of particular interest is whether collective or individual motion of particles reveals in liquid under the gravity field. The existence of concentration interface, which is an ambiguous interface between suspended particles and pure fluid, plays a significant role in these extreme behaviors.

Figure indicates the settling behaviors of stratified-suspended particles in a vertical Hele-Shaw cell filled with liquid [5]. In cases of small particle size with high concentration, the interfacial instability occurs at the lower concentration interface and the suspended particles behave as an immiscible fluid even though there is no distinct border with pure fluid [6]. Consequently the settling velocity is much faster than that of an isolated particle. On the other hand, in case of large particles with low concentration, the concentration interface is less distinct and the suspended particles settle individually. The transition from these collective to individual motions of suspended particles is controlled by the border resolution of concentration interface. We define the dimensionless parameter which describes the border resolution of concentration interface by the ratio of average particle distance $d_p/\phi^{1/3}$ (d_p : particle diameter, ϕ : concentration) to the dominant wavelength of the instability λ . As can be seen in Figure, the dimensionless parameter well describes the transition from fluid-like to particle-like behaviors. The suspended particles (and the interstitial fluid) perfectly behaves as continuum for $d_p/\phi^{1/3}\lambda < 0.03$ and behaves individually relative to fluid for $d_p/\phi^{1/3}\lambda > 0.2$ [5].

The similar collective motion of suspended particles has been studied on the settling of particle clouds in viscous fluid. Some researchers have suggested that the collective motion of particles in clouds can be explained by the swarm of Stokeslet [7]. They have found that the particle cloud behaves collectively when the flow generated by each particle (Stokeslet) enough screens the surrounding flow. If the above parameter is rewritten by number density of particles N , it is expressed as $(6/\pi)^{1/3}/N^{1/3}\lambda$. Therefore the border resolution of concentration interface express the discretization of space by Stokeslet $1/N^{1/3}$ for a given lengthscale λ .

One more interesting similarity to previous study is the wavelength of instability. From the linear stability analysis of Rayleigh-Taylor instability on both miscible and immiscible interfaces of pure fluids [8], it is found that the dominant wavelength of miscible interface with no diffusion and immiscible interfaces with no interfacial tension are asymptotically close to constant value. The wavelength at concentration interface is also close to the asymptotic value [9]. From this point of view, the concentration interface can be interpreted both as the the immiscible interface with no interfacial tension and the miscible interface with no diffusion.

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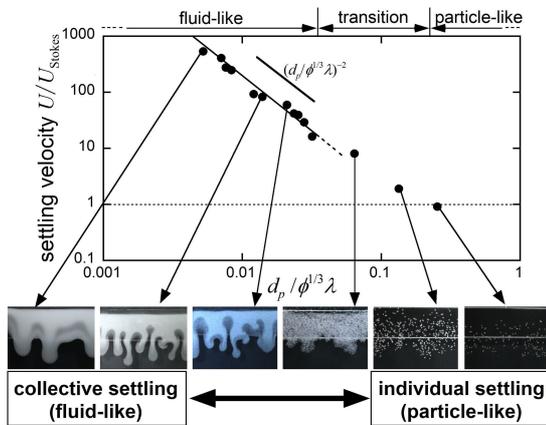


Figure 1: Collective and individual settlings of suspended particles in Hele-Shaw cell.

Reverse chemical garden reaction of cementitious materials

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Recent advances in the nano-scale mineralogy extend from the extraterrestrial materials known as in cosmic dusts and asteroids to ordinary industrial materials like the cementitious materials. The distinct property of nano materials can be characterized from the points of view of (1) nucleation, (2) self-assembly behavior and (3) flexibility in the form.

A very common industrial material, cement is a typical one consisted of nano particles of calcium silicate hydrates (C-S-H).

Crystal growth experiment of cementitious materials can be recently performed using interferometric and nanoscopic techniques. Although the cement reaction producing C-S-H from silicates with Ca(OH)₂ (portlandite: CH) or more alkaline solution is extensively occurring at buildings under and after construction, similar reaction is expected at the interface of natural rock and concrete-building such like tunnel, dam and underground repository for radioactive wastes.

Hyper alkaline alteration experiment using vertical scanning interferometer revealed the precipitation behavior of C-S-H by reverse chemical garden reaction on natural rock (Satoh et al., in press). Very slow growth rate of the C-S-H on rock was observed to be $\sim 2.4E-3$ nm/s. The ionic selection of the solutes through the C-S-H wall having nanopores like membrane was also confirmed.

Most recently, we applied newly developed ultramicroscopic technique with fluid reaction TEM (FR-TEM: Poseidon) for study of reverse chemical garden reaction between silica fume (Elkem Microsilica 940-U, ~ 150 nm) and CH-saturated solution. It revealed that the reaction caused silica hydration (volume expands) and subsequently form string and veil of C-S-H. The growth rate of string C-S-H was calculated to be $\sim 4.5E-2$ nm/s, which is fast enough to form frame network preparing veil-formation. It was chemically confirmed by FESEM-EDS that this C-S-H veil evolved toward Ca-rich over time. Our observed result could be a fundamental process of reverse chemical garden reaction, i.e., cement-solidification.

Ultramicroscopic investigation of C-S-H growths may improve the simulation of groundwater conditions in the future.

Keywords: reverse chemical garden reaction, cementitious material, C-S-H, fluid reaction TEM

General nature of liquid-liquid transition in aqueous organic solutions

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Contrary to the conventional wisdom that there exists only one unique liquid state for any material, there are growing experimental and numerical pieces of evidence for the existence of more than two liquid states in a single component substance. The transition between them is called liquid-liquid transition (LLT). LLT has attracted considerable attention because of its importance in the fundamental understanding of the liquid state. However, the physical nature of the transition has remained elusive. Particularly for water, the possible existence of LLT has special implications not only on its fundamental understanding, but also on a link of various thermodynamic and transport anomalies with critical anomaly associated with LLT. Here we reveal that 14 aqueous solutions of sugar and polyol molecules, which have an ability to form hydrogen bonding with water molecules, exhibit liquid-liquid transitions. We find evidence that both melting of ices and liquid-liquid transitions in all these aqueous solutions are controlled solely by water activity, which is related to the difference in the chemical potential between an aqueous solution and pure water at the same temperature and pressure. Our theory shows that water activity is determined by the degree of local tetrahedral ordering, indicating that both phenomena are driven by structural ordering towards ice-like local structures. This has a significant implication on our understanding of the low-temperature behaviour of water.

Keywords: liquid-liquid transition, water and aqueous solution, supercooled liquids and glasses

Direct Observation of Crystallization Process in a Solution using Transmission Electron Microscopy

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Nucleation is a fundamental event that determines the size, number and morphology of produced crystals. Therefore, the nucleation process must be clarified to form products efficiently and to predict mineralization in various environments. The direct approach to understanding nucleation would be atomic-scale in-situ observation, for which a transmission electron microscope (TEM) would be a most powerful tool. However, the experimental conditions for TEM are limited, and there have been only a few reports on the in-situ observation of nucleation processes to date. In particular, since TEM needs a high vacuum, crystallization experiments in a solution are generally impossible. Recently, the processes of formation of nanoparticles and coalescence in a solution were finally observed using specially designed cells in a TEM [1-3]. However, live observation of the dynamics of the earliest stages of nucleation - those taking place before the formation of a stable crystal - had never been achieved before our recent work [4]. We overcame the difficulty by using an ionic liquid, which has negligible vapor pressure and is not charged up by the electron beam due to its relatively high electron conductivity, and by aiming to visualize the dynamics of nucleation under conditions very close to equilibrium, where the nucleation rate must be small but the conditions for TEM observation are more stable. We used two TEMs at an acceleration voltage of 200 kV (Hitachi H-8100, installed at Tohoku University, Japan) for the nucleation experiment and 300 kV (Hitachi H-9500, installed at Hitachi High-Technologies Corporation, Ibaraki, Japan) for the in-situ heating experiment.

An ionic solution could be observed stably under normal electron irradiation conditions as expected. Nucleation of sodium chlorate crystals was directly observed in the TEM at room temperature. Then, the sample was heated up in the TEM. The main results of the heating experiment were as follows:

1. Nanocrystals were not only dissolved but also newly formed even in the totally dissolving system, i.e., probably an under-saturated condition.
2. Both stable and metastable crystals nucleated independently of their respective solubility. However, metastable crystals were dissolved in a shorter residence time.
3. The total number of smaller particles decreased with the formation of new particles by the Ostwald ripening at or near equilibrium conditions.
4. High-density fluctuations may lead to nucleation even under equilibrium conditions.

We describe the ongoing results to elucidate the dynamics of nucleation at the nanoscale, as well as the growth, coalescence and dissolution of nanocrystals in a solution.

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Keywords: Nucleation, In-situ observation, TEM, Ionic liquid

Emergence and Amplification of Chirality via Achiral-Chiral Polymorphic Transition in Sodium Chlorate Solution Growth

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Chirality is the concept that widely spreads in nature at various levels from elementary particles to morphology of plants. Although both the enantiomers have equal stability, lives on the earth preferentially selects one-type of the two enantiomers. This phenomenon is called homochirality, and its origin (the emergence of chirality) and the amplification of chirality are great puzzles in the evolution of life on the primitive earth. One candidate of the origin includes chiral crystallization of achiral compounds. Sodium chlorate (NaClO_3) undertakes chiral crystallization from achiral solution. NaClO_3 has chirality in its crystal structure due to the enantiomorphic space group of $P2_13$ (cubic). A *static* solution of the compound yields statistically equal numbers of the two enantiomorphs. However, Kondepudi *et al.* have strikingly revealed that a *stirred* solution yields only one-type of the enantiomorphs[1]. The mechanism of the significant chiral bias has not been elucidated. Diverse crystallization experiments have implied that the emergence and the amplification proceed during the early stage of crystallization. However, a direct investigation of the early stage is still missing. We therefore have carried out in-situ observations focusing on the early stage. The observations have revealed that achiral metastable crystals having $P2_1/a$ symmetry (monoclinic) appear prior to the formation of chiral crystals. The authors have reported this result in JpGU 2011[2]. Here, we present more detailed observations, and demonstrate that polymorphic transformation from the achiral phase to the chiral phase can be responsible for the emergence and the amplification.

A droplet (6 μl) of NaClO_3 aqueous solution saturated at 22 °C was put on a glass slide whose temperature is controlled at 22 °C by a Peltier device, allowing the droplet to evaporate isothermally. We observed crystallization process induced by the evaporation using a polarized light microscope. The microscope enables us to distinguish cubic crystals from non-cubic crystal by detecting birefringence, allowing us to distinguish chiral crystals from achiral crystals, and it can identify handedness of the chiral crystals by detecting optical rotation.

Polymorphic transformation from an achiral crystal to a chiral crystal was observed. The transformation could be classified into two kinds according to their transition rate. The slower one proceeds at 35 $\mu\text{m}/\text{sec}$ (Fig.A), and the faster did at 2000 $\mu\text{m}/\text{sec}$ (Fig.B). The slower transformation was induced by a contact with a chiral crystal. It is noteworthy that the resulting enantiomorph generated through the contact-induced transformation was certainly the same as the enantiomorph that contacted with the achiral crystal. The double digit difference in a rate of the two transformations is probably ascribed to difference in the mechanism, indicating the slower transformation and the fast one are solvent-mediated phase transformation (SMPT) and structural phase transition (SPT), respectively. The SPT probably generates both the enantiomorphs in equal probability since the activation energy required to transform should be equal. In contrast, the contact-induced SMPT preferentially generates the same enantiomorph as the contacted crystal. This inheritance of chirality through the contact-induced SMPT is possibly responsible for the amplification of chirality.

So far, the emergence and the amplification have been explained by primary nucleation of a chiral crystal and secondary nucleation from the crystal. In contrast, our observation provided a new sight based on the achiral-chiral polymorphic transformation: the emergence of chirality through the SPT and its amplification through the contact-induced SMPT.

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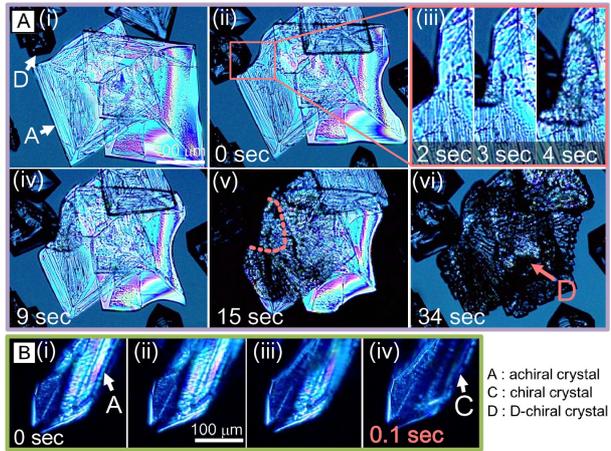
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Keywords: sodium chlorate, chiral symmetry breaking, chiral crystallization, metastable phase, polymorphic transformation, in-situ observation

MIS36-05

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Time:May 1 11:45-12:00



Theoretical analysis on the stability of divalent cations in the surface sites and clusters of calcium carbonate

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Formation process of calcium carbonate polymorphs, calcite, aragonite and vaterite has been extensively investigated, and impurity effect has been proposed as controlling phenomena in order to account for the formation of a particular polymorph. For example, it has been reported that an addition of Mg^{2+} in a solution inhibits calcite formation and promotes aragonite formation, however incorporation mechanism of this kind of impurities is poorly understood.

In general, smaller divalent cations than Ca^{2+} , like Mg^{2+} , cannot form solid solution with aragonite. However, the structure of a crystal surface or small cluster forming at an initial stage of crystal growth can be different from the bulk crystal because of its flexibility, and it can act as the site for incorporation of ions which is unstable in the bulk structure. In the present study, the stability of divalent cations, especially Mg^{2+} , (1) on hydrated aragonite surface and (2) in the cluster forming in an early stage of nucleation was investigated by quantum-chemical calculations, and the impurity effects on the formation of polymorphs were discussed.

The calculation results show that Mg^{2+} is easier to be incorporated into a small cluster, while the hydration energy of Mg^{2+} is higher than that of other divalent cations. This indicates that Mg^{2+} is difficult to be released from hydration shell, however, once released, it is easy to incorporate into the cluster. Atomic arrangement of these clusters including Mg^{2+} is different from that of additive-free $CaCO_3$ clusters. Furthermore, Mg^{2+} on the aragonite surface considerably affects the surface structure and has an influence on the stability of aragonite. Thus, incorporation of Mg^{2+} into the clusters and surfaces sites should play an important role on the formation of the crystalline nuclei and the consequent crystal growth.

Keywords: calcium carbonate, impurity, crystal growth

Atomic scale in situ observation of solid-liquid interface of calcite

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Calcium carbonate is one of common minerals on the earth. Calcium carbonate crystals are utilized industrially in various fields, so that the control of crystal growth is required. It has been known that organisms control the morphology and polymorph of calcium carbonate crystals by utilizing inorganic and organic additives in biomineralization. Understanding the additive effects on growth of calcium carbonate crystal is necessary to control the crystal growth.

The effect of additives on growth of calcite which is a stable polymorph of calcium carbonate has been investigated. The additive effect on calcite surface, such as incorporation of magnesium ions into calcite and pinning of step propagation by organic molecules has been confirmed. On the other hand, the additive effect on hydration of calcite has remained unclear even if that effect has been suggested by the measurement of growth rate of calcite in the presence of additives. Hydration affects adsorption and surface diffusion of ions on calcite surface. Also, the dehydration has been considered as rate-determining process in solution growth by the estimation of energy barriers of solution growth processes. Therefore, hydration is a key to control the kinetics of calcite growth.

Hydration at the vicinity of calcite surface has been measured by surface X-ray diffraction. Although this technique made the description of hydration structure clear, it does not show the local difference of hydration structure between on the terrace and the step front which is capture site of ions. Hence, we employed the newly frequency modulation atomic force microscopy (FM-AFM) for in situ observation of local hydration structure in atomic scale. This technique is expected to provide insight into the atomic scale distribution of hydrated water molecules in growth solution even at step front. This study describes the first in situ examination of the additive effect of organic molecules and magnesium ions on local hydration structure of calcite surface in atomic scale utilizing FM-AFM. The hydration images were compared with the growth rate of calcite measured using phase shift interferometry so as to validate the influence of hydration on the growth rate of calcite.

The findings are summarized as follows:

- (1) The synthetic polypeptide, even that with high hydrophilicity, does not affect hydration at the surface of calcite.
- (2) Combination of magnesium ions and the synthetic polypeptides provides a rigid hydration on calcite surface.
- (3) Magnesium ions and the synthetic polypeptides influence hydration and the surface pattern of calcite, respectively.
- (4) Structured water distribution eases the energy gap between the calcite surface and solution. As a result, the interfacial tension between the calcite surface and the solution is decreased.
- (5) Magnesium ions and the synthetic polypeptide act in unison to accelerate nucleation via changes in hydration structure.
- (6) Hydration contributes to interfacial energy between the calcite and the solution, but not for the adsorption of ions on the calcite steps.

This study demonstrated that additives affect the interfacial tension via altering hydration structure by application of FM-AFM for crystal growth experiment for the first time. Our results also showed that there is hardly any change in the adsorption of ions on calcite surface due to the hydration structure. That suggests that dehydration is not a rate-determining process, an observation that is contrary to the currently prevailing theory. The further observation of hydration of step front will be carried out by FM-AFM to demonstrate the effect of hydration on adsorption of ions. These findings indicate that the control of interfacial tension is possible utilizing the additive effect on hydration. That provides a new knowledge to regulate the polymorphism of calcium carbonate.

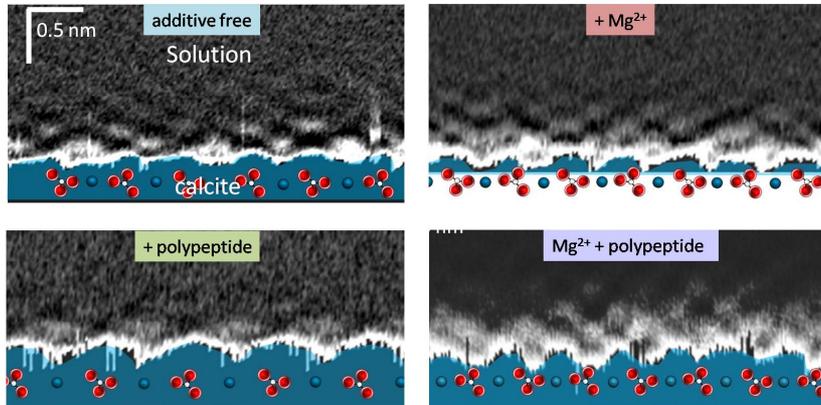
Keywords: Calcite, Hydration, FM-AFM

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Time:May 1 12:15-12:30

FM-AFM images of Hydration structure on calcite



Impurity partitioning in colloidal crystallization

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Colloidal crystals are regarded as a promising tool to investigate diverse basic physical phenomena. We have applied this colloidal crystal to impurity partitioning in the melt growth. Since no research has been focused to detail partitioning behavior of colloidal crystals, the objective of the present work is to reveal a partitioning behavior during colloidal crystallization.

A few amount of impurities (2 percent) were doped to the colloidal dispersion, from which colloidal crystals were grown with convective assembly method. Polystyrene particles (PS) were used for fabricating colloidal crystals, and different sizes of PS and fluorescent bearing PS (w/fluor.) were doped as impurity particles.

In each particle size for two kinds of impurity, effective partition coefficient (k_{eff}) were measured at various growth rates. Obtained k_{eff} gives k_0 by using BPS plot. The k_0 is decreased as the difference between the size of the impurity and the 500 nm host particle increased. The k_0 of each w/fluor. was larger than that of the corresponding pure PS. Moreover, the value of k_0 for the 520 nm w/fluor. surpassed unity, whereas the PS is always less than unity.

We have employed a Thurmond and Struthers (T&S) model (J. Phys. Chem. 57, 831 (1953)) to discuss the difference of k_0 for PS and w/fluor. particles. T&S model shows k_0 as; $k_0 = \exp((\Delta G_{Tr} - \Delta H)/RT)$. Here, ΔG_{Tr} is free energy difference between the solid and liquid phases of an impurity at the transition temperature, T, ΔH is the excess enthalpy which is caused by incorporation of the impurity into the host material, and R is a gas constant. We have determined the phase transition volume fraction for PS and w/fluor. to evaluate the ΔG_{Tr} . It was shown that ΔG_{Tr} of w/fluor. is positive whereas PS is zero. This leads to larger $\Delta G_{Tr} - \Delta H$ of w/fluor. than that of PS, which corresponds to larger k_0 of w/fluor., and in a small $-\Delta H$ range, k_0 of w/fluor. surpasses unity. We have found the difference of k_0 for different kinds of impurity particles, and succeeded in applying concept of T&S model to partitioning of colloidal crystals.

Keywords: Colloidal crystal, Impurity partitioning

Mechanism of ice nucleation on (100) plane of calcium oxalate monohydrate: a molecular dynamics simulation study

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Calcium oxalate monohydrate (COM) is the most thermodynamically stable polymorph of calcium oxalate. COM is known as an organic mineral formed on the surface of the Earth, under the bottom of sea, in atmosphere, in meteorites, in plants and in kidney stones. So far, COM has been studied in fields of mineralogy, biology and medical science.

Recently, Ishikawa et al. suggested that COM plays as an ice nucleation promoter, like silver iodide and ice nucleation-active bacteria. They speculated that the structure of COM (100) plane induces ice nucleation. Studies on the mechanism of ice nucleation promotion by COM are important, because the studies may help provide development of new materials to make artificial snow. Molecular dynamics (MD) simulation is a helpful method to investigate the mechanism of ice nucleation at the molecular scale. Thus, we performed a MD simulation to elucidate the mechanism of ice nucleation on the (100) plane of COM.

In the simulation, the intermolecular interaction between a pair of water molecules was estimated using a six-site model. The water-COM interaction was estimated using a COM potential model proposed by Tommaso et al. In the <100>direction of COM, two different molecular layers are piled up by turns; one is positively-charged Ox-1 layer consisting of calcium ions and oxalate ions, and the other is negatively-charged Ox-2 layer consisting of oxalate ions and water molecules. In this study, the simulation was performed for a rectangular parallelepiped system in which supercooled water consisting of 4000 water molecules was sandwiched by Ox-1 and Ox-2 layers. Temperature was set to 268 K. Total run was 4 ns or longer. The simulation indicated the formation of a polar cubic ice structure near the Ox-2 layer. However, the formation of a hexagonal ice structure was not observed. Details of the simulation results will be shown at the presentation.

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Keywords: crystal growth, nucleation, ice, organic mineral, computer simulation, calcium oxalate

Observation of admolecule on the crystal surface in liquid by non-contact atomic force microscopy

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The highest resolution AFM images are obtained by non-contact atomic force microscopy (NC-AFM). Fukuma et al. (2005) succeeded in obtaining true atomic resolution images by NC-AFM in spite of the liquid environment [1]. We are interested in the crystal growth process. However, previous NC-AFM studies were only about insoluble crystals in liquid. NC-AFM is not good at investigating the moving surface because NC-AFM is a very sensitive method for detecting weak interaction force. Therefore, we tried to observe several soluble crystals in liquid by NC-AFM at first.

At first, we observed tetragonal lysozyme (110) face in saturated solution by using homebuilt Non-Contact AFM (NC-AFM). We could observe individual molecules on the lysozyme (110) face in liquid for the first time and determine the crystallographic position of each molecule [2]. In addition, we also observed admolecule and point defect on the lysozyme surface in liquid.

Acknowledgments

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Keywords: AFM, Crystal growth, Atomic resolution image, Admolecule, Protein crystal

In-Situ Observation of Protein Crystal Growth in The International Space Station

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In-situ observation of protein crystal growth was conducted at the international space station in 2012. Both growth rate and surface topography of lysozyme crystals vs supersaturation and purity of the solution were measured for the first time by interferometry in space. The differences from ground-based experiments became clear to answer the question "Why better crystal could be grown in space?".

Keywords: crystal growth, space experiment, microgravity

In situ simultaneous SEM/STEM observation of Pt/C catalysts in a gaseous atmosphere

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In order to gain fundamental understanding of the degradation mechanisms of Pt/C catalyst, there is an increasing demand on the nanostructural characterization using TEM. We have developed the humid-air supply system in TEM, H-9500 300 kV TEM and we have success the deterioration mechanism of fuel cell electrocatalyst¹. Recently, we developed in situ simultaneous SEM/STEM observation technique for surface analysis of catalyst materials using a HF-3300 Cold-FE TEM with SEM/STEM function. We succeeded in visualizing of three-dimensional movement of the Pt particles on the carbon support in the gas atmosphere by this observation technique.

In situ simultaneous SEM/STEM observation of the platinum catalysts on carbon support (Pt/C; Pt: 29 wt.%) in the air conditions were carried out using HF-3300 equipped with the Cold-FE gun and the SEM/STEM function. A gas injection-heating specimen holder² was used for the Pt/C powder heating and gas injection. Pt/C powder mounted on the tungsten wire was heated to 200 deg C in a TEM, and then, while air was spraying (up to 1.2×10^{-2} Pa) from the injection nozzle to the Pt/C, the behavior of the Pt/C was recorded as the movie file. After the air injection at about 1.0×10^{-3} Pa, the coalescence growth between Pt particles on the carbon support was observed, and the Pt particles gradually started inserting into the carbon support. After that, most all of the Pt particles on the carbon support disappeared from the surface of the carbon support. And the carbon support structure was changing into a porous morphology.

We can observe that the behavior of the Pt particles on the carbon support was penetrated into the carbon support by in situ simultaneous SEM/STEM observation. These results demonstrate that the penetration of Pt particles to carbon support affects the degradation mechanism of a Pt/C electrocatalyst.

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Keywords: electron microscope, in situ observation

Low temperature crystallization of free-flying silicate nanoparticles investigated by in-situ IR measurement experiment

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Dust is typically 100 nm sized nanoparticles which can be observed ubiquitously in the universe. Dust forms from the high temperature gas in the out flow of evolved stars and dispersed into interstellar space. Silicate dust is one of the most abundant minerals in the universe including, shells around evolved stars [1], disks around young stars [2], comets [3] and so on. So its formation mechanism is the key process to understand the lifecycle of dust. Especially, 10 μm IR band structure from 8 μm to 12.5 μm in wavelength arising from Si-O stretching provides us mineralogical character of silicate. The Infrared Space Observatory mission revealed the existence of crystalline silicates around evolved stars based on the 10 μm band feature mainly attributed to amorphous silicate [4]. Numerous laboratory experiments to reproduce the observed spectra such as direct condensation [e.g. 5] and annealing of amorphous silicates [e.g. 6] showed variation in the IR spectra due to structure, chemical composition, temperature, size and shape, and proposed formation mechanisms of crystalline silicates. Nevertheless the scenario is not fully understood. One of the most important discrepancies concerning the dust formation process is a detection of an IR feature attributed to crystalline silicates at low temperature region, typically <300 K [1] in contrast to amorphous silicates at high temperature region [4]. Low temperature crystalline silicates cannot be explained by direct condensation or annealing involving high temperature process.

Recently, we have investigated new IR measurement technique for free-flying nanoparticles which enabled direct comparison with astronomical observation without KBr medium effects which pervert its band structure such as peak wavelength, FWHM and relative intensity [7]. Applying the new IR technique, we investigated condensation of Mg-bearing silicate from thermally evaporated magnesium and silicon oxide under the atmosphere of O₂ and Ar based on 10 μm band.

In-situ IR measurement revealed initial condensates were amorphous or droplet of Mg-bearing silicate and its crystallization took place at <500 K. Furthermore, crystallization kept proceeding through lower temperature region. Produced particles showed core-mantle like structure, amorphous silica covered with polycrystalline forsterite observed by Transmission Electron Microscope.

Prevailing annealing experiments reported that 1000 K is required for crystallization of forsterite [8]. This critical discrepancy may be explained by nano size effects. When immoderately small particle nucleates, a particle takes metastable amorphous or droplet phase because of lower melting point of a nanoparticle [9] and larger diffusion coefficient of molecules in a nanoparticle distinct from in bulk [10]. In case the condensates were droplet due to the size effects, activation energy of crystallization is significantly low compared to amorphous [11]. We concluded such characteristic phenomena in nanometer scale enabled low temperature crystallization in the same way as the circumstellar environments.

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Free energy of cluster formation and a new scaling relation for the nucleation rate

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Recently we performed molecular dynamics (MD) simulations of homogeneous nucleation from vapor for systems of $(1-8) \times 10^9$ Lennard-Jones atoms [Diemand et al. J. Chem. Phys. 139, 074309 (2013)]. The very large MD simulations allow us to determine the formation free energy of clusters accurately over a wide range of cluster sizes, for the first time. This is now possible because such large simulations allow for very precise measurements of the cluster size distribution in the steady state nucleation regime. The peaks of the free energy curves give critical cluster sizes, which agree well with independent estimates based on the nucleation theorem. Using these results, we derive an analytical formula and a new scaling relation for nucleation rates: $\ln J' / \eta$ is scaled by $\ln S / \eta$, where the supersaturation ratio is S , η is the dimensionless surface energy, and J' is a dimensionless nucleation rate. This relation can be derived using the free energy of cluster formation at equilibrium which corresponds to the surface energy required to form the vapor-liquid interface. At low temperatures (below the triple point), we find that the surface energy divided by that of the classical nucleation theory does not depend on temperature, which leads to the scaling relation and implies a constant, positive Tolman length equal to half of the mean inter-particle separation in the liquid phase.

Keywords: nucleation, molecular dynamics simulation, nucleation rate, scaling, free energy of cluster formation