Chapter 3

Scientific Vision for the Upgraded SPring-8

3.1 Comprehensive study of hierarchy in material and biological systems

3.1.1 SPring-8 II illuminates hierarchy and inhomogeneity

In material and biological systems, the hierarchy of structures is closely related to the function of these systems. To elucidate the relationship between the hierarchy and the function, the upgraded SPring-8 will play a vital role: coherent X-ray diffraction microscopy will allow imaging with a variable spatial resolution and field of view, and real-time observation with a variable temporal resolution will allow tracking the temporal development of systems with different characteristic time scales. In this chapter, we present the typical scientific targets for the study of hierarchical organization in systems, which are expected to be of great scientific importance and would be resolved using the upgraded SPring-8 facility in the next twenty years. We address most effective experimental techniques required at SPring-8 II for such scientific research.

All kinds of organisms, organic and inorganic materials have a certain degree of internal organization that is characterized by specific space and time scales. A good example is human body, in which various biological functional units are hierarchically organized, as shown in Fig. 3.1. All biological phenomenon such as thinking, sleeping, walking, eating, and so forth, are the results of combined functions of relevant organs such as brain, muscles, gastrointestinal tract etc. The functions of each organ also result from the combined functions of cells composing each organ. The cell functions are manifestations of functional collaboration of subcellular organelles and macromolecules. It is a simplified view of hierarchical layers in human body.

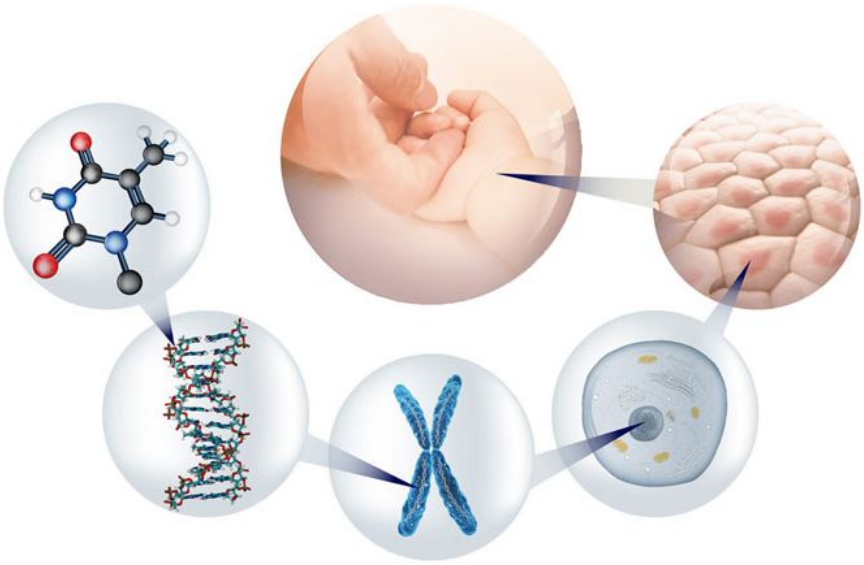

Figure 3.1: An example of hierarchy existing in the human body.

In addition, the layers do not function independently; even in a biological phenomenon there are dynamic and spatiotemporally regulated flows of inter- and intra-layer signals which allow the layers to function in a collaborative manner. Major entity of the dynamic flow of signal is a flow of molecules, such as ions, organic small molecules, macromolecules, and so forth. One of the essential contributor for the regulation of molecular flow of signal is proteins. Proteins themselves are belonging to a layer whose function is controlled spatiotemporally by other layers. Behind a biological phenomenon, there are many hierarchical layers interacting each other with spatiotemporal regulation. Therefore the major targets for biological science in the next two decades would be the understanding of the spatiotemporal collaboration of the layers behind a biological phenomenon and the clarificaion of dynamics and functions of each layer with subatomic resolution.

Inorganic materials are another example. Atoms and molecules correspond to the fundamental building blocks of materials. However, the nature of individual atoms and molecules is not always observable in matters at the macroscopic level. Actually, many layers of structural and functional units interact between the atomic and macroscopic scales. This hierarchy essentially contributes to the emergence of a wide variety of macroscopic properties of materials. A typical example could be seen in phase transition phenomena, one of the most fundamental but unresolved problems in physics. The general mechanism of phase transition could be studied using a hierarchy model: fluctuation of the electronic states–nucleation–clustering–macroscopic transition. To observe the spatial and temporal development of these hierarchical structures, which appear during the phase transition process, would be an exciting scientific topic using the SPring-8 II facility. This observation would greatly contribute to the comprehensive study of

the changes of physical properties caused by the phase transition. There are dozens of important topics such as high-Tc superconductivity, strongly correlated systems, quantum ordering. Additionally, in SPring-8 II, we could study systems in excited or non-equilibrium states, while those in ground or equilibrium states have been studied so far. When a material (or a device) exhibits some function, the system is in an excited or non-equilibrium state and this state evolves over a characteristic time scale.

The ultimate goal in material and biological science is the complete understanding of the hierarchies within systems, in other words, to explain the relationship between the activities and the functions at the top-level of a hierarchy and the properties of all the lower levels within the systems. This approach requires knowledge of the spatial and temporal structures at all the levels within a hierarchy. Using experimental techniques currently available, only a few particular levels of hierarchies could be studied. SPring-8 II offers new techniques for the seamless observation of these hierarchical structures, allowing a comprehensive understanding of the physical and biological phenomena. In the following subsections, we propose scientific subjects, unresolved today, where understanding the hierarchy of the system is an essential key and the upgraded SPring-8 would be a best suited facility for the research.

3.1.2 Static and dynamic structural biology

The minimum unit of life is a cell, which is separated from the outer space by lipid bilayer. Inside of the cell, there are various biological systems responsible for the fundamental activity of life, for instance, energy production, maintenance and duplication of genomic information on DNA, transcription of DNA into RNA, protein synthesis and so forth. Between the cells, there are inter-cellular signal transduction systems which are indispensable for functional unity of the biological body as a multi-cellular assembly. All of these biological systems are driven by biological macromolecules, such as a protein and a nucleic acid, whose function accompanies a dynamical motion, and sometimes accompanies a spatiotemporal cooperation of many biological macromolecules. To reveal the dynamical functions and collaboration of the biological macromolecules is one of the most attractive research areas using SPring-8 II, because it would help us to deeply understand the activities of life.

So far, synchrotron radiation has played an important role to study the three-dimensional structure of macromolecules by using X-ray crystallography. At present, only the static information is available using crystallography. The structure of biological macromolecules, however, helps us to clarify the mechanism of biological phenomenon with an atomic resolution. Highly brilliant synchrotron radiation boosted the throughput of the structure determination. The knowledge about the relationship between the structure and the function of biological macromolecule is accumulating rapidly, which results in the discovery of various useful drugs.

One example is G-protein coupled receptor (GPCR), which is the major target of the cur-

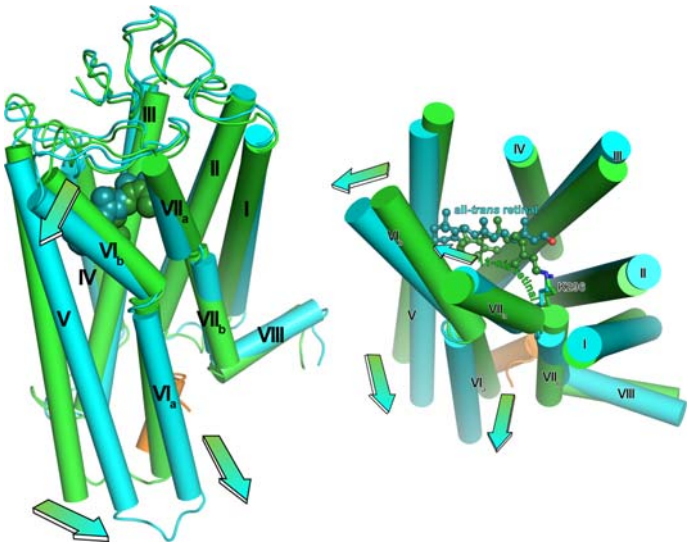

Figure 3.2: The structural comparison between the inactivated and activated states of rhodopsin as a G-protein coupled receptor (GPCR). The inactivated rhodopsin with 11-*cis*-retinal functioning as the inverse agonist is shown in green and the activated one with the all-*trans* retinal is shown in blue. Roman number shows the sequential number of α-helices from the N-terminal. The crystal structures provide the insight to the activation of rhodopsin essential for the eyesight. The structural change of retinal depending on photoreception induces the rearrangement of the transmembrane α-helices, resulting in the formation of the space for binding of the C-terminal part of Gα-protein (orange).

rently approved medicines [1]. The first crystal structure of GPCR was determined at SPring-8 one decade ago [2], and provided many insights into the signal transduction mechanism by GPCR (Fig. 3.2). After that, appearance of micro-beam MX beamlines, as well as development of techniques to improve the thermal stability of GPCR, has contributed to the structure determination of human GPCR, such as β_2 adrenergic receptor, A_{2A} adenosince receptor, chemokine receptor CXCR4, histamine H1 receptor [3–12]. Now, pharmaceutical companies are tackling to develope new drugs by using the structural information of GPCR [13, 14].

Since, there are still a lot of biological macromolecules whose structure is attracting researchers' interest from both scientific and applicative view points, the static structural study of biological macromolecule would definitely occupy one of the major area of synchrotron radiation research in the next few decades. Highly intense X-rays available at SPring-8 II would enable the structure determination using sub-micron crystal, and boosts the structure determination of challenging targets.

On the other hand, the direct and continuous observation of the structural transformation of biological macromolecule at atomic resolution has been the dream in the structural biology, because such a transformation is closely related with the dynamic function of the biological macromolecules (Fig. 3.3). Currently we need to imagine the dynamical motion of macromolecules

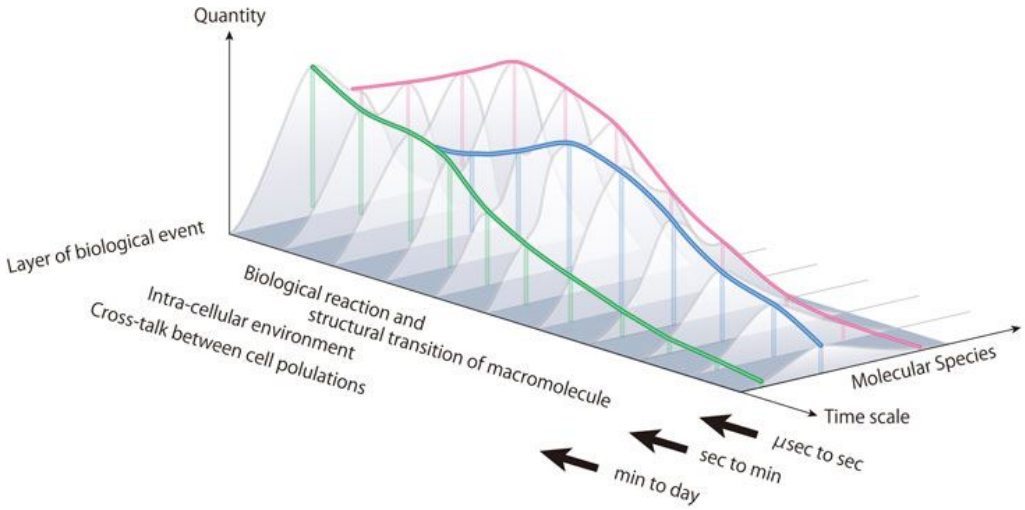

Figure 3.3: Dynamics of biological event. Life is composed of dynamic and layered biological events interacting closely each other and also having different time scale and spatial size. There must exist an optimized time and spatial resolution for observing each event. Such optimization would be easy using the upgraded SPring-8.

based on the stable intermediate state which appears in the time course of the structural transformation. For instance, the structural transformation of the calcium pump of sarcoplasmic reticulum, responsible for the ATP dependent Ca^{2+} transport, was determined at atomic resolution [15–17]. Another example is the molecular mechanisms of the pathogenesis of myopathy which were studied by means of the X-ray diffraction experiment of human muscle cells under different conditions at SPring-8. This study elucidated the effects of the myopathy-linked point mutation [18]. As such, the direct and continuous observation during the structural transformation would deepen our understanding of dynamical functioning of biological macromolecules.

The direct and continuous observation is also important for the understanding of the whole spatiotemporal collaboration of biological macromolecules driving the biological system. It would be an ambitious target for understanding the life in a comprehensive way (Fig. 3.4). The so-called "system biology" is a research area by which the whole map of the spatiotemporal collaboration of biological macromolecules could be described from the viewpoint of the gene expression. However, the spatiotemporal collaboration of biological macromolecules has been hardly studied from the structural aspect due to the technological difficulty. The direct and continuous observation of dynamical assemble/disassemble of macromolecules is informative even at low resolution to understand the collaboration of biological macromolecules. For example, the continuous small angle X-ray scattering measurement of the solution structure revealed that the periodic structural transformation of KaiC with a 24-hours cycle is the timing cue of the association/dissociation of other clock protein KaiA and KaiB [19]. These information were

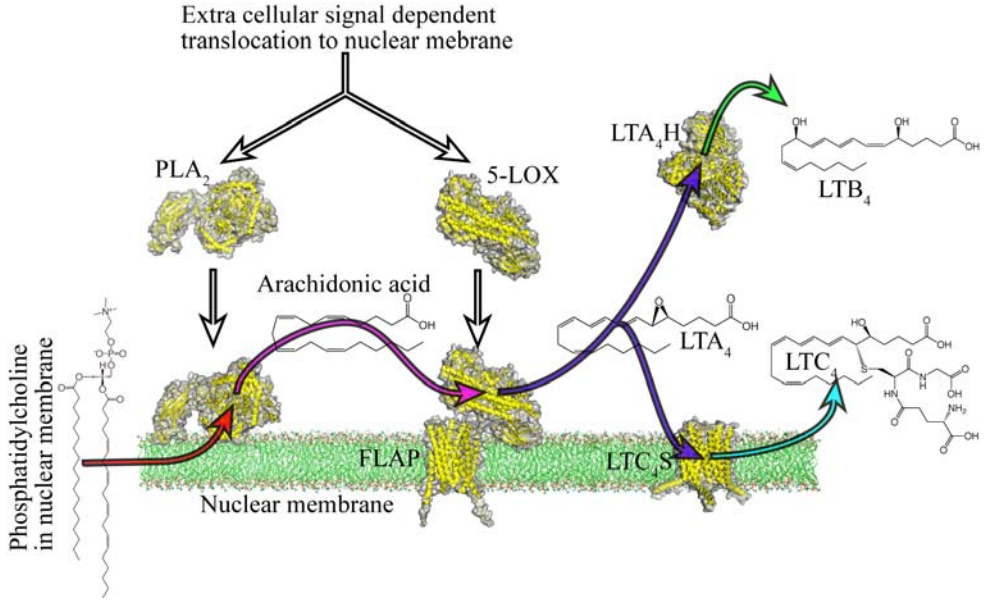

Figure 3.4: Spatiotemporal collaboration on the production of leukotrienes. Spatiotemporal collaboration of five proteins, that is, phospholipase A_2 (PLA_2); 5-lipoxygenase (5-LOX); five lipoxygenase activating protein (FLAP); leukotriene A_4 hydrolase (LTA_4H); leukotriene C_4 synthase (LTC_4S) produce leukotriene (LT) B_4 and LTC_4 as proinflammatory lipid mediators. The static structures of the proteins with an atomic resolution are available, but there is limited structural information on how structural transformation of the protein and the substrate proceeds during the catalysis and how the proteins collaborate to transport hydrophobic and reactive small molecules. Direct and continuous observation would make a definite contribution to solve these questions.

not detected by the static structural analysis until today.

The ultimate light from SPring-8 II with 1,000 times higher brilliance than the present SPring-8, and consecutive pulses with duration time of a few picoseconds would be suitable for the direct and continuous observation of biological event. It enables time-resolved Laue diffraction analysis using 2D or 3D micro-crystals, where a small size of the crystal is preferred in order to synchronize the biological events taking place inside. It also enables time-resolved solution scattering with a higher time resolution than currently available. The X-ray free-electron Laser (XFEL) facility, SACLA has a great advantage to provide the femtosecond snapshots of the biological systems, but it is difficult to observe the biological events continuously. SPring-8 II will compensate this point, and the combination of SPring-8 II and SACLA would be powerful for comprehensive understanding of life, and would contribute to the welfare of humankind through the various by-products such as the novel drugs.

3.1.3 Higher-order structures of relaxor ferroelectric

Materials science have been exploring the way to explain the properties of macroscopic materials on the basis of atoms and molecules, which are the smallest building blocks of materials. There are two extremes in this view. One is crystalline materials consisting of infinite regular array of atoms. The other extreme is amorphous materials in which atoms are uniformly distributed without periodicity. However, recent progress in materials science has revealed that intrinsic inhomogeneity or higher-order texture which connects the macroscopic materials and atoms often plays a significant role in the appearance of characteristic properties of materials. The higher-order structures sometimes show temporal fluctuations which are particularly prominent near the phase transition temperature. Such spatial or temporal fluctuations have already been studied in non-crystalline soft materials using coherent small angle X-ray scattering because the relatively large domain size and slow dynamics characteristic to soft materials fit the brilliance of the third-generation synchrotron light source. On the other hand, for the study of higher-order structures of crystalline materials, measurements at a large scattering angle is necessary in the geometry of Bragg diffraction rather than in the forward scattering. This leads to a demand for higher brilliance than that available with the existing light source.

A typical example of crystalline materials in which nm-scaled higher-order structures are important is found in a class of materials called relaxors. Since their discovery in 1958 [20], relaxors have attracted much attention both for their general scientific interest and technological importance. Relaxors are characterized by giant ferroelectric and piezoelectric responses, gentle temperature dependence of the dielectric susceptibility, and a distinctive dielectric relaxation in a low-frequency region. For the appearance of these complex dielectric properties, the intrinsic inhomogeneity of relaxors plays an essential role. From the structural viewpoint, the inhomogeneity of relaxors is originated from deeply buried domain structures. In the largest case,

relaxors show mm-sized domain structures observable with an optical microscope. Although each single domain is uniformly polarized, all the domains are randomly oriented to each other in the absence of external fields. The macroscopic ferroelectricity is achieved by the uniaxial orientation of the polarized domains complying with the applied electric fields. However, each domain that looks uniform at the mm-scale turns out to consist of many micro domains by observations at higher magnifications. These nested structures could eventually come down to atomic-scale polarization within a unit cell, through organization at the nm-scale. Generally, there is a scalable relationship between the spatial size of domains and the characteristic frequency of their dynamics. As the frequency of external electric fields is lowered, domain structures with a larger length scale start to contribute to the macroscopic dielectric response and thus lead to the giant ferroelectricity. Moreover, nonlinear ferroelectric responses shown by relaxors imply the presence of complex interplay between the domain structures belonging to different length scales [21]. Therefore, studying the higher-order domain structures and revealing the interaction among the buried domain structures are critical for understanding the complex ferroelectric properties of relaxors.

So far, inhomogeneous structures within relaxors have been studied by X-ray and neutron diffuse scattering methods [22] whereas inelastic scattering methods of neutrons and X-rays have been employed for the study of their dynamics on various time scales [23,24]. Beyond the existing techniques, coherent X-ray diffraction microscopy and X-ray photon correlation spectroscopy, by a highly brilliant light source, enables direct observations of higher-order domain structures and their low-frequency dynamics, respectively.

The roles of the higher-order structures are not limited to the ferroelectricity of relaxors. High magnetic resistivity of manganese oxides [25], shape memory effects of martensitic alloys [26] and superconductivity of high-T_c cuprates [27] also require explanation based on structural information bridging between the nanometer and micrometer scale rather than atomic scale structures within a unit cell. Further understanding of such complex materials strongly relies on the development of coherent X-ray diffraction microscopy, which widens the range of accessible spatial and temporal scales.

3.1.4 Nucleation and clustering

Nucleation and clustering are dynamic processes in which a state in a lower level of organization evolves into a more complicated structure. This is a universal phenomenon observed in a variety of systems including phase transition and crystallization. The cluster formation is sometimes energetically more favorable than uniform structures as seen in spontaneous formation of crystalline clusters in supersaturated solution. In other cases, clustering appears as a transient state from a stable uniform phase to another, for example, during a structural phase transition induced by temperature. So far, this process has mostly been described by macroscopic param-

eters, such as the total energy and diffusion coefficient. In such a mean-field model, however, important characteristics of clustering phenomena are unsatisfactorily described. In an atomistic view, clustering is initiated by nucleation whereby an initial distribution of stable nuclei is formed from the minimum number of diffusing units. After this stage, the clusters grow in size by adsorbing atoms or molecules on their surface from the environment. When the materials in the environment are nearly depleted, the average size of the clusters increases through coalescence of smaller clusters. Dynamical observation of the entire process from the nucleation in nm scale to clustering in larger scale has long been of great scientific interest and is still a challenging issue in modern materials science.

Clustering looks as if it were a one-way process on a macroscopic scale because of the huge number of atoms that are involved. On the atomic scale, however, structural fluctuation should be prevalent since the elemental processes of adsorption and desorption are reversible (see Fig. 3.5). Recently, dynamic scaling of fluctuation during the phase separation in a sodium borosilicate glass [28] and the development of long-range ordered phase out of a disordered Cu_3Au alloy [29] have been demonstrated using a third-generation X-ray source. With the increasing brilliance of the X-ray source, initial nucleation process prior to clustering in bulk would become accessible. At this stage, interesting phenomena, such as magic clusters having a preferred size [30] and bcc cluster in liquid fcc metal [31], are suggested. Dynamical feature of these initial nuclei is an open issue. The dynamics of nucleation and clustering would be more complex and profound for low-dimensional systems than for three-dimensional bulk because of the increased degree of freedom [32]. For example, on a surface, both three-dimensional clusters and monolayer islands could exist whereas the exchange of material amongst clusters is limited to two-dimensional surface diffusion. Since the atoms and the molecules always enter and leave the materials through their surfaces or interfaces, the dynamics of surfaces or interfaces is an important issue to understand and control physical and chemical phenomena occurring during the catalytic reactions, electrochemistry and crystal growth. Considering that the signals from the surfaces or interfaces is several-orders of magnitude weaker than those from the bulk matters, a highly brilliant light source would be required for promoting the re-

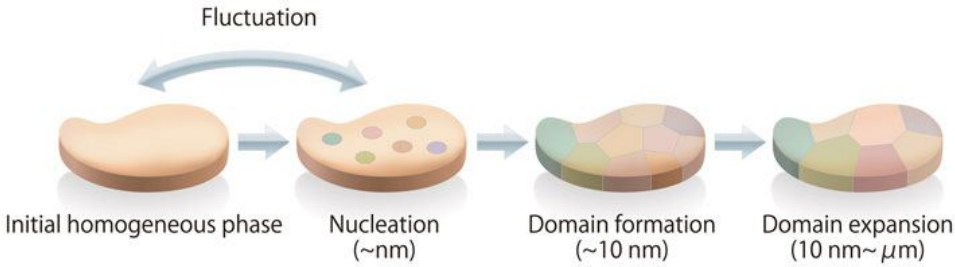

Figure 3.5: The schematic illustration of model for phase transition phenomenon.

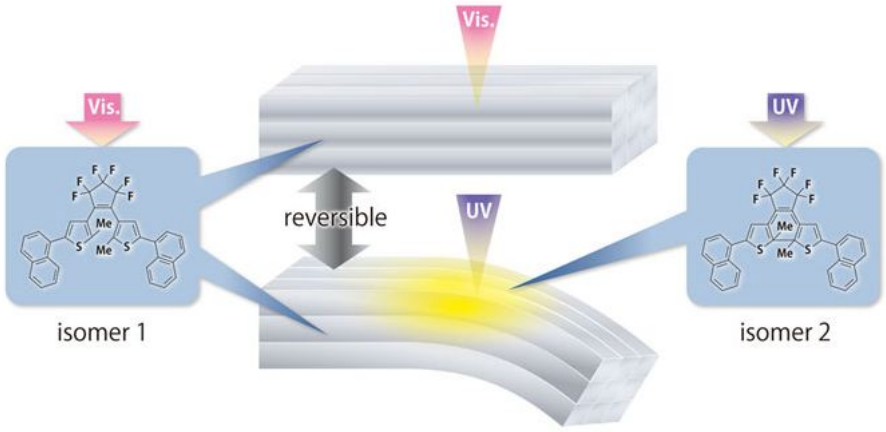

Figure 3.6: Plastic deformation of co-crystal of diarylethene by light irradiation

lated research using the time-resolved coherent X-ray diffraction microscopy or X-ray photon correlation spectroscopy [33].

3.1.5 Photochromism of functional organic materials at the molecular level

Organic materials are becoming one of the key materials for multi-function device having switching and light emitting function. Recently, great efforts have been made in the development of technologies to replace current devices with new organic and/or hybrid ones that have improved functions.

A photochromic crystal is one of the most important organic materials with useful applications such as organic light emitting displays, organic light-emitting diodes, organic transistors, organic solar cells, and molecular electronic devices [34–37]. Photochromism is a phenomenon where reversible transformation between two forms (isomer 1 and 2) of chemical species is induced by the light irradiation whilst chemical formula and molecular weight are unchaged during the transformations. When an isomer 1 absorbs light of a particular wavelength, it is transformed into isomer 2 through a conformational change driven by a change of its bonding structure or electronic state (see Figure 3.5). This structural phase transition results in a color change due to the change in its absorption spectrum or electronic state. The second isomer can also return to its original state (isomer 1), by irradiation with another specific wavelength of light, and will regain its original color or electronic state.

Photochromic materials are expected to broaden industrial applications. Azobenzene spiropyrans, and diarylethene are typical candidates for organic compounds exhibiting photochromism. These compounds exhibit a structural phase transition (cis/trans or open/close transformation) following light irradiation. Figure 3.6 shows an example where the photochromic compound

changes the shape by an exposure to light. This plastic deformation occurs because a conformational change takes place around the irradiated surface of a single crystal [38–40]. However, the flexible feature is sometimes lost under exposures at a high repeatition rate. Therefore more durable organic materials need to be developed for industrial applications. For understanding the mechanism of the durability to degrade, acquiring atomic-scale information as a function of time is highly required.

A high-energy synchrotron X-ray beam is one of the most powerful tools to monitor the durability of organic materials to degrade during repeated photochromic processes. Time-resolved measurements using the coherent and intense X-ray beam from SPring-8 II would enable us to trace the procedure where the atomic-scale structural change of a single organic molecule results in the large-scale morphological change of the material after the light irradiation [41]. Through such researches, a clearer understanding would be achieved for designing organic materials with improved durability and with various new functions.

3.2 Statistical characterization of inhomogeneous system

3.2.1 Access to inherent diversity

In the upgraded SPring-8, the throughput of analysis would be drastically improved, because the photon density on the sample would be raised to a 1000 times higher level than that of present SPring-8. To make best use of the light source property at the upgraded SPring-8, we here propose a scheme using the statistical characterization to access the diversity or inhomogeneity inherent in nature and in various systems.

The nature is highly diverse. A good example is individuality of humankind. More than five billion people live on the earth. Although all people share common features as human beings, there are no people exactly alike. That is, people have their individual specificity. This phenomenon is not just limited to human beings. There are inhomogeneous properties in all natural materials. For example, in the field of biology and environmental science, a large inhomogeneity and individual difference exists such as in cells, small tissues, or aerosol microparticles. Even if a specific trait is determined very precisely using a few specimens, one cannot conclude that it is a common feature of the system. To approach the essence of the natural materials, the statistical nature of observed properties should be elucidated. For this purpose, analyses of a huge number of specimens are indispensable.

Moreover, it is indispensable to analyze the individual specimen without averaging the information from multiple-specimens. Recent progresses in X-ray analysis techniques have enabled a detailed research at the micrometer to nanometer scale of single specimen. However, several hours of measurement time is usually required for one specimen. As a result, the number of ana-

lyzed sample is highly restricted,thus limiting the statistical significance. The ability to analyze a large amount of samples is crucial to obtain statistical information with high accuracy.

The upgrade of SPring-8 leads to the significant reduction in the measurement time and enable us to analyze a large number of analogous samples with inhomogeneous properties. By using X-rays from the diffraction limited ring at SPring-8 II, an X-ray beam could be focused to $\leq$ 50 nm without the use of a virtual source (See Section 6.3.3). We could expect that the photon densities on the sample would be improved by 1000 times higher than those currently available. This means that the throughput of measurement would be drastically improved assuming the present spatial resolution. This approach feasible with the upgraded SPring-8 would give us new opportunities to understand the essence of the natural materials with their hidden properties. In the following sections, we introduce several examples of such scientific targets: the statistical characterization in organisms, environmental science, and new materials design will be discussed.

3.2.2 Organisms

Living creatures are a classical example of systems displaying diversity. It is well known that humans show individual differences. A cell from one person whilst appearing similar in basic function to the same cell type of another would not be completely identical. The immunogenic properties of individual pathogens and the response they promote is another poignant example of this variation. The composition and density of intracellular signaling peptides and proteins is also different from cell to cell. These examples illustrate the diversity that exists at each level of the hierarchical organization within living creatures.

Recently, the presence and the quantity of metal elements inside cells has been reported to play a critical role in intracellular signaling and the outbreak of disease. Scanning X-ray Fluorescence Microscopy (SXFM) combines hard X-ray focusing techniques with fluorescence X-ray analysis and facilitates multiple elemental mapping at the cellular level. The high intensity beam focused into 10 nm size that would be made available at SPring-8 II using elaborate focusing systems (see Section 6.3.3) is well suited for elemental mapping with a high spatial resolution and a high sensitivity. Application of this technique to medical science would potentially play a major role in solving the problems our nation will confront in the future. A good example of the medical application is outlined here. By performing elemental mapping, scientists have obtained information about metals involved in drug metabolism and have conceived a novel strategy for anticancer chemotherapy [42]. By SXFM analysis, Shimura et al. [42] successfully found that Zn in cells increased according to Pt (cisplatin: anti-cancer drug) uptake. Further laboratory experiments suggested that Zn in cisplatin-treated cells was highly correlated with reduced Gulthathion (rGSH), and that Zn-biniding GSH was a key protein for drug resistant. The elemental mapping using SXFM [42] took more than 6 hours for 5~6 cells and

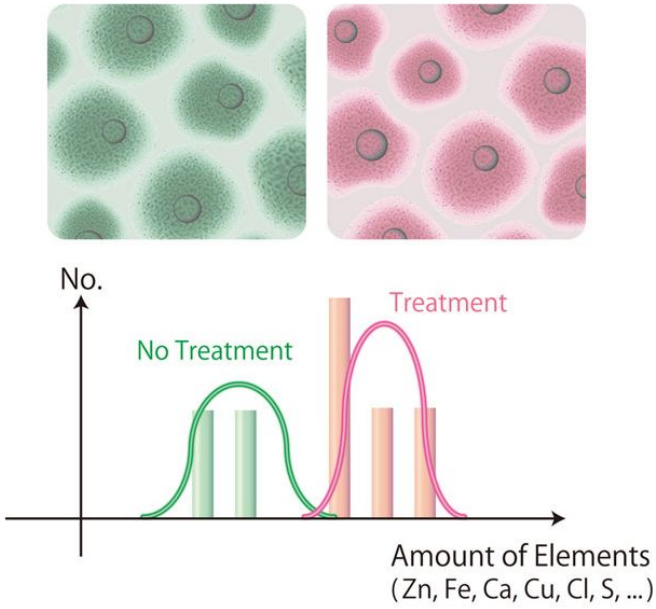

Figure 3.7: Schematic diagram showing that confidence of analysis is strongly dependent on the number of measurements. Histograms show the data with few number of measurements which approach the smooth curves by increasing the number of measurements.

more than10 repeats were required for the time-course analysis. X-ray focusing size was set wider in order to shorten the required time of experiments, resulting in lower resolution. With a higher resolution, they could investigate intracellular localization of each element as in conventional cell biology method, e.g. immunostaining using antibodies. Element mapping in a higher resolution is definitely required for the future cell biology.

In medical and biological sciences, it is important to detect a significant difference between specimens through repeated measurements, due to the individual variation of samples. The growth of cells is heavily dependent on their environment. As such, it is important to collect cells grown in a well-controlled environment and to investigate the diversity of these cells using statistical analysis. The confidence in the statistical analysis could be increased by performing more measurements. As noted above, various scientific discoveries have been made through the use of SFXM at SPring-8 beamlines. It is, however, important that more measurements could be made to increase the statistical significance of each experiment and overcome the problem of variation between biological specimens (see Fig. 3.7). The further development of medical and biological science would be facilitated by the realization of SPring-8 II with an highly brilliant and diffraction limited beam.

To elucidate the hierarchy and function existing within living systems, the detection of fluorescence X-ray signal from cells at the highest achievable sensitivity is essential. Moreover, high-resolution elemental mapping is required for clarifying the internal structure of the cell,

where the size of a cell, a nucleus and a mitochondrion are approximately 20, 10 and 1 micrometers, respectively. In the ideal case, a statistically significant result could be achieved from a 50 nm square region of biological sample, during a 1 millisecond exposure, by increasing the intensity of a focused beam by several orders of magnitude (see Section 6.3.3). Thus, the best SFXM station would be realized by focusing the intense and coherent beam from SPring-8 II with a high precision X-ray focusing system. A rapid measurement system is vital for measuring thousands of biological specimens per day and performing statistical analysis of all the measured data. The X-ray optics, detectors and data storage system need to be optimized to achieve such a high throughput.

To develop this new direction in elemental mapping of biological specimens using the synchrotron radiation, four key parameters need to be improved, namely, resolution, sensitivity, efficiency and the ease of handling both measured data and the sample itself. By upgrading SPring-8 into SPring-8 II, the first three parameters would be raised to an unrivaled level in the world, allowing innovative progress in medical and biological sciences.

3.2.3 Environmental science

Another important field of research where the statistical characterization would be powerful is the environmental science. In this section we describe a promising future prospect of research on the aerosol particles using a highest ever data-acquisition throughput using the upgraded SPring-8.

Aerosols, suspended particles in the atmosphere, are closely related to natural environments such as global warming, acid rains, and depletion of ozone layer, and eventually, human health. The size of aerosol particles ranges from a few nanometer,similar to the size of a molecule, to nearly 100 μm, comparable to the size of a pollen. The chemical composition of aerosols varies as well; aerosols with more than 3,000 different organic molecules have been reported. Particles of various sizes can absorb and/or scatter solar radiation and could become nuclei in the formation of clouds. The sizes and chemical compositions of individual particles could determine the climate. For example, a smoke dust strongly absorbs solar radiation and has been assumed to act as a warming gas. In contrast, sulfate and its organic compounds are more reflective to sun lights and have been assumed to cause cooling of the earth. The influence of aerosols on global warming has been pointed out in the IPCC report. The role of aerosols in climate change, however, still remains unresolved [43]. To understand the effects of aerosol particles to the natural environment in more detail, an analytical method of individual aerosol particle would be indispensable.

Most previous studies, such as by chromatography, have treated bulk aerosols, by evaluating the averaged characteristics of many aerosol particles. With this averaged approach, important information on distribution of compositions, sizes, and shapes of particles may have been lost.

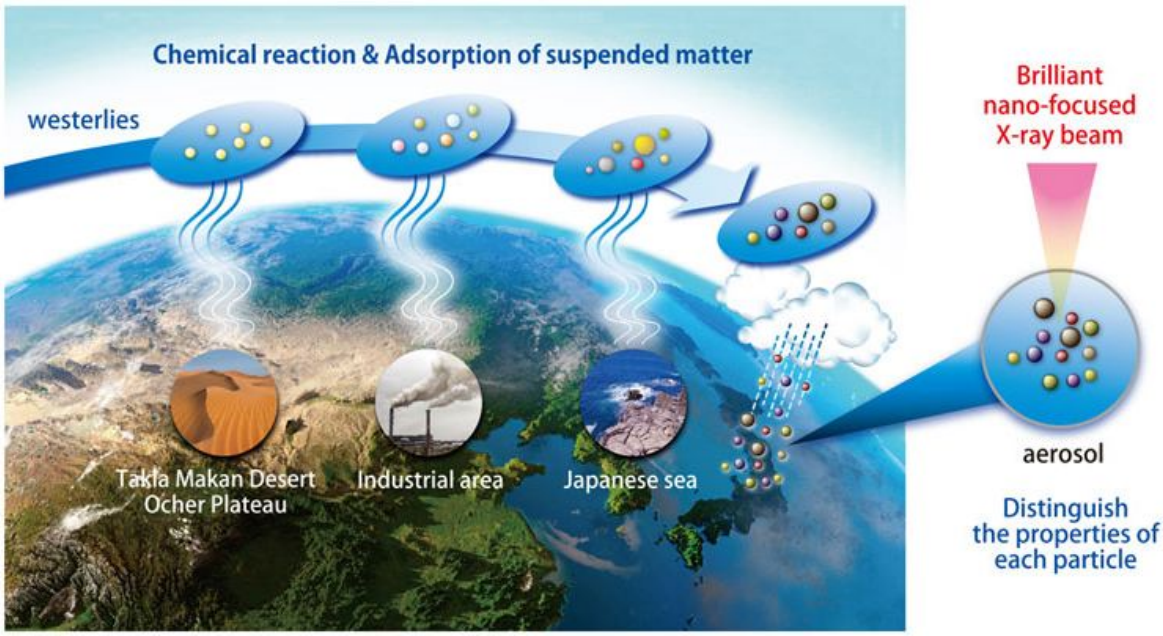

Figure 3.8: Proposed formation and transport mechanisms of yellow dust [48]

Several new techniques including X-ray fluorescent imaging using synchrotron radiation, electron microscopy, and mass spectrometry have recently been developed to analyze the properties of individual particles [44]. However, the measurable number of particles is still restricted due to the low data-acquisition throughput. Analysis of a large number of particles is required for the statistical characterization to clarify the role of these aerosol particles in the climate change. The highest ever throughput with the upgraded SPring-8 would be extremely powerful for making best use of this new experimental scheme.

Another important issue is to clarify the effect caused by the aerosol particles on the natural environment and the dependence on the mixing states of particles [45]. The mixing states of aerosol particles can be classified into two different states, external and internal mixtures [46]. In an external mixture, aerosol particles with different pure compositions are mixed, whereas, in an internal mixture, every particles have the same mixture of different composition. The conventional bulk analyses are not capable to distinguish these states. This problem could be overcome using the statistical analysis of a large number of particles.

Aerosol particles generally have a single composition when emitted in the primary source region. Then, the particles are transported in the atmosphere and changed into a mixing state, reacting with other particles and/or atmospheric components. Finally, the particles can reach an intermediate state between the external and internal mixture in the atmosphere. A thorough analysis of the mixing state would provide knowledge of the primary source region and the transportation pathways of the aerosol particles.

One of the key topics involving aerosols in the mixed state is yellow dust which are trans-

ported from the Chinese continent to Japan by the strong winds (Fig. 3.8). In 2010, an outbreak of the cattle disease, "foot-and-mouth disease" hit Japanese farmers. Yellow dusts originating from the deserts in China and Mongolia are considered to be a significant transport media of the infectious viruses [47]. To identify the primary source region and the transportation pathway of the dusts, it is necessary to analyze the yellow dusts in the mixed states. The statistical characterization of a large number of yellow dust particles would allow precise characterization of individual particles as well as the diverse properties of the particles. These results would contribute to the understanding of the mixed states of the aerosol particles, helping to unveil the effect of aerosols on the global and social environments.

The statistic characterization approach, which will be available with the upgraded SPring-8, would provide a new way to evaluate characteristics of various aerosol particles. It would contribute to resolve important issues in environmental science.

3.2.4 Quick and fine screening of synthesized materials

The statistical characterization would accelerate the research for developing useful functional materials by quick and fine screening of synthesized materials. SPring-8 II offers ideal X-ray beam properties for applying this approach to various kinds of materials. Despite of the huge demands for analyzing novel materials, homogeneous specimens with high purities and large volumes have been evaluated so far in most cases. For example, synchrotron X-ray experiments usually require specimens synthesized under well controlled conditions so that the analyzed results are attributed to known conditions. In a word, purification process is essential in order to characterize synthesized materials. This hinders the rapid progress of the materials research. Here, we propose two research methods to overcome these difficulties using the world-leading light source of the SPring-8 II, suited for the experiments using an intense nano-focused X-ray beam with a highest ever throughput. A fast data processing using a super-computer would accerelate the research speed.

The first method is useful to find new materials, forming small grains (sub-μm $\sim$ μm), inside the parent materials. Scanning microscopy experiment, acquiring X-ray spectra and/or X-ray diffraction signals, would be carried out on the samples using a nano-focused X-ray beam from the SPring-8 II. Unique signal from the novel material could be quickly and elaborately screened out of the huge datasets. Once the novel material is successfully located, more diverse information could be obtained from the same region of the sample, such as the electronic state, structures, magnetic properties and so on. Fig. 3.9 illustrates a scheme of this method. This approach would thus allow X-ray characterization of the newly-synthesized material without any purification process.

The second method makes best use of the combinatorial material synthesis. By changing the conditions and moving the synthesizing spot as a function of time, the properties of material is

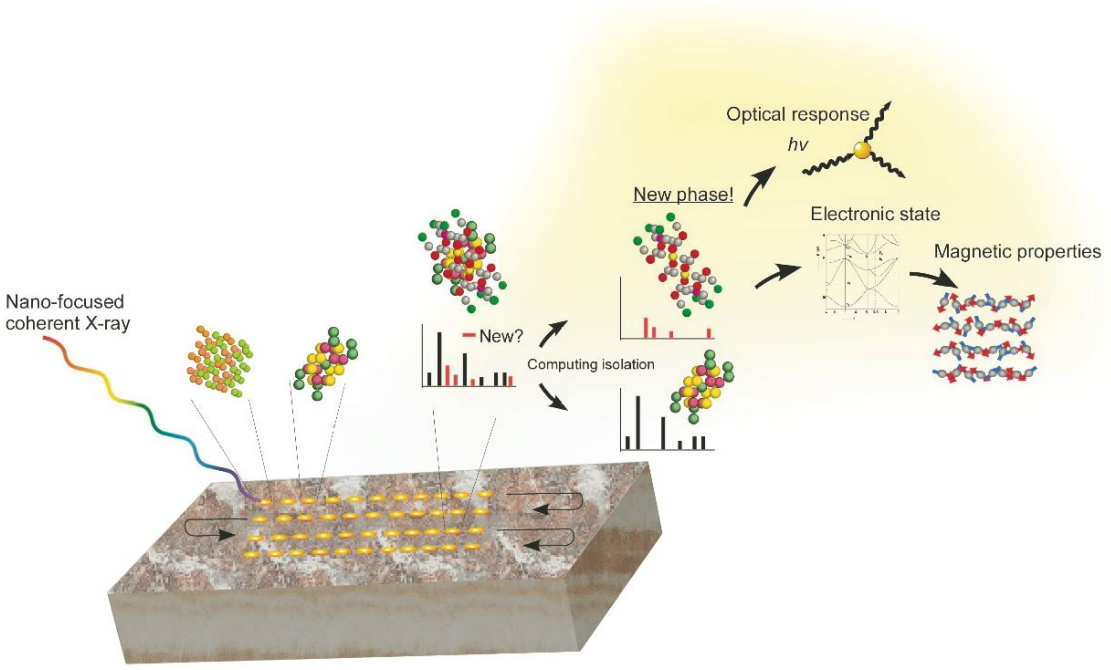

Figure 3.9: Concept of quick and fine screening of the newly synthesized materials which have a texture. A nano-focused beam would make it possible to discover the new material.

varied as a function of position at the sample substrate. More than hundred regions with different compositions of materials would be produced on a single substrate, by changing the parameters controlling the process of the material synthesis. However, we have been able to measure only a few regions due to the limited beamtime at the present SPring-8. The upgraded SPring-8, on the other hand, would allow us to characterize hundreds of regions on the samples in a short beamtime. Novel materials with new structures and new properties could be discovered from the huge data sets. An in-situ measurement with the combinatorial synthesis would be even more effective for synthesizing materials having ideal properties. The "process and characterize" scheme would become practical.

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