

Preview

Energy Dissipation at Interfaces Drives Multicompartment Remodeling

Jan Steinkühler¹ and Neha P. Kamat^{1,2,*}

In this issue of *Chem*, Cheng and Perez-Mercader use the dissipative assembly of amphiphilic polymers coupled to a Belousov-Zhabotinsky reaction to generate dynamic compartments. The results highlight the importance of active interfacial processes in driving compartment formation and provide a route for controlling the dynamic self-assembly of molecules into life-like assemblies.

Biological cells segregate their chemical reaction space with multicompartment and multiphase assemblies. In order to achieve a large surface-area-to-volume ratio, individual cells can utilize multicompartmentalization to generate a high density of interfaces. Accordingly, the interfacial phenomena of many types of biological structures, from catalytic activities at the membrane-cytosol interface to the wetting behavior of protein droplets, are now being actively investigated.¹ Given that cells are active, energy-dissipating systems, their many interfaces, from membranes to protein droplets, are likely to experience dynamics far from equilibrium. In recent years, researchers have aimed to reconstitute some of the dynamic behavior of biological assemblies by coupling chemical reactions that display a dynamic equilibrium to an element capable of assembly.^{2,3} Here and in other dissipative systems, the challenge is not only to simply burn energy but also to do so in a useful and constructive manner that enables morphological changes or generates mechanical or chemical work.

In this issue of *Chem*, Cheng and Perez-Mercader study the self-assembly and morphological changes of compartments formed from amphiphilic poly-

mers.⁴ A subset of hydrophilic polymers are conjugated to a photosensitive $\text{Ru}(\text{bpy})_3^{2+}$ moiety that takes part in a Belousov-Zhabotinsky (BZ) reaction. Importantly, the BZ reaction enables the hydrophilic precursor molecule to play a dual role as both a catalyst and a building block for compartment assembly and structural rearrangement. Upon the addition of sodium bromate, the system undergoes radical-driven polymerization to form amphiphilic polymers by a reversible addition-fragmentation chain-transfer (RAFT) reaction. Strikingly, the system is driven to assemble highly dynamic supramolecular structures visible under an optical microscope. The structures phase separate from the surrounding water to form spherical, polymer-dense multicompartment. Additional exposure to light activates the $\text{Ru}(\text{bpy})_3$ moieties to induce shifts in hydrophilicity of the polymer segments, leading to a high degree of interfacial remodeling of the multicompartment structure even after its initial formation.

The BZ reaction is the prototype of an out-of-equilibrium, non-linear feedback system, which gives rise to a wide range of dynamic phenomena. Originally studied in spatially homogeneous conditions, the BZ reaction has also been confined to material bound-

aries, including being coupled to systems such as heterogeneous water-oil microemulsions and hydrogels.^{5,6} In the system by Cheng and Perez-Mercader, the dissipative nature of the BZ reaction is what creates a dynamic, multicompartment structure from an initially homogeneous solution of polymers. Importantly, Cheng and Perez-Mercader were able to show that the multicompartment assemblies form only when enough energy is dissipated from the polymerizing molecules.⁴ This is the heart of a high-energy, dissipative assembly process.⁷ In the following paragraphs, we highlight the importance of dissipative interactions at the polymer-water interface for the development of multicompartment structures.

From the observed spherical shapes of the polymer-water interfaces, we can deduce a significant interfacial energy, which is set by the polymer-water surface tension and area. The interfacial area increases during compartment formation, and the corresponding increase in interfacial energy indicates the active nature of the system. Additional complexity is added to this system because during the BZ cycle, the $\text{Ru}(\text{bpy})_3$ moieties change their polarity as they undergo oxidation and reduction. Because the $\text{Ru}(\text{bpy})_3$ moieties are linked to the amphiphilic polymers, shifts in $\text{Ru}(\text{bpy})_3$ polarity lead the amphiphilic polymers to move toward interfaces between water and polymer phases and lead energy to subsequently be dissipated at these interfaces. This movement leads to a situation where the system can increase its surface area as long as the reaction dissipates the required energy for polymer

¹Department of Biomedical Engineering, Northwestern University, Evanston, IL 60657, USA

²Center for Synthetic Biology, Northwestern University, Evanston, IL 60657, USA

*Correspondence: nkamat@northwestern.edu
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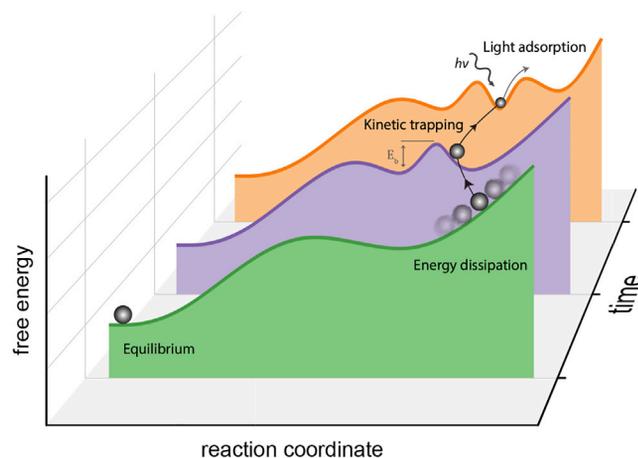


Figure 1. Time-Dependent Energy Landscape of a Dissipative Process that Forms Barriers during Compartment Formation and Maturation

Arrows show the direction of time, and E_b is the energy barrier associated with the remodeling of polymer-water interfaces, which evolve as the reaction progresses. Light adsorption provides energy to overcome the formed energetic barriers and enables further evolution of the system.

rearrangement. Over time, the progress of compartment rearrangement induces barriers to further coarsening of the system as high-energy intermediates arise during interface remodeling, such as rearrangement and fission of the polymer walls between compartments.⁸ A dynamic change in the energy landscape over time ultimately drives the system to a kinetically trapped, multicompartment structure after exhaustion of the chemical fuel (Figure 1). Quite clearly, the system undergoes a time-irreversible evolution that can be interpreted as a signature of life-like processes. The exact structure and final size of the compartments will be sensitive to the details of the interfacial energy-dissipation process and might be controlled by features of the system, such as the polymer structure.

In a second set of experiments, Cheng and Perez-Mercader used the inherent light sensitivity of the polymer amphiphiles to demonstrate the remarkable remodeling capabilities of this system. Adsorption of blue light changed the polarity of the oxidized Ru(bpy)₃ moieties, and the induced energy dissipation at the polymeric-water interfaces

allowed further compartment remodeling. This remodeling allowed for additional compartments to form under light exposure, increasing the total energy of the system as the total interfacial area between the polymer and water increased.⁴

To gain even better control of complex multicompartment assemblies in the future, it will be interesting to see how modification of the chemical structure of precursor materials can control dissipative self-assembly. One attractive property that can be modulated is the equilibrium interfacial tension of the polymer-water system. On the one hand, the high interfacial energy favors stable multicompartment formation, but on the other hand, it restricts the interfaces to spherical shapes. Interfacial tensions of biological interfaces are often lower, making the interfaces more dynamic and deformable into non-spherical shapes by active processes.⁹ In addition to interfacial tension, control over the volume-to-area ratio, the chemical environment, and the resulting energy flux are also crucial for generating more complex multicompartment structural rearrangements, such as compartment fission.¹⁰

Yet another way to enhance the complexity of such systems might be the addition of a disassembly step to form a dissipative cycle.¹¹ In order to achieve these behaviors, it will be important to use self-assembling building blocks that are modular. Ultimately by enhancing our control over active interfaces, we will expand our capacity to construct additional life-like processes with broad applications in biosensors, microreactors, or molecular delivery.

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