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Use of light to control the formation of functional nanostructures in solution

Introduction

For decades, block copolymers have proven to be powerful tools for the preparation of nanostructured materials in bulk and in solution [1]-[3]. Their ability to self-assemble is the key feature explaining their success story. Indeed, block copolymers commonly undergo a phase separation process which is limited in space, and thus arrange themselves in well-defined morphologies at the nanoscale. In the mid 90's, a new class of polymer, *i.e.* stimuli-responsive polymers, was developed and totally changed the way to apprehend self-assembly. Indeed, such polymers are able to modify their physical and chemical properties in response to slight changes of their environment such as pH, temperature, ionic strength, light, etc. The self-assembly of block copolymers was thus transformed from a “static” process, where the morphology of the self-assembled nanostructures was mainly influenced by the block copolymer nature and composition, to a “dynamic” process, where the environmental constraints drastically influence the morphology of the nanostructures.

Among the available stimuli, light has attracted special attention due to its spatiotemporal characteristics. Indeed, the irradiation can be localized in time and space and it can be triggered from outside of the system [4], [5]. Moreover, it does not require the addition of reagents in the medium, and the tuning of the parameters (wavelength, intensity and duration) is very easy [6]-[8].

The irradiation of photosensitive moieties generally leads to three different phenomena [7]. Azobenzene,

dithienylethene and spiropyran moieties for example undergo an isomerisation when irradiated in the UV range. Moreover, this photoisomerization can be reversed by visible light irradiation. Photocycloaddition is realized by the irradiation of coumarin, cinnamic ester and truxilic acid moieties. The last phenomenon is characterised by the cleavage of the photosensitive moiety into two different molecules. Coumarinyl esters, *o*-nitrobenzyl esters, phenacyl esters and pyrenylmethyl esters typically cleave themselves when irradiated by UV light [6], [7].

My thesis focused on the development of block copolymers bearing photocleavable group(s) and the use of light as stimulus to control the formation of nanostructures (nanocages and micelles) in solution.

1. Polymer synthesis

The synthesis of two families of photosensitive block copolymers has been realized. The first family is characterized by the presence of a sequence bearing photocleavable side groups (Figure 1). The photosensitive moieties are photolabile protecting groups of carboxylic acids. Therefore, the photocleavable sequence of the investigated copolymers is composed of *o*-nitrobenzyl acrylate (PNBA), dimethoxynitrobenzyl acrylate (PDMNBA) or *p*-methoxyphenacyl methacrylate (PMPMA). The second family of photocleavable block copolymers is characterized by the introduction of a photocleavable *o*-nitrobenzyl ester junction between the two sequences of the copolymer (Figure 1).

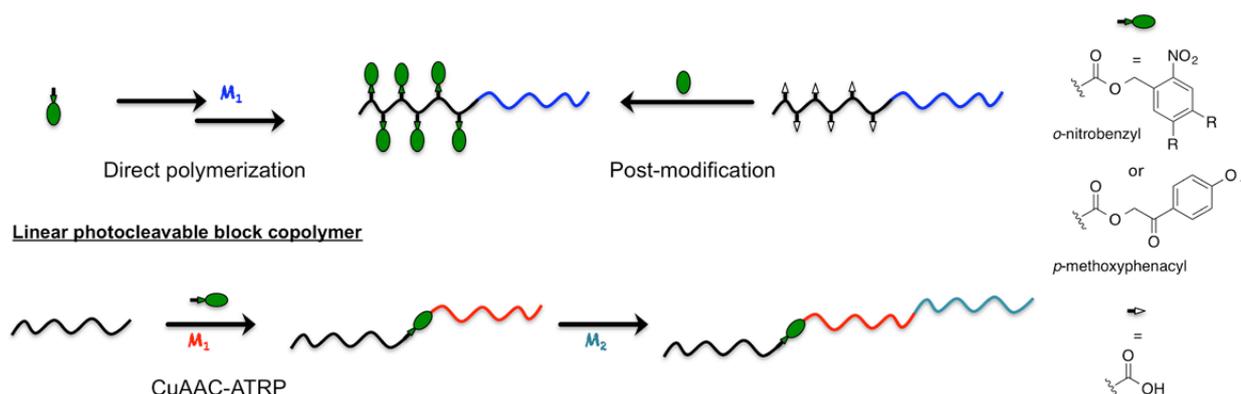
Block copolymer bearing photocleavable side groups

Figure 1: Synthetic pathways for the production of photocleavable block copolymers.

The copolymers bearing *o*-nitrobenzyl derivatives were synthesized by post functionalization of a poly(acrylic acid)-*block*-polystyrene (PAA-*b*-PS) precursor [9], [10]. We selected this synthetic approach because we previously demonstrated that the controlled radical polymerization of monomers bearing a nitroaromatic group is a big challenge [11]. On the other hand, copolymers bearing *p*-methoxyphenacyl side groups have been synthesized via direct polymerization by atom transfer radical polymerization (ATRP) since the absence of nitroaromatic groups in their chemical structure is an undeniable advantage for the synthesis of well-defined polymers [12].

The introduction of the photocleavable junction between the blocks was realized by a “one-pot” copper(I)-catalyzed azide alkyne cycloaddition (CuAAC)-ATRP reaction. This approach allows simultaneously the polymerization of a polymer sequence at one side of the photocleavable junction and the attachment of the other sequence by a Huisgen 1,3 dipolar cycloaddition on the other side of the junction. Following this strategy a wide range of linear photocleavable block copolymers were synthesized [13]-[16].

2. Light induced micellization and micelle disruption

The micellization promoted by light irradiation was performed in organic media on the block copolymers bearing photocleavable moieties as side groups. The investigated copolymers were PNBA-*b*-PS and PDMNBA-*b*-PS. These copolymers when dissolved

in a non-selective solvent (chloroform) exist as free chains (unimers). Upon light illumination, the cleavage of the side chromophores occurs, unmasking the acrylic acid (AA) functions. As a result, the photosensitive block is turned into a fully hydrophilic PAA block, which is insoluble in the used solvent. Self-assembly thus occurs, forming micelles consisting of a PAA core and a PS corona (Figure 2a). Dynamic light scattering (DLS) and transmission electron microscopy (TEM) were used to monitor the light induced micellization (Figure 2b). With irradiation, an increase of the hydrodynamic radius of the objects is observed, indicating the formation of micelles in solution. The possibility to encapsulate guest molecules into the accordingly obtained PAA micellar cores was further demonstrated by fluorescence spectroscopy [9], [10].

The light induced disruption of micelles was investigated with a diblock copolymer composed of a photosensitive PMPMA sequence and a thermosensitive poly(oligoethyleneglycol methacrylate) (POEGMA) sequence. This block copolymer self-assembles in water to form micelles with a PMPMA core and a POEGMA corona. The irradiation of this copolymer induces the cleavage of the *p*-methoxyphenacyl side groups and the formation of a fully hydrophilic PMAA-*b*-POEGMA copolymer alongside with the micelle disruption (Figure 3a) [17]. The disruption was monitored by DLS and TEM. The disruption of the micelles is here clearly demonstrated by the TEM images (Figure 3b). Indeed, the TEM image before irradiation shows the presence of micelles, whereas a polymer film resulting from the drying of a solution of unimers is observed after irradiation.

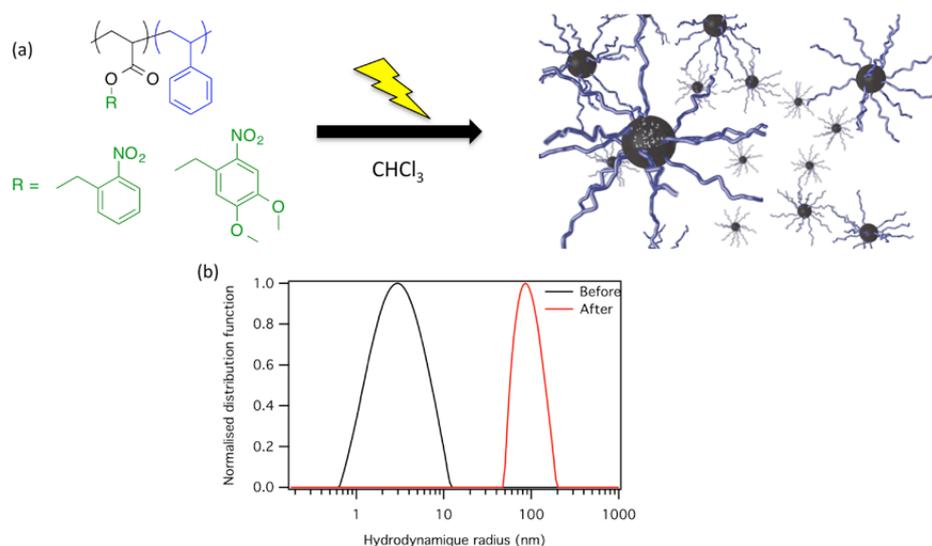


Figure 2: (a) Schematic representation of the light-induced micellization of block copolymers bearing photocleavable side groups, (b) CONTIN¹ size distribution diagram of the PNBA-*b*-PS before and after irradiation.

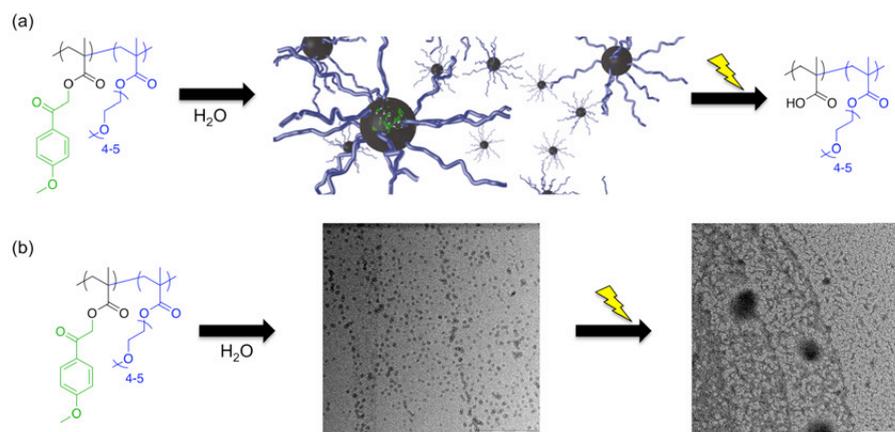


Figure 3: (a) Schematic representation of light-induced disruption of PMPMA-*b*-POEGMA micelles in water, (b) TEM images before and after irradiation of a solution of PMPMA-*b*-POEGMA micelles.

3. Formation of nanocages by a photocleavable approach

Nanocages were prepared by using linear photocleavable block copolymers bearing a photocleavable junction. The different investigated copolymers were designed with a hydrophobic (PS or poly(*tert*-butyl acrylate), PtBA) and a hydrophilic part (PAA poly(dimethylaminoethylmethacrylate), PDMAEMA, or PDMAEMA-*b*-POEGMA) linked by the photocleavable junction. Upon dissolution in water, these amphiphilic copolymers self-assemble into micelles with the photocleavable junction localized precisely at the core-corona interface (PS-*hν*-PAA and PtBA-*hν*-PDMAEMA) or at the core-shell interface (PtBA-*hν*-PDMAEMA-*b*-POEGMA) (Figure 4). The corona (for diblocks) or the shell (for triblocks) is then cross-linked using a diamine or a dihalide according to the

chemical nature of the considered block (PAA or PDMAEMA, respectively). These shell cross-linked micelles are then irradiated with UV light, leading to the cleavage of the *o*-nitrobenzyl ester junction and the detachment of the core from the shell. The extraction of the core allows the formation of the desired nanocages (Figure 4).

The main advantage of this approach is the fact that the cleavage of the copolymer junction is a soft technique that does not require any reagents. Moreover, the photocleavable approach allows the formation of nanocages with an empty core patterned by carboxylic acid functions, which can be afterwards easily functionalized [14]-[16]. Moreover, the stimuli-responsive behavior of the investigated polymers allows the tuning of the nanocage size *via* thermal and pH stimuli [14].

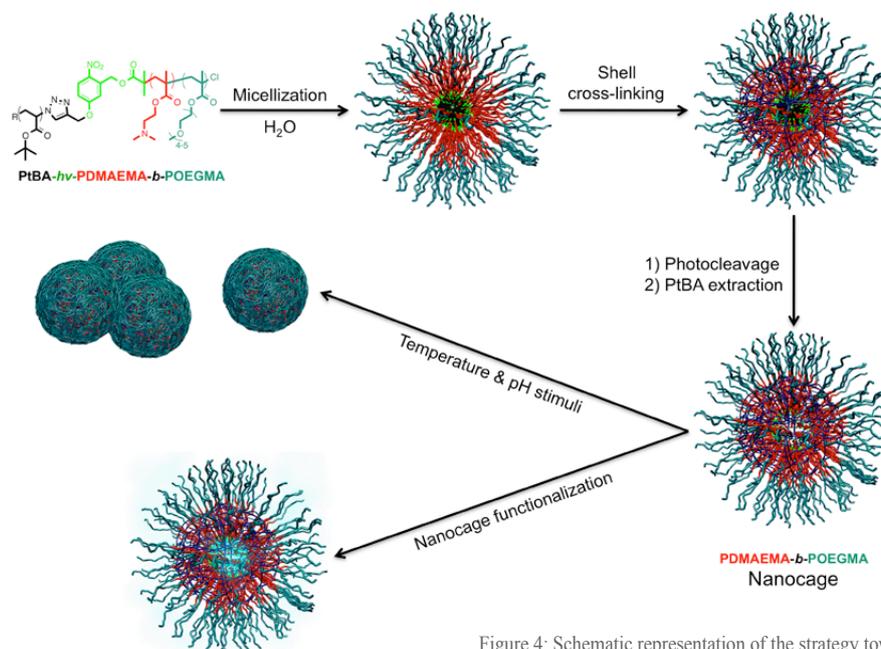


Figure 4: Schematic representation of the strategy toward nanocage.

Conclusions

This work was devoted to the production of functional nanostructures in solution and more particularly on how to combine light and photocleavable block copolymers to control the formation of these nanostructures in solution. The synthesis of new well-defined photosensitive copolymers was realized by a combination of ATRP and polymer modification techniques. The response of the pho-

tosensitive copolymers to UV irradiation was studied. Finally, the copolymers were self-assembled in solution and the light stimulus was applied to induce the micellization, the disruption of micelles or the formation of nanocages.

¹ CONTIN corresponds to the fitting method used to analyse heterodisperse, polydisperse and multimodal systems.

References

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