## ChemComm

## COMMUNICATION

## **RSC**Publishing

View Article Online View Journal | View Issue

# Published on 13 May 2013. Downloaded by Brown University on 14/07/2013 21:25:42.

# Photoswitchable NHC-promoted ring-opening polymerizations<sup>†</sup>

Cite this: Chem. Commun., 2013, 49, 5453 Bethany M. Neilson and Christopher W. Bielawski\*

Received 3rd April 2013, Accepted 30th April 2013

DOI: 10.1039/c3cc42424c

www.rsc.org/chemcomm

The UV-induced photocyclization of a dithienylethene-annulated *N*-heterocyclic carbene precatalyst enabled photoswitchable ringopening polymerizations of  $\varepsilon$ -caprolactone and  $\delta$ -valerolactone. The polymerizations proceeded efficiently in ambient light, however UV irradiation attenuated the reaction rate ( $k_{amb}/k_{UV} = 59$ ). Subsequent visible light exposure reversed the photocyclization and restored catalytic activity.

Externally-regulated polymerizations offer the potential to achieve unsurpassed control over the structures and properties of synthetic macromolecular materials.<sup>1</sup> Light is an ideal stimulus for controlling polymerization reactions because it is non-invasive, chromophore selective, and provides excellent spatial and temporal control.<sup>2</sup> Over the past few years, a number of successful photoswitchable polymerizations have been developed. In a seminal contribution, Manners reported<sup>3</sup> the photo-controlled living ring-opening polymerization (ROP) of ferrocenophane monomers via reversible photo-induced metal-ligand bond dissociation. More recently, reversible photo-induced bixanthene dissociation and electron transfer processes were reported by Yang<sup>4</sup> and Hawker,<sup>5</sup> respectively, as methods to control living radical polymerizations.<sup>6</sup> However, of the reported examples,<sup>3-6</sup> none have involved the use of a photoswitchable organocatalyst to promote the ROPs<sup>7</sup> of cyclic esters.<sup>8,9</sup> Such a photoswitchable ROP catalyst is expected to offer a new level of control over the synthesis of biologically and industrially relevant polyesters, and may enable the development of novel materials with sophisticated macromolecular architectures and advanced functions.

*N*-Heterocyclic carbenes (NHCs)<sup>10</sup> have been shown by Hedrick and Waymouth<sup>11</sup> to be efficient organocatalysts for facilitating the ROP of cyclic esters. Recently, we reported<sup>12</sup> that the intrinsic catalytic activities displayed by NHCs in transesterification<sup>13</sup> and transamidation<sup>14</sup> reactions may be photomodulated *via* annulation to a photochromic diarylethene.



As shown in Scheme 1, cyclization of the NHC precatalyst **10 HPF**<sub>6</sub> was found to reduce the electron density at the corresponding carbene nucleus<sup>15</sup> and resulted in a catalytically inactive species upon UV irradiation. Subsequent exposure to visible light reversed the cyclization reaction and regenerated an active catalyst.<sup>12</sup> Given this initial success, we envisioned that photoswitchable NHCs could be extended to gain control over ROPs.

$$\bigcirc O + OH \xrightarrow{\text{10-HPF}_6} O \xrightarrow{\text{NaHMDS}} O \xrightarrow{\text{NAH$$

In an initial experiment,  $10 \cdot \text{HPF}_6^{12}$  (0.01 mmol) was treated with NaHMDS (0.0095 mmol) in THF followed by  $\varepsilon$ -caprolactone (2 mmol) and benzyl alcohol (BnOH; 0.02 mmol) (eqn (1)). After 1 h at room temperature, complete conversion (>95%) of  $\varepsilon$ -caprolactone to the corresponding polymer was observed by <sup>1</sup>H NMR spectroscopy. Gel permeation chromatography (GPC) of the resulting material revealed that the polymer with a number average molecular weight ( $M_n$ ) of 15 900 Da and polydispersity index (PDI) of 1.15 was formed.<sup>16</sup> Although the measured molecular weight was higher than its theoretical value ( $M_{n(\text{theor})} = 11 \, 400 \text{ Da}$ ),<sup>17</sup> the narrow PDI was consistent with a controlled chain growth process.<sup>7</sup>

To determine if UV irradiation would affect the rate of the aforementioned polymerization, a solution of **10** was freshly prepared by treatment of **10**  $\cdot$ **HPF**<sub>6</sub> with 0.95 equiv. of NaHMDS in C<sub>6</sub>H<sub>6</sub> and then equally divided into two quartz cuvettes. One of the cuvettes was exposed to UV irradiation for 1 h, while the other was kept in ambient light.  $\varepsilon$ -Caprolactone (1.0 M) and BnOH (0.01 M) were then added to each reaction vessel. After 1 h, an aliquot was removed from each cuvette and quenched

Department of Chemistry and Biochemistry, The University of Texas, Austin,

Texas 78712, USA. E-mail: bielawski@cm.utexas.edu

<sup>†</sup> Electronic supplementary information (ESI) available: Detailed experimental procedures and kinetic data. See DOI: 10.1039/c3cc42424c

by exposure to methanol. Upon concentration and dissolution in  $CDCl_3$ , <sup>1</sup>H NMR spectroscopic analysis of each aliquot revealed that the reaction in ambient light had reached complete conversion to polymer (>95%), while the mixture exposed to UV radiation did not react (<5% conversion). The lack of reactivity observed upon exposure to UV light was consistent with the reduced catalytic activity of **1c** compared with **1o**.<sup>12</sup>

Unfortunately, the polymerization of *ɛ*-caprolactone in ambient light was too fast to accurately measure at a practical temperature (>95% conversion in 5 min; 25 °C), even at lower concentrations and catalyst loadings. However, the photoswitchable nature of 1 was demonstrated by a photo-gated<sup>2</sup> chain extension experiment. First, a reaction mixture similar to that described above (2 mmol ɛ-caprolactone; 0.5 mol% 1, 1.0 mol% BnOH) was allowed to react in ambient light for 30 min, during which time it reached complete conversion (>95% by <sup>1</sup>H NMR spectroscopy) and formed a polymer with a  $M_{\rm n}$  of 12 500 Da ( $M_{\rm n(theor)}$  = 11 414 Da<sup>17</sup>) and a PDI of 1.57. The same reaction vessel was then irradiated with UV light for 1 h, after which a second equivalent of  $\varepsilon$ -caprolactone (2 mmol) was added. The reaction vessel was kept under UV irradiation for a further 3 h, during which time neither the monomer conversion nor the molecular weight of the polymer increased, consistent with the formation of the inactive photocyclized catalyst 1c. Subsequent exposure to visible light, however, resulted in a significant increase in the  $M_{\rm n}$  of the resulting polymer to 19000 Da (PDI = 1.31;  $M_{n(theor)}$  = 16000 Da), and <sup>1</sup>H NMR analysis revealed that 40% of the second monomer fraction had undergone polymerization. The observed increase in molecular weight coupled with the enhanced monomer conversion suggested to us that the inactive catalyst 1c underwent the photocycloreversion to regenerate the active catalyst 10, which facilitated polymer growth.<sup>12</sup> Collectively these results demonstrated a rare example of a latent photo-activated ROP.8

Subsequent attention was shifted to  $\delta$ -valerolactone, which was expected to polymerize more slowly than its sevenmembered analogue on account of its lower ring-strain, and thus provide greater control over the reaction. After an initial experiment revealed that 10 efficiently catalyzed the polymerization of  $\delta$ -valerolactone (eqn (2)),<sup>18</sup> a comparative kinetics experiment was conducted to determine if UV irradiation would affect the rate of the polymerization. A freshly prepared solution of 10 (0.016 mmol 10 HPF<sub>6</sub> and 0.015 mmol NaHMDS) and the internal standard durene (1 mmol) in benzene (4.0 mL) was divided evenly into two quartz cuvettes, which were then each sealed with teflon-lined septum caps. One of the cuvettes was then exposed to UV irradiation ( $\lambda = 313$  nm) for 1 h with stirring, while the second cuvette was stirred in ambient light. The monomer, δ-valerolactone (2 mmol), and BnOH (0.016 mmol), were then added via N2 purged syringes to each reaction vessel. Aliquots were periodically removed from each reaction, diluted into methanol, filtered through 0.2 µm PTFE and analyzed by gas chromatography (GC). Inspection of these data revealed that the reaction in ambient light proceeded with a pseudo-first order rate constant,  $k_{\rm amb}$ , of 1.2  $\pm$  0.5  $\times$  10<sup>-3</sup> s<sup>-1</sup>, while the reaction conducted in UV radiation was significantly slower  $(k_{\rm UV} = 2.0 \pm 1.0 \times 10^{-5} \text{ s}^{-1}; k_{\rm amb}/k_{\rm UV} = 59;$  Fig. 1a).<sup>19</sup>



**Fig. 1** Plots of reaction conversion *versus* time for the ROP of δ-valerolactone catalyzed by **1** (prepared *in situ* from **1·HPF**<sub>6</sub> and NaHMDS) in C<sub>6</sub>H<sub>6</sub>. The reactions were monitored over time by GC using durene as an internal standard. Conditions: [δ-valerolactone]<sub>0</sub> = 0.5 M; [BnOH]<sub>0</sub>/[**10**]<sub>0</sub> = 4; [δ-valerolactone]<sub>0</sub>/[**10**] = 250, unless otherwise noted. (a) Two reactions were run concurrently with one irradiated with UV light ( $\lambda_{irr}$  = 313 nm) for 1 h prior to substrate addition (blue diamonds) and the other kept in ambient light (red squares). (b) A single reaction vessel was allowed to proceed in ambient light for 10 min prior to UV exposure (blue diamonds). For this experiment, [δ-valerolactone]<sub>0</sub>/[**10**] = 333. (c) A single reaction vessel was exposed to UV irradiation for 1 h prior to substrate addition and then was kept in UV light for 30 min (blue diamonds) prior to visible light irradiation ( $\lambda_{irr}$  > 500 nm) (red squares). (d) A single reaction was exposed to UV irradiation, then kept in UV light for 30 min (blue diamonds) prior to visible light irradiation (red squares). After 45 min the reaction was exposed to UV radiation (blue diamonds).

The disparity in the rates of the ROP of  $\delta$ -valerolactone in ambient versus UV light, coupled with the reversibility of the photocyclization of the catalyst, enabled the rate of the polymerization to be photoswitched over time. First, when the polymerization of  $\delta$ -valerolactone (2 mmol) with BnOH (0.012 mmol) and 10 (0.3 mol%) was allowed to proceed in ambient light, a rate constant,  $k_{
m amb}$ , of 8.0  $\pm$  3.0 imes 10<sup>-4</sup> s<sup>-1</sup> was measured. Subsequent exposure to UV light to effect the photocyclization to 1c  $(\lambda = 313 \text{ nm})$  resulted in a significant decrease in the rate constant ( $k_{\rm UV}$  = 7.0 ± 2.0 × 10<sup>-6</sup> s<sup>-1</sup>;  $k_{\rm amb}/k_{\rm UV}$  = 114; Fig. 1b). Alternatively, when the reaction was initially subjected to UV irradiation, negligible reactivity was observed ( $k_{
m UV}$  = 2.0  $\pm$  1.0 imes $10^{-5}$  s<sup>-1</sup>), however subsequent irradiation with visible light ( $\lambda$  > 500 nm) triggered the polymerization ( $k_{\rm vis}$  = 3.5  $\pm$  1.0  $\times$  $10^{-4} \text{ s}^{-1}$ ;  $k_{\text{vis}}/k_{\text{UV}} = 17$ ; Fig. 1c).<sup>20</sup> By alternating exposure to UV and visible light, the reactivity could be switched between slow and fast states. For example, the polymerization rate was initially suppressed by UV irradiation, restored upon exposure to visible light, and again attenuated upon a second exposure to UV light  $(k_{\rm UV'} = k_{\rm UV} = 1.1 \pm 0.9 \times 10^{-5} \text{ s}^{-1}; k_{\rm vis}/k_{\rm UV'} = 32; \text{ Fig. 1d}).^{21}$ 

A proposed catalytic cycle for the photoswitchable ROP of  $\delta$ -valerolactone is given in Scheme 2. In accord with the mechanism proposed for NHC-promoted ROPs<sup>7,11a</sup> and previously reported <sup>13</sup>C NMR experiments,<sup>12</sup> **10** facilitates the ring-opening of the ester to form the resting state of the active catalyst.<sup>22,23</sup> The corresponding imidazolium alkoxide can then turn over to form product or, upon UV irradiation, converts to



**Scheme 2** Proposed catalytic cycle for a photoswitchable NHC-catalyzed ringopening polymerization.<sup>22</sup>

an NHC–alcohol adduct that is catalytically inactive due to the decreased electron density at the carbenoid center.<sup>15</sup> Catalytic activity is restored by exposure to visible light to effect the cycloreversion, which regenerates the active imidazolium species and re-engages the catalytic cycle.<sup>12</sup>

In summary, we have developed a photoswitchable ROP of cyclic esters using a photochromic NHC catalyst. The ROPs of  $\epsilon$ -caprolactone and  $\delta$ -valerolactone were promoted by 10 in ambient light, however UV irradiation afforded the photocyclized catalyst 1c and significantly attenuated the polymerization activity ( $k_{amb}/k_{UV}$  = 59 for  $\delta$ -valerolactone). Moreover, the ROP of  $\delta$ -valerolactone was reversibly activated and deactivated through alternate exposure to visible and UV light. To the best of our knowledge, 10 is the first example of a photoswitchable ROP organocatalyst, as well as the first photoswitchable NHCbased polymerization catalyst. Given the versatility of NHCs for promoting various ring-opening and other polymerizations,<sup>7,11</sup> we believe that the methodology described herein may be extended to a wide variety of monomers and has potential to facilitate the synthesis of novel polymers and copolymers<sup>24</sup> with sophisticated architectures.<sup>25</sup>

This material is based upon work supported in part by the U. S. Army Research Laboratory (W911NF-09-1-0446). Additional support from the NSF (CHE-0645563) and the Welch Foundation (F-0046) is also acknowledged.

### Notes and references

- 1 F. A. Leibfarth, K. M. Mattson, B. P. Fors, H. A. Collins and C. J. Hawker, *Angew. Chem., Int. Ed.*, 2013, **52**, 199.
- 2 R. S. Stoll and S. Hecht, Angew. Chem., Int. Ed., 2010, 49, 5054.
- 3 M. Tanabe, G. W. M. Vandermeulen, W. Y. Chan, P. W. Cyr, L. Vanderark, D. A. Rider and I. Manners, *Nat. Chem.*, 2006, **6**, 467.
- 4 X. Zheng, M. Yue, P. Yang, Q. Li and W. Yang, *Polym. Chem.*, 2012, 3, 1982.
- 5 B. P. Fors and C. J. Hawker, Angew. Chem., Int. Ed., 2012, 51, 8850.
- 6 For additional examples of photoswitchable controlled radical polymerizations, see: (a) Y. Kwak and K. Matyjaszewski, *Macromolecules*, 2010, 43, 5180; (b) J. Mosnáček and M. Ilčíková, *Macromolecules*, 2012, 45, 5859; (c) H. Zhou and J. A. Johnson, *Angew. Chem., Int. Ed.*, 2013, 52, 2235; (d) G. Zhang, I. Y. Song, K. H. Ahn, T. Park and W. Choi, *Macromolecules*, 2011, 44, 7594.
- 7 N. E. Kamber, W. Jeong, R. M. Waymouth, R. C. Pratt, B. G. G. Lohmeijer and J. L. Hedrick, *Chem. Rev.*, 2007, **107**, 5813.
- 8 For an elegant example of a latent photo-activated organocatalyst for ROP, see: X. Sun, J. P. Gao and Z. Y. Wang, *J. Am. Chem. Soc.*, 2008, 130, 8130.

- 9 For an example of a photo-activated and thermally-deactivated ringopening metathesis polymerization, see: A. Ben-Asuly, A. Aharoni, C. E. Diesendruck, Y. Vidavsky, I. Goldberg, B. F. Straub and N. G. Lemcoff, *Organometallics*, 2009, 28, 4652.
- For reviews on NHC-based organocatalysts, see: (a) K. Zeitler, Angew. Chem., Int. Ed., 2005, 44, 7506; (b) D. Enders, O. Niemeier and A. Henseler, Chem. Rev., 2007, 107, 5506; (c) N. Marion, S. Díez-González and S. P. Nolan, Angew. Chem., Int. Ed., 2007, 46, 2988; (d) V. Nair, S. Vellalath and B. P. Babu, Chem. Soc. Rev., 2008, 37, 2691; (e) V. Nair, R. S. Menon, A. T. Biju, C. R. Sinu, R. R. Paul, A. Jose and S. Vellalath, Chem. Soc. Rev., 2011, 40, 5336; (f) A. T. Biju, N. Kuhl and F. Glorius, Acc. Chem. Res., 2011, 44, 1182; (g) M. Fèvre, J. Pinaud, Y. Gnanou, J. Vignolle and D. Taton, Chem. Soc. Rev., 2013, 42, 2142.
- 11 (a) E. F. Connor, G. W. Nyce, M. Myers, A. Möck and J. L. Hedrick, J. Am. Chem. Soc., 2002, 124, 914; (b) G. W. Nyce, T. Glauser, E. F. Connor, A. Möck, R. M. Waymouth and J. L. Hedrick, J. Am. Chem. Soc., 2003, 125, 3046; (c) N. E. Kamber, W. Jeong, S. Gonzalez, J. L. Hedrick and R. M. Waymouth, Macromolecules, 2009, 42, 1634.
- 12 B. M. Neilson and C. W. Bielawski, J. Am. Chem. Soc., 2012, 134, 12693.
- (a) G. W. Nyce, J. A. Lamboy, E. F. Connor, R. M. Waymouth and J. L. Hedrick, Org. Lett., 2002, 4, 3587; (b) G. A. Grasa, R. M. Kissling and S. P. Nolan, Org. Lett., 2002, 4, 3583; (c) G. A. Grasa, T. Güveli, R. Singh and S. P. Nolan, J. Org. Chem., 2003, 68, 2812; (d) R. Singh, R. M. Kissling, M.-A. Letellier and S. P. Nolan, J. Org. Chem., 2004, 69, 209.
- 14 M. Movassaghi and M. A. Schmidt, Org. Lett., 2005, 7, 2453.
- 15 B. M. Neilson, V. M. Lynch and C. W. Bielawski, Angew. Chem., Int. Ed., 2011, 50, 10322.
- 16 Molecular weight and polydispersity data are reported relative to polystyrene standards in THF.
- 17 The theoretical molecular weight was based on the initial ratio of  $\epsilon$ -caprolactone to BnOH.
- 18 Conditions: [δ-valerolactone]<sub>0</sub> = 0.5 M; [BnOH]<sub>0</sub>/[**10**]<sub>0</sub> = 4; [δ-valerolactone]<sub>0</sub>/[**10**] = 250; 25 °C; 30 min; 93% conversion;  $M_n$  = 7400 Da; PDI = 1.16;  $M_n$ (theor) = 5900 Da.
- 19 All reported rate constants ( $k_{amb}$ ,  $k_{UV}$ ,  $k_{vis}$ ,  $k_{UV'}$ ) were obtained from the average of at least three separate experiments.
- 20 We have previously shown that approximately 13% of the catalyst **10** decomposes to insoluble byproduct(s) over the course of a UV ([**10**]<sub>0</sub> =  $1.0 \times 10^{-3}$ ;  $\lambda_{irr}$  = 313 nm; 1 h) and visible ( $\lambda_{irr}$  > 500 nm; 2 h) irradiation cycle; see ref. 12. The decomposition may preclude full restoration of the initial catalytic activity after irradiation.
- 21 When a control reaction was performed in the absence of **10** under ambient light, a background reaction was observed with the NaHMDS acting as the catalyst (>95% conversion in 5 min). However when an analogous reaction was exposed to UV ( $\lambda_{irr} = 313$  nm) or visible ( $\lambda_{irr} >$ 500 nm) light, no significant alteration of catalytic activity was observed (>95% conversion after 5 min in UV or visible light), indicating that light alone did not impede or promote the reaction. Similarly, UV irradiation did not alter the catalytic activity when 1,3-dimethylimidazolylidene, an NHC-based organocatalyst that was generated *in situ* from the corresponding HPF<sub>6</sub> salt and lacks a photochromic moiety, was used in lieu of **10** under otherwise identical conditions (>95% conversion after 5 min in ambient, UV, or visible light).
- 22 Although multiple distinct mechanisms have been proposed for NHC-promoted ROPs, they all result in the formation of an imidazolium alkoxide intermediate; see ref. 7 and 12.
- 23 Combining equimolar concentrations of **10** (generated *in situ*), BnOH, and  $\delta$ -valerolactone resulted in the formation of benzyl 5-hydroxypentanoate; see ESI<sup>†</sup> for additional details.
- 24 When an equimolar mixture of  $\varepsilon$ -caprolactone (1 mmol) and  $\delta$ -valerolactone (1 mmol) was added to a solution of **10** (0.01 mmol) and BnOH (0.04 mmol) in benzene (4.0 mL), complete consumption of both monomers was observed by <sup>1</sup>H NMR spectroscopy after 5 min in ambient light. After precipitation from methanol, GPC analysis revealed that the resulting polymer displayed a  $M_n$  of 14 300 Da, which was in good agreement with the theoretical molecular weight of the expected copolymer ( $M_{n(theor)} = 11300$  Da). When an identical reaction was performed in UV light ( $\lambda_{irr} = 313$  nm) negligible conversion (<5%) of either monomer was observed.
- 25 For example, photoswitchable syntheses of cyclic polyesters may be possible using 1; see: (a) W. Jeong, E. J. Shin, D. A. Culkin, J. L. Hedrick and R. M. Waymouth, J. Am. Chem. Soc., 2009, 131, 4884; (b) D. A. Culkin, W. Jeong, S. Csihony, E. D. Gomez, N. P. Balsara, J. L. Hedrick and R. M. Waymouth, Angew. Chem., Int. Ed., 2007, 46, 2627.