

Supporting Information

Reversible Ionically-crosslinked Single Chain Nanoparticle as Bioinspired and Recyclable Nanoreactors for *N*-Heterocyclic Carbene Organocatalysis

Sofiem Garmendia,^{a,b,c} Andrew P. Dove,^c Daniel Taton^a and Rachel K. O'Reilly^{*c}

^a*Laboratoire de Chimie des Polymères Organiques, Université de Bordeaux IPB-ENSCBP, F-33607 Pessac Cedex, France; Laboratoire de Chimie des Polymères Organiques Centre National de la Recherche Scientifique, 16 Avenue Pey-Berland, F-33607 Pessac Cedex, France*

^b*Department of Chemistry, University of Warwick, Coventry, CV4 7AL, UK*

^c*School of Chemistry, The University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*

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Experimental Section

Synthesis of different monomers

Synthesis of *N*-ethylbenzimidazole (1). Benzimidazole (5 g, 42.32 mmol) was dissolved in DMF (20 mL) and 4.75 g of potassium hydroxide was added (2.5 eq., 106 mmol). The solution was stirred for 15 minutes and 3.45 mL (5.07 g, 46.55 mmol) of ethyl bromide was then added drop-wise. After stirring at room temperature for 24h, the solution was diluted with 50 mL of water and extracted with dichloromethane (4 x 25 mL). The organic phases were combined, dried over MgSO₄ and evaporated, yielding a yellow viscous oil (4.93 g, 33.8 mmol, yield = 80%) ¹H NMR (DMSO-*d*₆): δ = 8.25 (s, 1H, N-CH-N), 7.69-7.20 (m, 4H, aromatics), 4.12 (t, 2H, N-CH₂-CH₃), 1.32 (t, 3H, -CH₃). ¹³C NMR (DMSO-*d*₆): δ = 144.5, 143.7, 123, 119.8, 110.0, 43.1, 14.8.

Synthesis of 4-vinylbenzylethylbenzimidazolium chloride ([ViEBIm]Cl) (2). *N*-ethylbenzimidazole **1** (4.82 g, 33 mmol) was dissolved in 25 mL of acetonitrile and 4.65 mL (1 eq. 5.03 g) of 4-vinylbenzylchloride were added into a schlenk tube. After stirring 24 h at 80 °C, the monomer was precipitated in EtOAc and dried under vacuum to remove the solvent leading to a white powder (8.87 g, 42 mmol, yield = 91%). ¹H NMR (DMSO-*d*₆): δ = 9.68 (s, 1H, N-CH-N), 8.12-7.14 (m, 8H, aromatics), 6.72 (dd, 1H, Ph-CH-CH₂), 5.95 (s, 2H, Ph-CH₂-N), 5.76 (d, 2H, CH=CH₂), 5.25 (d, 1H, CH=CH₂), 4.15 (dd, 2H, N-CH₂-CH₃), 1.31 (t, 3H, -CH₂-CH₃). ¹³C NMR (DMSO-*d*₆): δ = 142, 136.2, 135, 133.8, 131.5, 128.8, 128.7, 126.5, 126.3, 114.1, 113.5, 58.6, 44.5, 14.9.

Synthesis of 4-vinylbenzyl-PEO₁₆ (3). The hydroxy-containing polyoligo(ethylene oxide) monomethylester (CH₃O-PEO₁₆-OH, 750 g.mol⁻¹) (11.87 g, 15.82 mmol) was dissolved in THF (40 mL) and an excess of NaH (0.8 g, 40 mmol) was added slowly. After 1 hour stirring, 2.9 mL (3.14 g, 23.73 mmol) of 4- vinylbenzylchloride were added drop-wise. The reaction was stirred at rt for 24h. The excess NaH was quenched with water. After filtration an extraction with chloroform was performed. The chloroform was then removed under vacuum and the monomer purified by precipitation in cold heptane. The pure product was recovered as a yellow viscous oil (7.3 g, 8.31 mmol, yield = 70%). ¹H NMR (DMSO-*d*₆): δ = 7.4 (m, 4H, aromatics), 6.7 (dd, 1H, Ph-CH-CH₂), 5.5 (d, 2H, CH=CH₂), 4.5 (s, 2H, Ph-CH₂-O), 3.5 (m, 64H, O-CH₂-CH₂-O-), 3.22 (s, 3H, O-CH₃). ¹³C NMR (DMSO-*d*₆): δ = 137.2, 137.0, 129.6, 128.2, 114.5, 73.1, 71.5, 70.3, 70, 59.1.

Synthesis of linear precursor 4. The CTA (15 mg, $6.77 \cdot 10^{-2}$ mmol), styrene (0.860 mL, 7.53 mmol) 4-vinylbenzylethylbenzimidazolium chloride (570 mg, 1.89 mmol), 4-vinylbenzoic acid (280 mg, 1.89 mmol), 4-vinylbenzyl-PEO₁₆ (1.8 g, 2.025 mmol), and AIBN (11.12 mg, $6.77 \cdot 10^{-2}$ mmol) were dissolved in methanol. The solution was degassed by five successive freeze-pump cycles and stirred for 24 h at 80 °C. The obtained copolymer was purified by dialysis against methanol (3.5 kDa MWCO dialysis membrane) and obtained as a pink powder (1.134 g); conversion = 40%, yield = 33%, (**Figure S1A, 2A**).

Synthesis of SCNP 5. Polymer 4 (1 g) was dissolved in 1 L of dry MeOH and a large excess (10 eq.) of trimethylamine (TEA) was added in a Schlenk flask. The solution was stirred at rt for 24 h and then the solvent was evaporated and polymer dialyzed leading to SCNP 5 (880 mg, yield = 90%). (**Fig. S.1B, 2B, 3**)

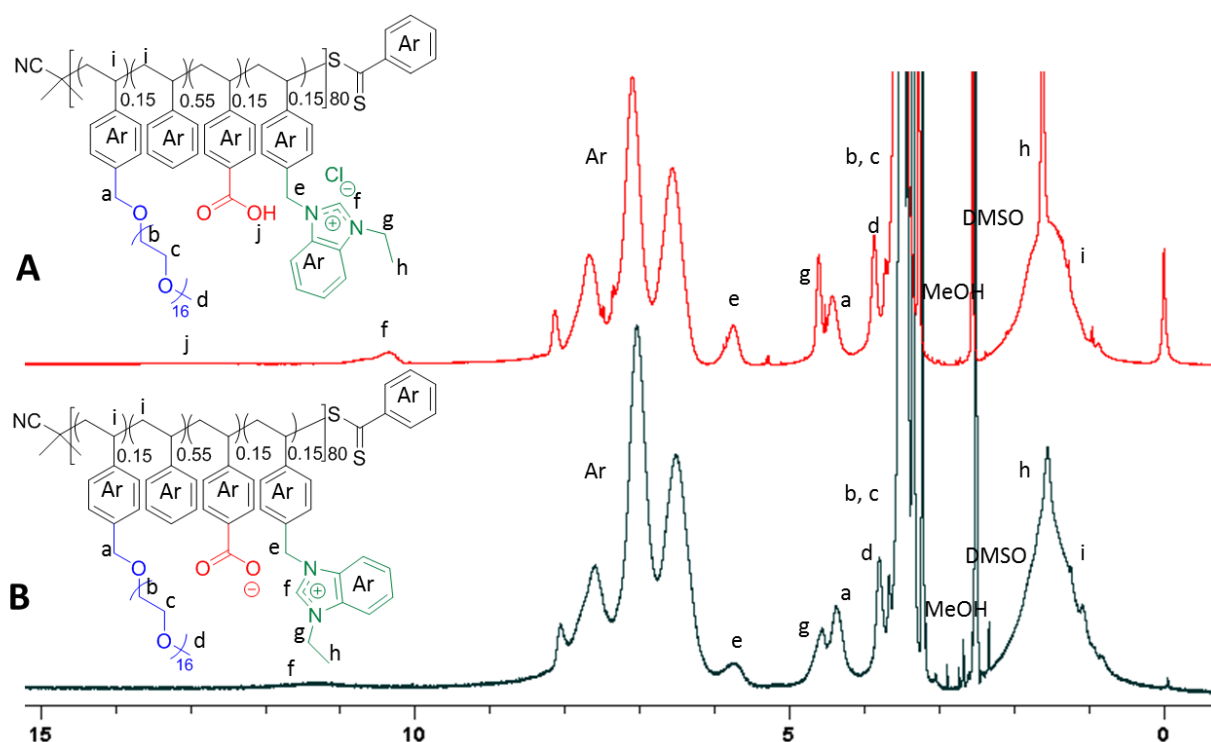


Figure S1: ¹H NMR spectrum in DMSO-*d*₆ of linear precursor 4 (A) and SCNP 5 (B) after folding.

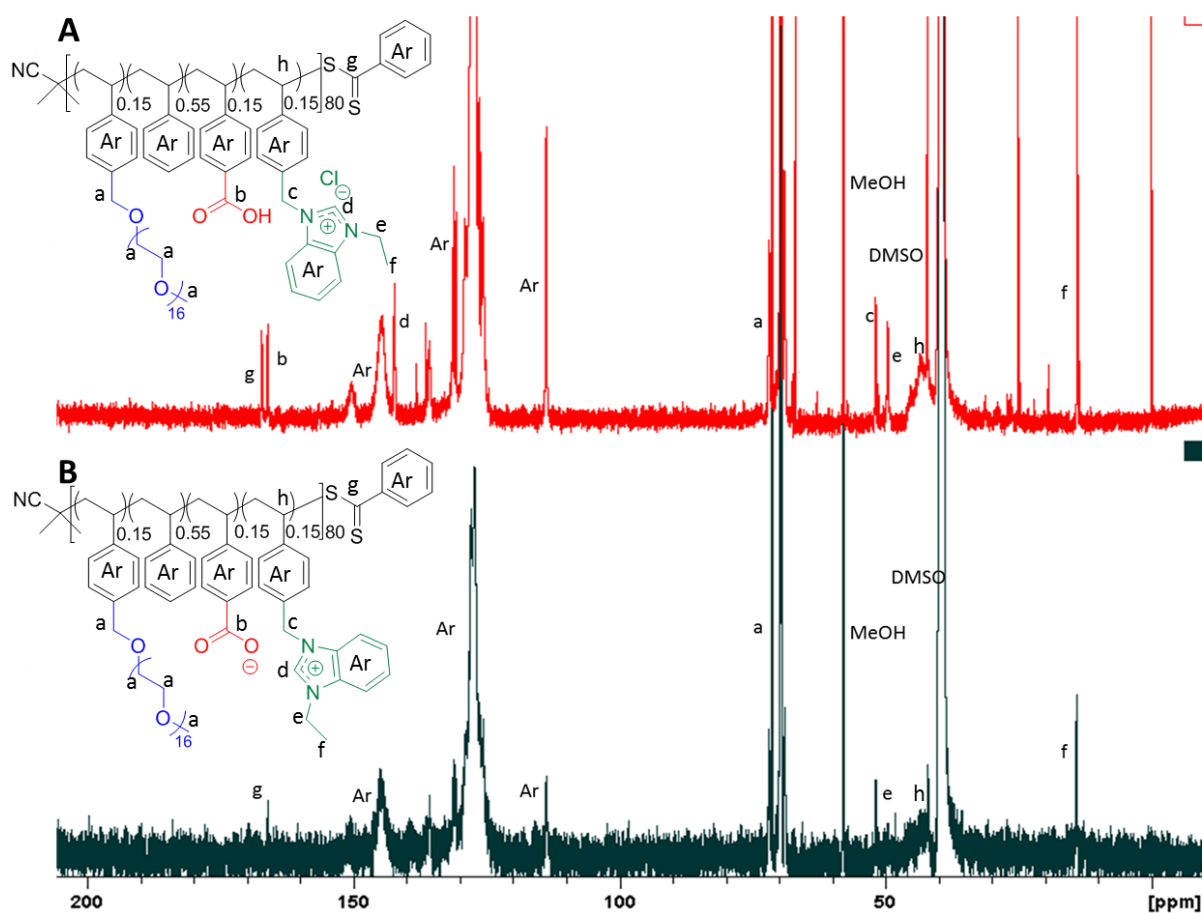


Figure S2: ^{13}C NMR spectrum in $\text{DMSO-}d_6$ of linear precursor **4** (A) and SCNP **5** (B) after folding.

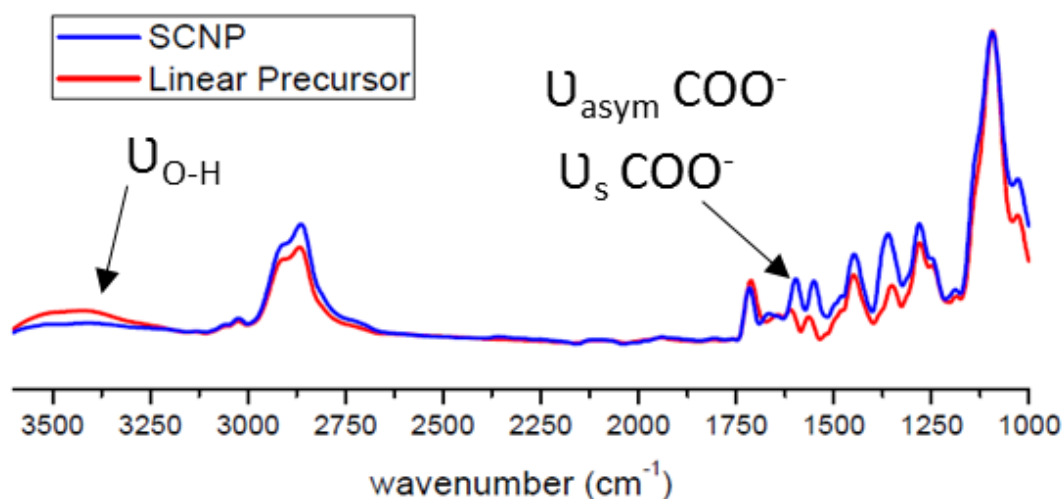


Figure S3: Attenuated total reflection Fourier transform infrared (ATR-FTIR) analysis for linear starting copolymeric precursor **4** (red) and folded SCNP **5** (blue).

Synthesis of coPILs 6: Because the NHC active version took part in the thermal equilibrium in the presence of the corresponding acid and the correspondent electrostatic interactions, the separation and further isolation was not possible. Thus, an indirect method to prove the

generation of the active NHC was performed using CS₂ electrophilic reagent to irreversibly form the NHC-CS₂ adduct. For this purpose, SCNPs **5** (155 mg) were dissolved in 2 mL of dry THF and a large excess of CS₂ (0.4 mL) was added into the Schlenk tube. After 24 h stirring at 80 °C the solution was cooled down and the excess of CS₂ and THF removed under reduced pressure. Polymer **6** was obtained as a red viscous oil (165 mg, yield >95%), (**Fig. S4**)

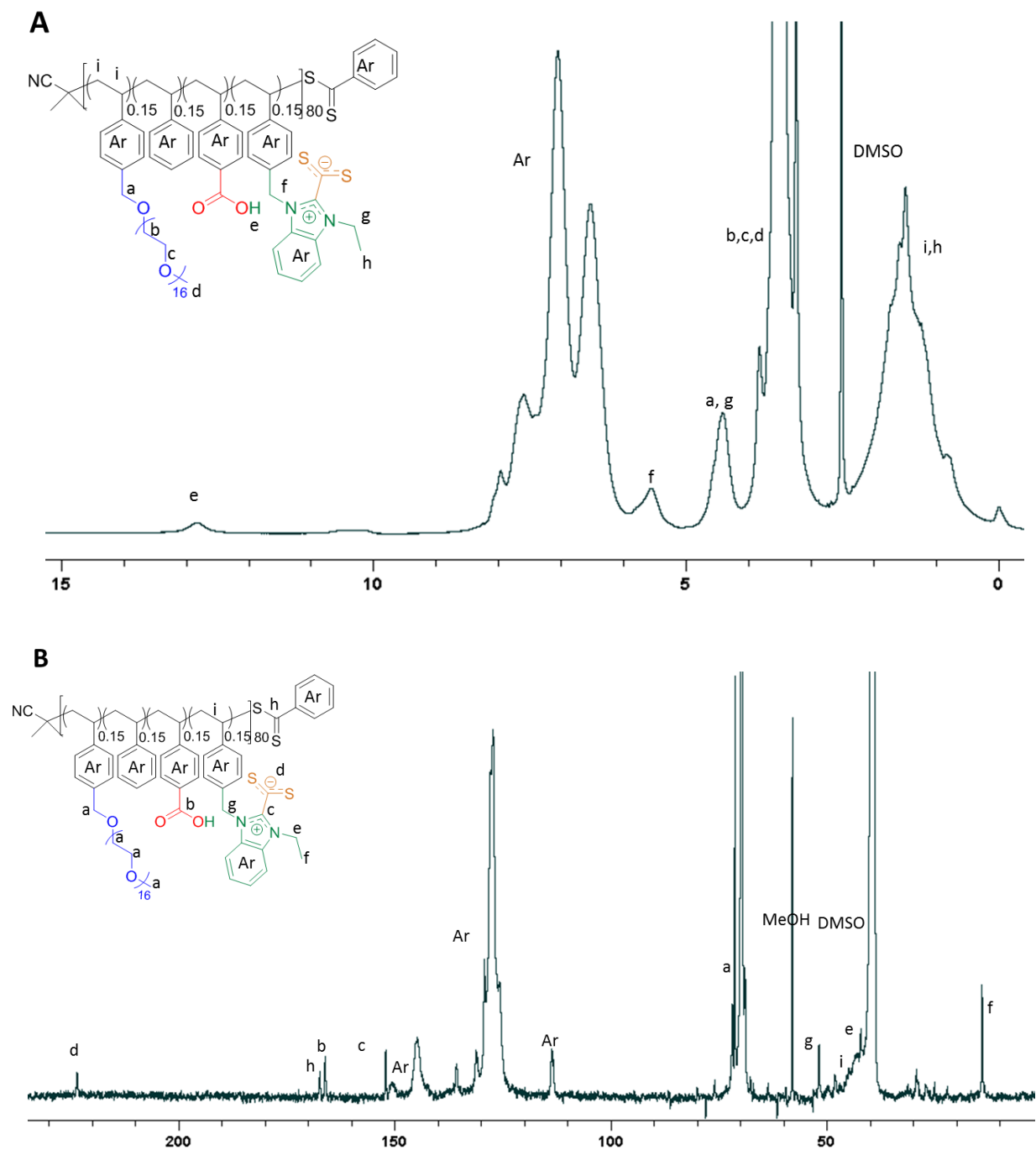
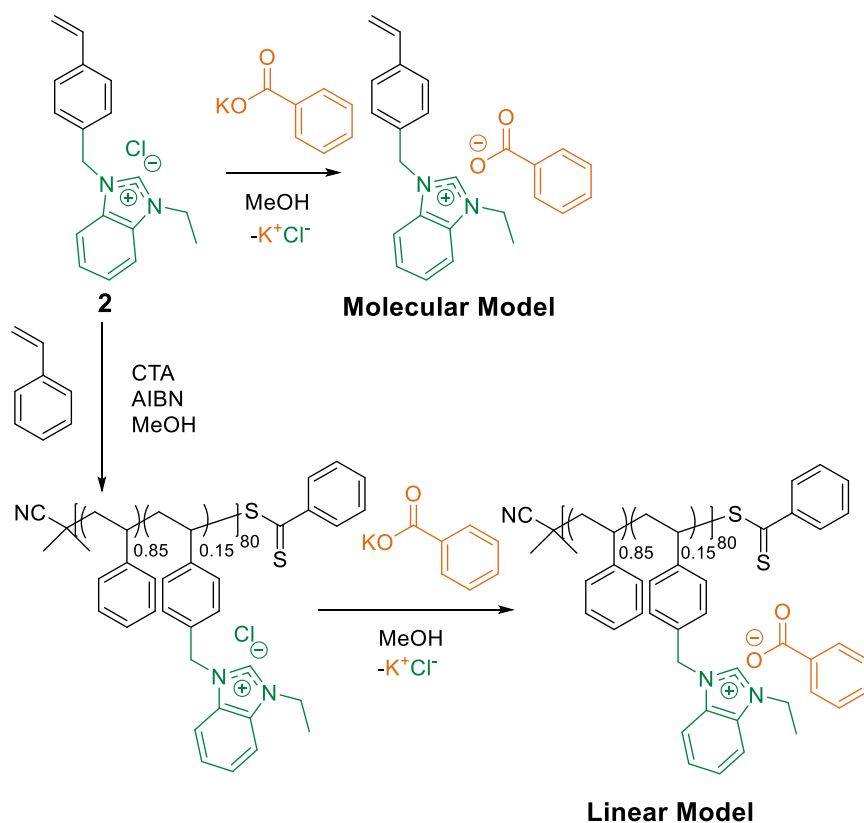


Figure S4: ¹H NMR (**A**) ¹³C NMR (**B**) spectra of CS₂ post-functionalization reaction in SCNP **6** in DMSO-*d*₆.

Synthesis of model catalysts



Scheme S1. Synthetic route to prepare molecular catalyst model based on the active monomer and linear catalyst model.

Synthesis of molecular model. Previously prepared 1.67 mmol of monomer **2** (500 mg) were dissolved in methanol and 1.84 mmol (1.1 eq, 180 mg) of potassium benzoate was added and let stirring overnight. The solution was filtered to remove KCl and dried under vacuum (590 mg; yield : >95%) (**Fig. S5**)

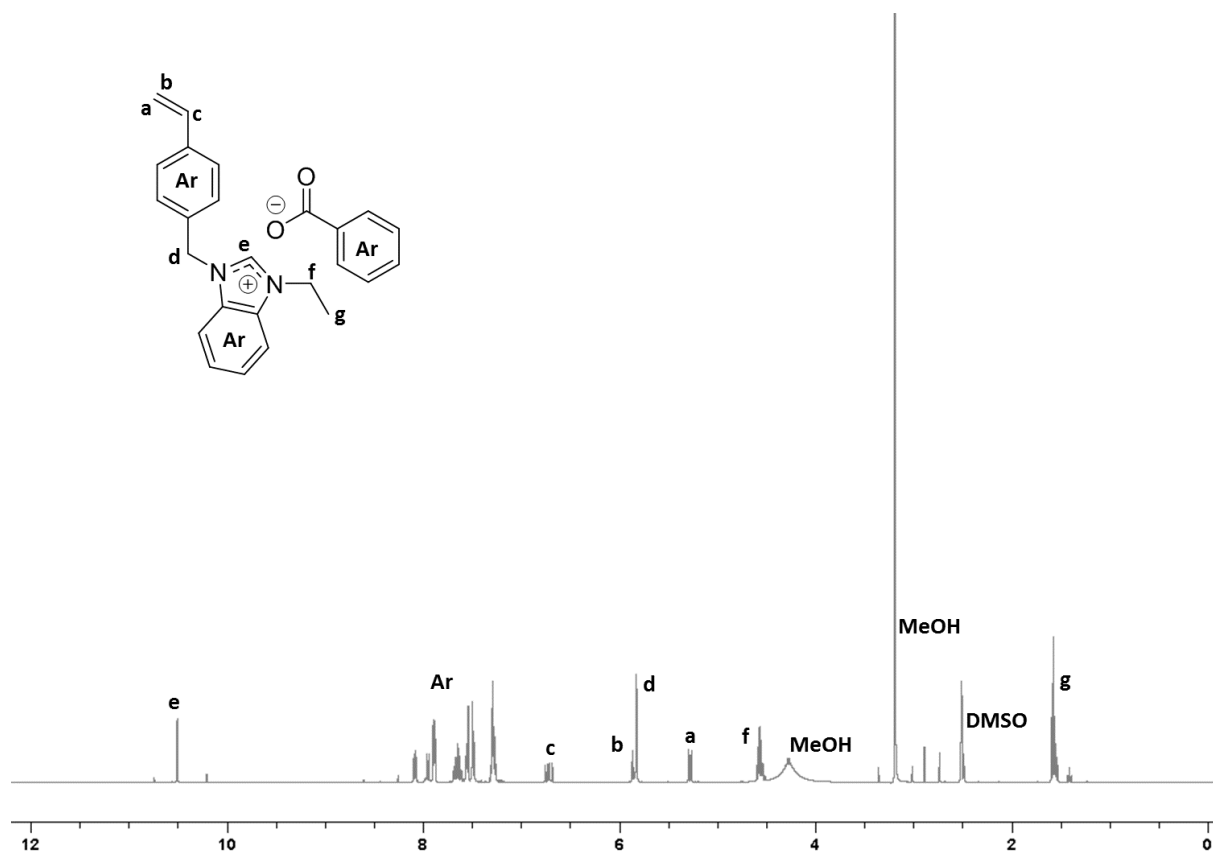


Figure S5. ^1H NMR spectrum of molecular model catalyst in $\text{DMSO-}d_6$.

Synthesis of linear copolymer model 2-cyano-2-propyl benzodithioate CTA (30 mg, 0.13 mmol), styrene (2.64 mL, 23 mmol) 4-vinylbenzylethylbenzimidazolium chloride (1.21 mg, 4 mmol) and AIBN (27 mg, 0.11 mmol) were dissolved in methanol. The solution was degassed by five successive freeze-pump cycles and stirred for 17 h at 80 °C. The copolymer was then purified by dialysis against methanol (3.5 kDa dialysis membrane) and obtained as a pink powder (m = 1.77 g); conversion = 46%, yield = 39%.

1 g of chloride-containing linear copolymer **4** was subjected to anion exchange to insert the acetate basic counter anion using potassium acetate (1 eq.; 0.7 g). The reaction was left to stir overnight, filtered and dialyzed against methanol (3.5 kDa pore cut off). Conversion = >95%; Yield; 90%; m = 0.92 g (**Fig. S6, S7**)

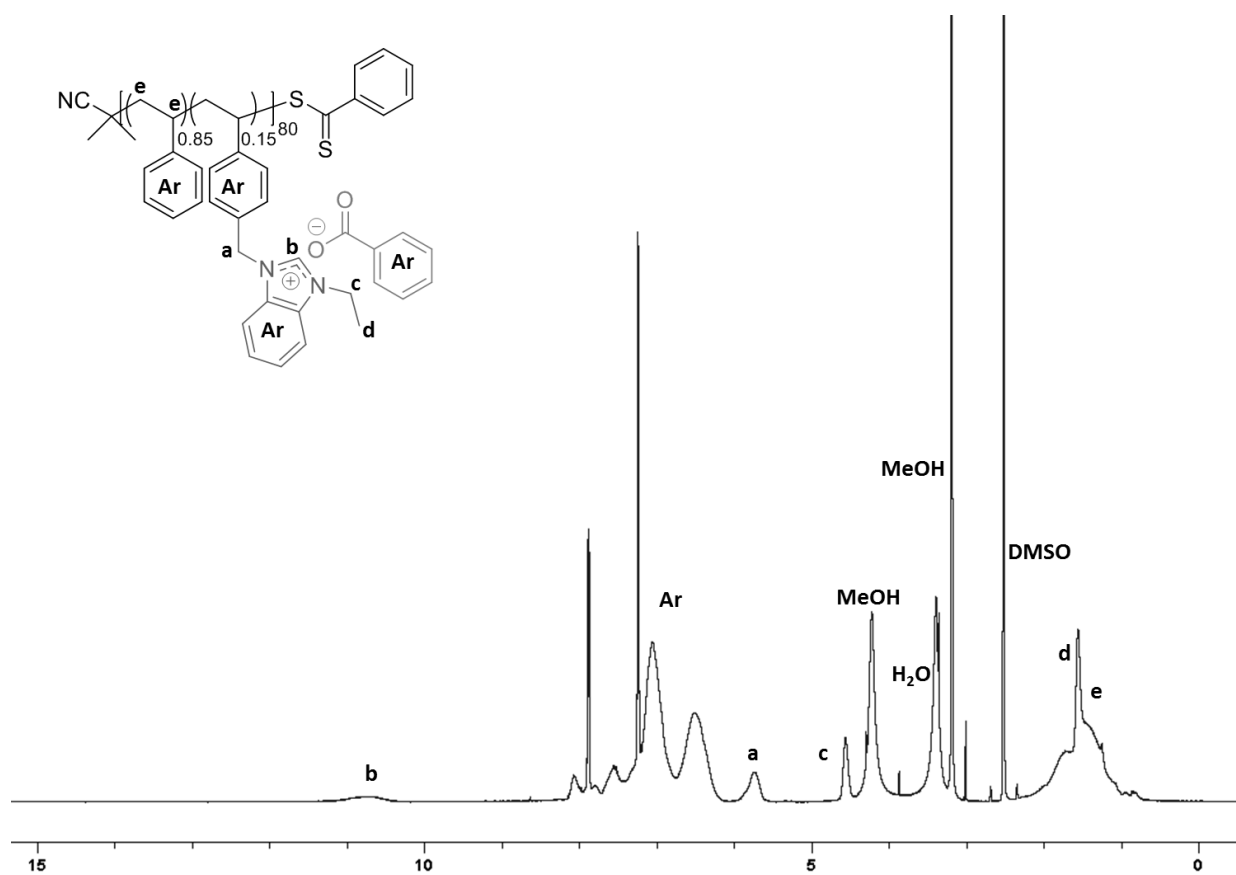


Figure S6. ^1H NMR spectrum of catalyst linear copolymer model in $\text{DMSO-}d_6$.

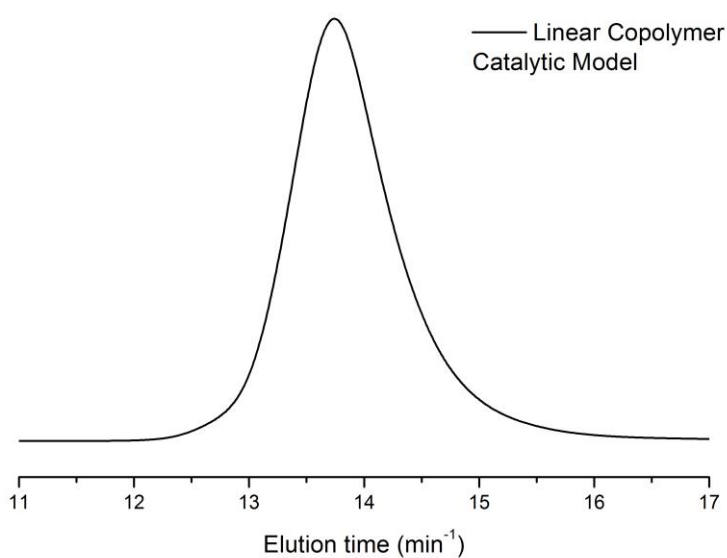


Figure S7. SEC traces of Linear Copolymer model (in Cl^- anion form) in DMF (10 mM ammonium tetrafluoroborate) with RI detector ($\langle D \rangle = 1.18$; $M_n = 14.8$ kDa; Universal calibration).

Organocatalysis applying SCNP and different models In a typical experiment, 10 mol% of dry **5** (100 mg) (based on benzimidazolium) was introduced in a Schlenk tube. A 4 mL portion of solvent (THF or water) were then added, followed by benzaldehyde (0.05 mL; 0.5 mmol). The reaction mixture was stirred for 24 h at 80 °C. The mixture was allowed to cool to room temperature. An aliquot of the solution was analyzed by ^1H NMR in $\text{DMSO-}d_6$. Benzoin conversion was determined by ^1H NMR in $\text{DMSO-}d_6$ by comparing the integral value of the aldehyde signal of benzaldehyde (d, 10 ppm) with that of the $-\text{CH}-$ benzoin signal (s, 6 ppm; **Fig. S8-9**). For the molecular and polymer models the same conditions were used in catalyst concentration (referred to active catalyst part) and conversion calculated equally. In the case of the linear copolymer model, both the $-\text{CH}-$ (d, 6.1 ppm) and $-\text{OH}$ (d, 6.04 ppm) were observed and therefore only the one corresponding to $-\text{CH}-$ was integrated (**Fig. S10**).

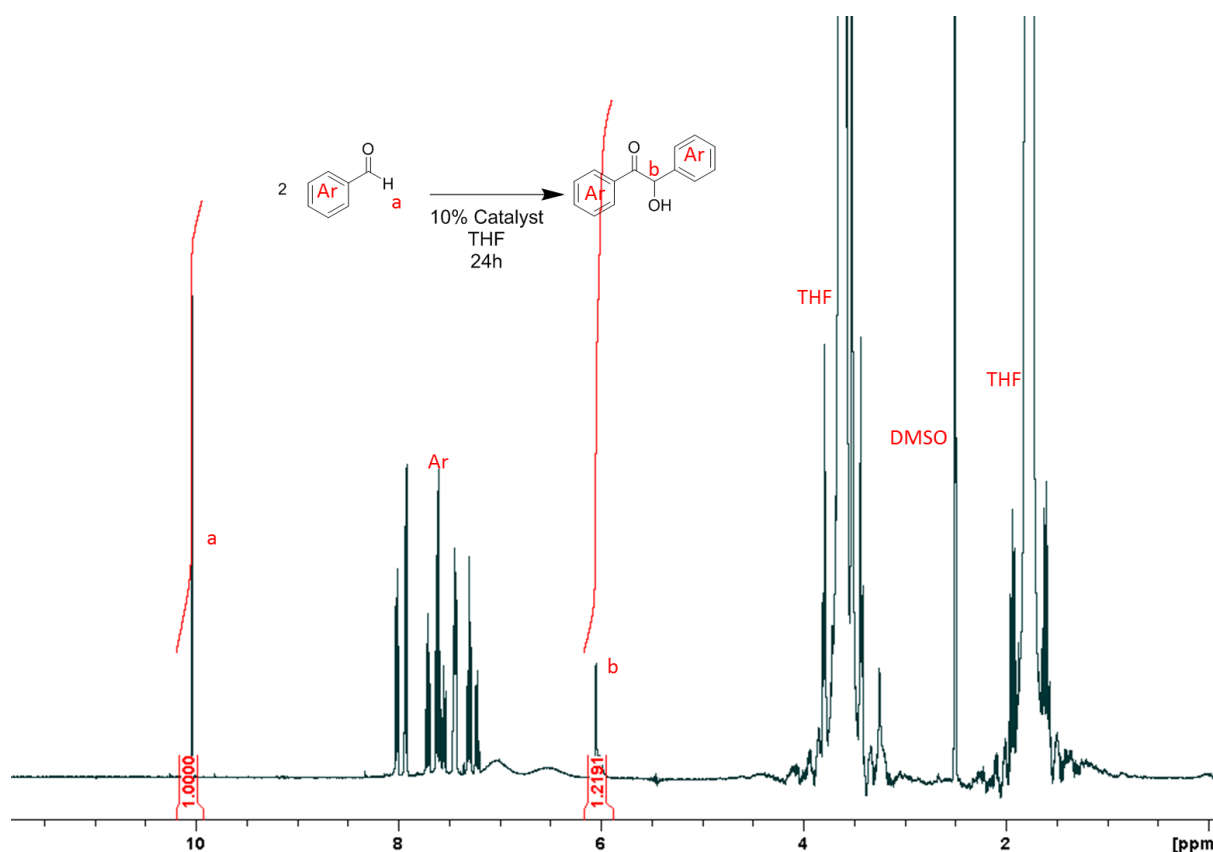


Figure S8. Reaction of benzoin condensation with benzaldehyde catalyzed by SCNP **5** and conversion obtained ^1H NMR spectroscopy in $\text{DMSO-}d_6$.

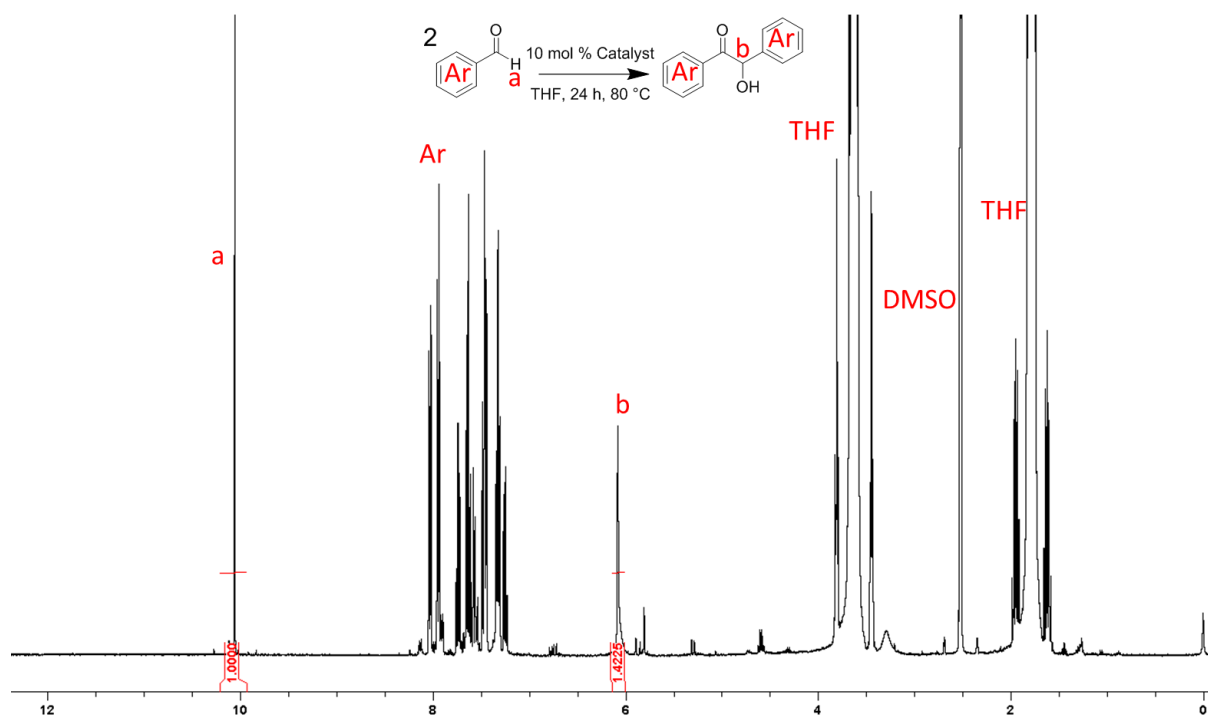


Figure S9. Reaction of benzoin condensation with benzaldehyde catalyzed by molecular model and conversion obtained ^1H NMR spectroscopy in $\text{DMSO-}d_6$.

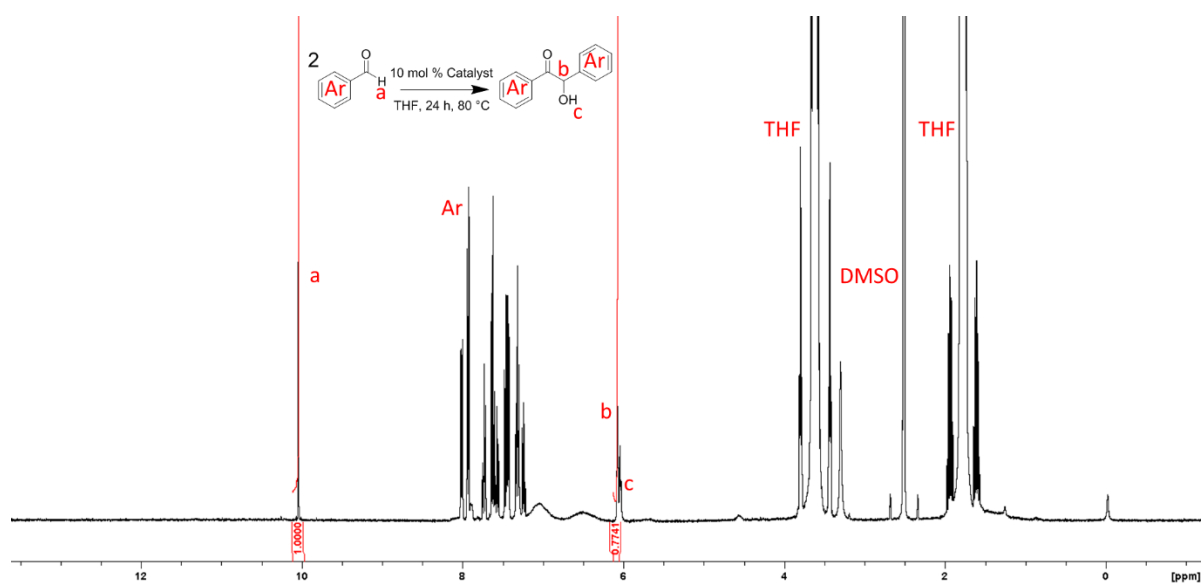


Figure S10. Reaction of benzoin condensation with benzaldehyde catalyzed by linear copolymer model and conversion obtained ^1H NMR spectroscopy in $\text{DMSO-}d_6$.

Basic-anion dependence for catalysis

A control experiment was performed with the polymeric linear precursor **4**, to validate the predominant role and need for basic carboxylate counter-anion to generate *in situ* the catalytic poly-NHC species. Thus, the anion-exchange procedure for folding would also provide the

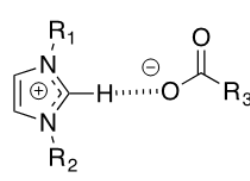
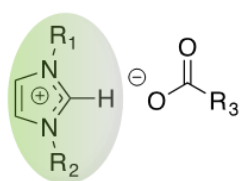
presence of an acetate-derivative basic anion to deprotonate the (benz)imidazolium units upon heating, forming catalytic NHC active species. A benzoin condensation catalysis experiment was performed using the same amount of catalyst (10 mol.%) of the linear precursor **4** using the same concentration (20 mg/ml catalyst). After 24 h at 80 °C, no conversion of benzoin was seen, clearly indicating the main role of the anion in its form of carboxylate. Therefore, rendering the benzoic acid into an acetate-derivate was proven to be a critical step, for both the SCNPs folding and the SCNPs catalytic activity.

Thermally latent behavior (of SCNP 5)

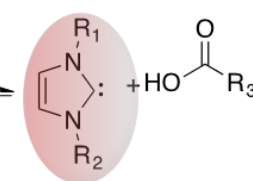
The generation of momentary NHC active species is ruled by the equilibrium displayed below, favoring the active species formation upon heating. To verify the need for heating during catalysis due to the thermally latent behavior of SCNPs as nanoreactors, a control experiment was carried out at room temperature conditions. In other words, in this experiment the same conditions were used as in a typical benzoin condensation using SCNP **5**, but simply switching the temperature from 80 °C to room temperature. After 24 h, no catalyzed product (benzoin) was observed, revealing the importance of heating the system to displacing the equilibrium towards the active NHC species.

In addition, cooling down the system lead a deactivation of the NHC towards the masked form, allowing a much easier handling and storage of the precatalyst as well as a facile recycling.

Masked NHC



Active NHC



The active NHC generation was triggered by increasing the temperature. However, the 3-D structure of SCNP **5** was crosslinked via ionic interactions which served as catalyst at the same time. In order to prove that different SCNPs were not undergoing aggregation or any intermolecular rearrangement due to crosslink scissions, a Multi-T DLS analysis, setting a temperature range from 20 to 80 °C in THF was carried out. As it is depicted in **Fig. S11**, SCNP **5** mean diameter (in both volume (black line) and number (red line) remained relatively constant in the mentioned temperature range (*i.e.* 8 nm (in number) and 12 nm (in volume)).

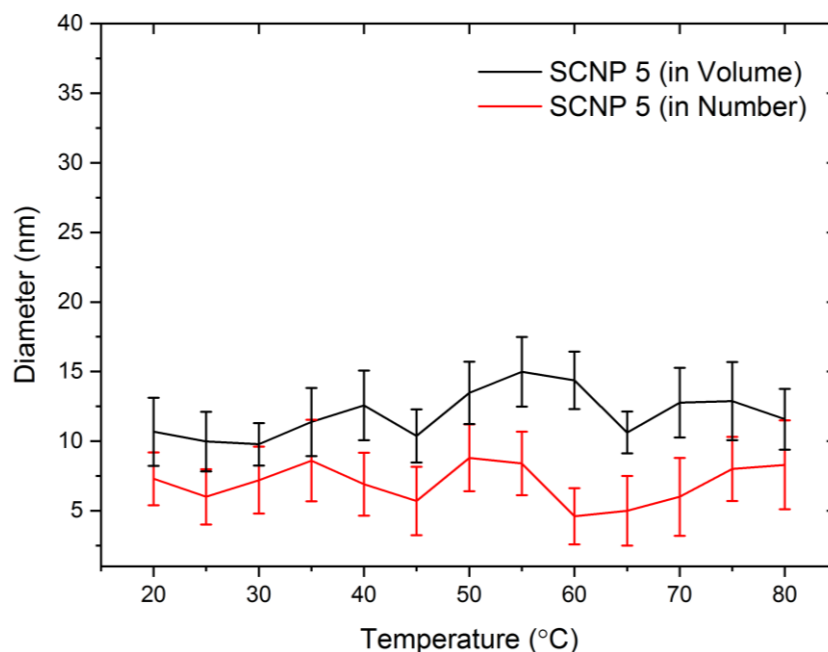


Figure S11. Multi-T DLS analysis of SCNP **5** from 20 to 80 °C in THF with volume (black line) and number (red line) distributions (Conc: 5 mg/mL).

Diffusion Ordered Spectroscopy

Molecules are distinguished according to their diffusion, which correlates with their hydrodynamic radius. Samples of polymer **4** as well as the SCNP **5**, were analyzed in DMSO- d_6 employing the conditions displayed in experimental part. Calculation of the diameter, applying the Stokes-Einstein-Equation.

Stokes-Einstein-Equation:

$$D = \frac{kT}{6\pi\eta r}$$

$$k = 1.38 \times 10^{-23} \text{ J.K}^{-1}$$

$$D = 3.14 \cdot 10^{-11} \text{ m}^2/\text{s}$$

$$T = 298 \text{ K}$$

$$\eta \text{ DMSO viscosity} = 1.99 \cdot 10^{-3} \text{ Pa.s}$$

$$R = 3.5 \text{ nm } D = 7 \text{ nm (SCNP 5)}$$

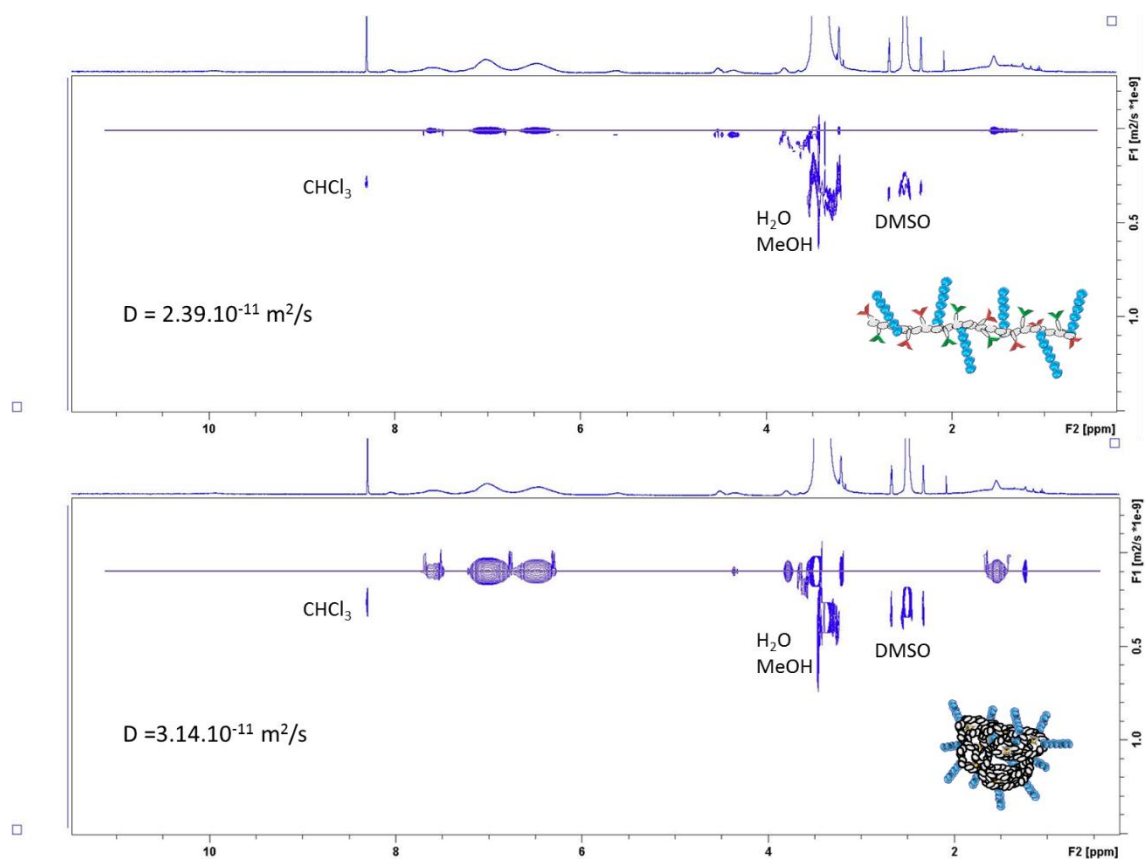


Figure S12. Original figure of DOSY measurements of the precursor copolymer **4** and SCNP **5**, recorded in $\text{DMSO-}d_6$.

Waterborne catalysis conditions

PEG-based side-oligopolymers were incorporated along the (co)polymer chain to render this system soluble in water. When a ^1H NMR analysis experiment was performed using D_2O as deuterated solvent, only the PEG side chains were observed due to the external conformation of the SCNP **5** (Fig. S13).

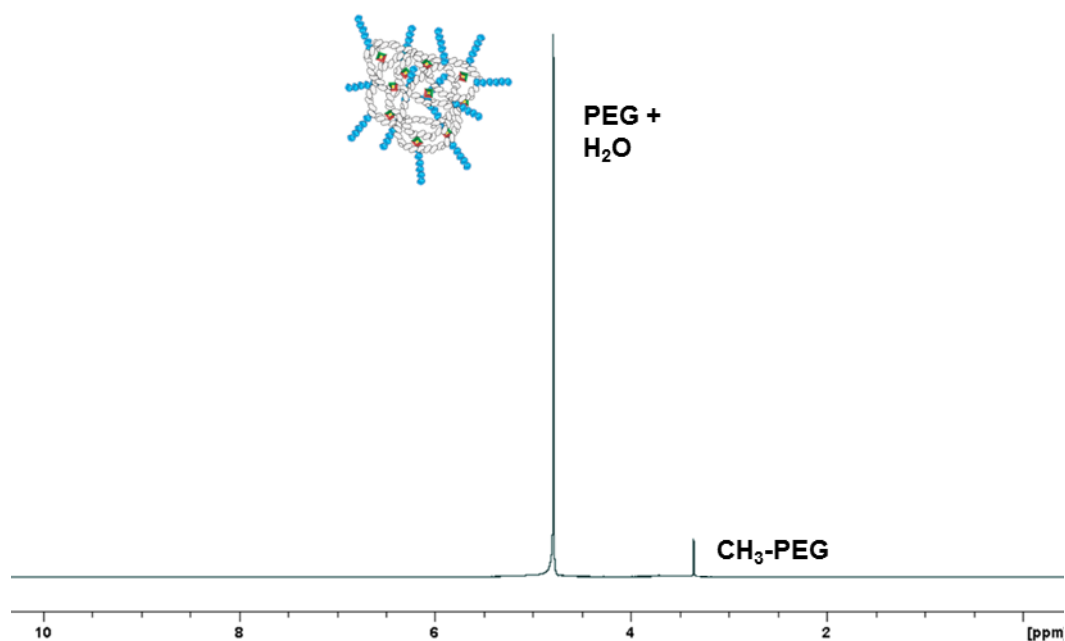


Figure S13. ^1H NMR spectra of the SCNP **5** in D_2O .

Despite the water stability of the SCNP, in the benzoin condensation reaction the SCNP did not show any catalytic activity, making this system not suitable for these conditions. Further investigations were performed increasing the temperature to $100\text{ }^\circ\text{C}$, increasing the concentration of the catalyst up to 150 mg/mL or performing the catalysis in different $\text{H}_2\text{O}/\text{THF}$ proportions. Neither of these variations showed any improvement. Therefore, despite the relative incompatibility of ions (charges) in an relatively apolar solvent such as THF, thanks to high amount of styrenic units and the PEG-side chains, SCNP resulted a homogeneous catalyst and yet relatively easy to recycle as detailed previously.