

*Electronic Supplementary Information*

**Self-Assembly of a Redox-Active Bolaamphiphile into  
Supramolecular Vesicles**

Simon Rothenbühler, Caroline D. Bösch, Simon M. Langenegger, Shi-Xia Liu and  
Robert Häner\*

Department of Chemistry and Biochemistry, University of Bern, Freiestrasse 3, 3012  
Bern, Switzerland

\*email: robert.haener@dcb.unibe.ch

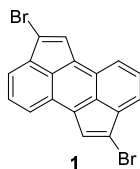
Table of contents

1. General methods	S2
2. Organic synthesis	S3
3. NMR spectra	S6
4. UV-vis spectra	S11
5. AFM measurements	S13
6. TEM measurements	S16
7. Dynamic light scattering	S17
8. Cyclic voltammetry	S19
Bibliography	S20

## 1. General methods

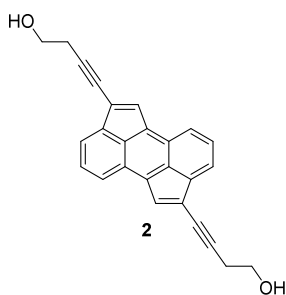
All reagents and solvents were purchased from commercial suppliers and used without further purification. All reactions were accomplished under argon atmosphere using anhydrous solvents. Flash column chromatography was performed on silica gel, pore size 60 Å, 230-400 mesh particle size. Water was used from a Milli-Q system. NMR spectra were either obtained on a Bruker Avance III HD (300 MHz) or on a Bruker Avance II (400 MHz) spectrometer at 298 K. Mass spectra were obtained on a Thermo Fisher LTQ Orbitrap XL using Nano Electrospray Ionization (NSI) from the Analytical Research and Services (ARS) of the University of Bern. UV-vis spectra were recorded on an Agilent Cary 100 spectrophotometer using quartz cuvettes with an optical path of 1 cm. Dynamic light scattering (DLS) experiments were performed on a Malvern Zetasizer Nano Series instrument ( $\lambda = 633$  nm) in particle size distribution (PSD) mode (*number value*). The accuracy of the instrument was verified with latex beads in H<sub>2</sub>O that exhibit an average diameter of 100 nm. Spectroscopic data were collected from at least five minutes thermally equilibrated samples at the corresponding temperature. Cyclic voltammetry (CV) was operated on a Metrohm 663 VA Stand with an Autolab Potentiostat 101 using a glassy carbon working electrode, glassy carbon counter electrode, and an Ag/AgCl reference electrode at a scan rate of 100 mV/s. The oxidation potential of Fc<sup>+</sup>/Fc against Ag/AgCl was recorded in a NaClO<sub>4</sub>-EtOH (0.1 M) solution to be 0.52 V, therefore the onset of the reduction potential is converted to Fc<sup>+</sup>/Fc by subtracting 0.52 V from the corresponding Ag/AgCl value. Prior to each CV measurement, the sample was degassed with argon for at least 30 seconds and equilibrated afterwards for 5 seconds. Supramolecular polymerization of the vesicles proceeded *via* thermal disassembly and reassembly: the sample solution was heated to 75 °C in a heating block (Eppendorf Thermomixer Compact) while shaking (550 rpm), equilibrated at this temperature for 5 minutes, before the thermomixer was switched off. The sample was left in the heating block and slowly cooled to room temperature over a period of approximately 2 hours.

## 2. Organic synthesis



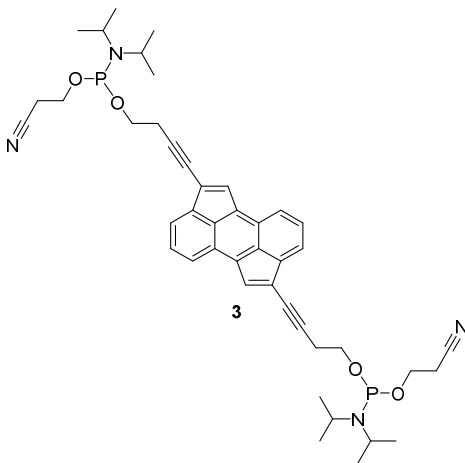
Organic synthesis of compound **1** followed published procedures starting with the commercially available 9,10-dibromoanthracene.<sup>1</sup>

### 4,4'-(Cyclopenta[hi]aceanthrylene-2,7-diyl)bis(but-3-yn-1-ol) (**2**)



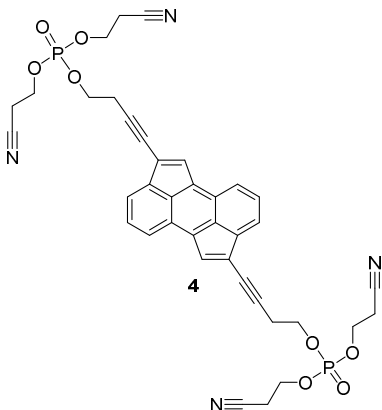
2,7-Dibromocyclopenta[hi]aceanthrylene **1** (741.9 mg, 1.93 mmol), Pd(PhCN)<sub>2</sub>Cl<sub>2</sub> (45.6 mg, 0.12 mmol), and CuI (23.1 mg, 0.12 mmol) were placed in a flask and dissolved in toluene (44 mL). Diisopropylamine (4.8 mL), P<sup>t</sup>Bu<sub>3</sub> (0.23 mL of a 1 M solution in toluene), and 3-butyn-1-ol (306.9 mg, 0.33 mL, 4.38 mmol) were then added. The black reaction mixture was heated to 50 °C and stirred at this temperature for 44 h until TLC (DCM/toluene/<sup>i</sup>PrOH 87:10:3) showed disappearance of the starting material **1**. After the solvent was removed *in vacuo*, the residue was dissolved in a minimal volume of THF (20 mL) and precipitated into an excess of cold MeOH. The solid was filtered off and washed with cold MeOH to yield compound **2** as a black solid (559.3 mg, 1.54 mmol, 80%). <sup>1</sup>H NMR (300 MHz, DMSO) δ 8.41 (d, *J* = 8.4 Hz, 2H, Ar*H*), 7.96 (d, *J* = 6.5 Hz, 2H, Ar*H*), 7.85 (s, 2H, Ar*H*), 7.81 (dd, *J* = 8.4, 6.6 Hz, 2H, Ar*H*), 5.00 (t, *J* = 5.6 Hz, 2H, RO*H*), 3.69 (td, *J* = 6.8, 5.6 Hz, 4H, RCH<sub>2</sub>OH), 2.74 (t, *J* = 6.8 Hz, 4H, RC≡CCH<sub>2</sub>). <sup>13</sup>C NMR (101 MHz, DMSO) δ 139.77, 137.30, 129.90, 129.69, 126.71, 126.69, 125.59, 123.68, 123.12, 96.86, 76.86, 59.86, 24.00. HRMS-NSI (*m/z*): [M+Na]<sup>+</sup> calcd for C<sub>26</sub>H<sub>18</sub>O<sub>2</sub>Na, 385.1199; found, 385.1204.

**Bis(2-cyanoethyl) (cyclopenta[hi]aceanthrylene-2,7-diylbis(but-3-yne-4,1-diyl)) bis (diisopropylphosphoramidite) (3)**



Compound **2** (201.0 mg, 0.55 mmol) was dissolved in toluene (7 mL), 1,2-dichloroethane (2 mL), and DIPEA (0.38 mL). 2-Cyanoethyl *N,N*-diisopropylchlorophosphoramidite (282.3 mg, 1.19 mmol) was added dropwise and the reaction mixture was stirred at room temperature for 1 h until TLC (hexane/ethyl acetate 7:3 + 1% Et<sub>3</sub>N) showed completion of the reaction. The intense, dark-green reaction mixture was concentrated *in vacuo* and the resulting residue was purified by a short silica gel flash column chromatography (hexane/ethyl acetate 7:3 + 1% Et<sub>3</sub>N). Compound **3** was isolated as a dark-green solid (186.1 mg, 0.24 mmol, 44%). <sup>1</sup>H NMR (300 MHz, DMSO) δ 8.42 (d, *J* = 8.4 Hz, 2H, ArH), 7.96 (d, *J* = 6.6 Hz, 2H, ArH), 7.85 (s, 2H, ArH), 7.81 (dd, *J* = 8.3, 6.7 Hz, 2H, ArH), 3.91 – 3.76 (m, 8H, RCH<sub>2</sub>OP, POCH<sub>2</sub>CH<sub>2</sub>CN), 3.67 – 3.58 (m, 4H, NCH(CH<sub>3</sub>)<sub>2</sub>), 2.91 (t, *J* = 6.4 Hz, 4H, RC≡CCH<sub>2</sub>), 2.81 (t, *J* = 5.8 Hz, 4H, RCH<sub>2</sub>CN), 1.17 (dd, *J* = 6.8, 4.9 Hz, 24H, NCH(CH<sub>3</sub>)<sub>2</sub>). <sup>13</sup>C NMR was difficult due to solubility. <sup>31</sup>P NMR (121 MHz, DMSO) δ 147.15. HRMS-NSI (*m/z*): [M+H]<sup>+</sup> calcd for C<sub>44</sub>H<sub>53</sub>O<sub>4</sub>N<sub>4</sub>P<sub>2</sub>, 763.3537; found, 763.3590.

**Tetrakis(2-cyanoethyl) (cyclopenta[hi]aceanthrylene-2,7-diylbis(but-3-yne-4,1-diyl)) bis(phosphate) (4)**

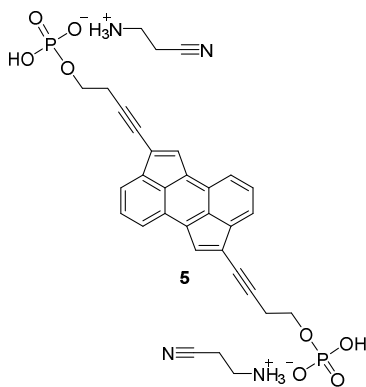


To a solution of compound **3** (68.7 mg, 0.09 mmol) in 1,2-dichloroethane (0.6 mL), was added 3-hydroxypropionitrile (104.5 mg, 0.1 mL, 1.47 mmol), followed by a solution of 5-(ethylthio)-1*H*-tetrazole (39.4 mg, 0.30 mmol) in 1,2-dichloroethane (1.2 mL). The intense, dark-green reaction mixture was stirred at room temperature for 30 min until TLC (CHCl<sub>3</sub>/MeOH



96:4) showed disappearance of the starting material **3**. *Tert*-butyl hydroperoxide solution (70 wt% in H<sub>2</sub>O, 80  $\mu$ L) was then added and the reaction mixture was stirred at room temperature for further 30 min. TLC (CHCl<sub>3</sub>/MeOH 96:4) showed completion of the oxidation step and the reaction mixture was diluted with CHCl<sub>3</sub> (50 mL). The organic layer was washed three times with saturated NaHCO<sub>3</sub> (50 mL), once with brine (50 mL), dried over MgSO<sub>4</sub>, filtered, and the solvent was removed *in vacuo*. The residue was purified by flash column chromatography on silica gel (CHCl<sub>3</sub>/MeOH 96:4) to afford **4** as a dark-green solid (20.5 mg, 0.028 mmol, 31%). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  8.15 (d, *J* = 8.4 Hz, 2H, Ar*H*), 7.90 (d, *J* = 6.6 Hz, 2H, Ar*H*), 7.70 (dd, *J* = 8.5, 6.6 Hz, 2H, Ar*H*), 7.61 (s, 2H, Ar*H*), 4.41 (dt, *J* = 8.0, 6.5 Hz, 4H, RCH<sub>2</sub>OP), 4.34 (dt, *J* = 8.2, 6.1 Hz, 8H, POCH<sub>2</sub>CH<sub>2</sub>CN), 3.03 (t, *J* = 6.5 Hz, 4H, RC $\equiv$ CCH<sub>2</sub>), 2.77 (td, *J* = 6.1, 1.0 Hz, 8H, RCH<sub>2</sub>CN). <sup>13</sup>C NMR (101 MHz, CDCl<sub>3</sub>)  $\delta$  140.40, 137.81, 130.57, 129.46, 127.80, 126.42, 125.48, 124.37, 122.97, 116.45, 92.29, 78.58, 66.66 (d, *J*<sub>C,P</sub> = 6.0 Hz), 62.52 (d, *J*<sub>C,P</sub> = 5.3 Hz), 22.42 (d, *J*<sub>C,P</sub> = 7.2 Hz), 19.85 (d, *J*<sub>C,P</sub> = 7.2 Hz). <sup>31</sup>P NMR (121 MHz, CDCl<sub>3</sub>)  $\delta$  -2.55. HRMS-NSI (*m/z*): [M+H]<sup>+</sup> calcd for C<sub>38</sub>H<sub>33</sub>O<sub>8</sub>N<sub>4</sub>P<sub>2</sub>, 735.1768; found, 735.1785.

**Bis(2-cyanoethyl ammonium) cyclopenta[hi]aceanthrylene-2,7-diylbis(but-3-yne-4,1-diyl) bis(hydrogen phosphate) (**5**)**



Compound **4** (20.5 mg, 0.028 mmol) was dissolved in a 2 M ammonia solution in MeOH (5 mL) and stirred at room temperature for 1 h until TLC (CHCl<sub>3</sub>/MeOH 9:1) showed no remaining starting material **4**. The intense, dark-green reaction mixture was concentrated to dryness *in vacuo*. Compound **5** was isolated as a dark-green powder (18.4 mg, 0.028 mmol, quant.). <sup>1</sup>H NMR (300 MHz, MeOD)  $\delta$  8.18 (d, *J* = 8.4 Hz, 2H, Ar*H*), 7.87 (d, *J* = 6.2 Hz, 2H, Ar*H*), 7.70 (dd, *J* = 8.5, 6.7 Hz, 2H, Ar*H*), 7.57 (s, 2H, Ar*H*), 4.17 (t, *J* = 6.9 Hz, 4H, NCH<sub>2</sub>CH<sub>2</sub>CN), 4.11 (dt, *J* = 7.2, 6.2 Hz, 4H, RCH<sub>2</sub>OP), 2.97 (t, *J* = 6.8 Hz, 4H, RC $\equiv$ CCH<sub>2</sub>), 2.80 (t, *J* = 6.1 Hz, 4H, RCH<sub>2</sub>CN). <sup>13</sup>C NMR (101 MHz, MeOD)  $\delta$  141.78, 138.83, 130.65, 130.33, 128.69, 127.12, 126.16, 125.32, 124.84, 119.32, 95.29, 78.30, 65.16 (d, *J*<sub>C,P</sub> = 5.7 Hz), 61.69 (d, *J*<sub>C,P</sub> = 5.2 Hz), 23.18 (d, *J*<sub>C,P</sub> = 7.8 Hz), 20.33 (d, *J*<sub>C,P</sub> = 7.5 Hz). <sup>31</sup>P NMR (162 MHz, MeOD)  $\delta$  -0.33. HRMS-NSI (*m/z*): [M+NH<sub>4</sub>]<sup>+</sup> calcd for C<sub>26</sub>H<sub>24</sub>O<sub>8</sub>NP<sub>2</sub>, 540.0971; found, 540.0956.

### 3. NMR spectra

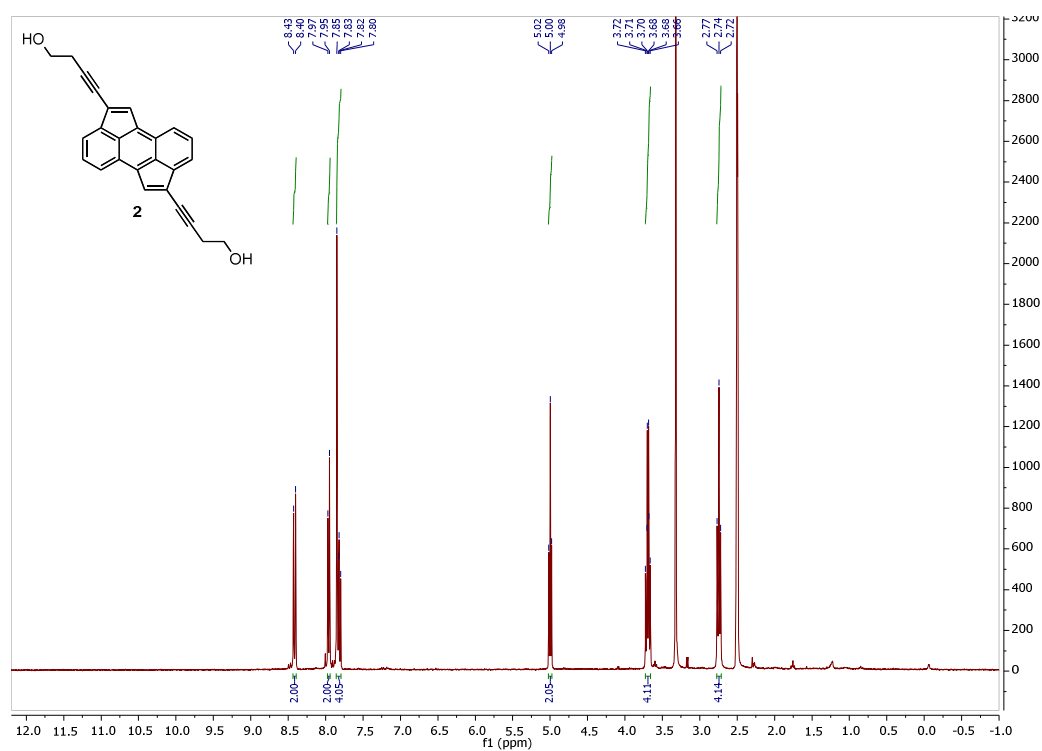


Figure S1: <sup>1</sup>H NMR of compound 2 in DMSO.

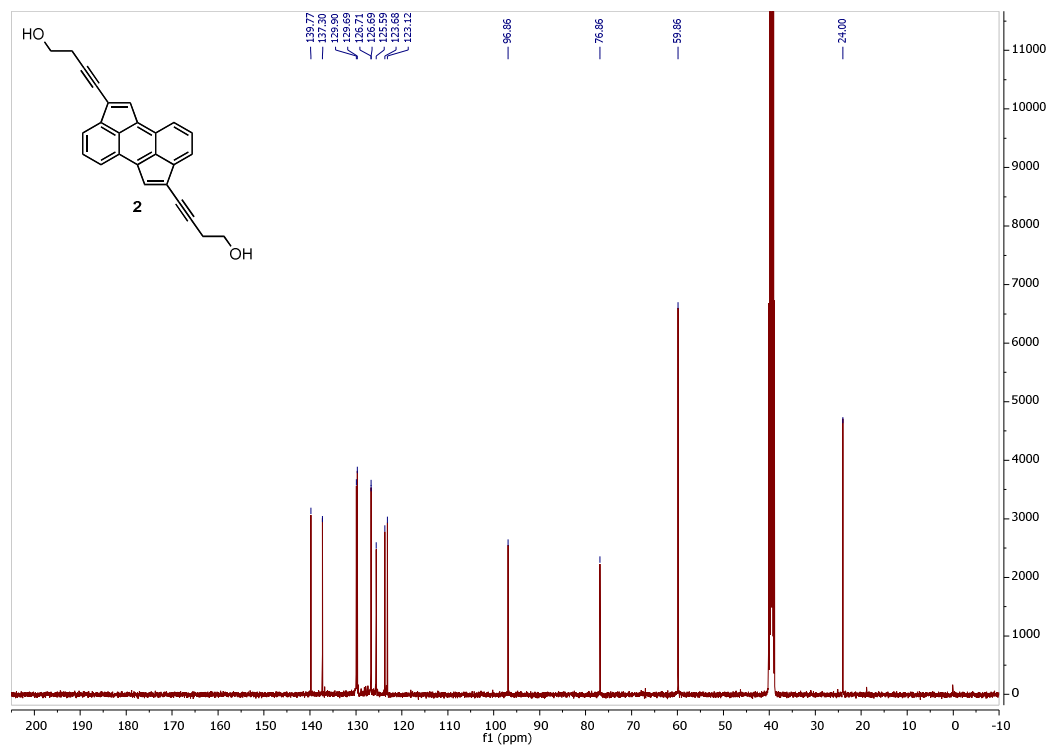


Figure S2: <sup>13</sup>C NMR of compound 2 in DMSO.

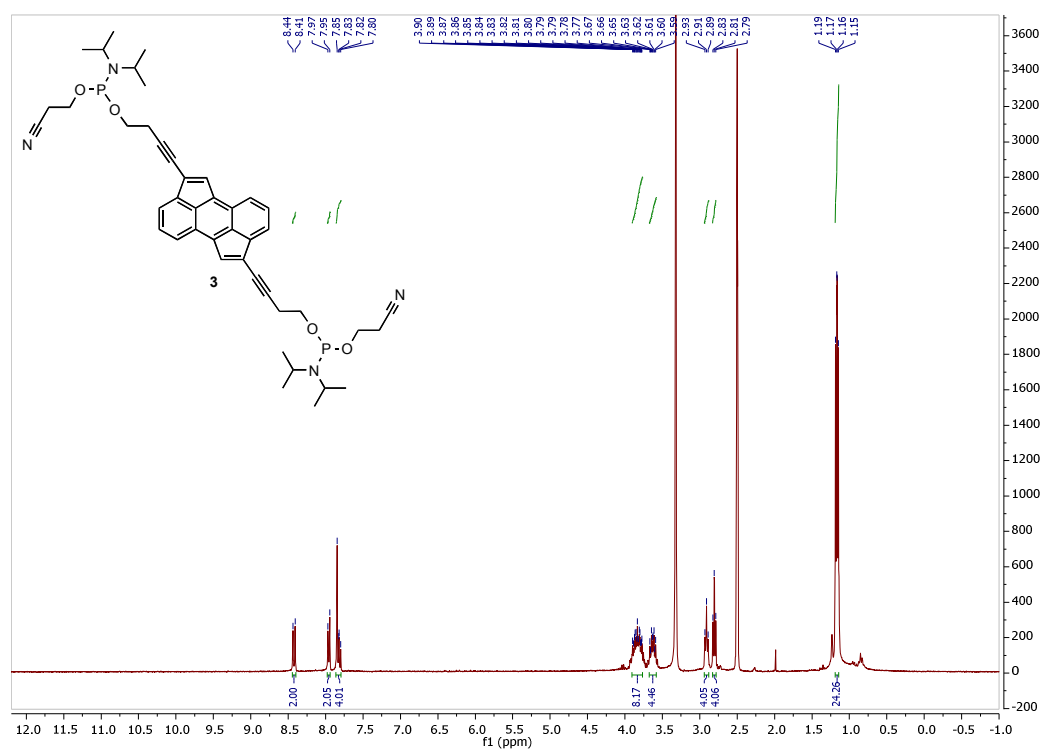


Figure S3:  $^1\text{H}$  NMR of compound **3** in DMSO.

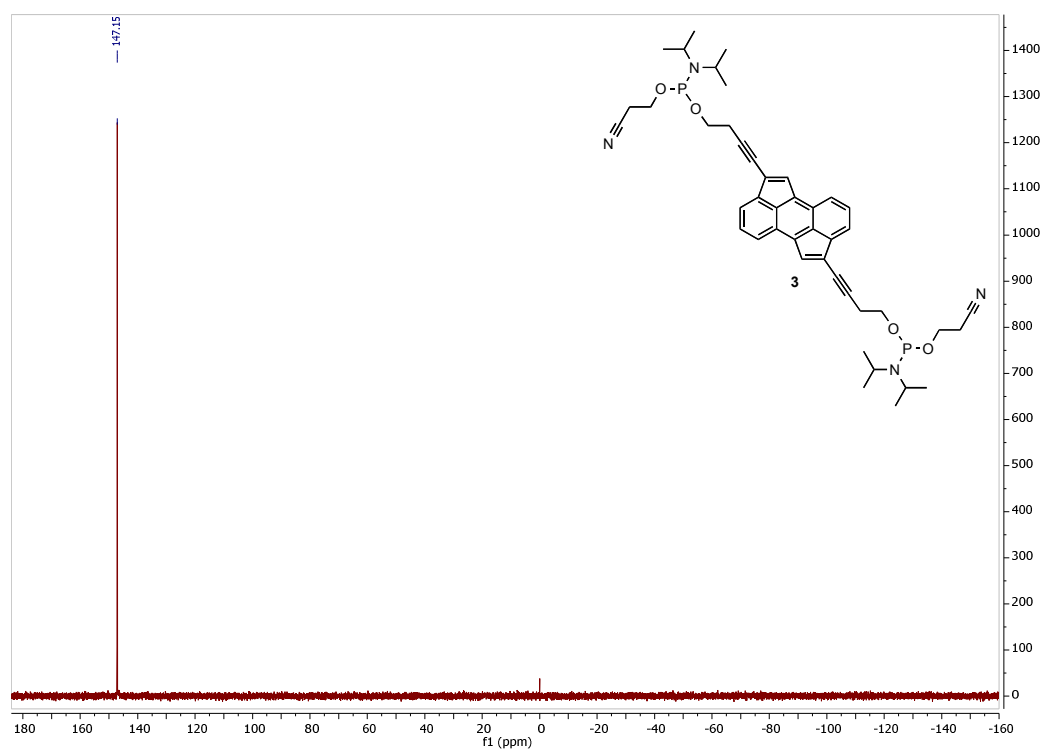


Figure S4:  $^{31}\text{P}$  NMR of compound **3** in DMSO.

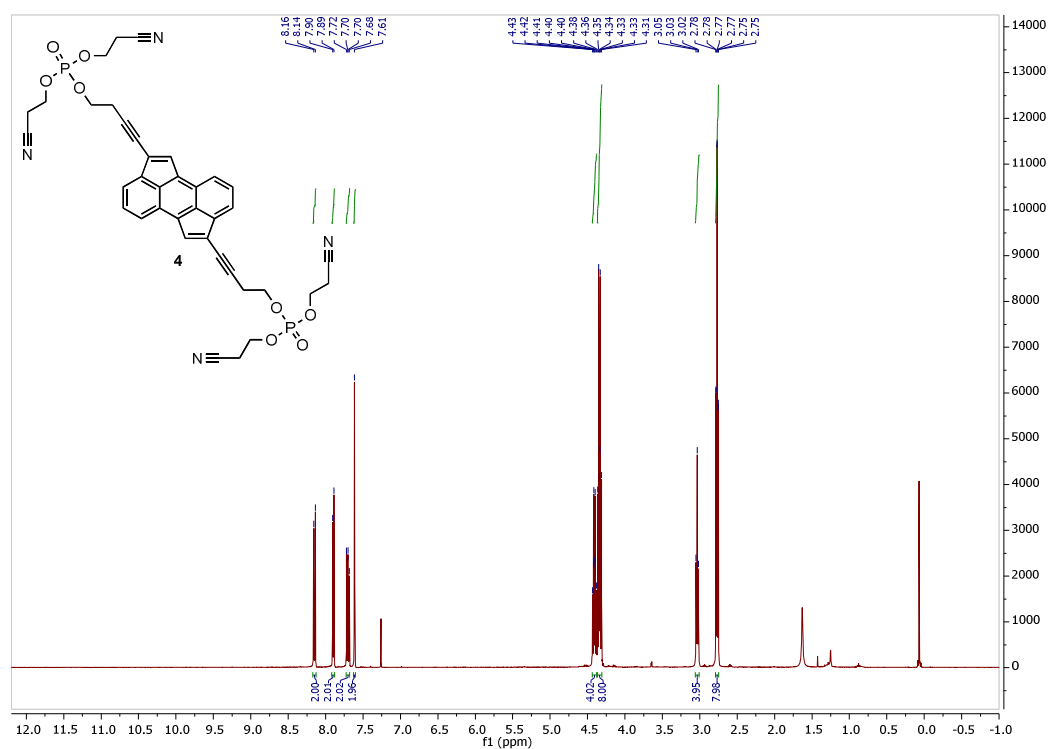


Figure S5: <sup>1</sup>H NMR of compound **4** in CDCl<sub>3</sub>.

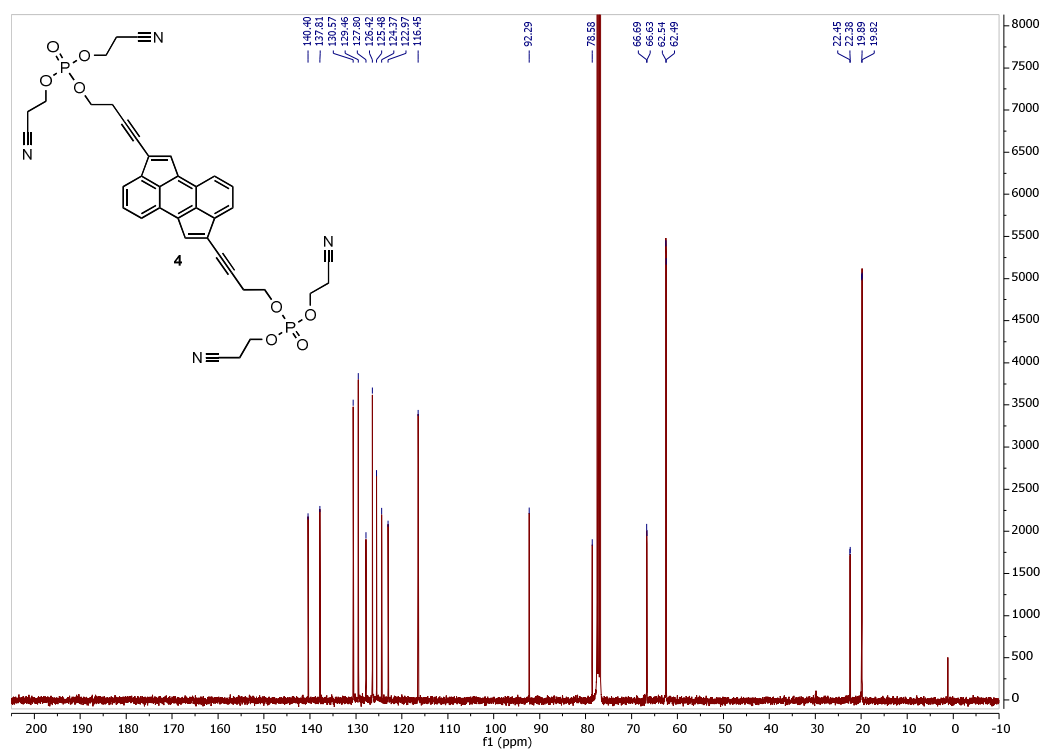


Figure S6: <sup>13</sup>C NMR of compound **4** in CDCl<sub>3</sub>.

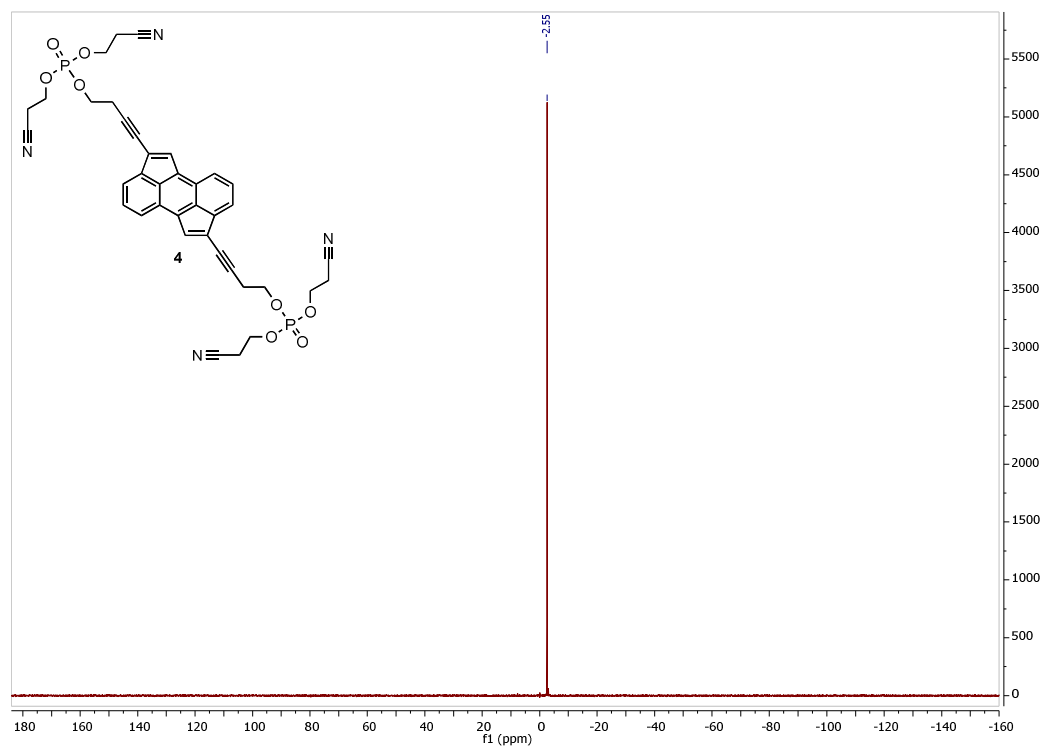


Figure S7:  $^{31}\text{P}$  NMR of compound **4** in  $\text{CDCl}_3$ .

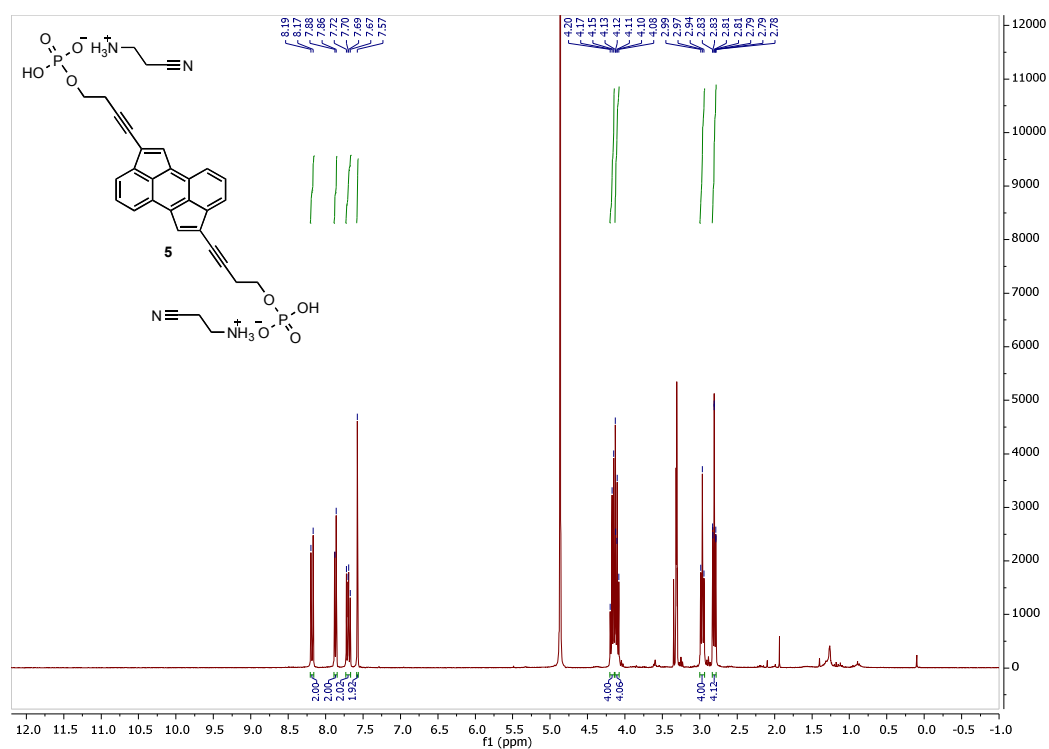


Figure S8:  $^1\text{H}$  NMR of compound **5** in  $\text{MeOD}$ .

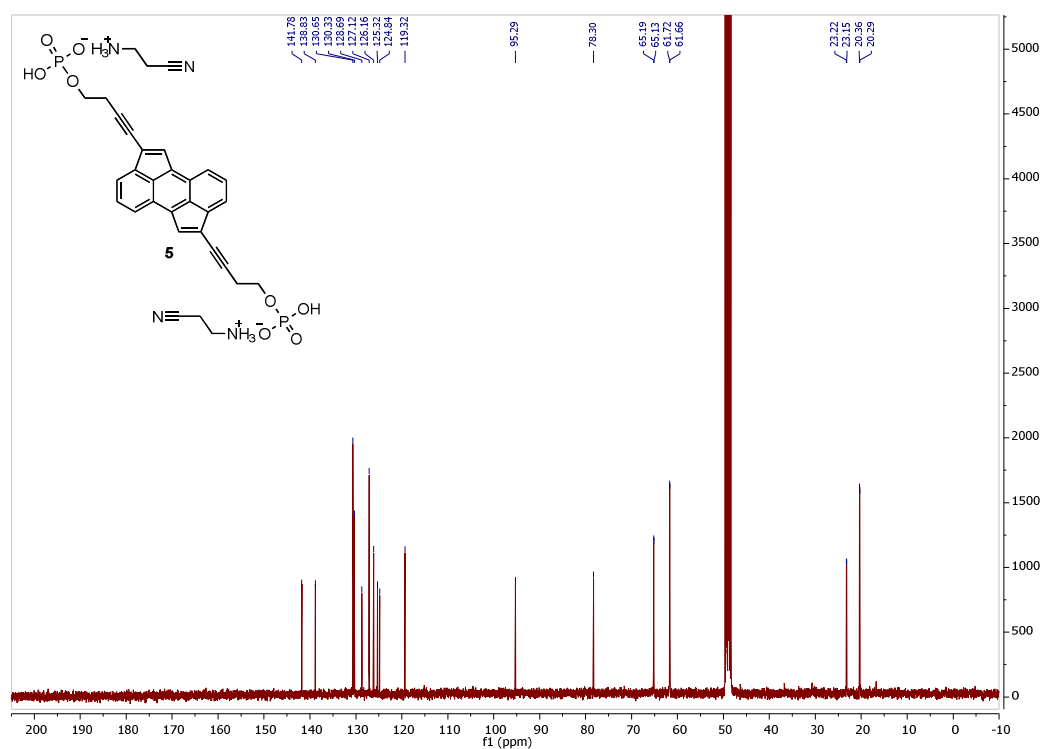


Figure S9: <sup>13</sup>C NMR of compound **5** in MeOD.

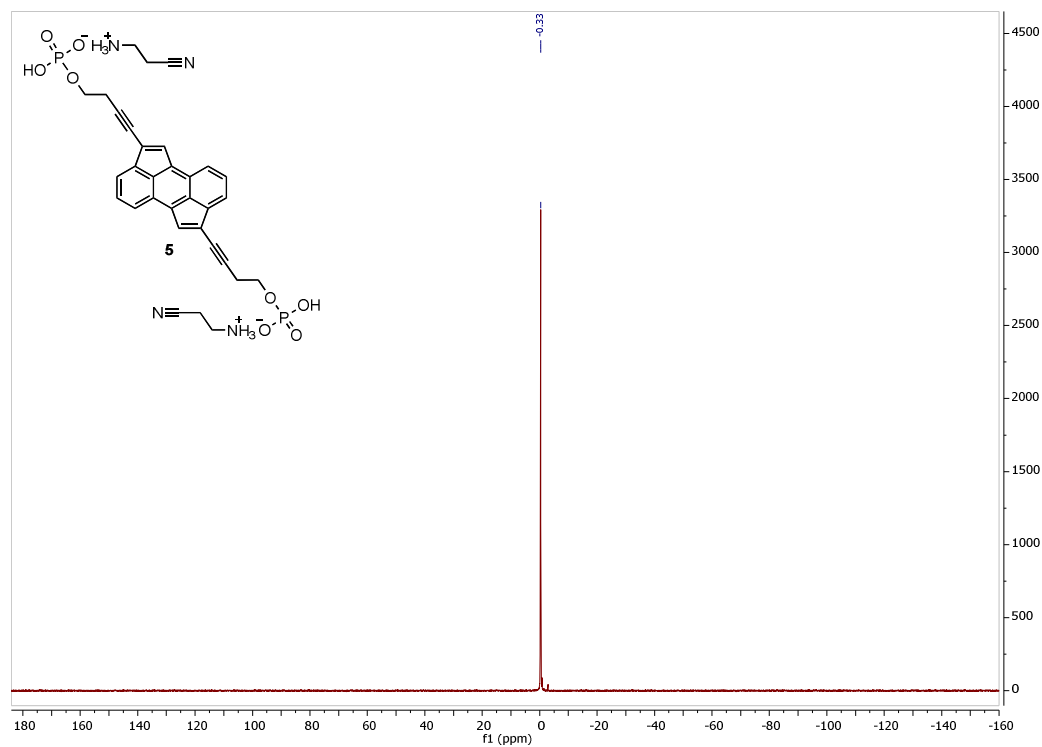


Figure S10: <sup>31</sup>P NMR of compound **5** in MeOD.

#### 4. UV-vis spectra

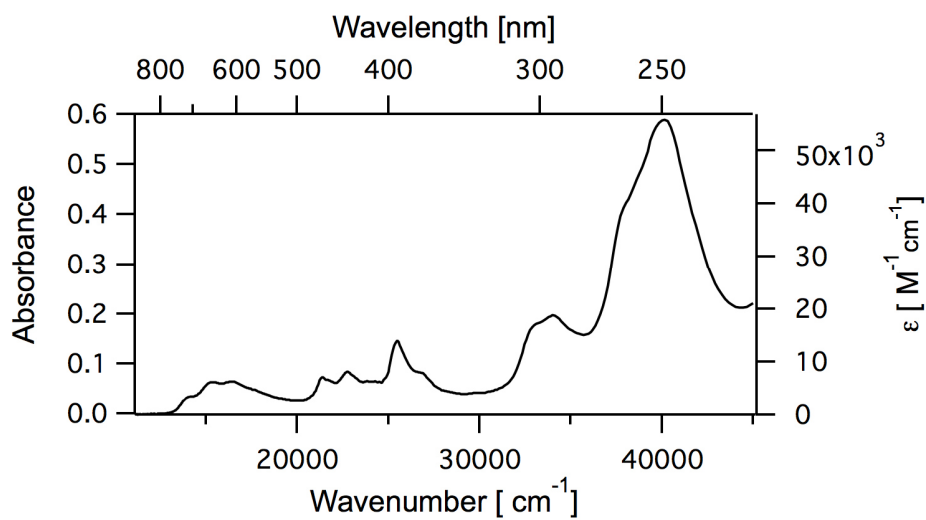


Figure S11: Absorption spectrum of cypac-diol **2**. Conditions: 10  $\mu\text{M}$  of **2** in THF, 20 °C.

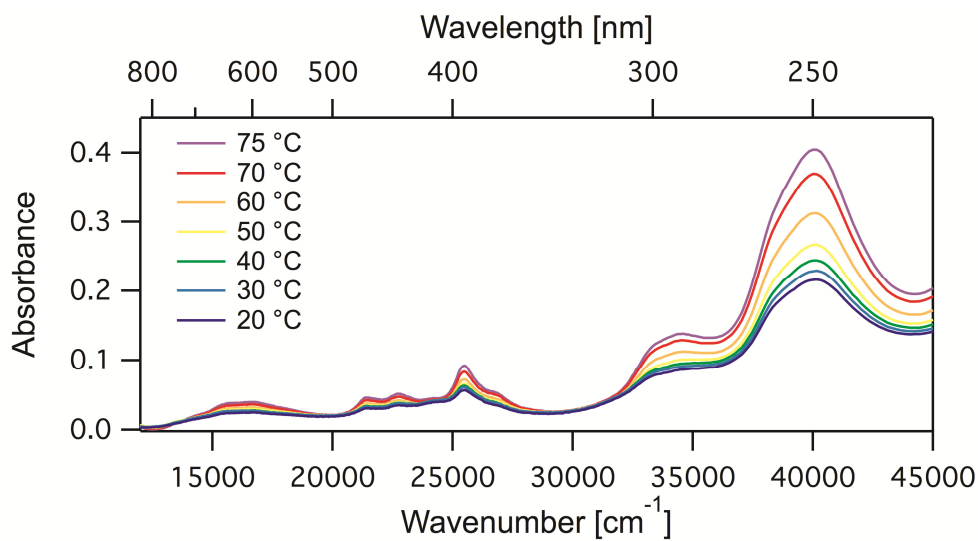


Figure S12: Temperature dependent absorption spectra of cypac-bis-phosphate **5** in aqueous medium. Conditions: 10  $\mu\text{M}$  of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

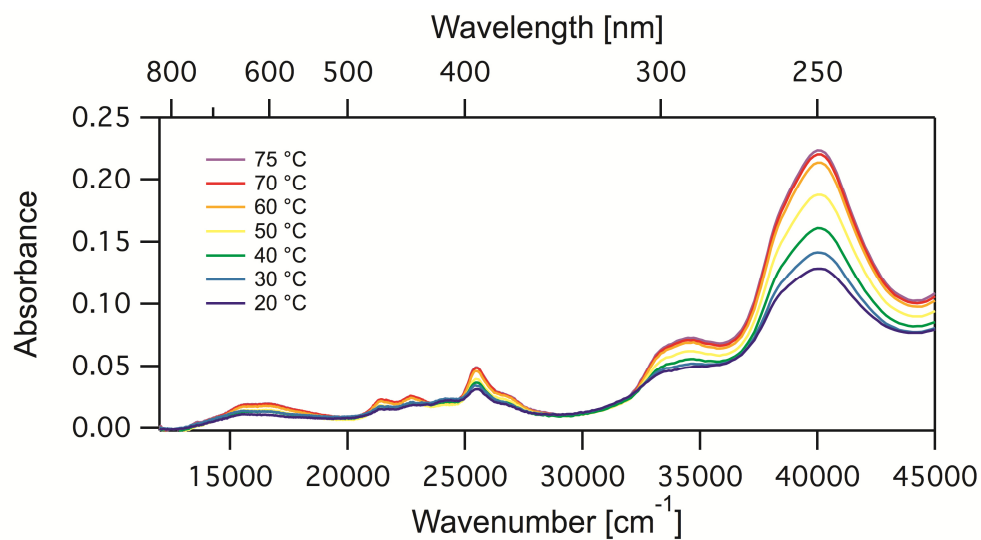


Figure S13: Temperature dependent absorption spectra of cypac-bis-phosphate **5** in aqueous medium. Conditions: 5  $\mu\text{M}$  of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

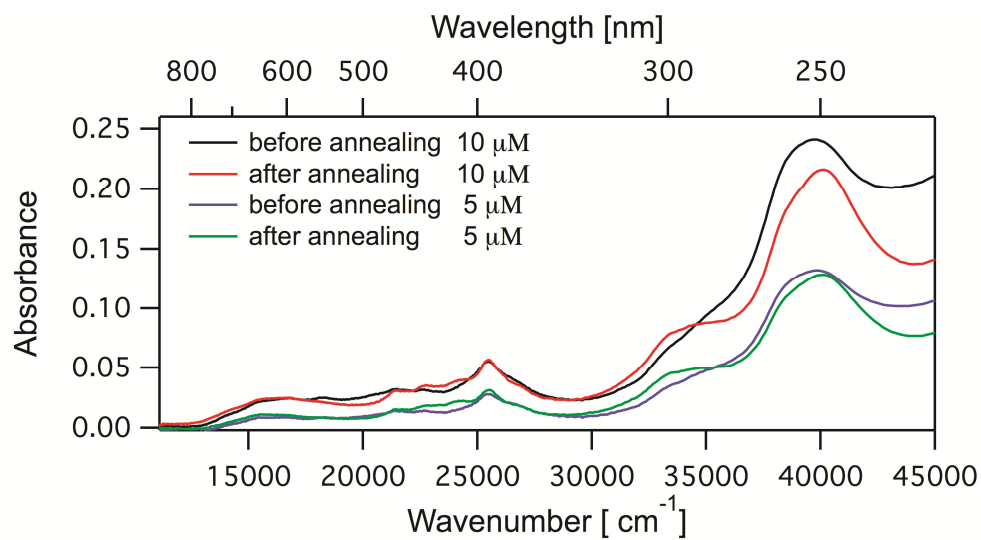


Figure S14: Absorption spectra of cypac-bis-phosphate **5** (5  $\mu\text{M}$  and 10  $\mu\text{M}$ ) in aqueous medium before and after annealing. Conditions: 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol, 20  $^{\circ}\text{C}$ .



## 5. AFM measurements

AFM experiments were conducted on a Nanosurf FlexAFM in tapping mode under ambient conditions. AFM samples were prepared on 3-aminopropyltriethoxy silane (APTES) modified mica sheets according to published procedures (in the supporting information of the reference).<sup>2</sup>

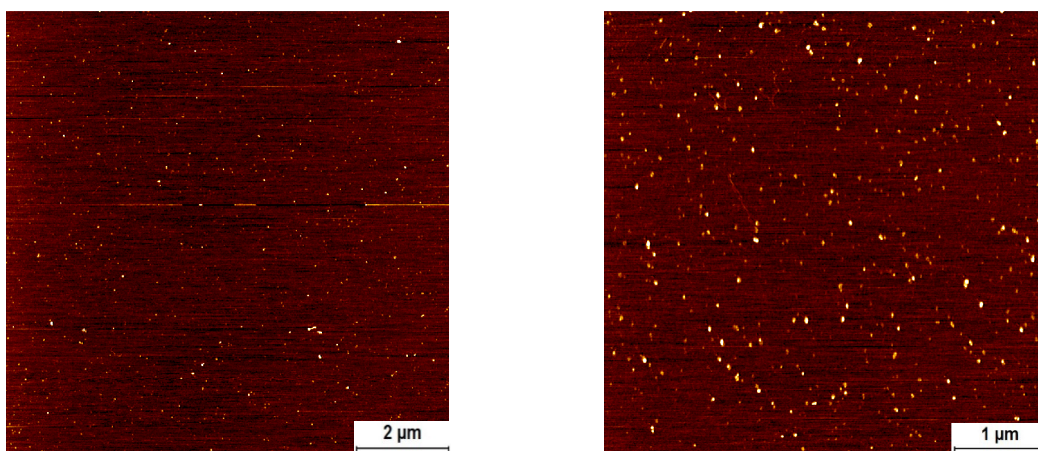


Figure S15: AFM images of cypac-bis-phosphate **5** in aqueous medium. Conditions: 5  $\mu$ M of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

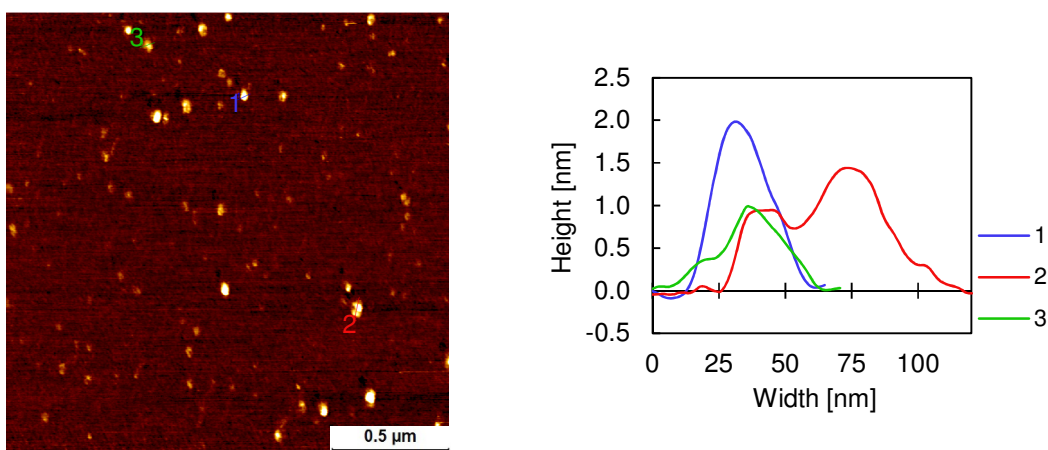


Figure S16: AFM image (left) and corresponding cross sections (right) of cypac-bis-phosphate **5** in aqueous medium. Conditions: 5  $\mu$ M of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

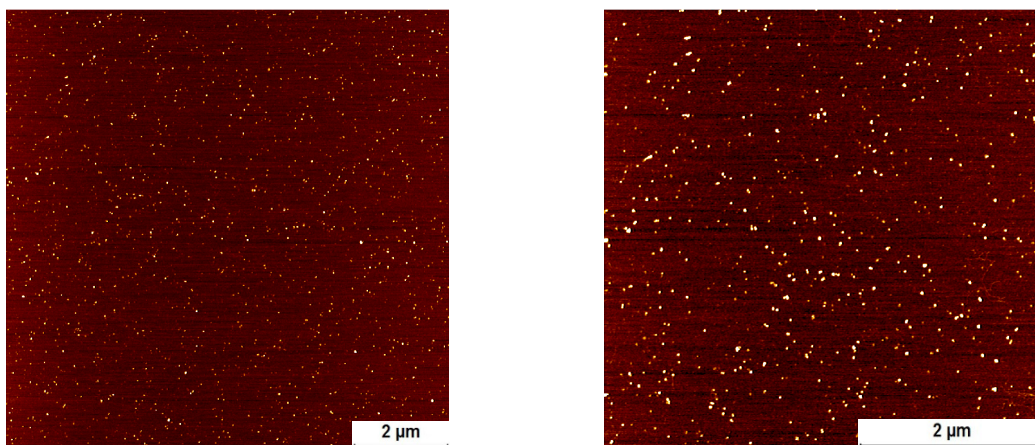


Figure S17: AFM images of cypac-bis-phosphate **5** in aqueous medium. Conditions: 10 μM of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

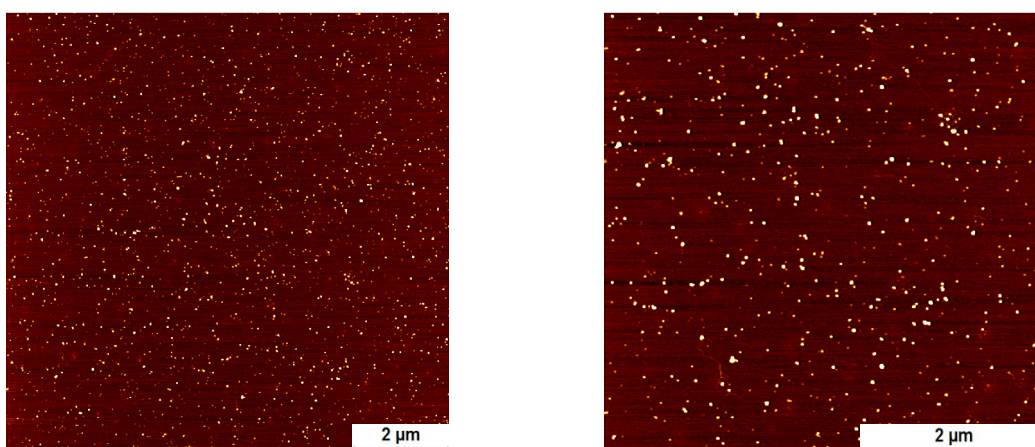


Figure S18: AFM images of cypac-bis-phosphate **5** in aqueous medium. Conditions: 20 μM of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

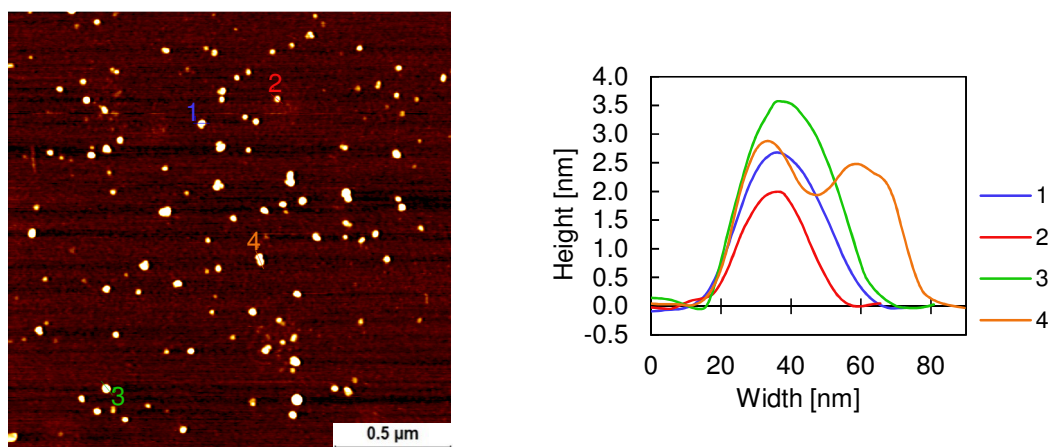


Figure S19: AFM image (left) and corresponding cross sections (right) of cypac-bis-phosphate **5** in aqueous medium. Conditions: 20 μM of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

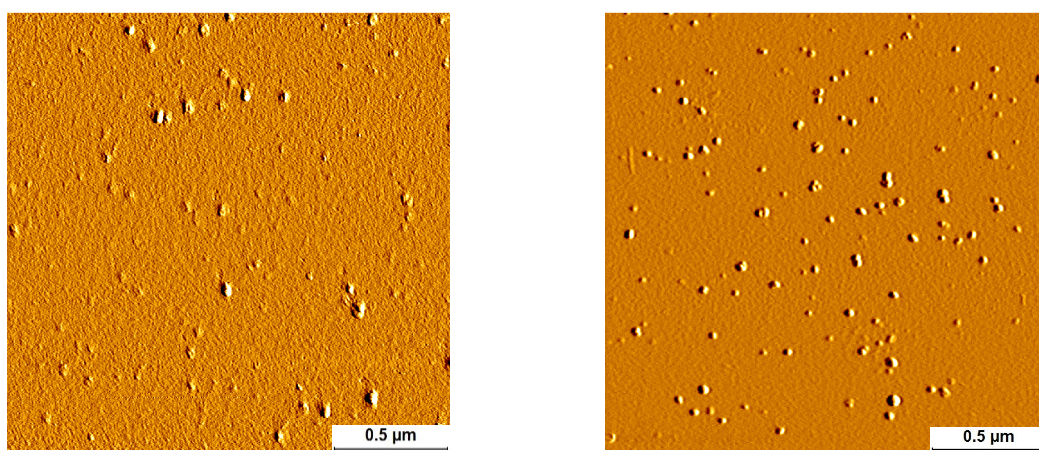


Figure S20: Deflection scans of cypac-bis-phosphate **5** in aqueous medium. Conditions: 5 μM (top left), 10 μM (top right), 20 μM (bottom left) of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

## 6. TEM measurements

TEM images were recorded on a Tecnai Spirit using an operating voltage of 80 kV and with either an Olympus-SIS Veleta CCD camera or FEI Eagle CCD camera. Samples were prepared by dropping 4  $\mu\text{L}$  of a 20  $\mu\text{M}$  sample solution of **5**, containing 1 mM of aqueous uranyl acetate, on a carbon-coated copper grid (300 Mesh, Agar Scientific). After 10 minutes of adsorption, the solution was blotted. Then, the grid was dipped into 30  $\mu\text{L}$  of  $\text{H}_2\text{O}$ , before the solution was blotted. This washing step was repeated once.

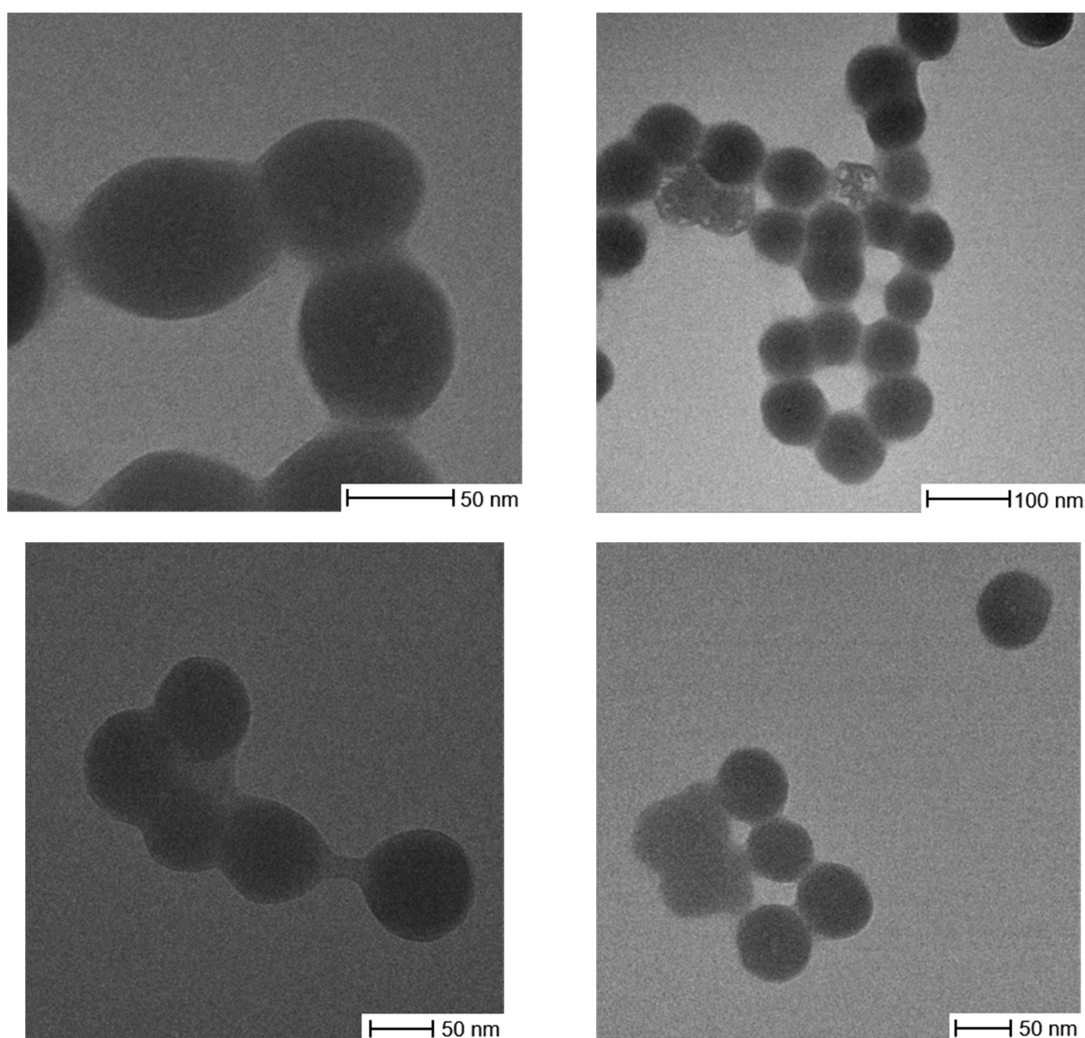


Figure S21: TEM images of self-assembled cypac-bis-phosphate **5** in aqueous medium. Conditions: 20  $\mu\text{M}$  of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol, 1 mM aqueous uranyl acetate.

## 7. Dynamic light scattering

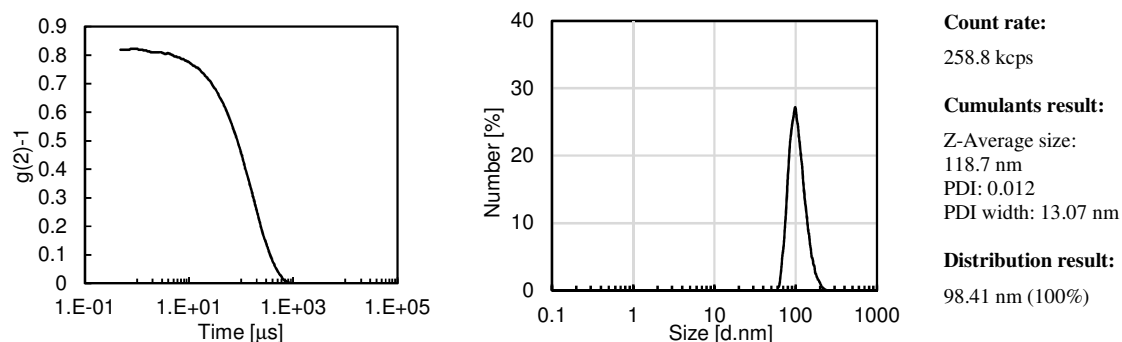


Figure S22: DLS data of latex beads (100 d.nm in average) in H<sub>2</sub>O at 25 °C,  $\lambda = 633$  nm.

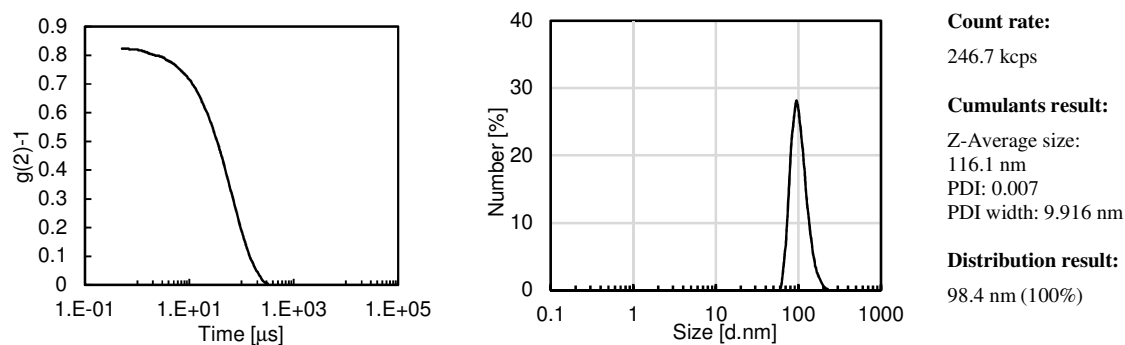


Figure S23: DLS data of latex beads (100 d.nm in average) in H<sub>2</sub>O at 70 °C,  $\lambda = 633$  nm.

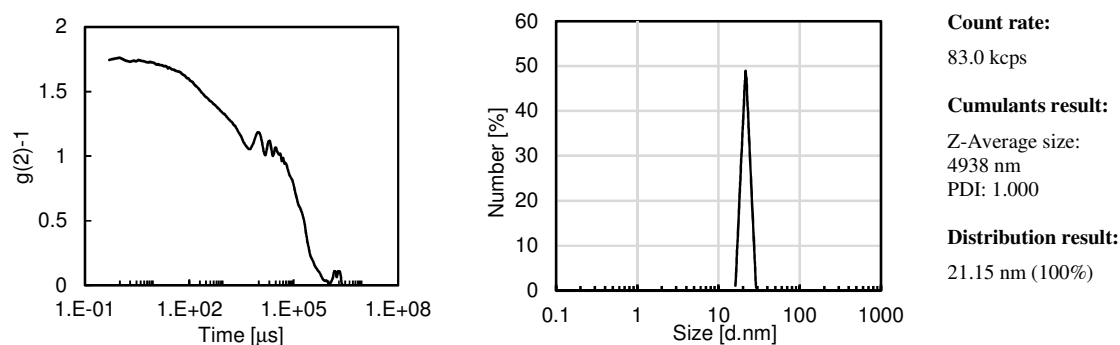
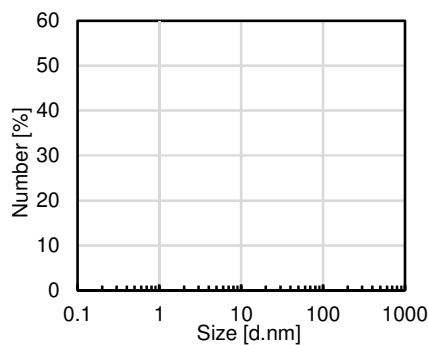
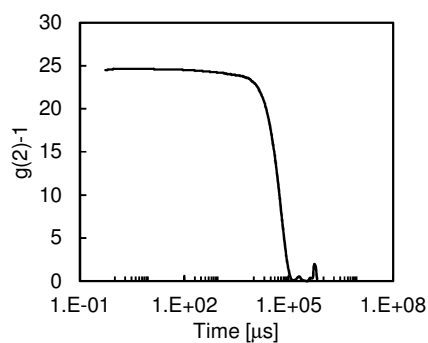


Figure S24: DLS data of cypac-bis-phosphate **5** in aqueous medium. Conditions: 5  $\mu$ M of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol,  $\lambda = 633$  nm, 25 °C.



**Count rate:**

43.5 kcps

**Cumulants result:**

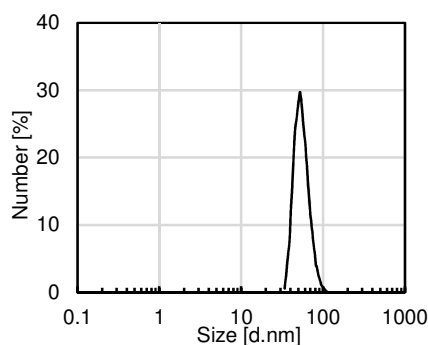
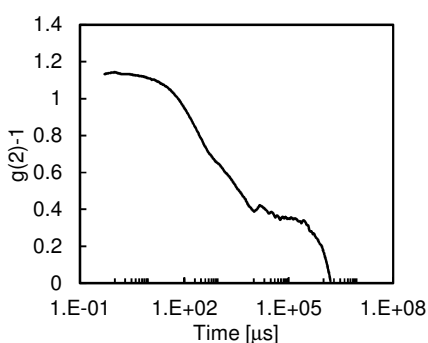
Z-Average size:

$3.29 \cdot 10^4$  nm

PDI: 0.036

PDI width: 6285 nm

Figure S25: DLS data of cypac-bis-phosphate **5** in aqueous medium. Conditions: 5  $\mu$ M of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol,  $\lambda$  = 633 nm, 70 °C.



**Count rate:**

161.5 kcps

**Cumulants result:**

Z-Average size:

352.6 nm

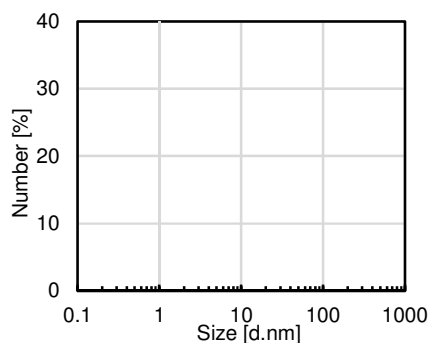
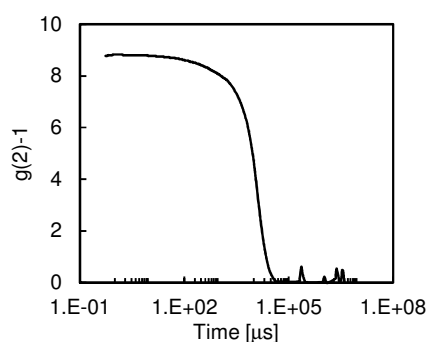
PDI: 0.396

**Distribution result:**

53.67 nm (99.9%)

327 nm (0.1%)

Figure S26: DLS data of cypac-bis-phosphate **5** in aqueous medium. Conditions: 10  $\mu$ M of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol,  $\lambda$  = 633 nm, 25 °C.



**Count rate:**

116.0 kcps

**Cumulants result:**

Z-Average size:

$3.368 \cdot 10^4$  nm

PDI: 0.270

PDI width:  $1.751 \cdot 10^4$  nm

Figure S27: DLS data of cypac-bis-phosphate **5** in aqueous medium. Conditions: 10  $\mu$ M of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol,  $\lambda$  = 633 nm, 70 °C.



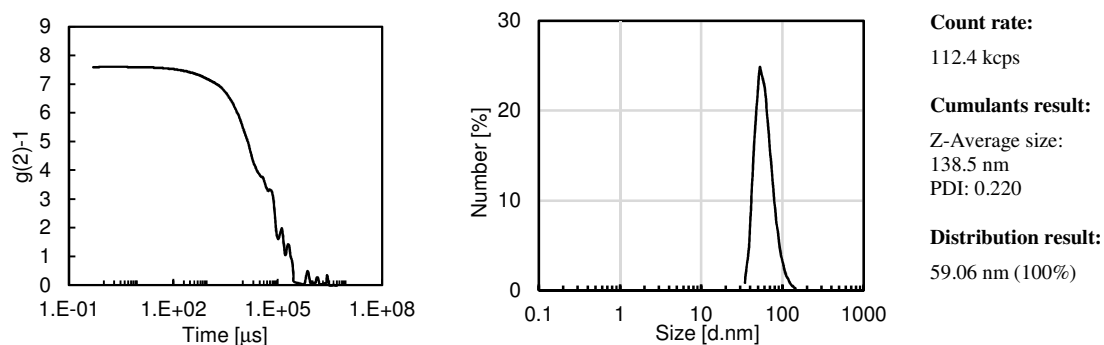


Figure S28: DLS data of cypac-bis-phosphate **5** in aqueous medium. Conditions: 20  $\mu\text{M}$  of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol,  $\lambda = 633$  nm, 25  $^{\circ}\text{C}$ .

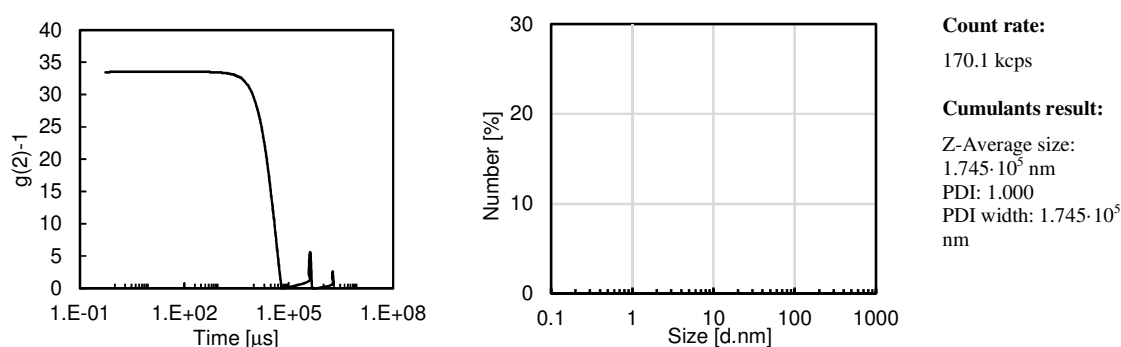


Figure S29: DLS data of cypac-bis-phosphate **5** in aqueous medium. Conditions: 20  $\mu\text{M}$  of **5**, 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol,  $\lambda = 633$  nm, 70  $^{\circ}\text{C}$ .

## 8. Cyclic voltammetry

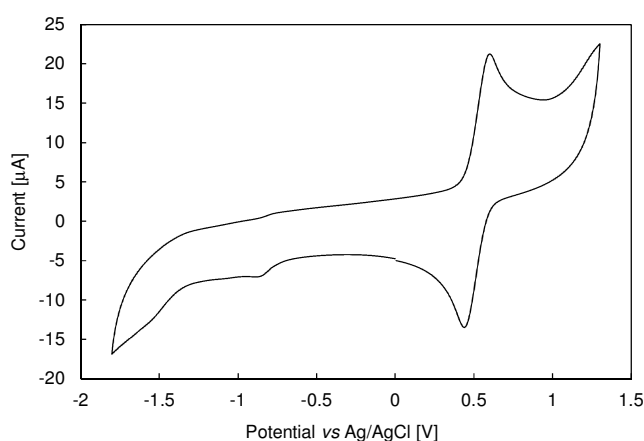


Figure S30: Cyclic voltammogram of cypac-bis-phosphate **5** with ferrocene ( $E_{1/2} = 0.52$  V) as internal standard. Conditions: 0.5 mM of **5** in 0.1 M  $\text{NaClO}_4$ -ethanol solution, 20  $^{\circ}\text{C}$ , glassy carbon working electrode, glassy carbon counter electrode, Ag/AgCl reference electrode, scan rate = 100 mV/s.

## **Bibliography**

1. J. D. Wood, J. L. Jellison, A. D. Finke, L. Wang and K. N. Plunkett, *J. Am. Chem. Soc.*, 2012, **134**, 15783–15789.
2. C. D. Bösch, S. M. Langenegger and R. Häner, *Angew. Chem. Int. Ed.*, 2016, **55**, 9961–9964.