Electronic Supplementary Material (ESI) for Chemical Communications


# Simple Chemical Models of Clathrate Hydrate Inhibition by Polyvinylcaprolactam and Polyvinylpyrolidinone

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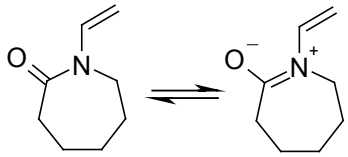
## Supplementary Information



**Scheme S1** Resonance forms of VCap.

## Synthesis of 1,3-bis(caprolactamyl) but-1-ene

N-vinyl caprolactam (2.0 g, 14 mmol) was dissolved in dichloromethane (20 mL), to this solution was added a drop of trifluoroacetic acid. The resulting solution was allowed to stand at room temperature for 24 hours; the solvent was then evaporated under reduced pressure. The remaining white solid (2.0 g, 7 mmol) was product, this was then recrystallised from acetone. $^{1}$H NMR (700 MHz, $CDCl_3$) δ 7.19 (dd, *J* = 14.9, 1.7 Hz, 1H, vinyl NCH), 5.36 (qd, *J* = 6.8, 3.4 Hz, 1H, NCH ), 4.94 (dd, *J* = 14.9, 5.1 Hz, 1H, vinyl CH), 3.55 – 3.48 (m, 2H, $CH_2$), 3.16 – 3.08 (m, 2H, $CH_2$), 2.61 – 2.54 (m, 2H, $CH_2$), 2.51 – 2.44 (m, 2H, $CH_2$), 1.77 – 1.39 (m, 12H), 1.18 (d, *J* = 6.9 Hz, 3H, $CH_3$); $^{13}$C NMR (176 MHz, $CDCl_3$) δ 175.24, 174.15, 128.01, 110.27, 48.36, 45.22, 43.08, 37.59, 37.11, 30.52, 29.97, 29.63, 29.32, 27.20, 23.36, 16.80; IR: υ = 1667 (s, C=C), 1639 (w, C=O) 1622 cm$^{-1}$ (w, C=O); MS (GC EI+) *m/z*: 278.3 ($M^+$); elemental analysis calcd (%) for $C_{16}H_{26}N_2O_2$ : C 69.03, H 9.41, N 10.06; found: C 68.77, H 9.51, N 10.02.

## Synthesis of 1,3-bis(caprolactamyl) butane

The hydrogenation reaction was carried out in the ThalesNano H-Cube® Continuous-flow Hydrogenation Reactor. Standard hydrogenation instructions were followed; a 0.02 mol dm$^{-3}$ solution of 1,3-bis(caprolactamyl) but-1-ene (0.5 g, 1.8 mmol) in HPLC grade MeOH (90 mL) was made up in a round bottomed flask. The temperature was set to 60°C and the pressure of hydrogen was set to 30 bar using the H-cube console, a 10% Pd/C catalyst was used. The 1,3-bis(caprolactamyl) but-1-ene solution was then passed through the

hydrogenation reactor at a flow rate of 1 mL $min^{-1}$, a conical flask was used to collect the product. The solvent was removed under reduced pressure to give a clear oil, the oil was then dried further under high vacuum for 6 hours. The yield of the reaction was determined by NMR as 100%, with no traces of starting product present $^{1}H$ NMR (400 MHz, $CD_3CN$) δ 4.70 – 4.52 (m, 1H, CH), 3.44 – 3.37 (m, 1H), 3.37 – 3.32 (m, 2H, $CH_2$), 3.29 – 3.22 (m, 2H, $CH_2$), 3.09 (ddd, $J$ = 13.4, 9.0, 6.1 Hz, 1H), 2.58 – 2.36 (m, 4H), 1.82 – 1.45 (m, 14H), 1.08 (d, $J$ = 6.9 Hz, 3H, $CH_3$); $^{13}C$ NMR (176 MHz, $CDCl_3$) δ 175.24, 174.15, 128.01, 110.27, 48.36, 45.22, 43.08, 37.59, 37.11, 30.52, 29.97, 29.63, 29.32, 27.20, 23.36, 16.80. IR: υ = 1628 $cm^{-1}$ (w, CO); MS (GC EI+) *m/z*: 280.3 ($M^+$); elemental analysis calcd (%) for $C_{16}H_{28}N_2O_2$ : C 68.53, H 10.06, N 9.99; found: C 68.70, H 10.72, N 9.83.

## Polyvinylcaprolactam

PVCap (av. $M_w$ = 2000 – 3000) was supplied by ISP Corp. as a 50 wt% solution in 2-butoxyethanol. The sample was isolated by repeated precipitation with diethyl ether followed by drying under reduced pressure. After each cycle the resulting off-white solid was ground using a Retsch MM200 ball mill.

## General procedure for solution Infrared spectroscopic experiments

Solution Infrared measurements were carried out using a Perkin Elmer Spectrum 100 FTIR spectrometer fitted with a Specac solution IR cell with $CaF_2$ windows, and controlled by means of Perkin Elmer spectrum express software. In the measurements of PVCap as a function of concentration in $D_2O$, the required mass of PVCap was weighed into a vial, 1.0 mL of $D_2O$ was then added. The PVCap solution was then mixed properly by sonication. In the titration type measurements a specific concentration of host in acetonitrile (0.5 mL) was made up in a vial. The guest, $D_2O$, was then added in 10 μL aliquots until the required number of equivalents of guest were added to the host solution. The host-guest solution was allowed to mix and then syringed into the solution IR cell. All infrared titration type measurements were taken at a resolution of 1 $cm^{-1}$ and 16 scans.

## General procedure for $^{1}H$ NMR spectroscopic experiments

$^{1}H$ NMR spectroscopic titration experiments were carried out by using Varian Mercury 400 spectrometer running at 400 MHz, at room temperature. All chemical shifts are reported in ppm. A specific concentration of host, typically 2.16-5.53 mM, was made up in a single

NMR tube in $CD_3CN$ (0.5 mL). The guest, $D_2O$ was used neat except in the 1, 3 Bis(caprolactamyl) But-1-ene in which $D_2O$ was made up to 1 mL with dry acetonitrile. 10 μL aliquots of the guest were added to the NMR tube and the spectra were recorded after each addition. Results were analysed by using HypNMR 2006.

| Compound | NVC | NVP | Unsat dimer | Sat dimer |
|---|---|---|---|---|
| Mass used/g | 0.0077 | 0.0061 | 0.006 | 0.0155 |
| Moles | $5.53 \times 10^{-5}$ | $5.49 \times 10^{-5}$ | $2.16 \times 10^{-5}$ | $5.53 \times 10^{-5}$ |
| Host solution volume/mL | 0.5 | 0.5 | 0.5 | 0.5 |

## Crystallographic data for 1

$C_{16}H_{26}N_2O_2$, $M = 278.39$, triclinic, space group $P$-1 (No. 2), $a = 6.6087(14)$, $b = 9.292(2)$, $c = 13.114(3)$ Å, $\alpha = 109.100(10)$, $\beta = 98.253(11)$, $\gamma = 91.170(8)°$, $V = 751.1(3)$ Å$^3$, $Z = 2$, $D_c = 1.231$ g/cm$^3$, $F_{000} = 304$, MoKα radiation, $\lambda = 0.71073$ Å, $T = 120(2)$K, $2\theta_{max} = 55.0°$, 9698 reflections collected, 3445 unique ($R_{int} = 0.0312$). Final *GooF* = 1.007, *R1* = 0.0436, *wR2* = 0.1111, *R* indices based on 2598 reflections with I >2σ(I) (refinement on $F^2$), 181 parameters, 0 restraints. Lp and absorption corrections applied, $\mu = 0.081$ mm$^{-1}$.

## Crystallographic data for 2

$C_{16}H_{28}N_2O_2$, $M = 280.40$, yellow plate, $0.02 \times 0.02 \times 0.001$ mm$^3$, monoclinic, space group $P2_1/c$ (No. 14), $a = 12.540(3)$, $b = 12.897(3)$, $c = 9.964(2)$ Å, $\beta = 96.050(3)°$, $V = 1602.5(6)$ Å$^3$, $Z = 4$, $D_c = 1.162$ g/cm$^3$, $F_{000} = 616$, synchrotron radiation Diamond beamline I19, $\lambda = 0.68890$ Å, $T = 150(2)$K, $2\theta_{max} = 54.7°$, 15488 reflections collected, 3955 unique ($R_{int} = 0.0716$). Final *GooF* = 1.101, *R1* = 0.0571, *wR2* = 0.1499, *R* indices based on 3085 reflections with I >2σ(I) (refinement on $F^2$), 183 parameters, 0 restraints. Lp and absorption corrections applied, $\mu = 0.076$ mm$^{-1}$.

We thank Prof. W. Clegg for help processing the synchrotron X-ray data and STFC for a beamtime allocation.

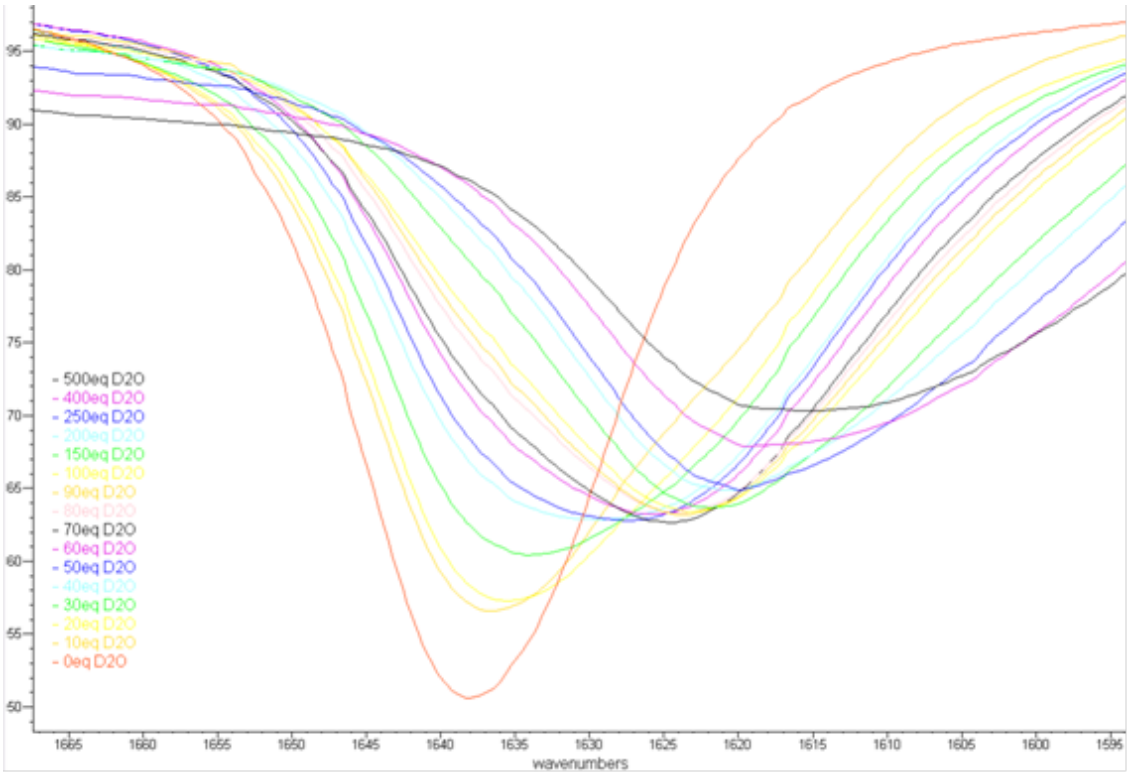



**Fig. S1** IR spectroscopic titration of **2** with $D_2O$ in acetonitrile.

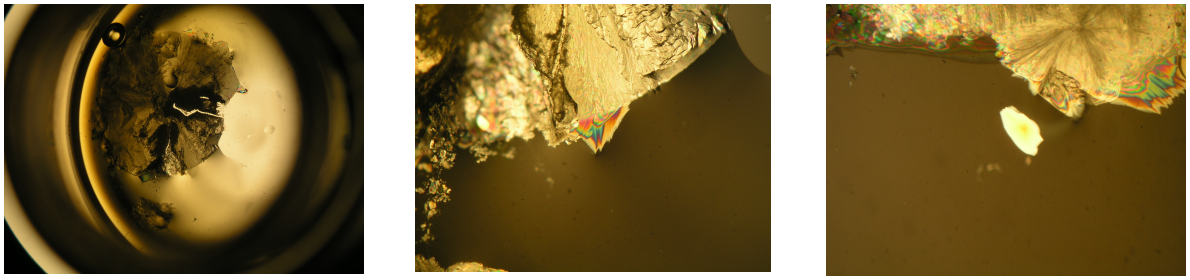
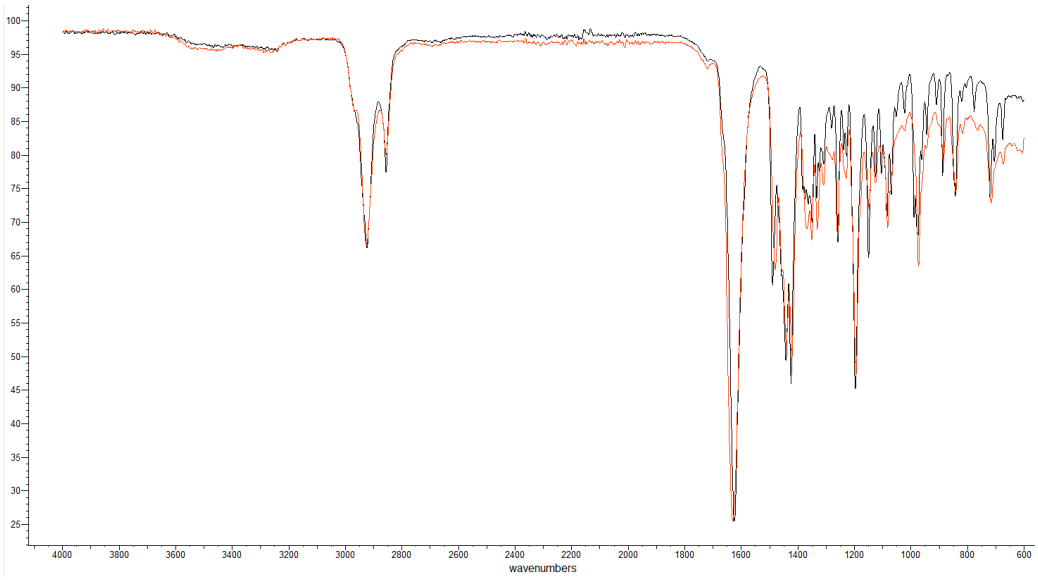


**Fig. S2** Photo micrographs of the crystalline **2** obtained upon rigorous drying

(a)




(b)

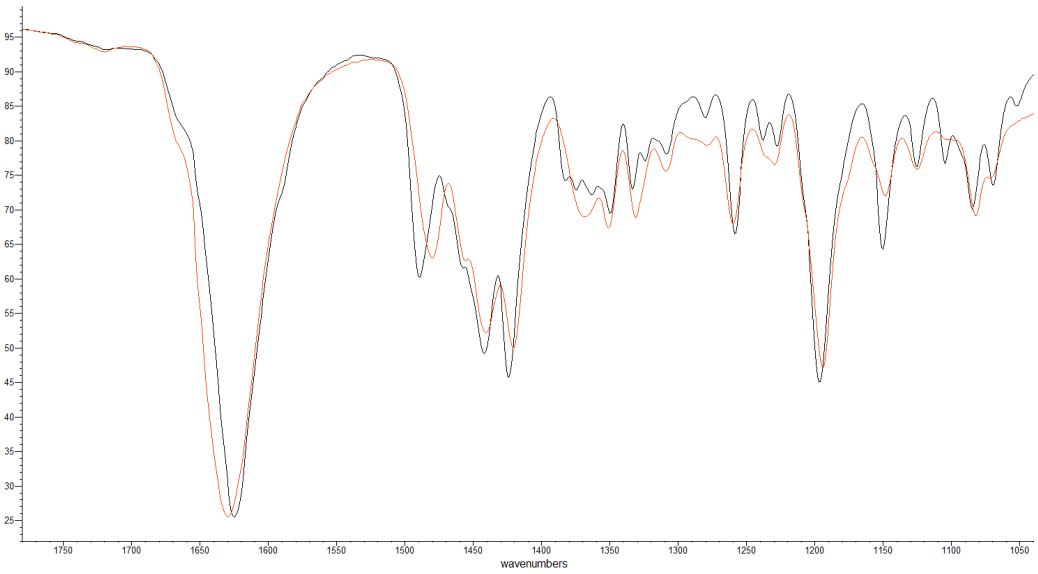
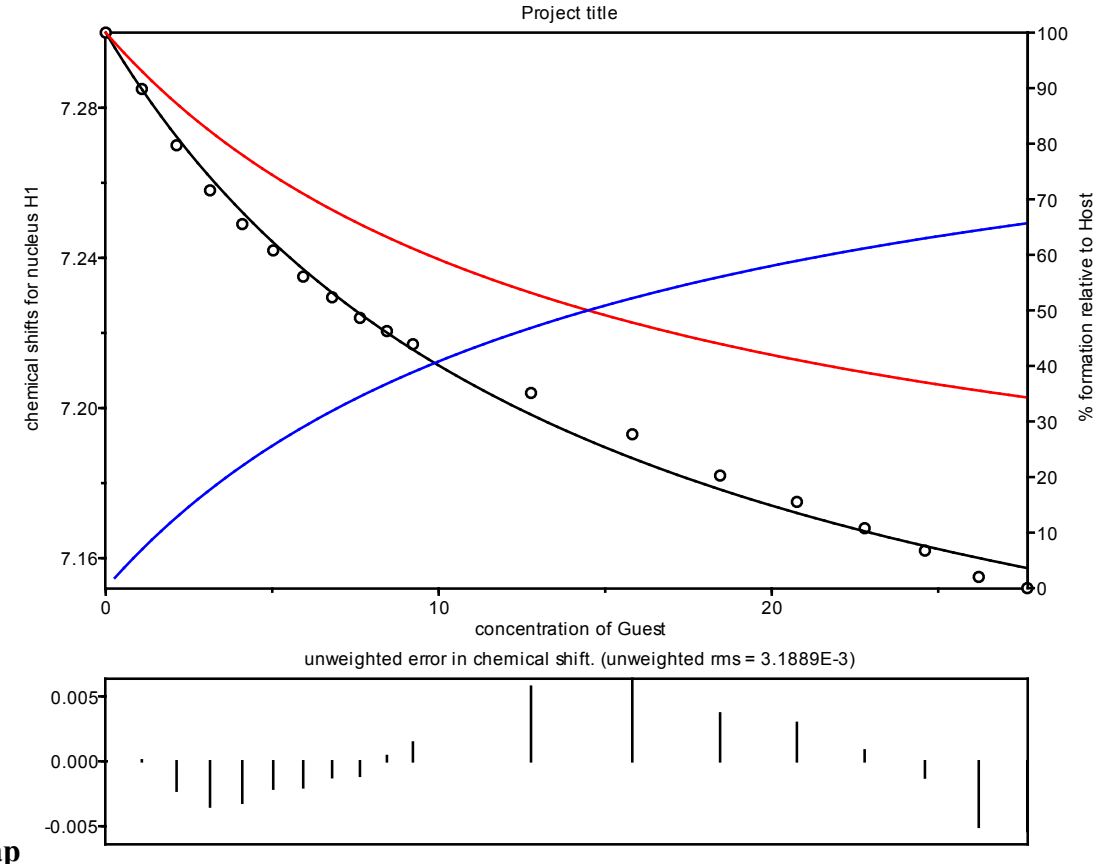
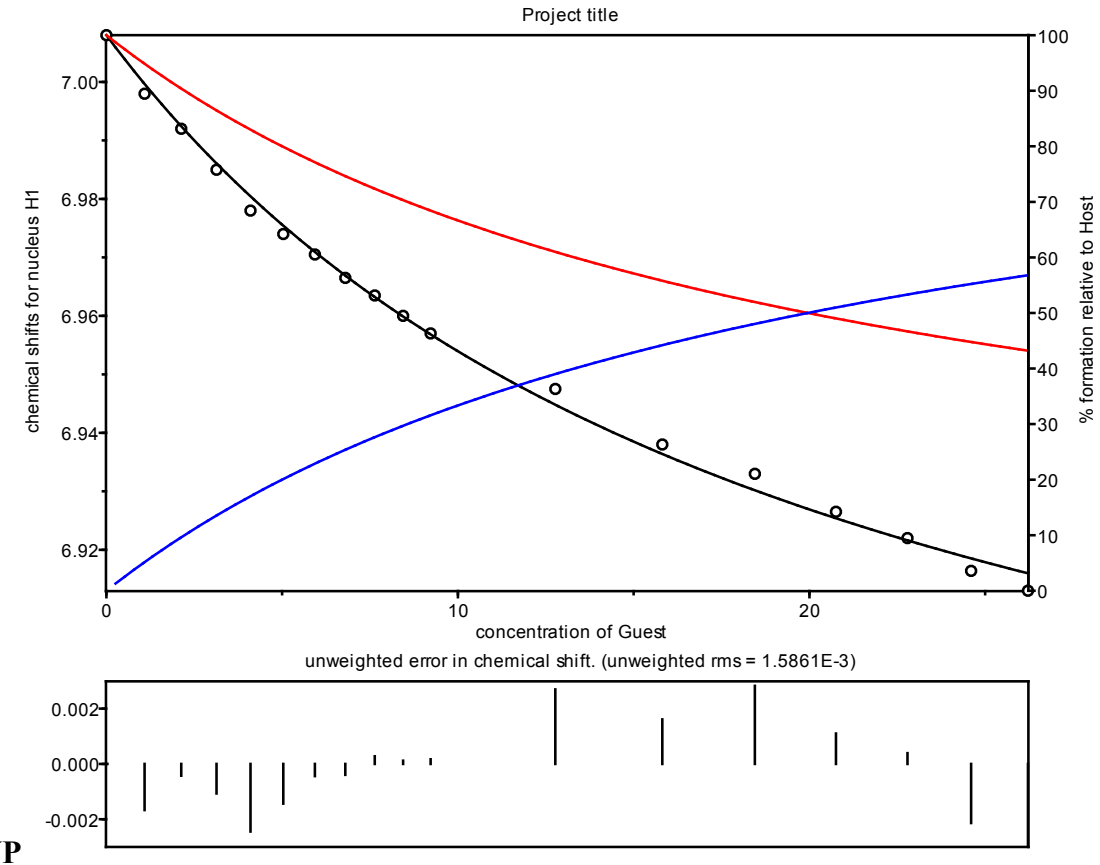



**Fig. S3** (a) IR spectra of the oil (red) and the crystalline phase (black) of **2** (b) Detail of the IR spectra of the oil (red) and the crystalline phase (black) of **2**. Changes are visible in the region of the C-H asymmetric stretch vibrations (1540 to 1400 $cm^{-1}$) and the C-N stretch vibrations (1400 to 1300 $cm^{-1}$).

## NMR Fitting

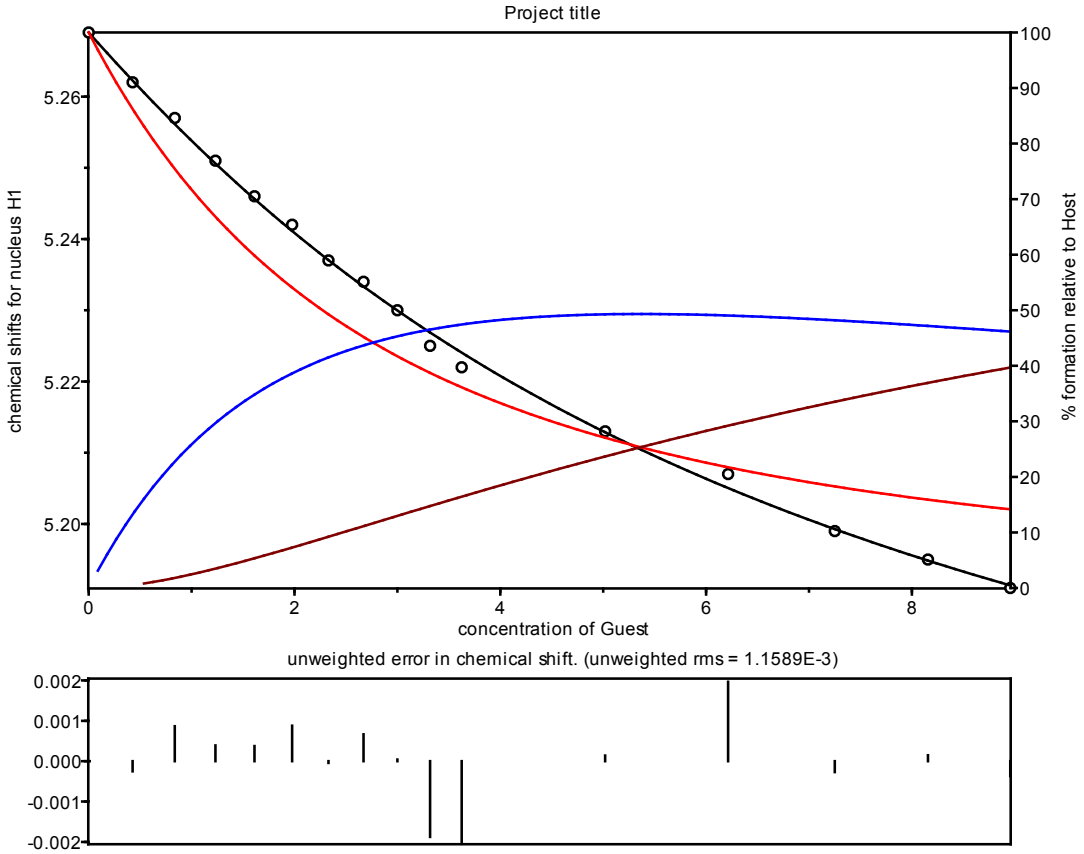



**VCap**

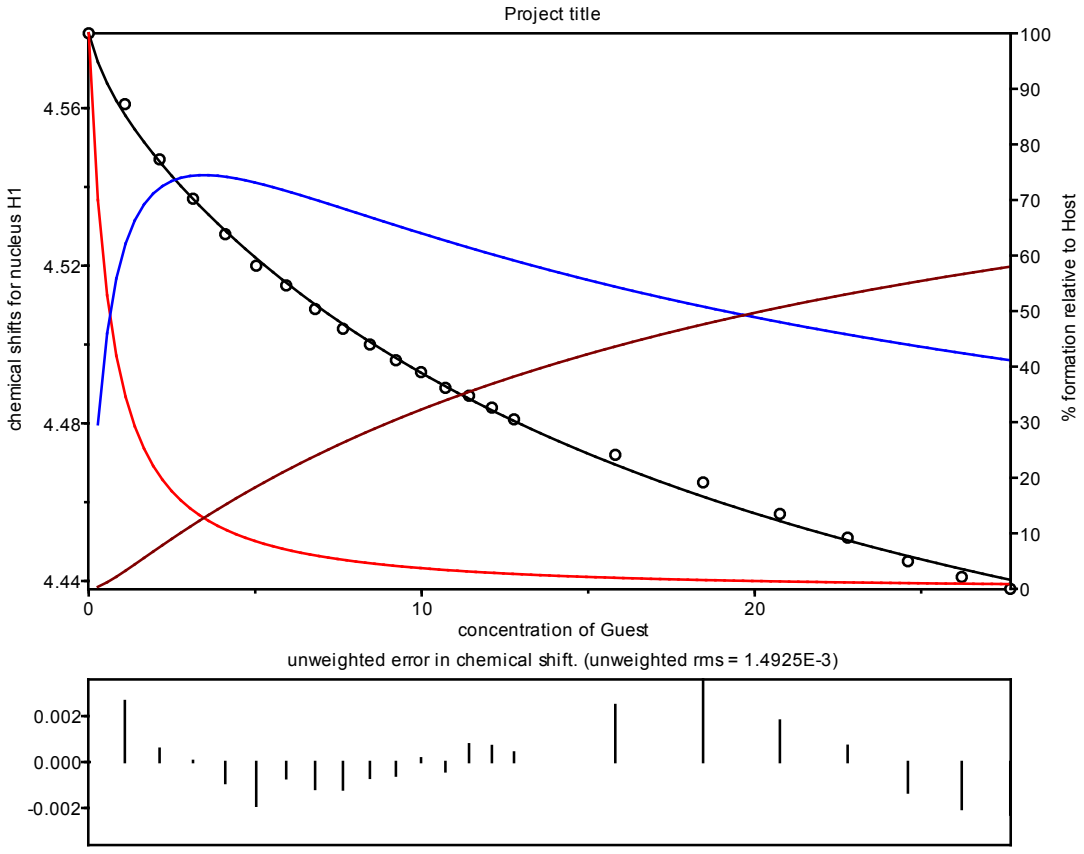



**VP**

Compound **1**

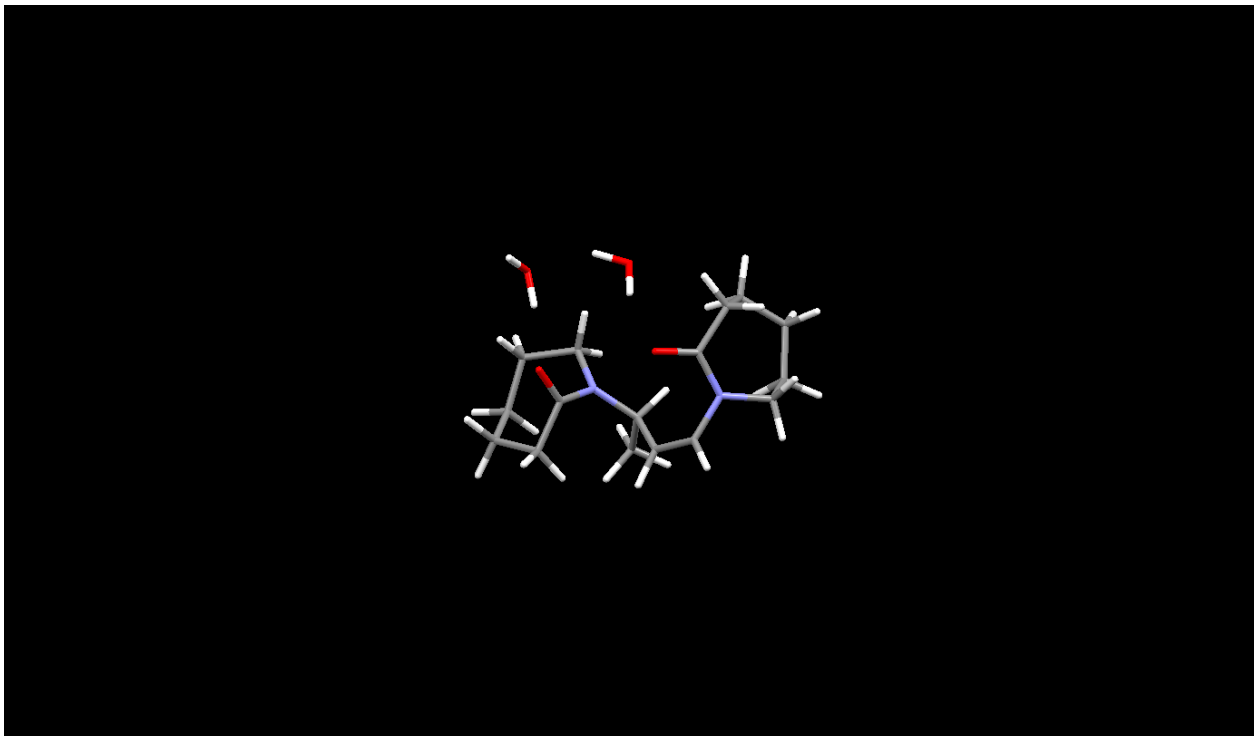



Compound **2**

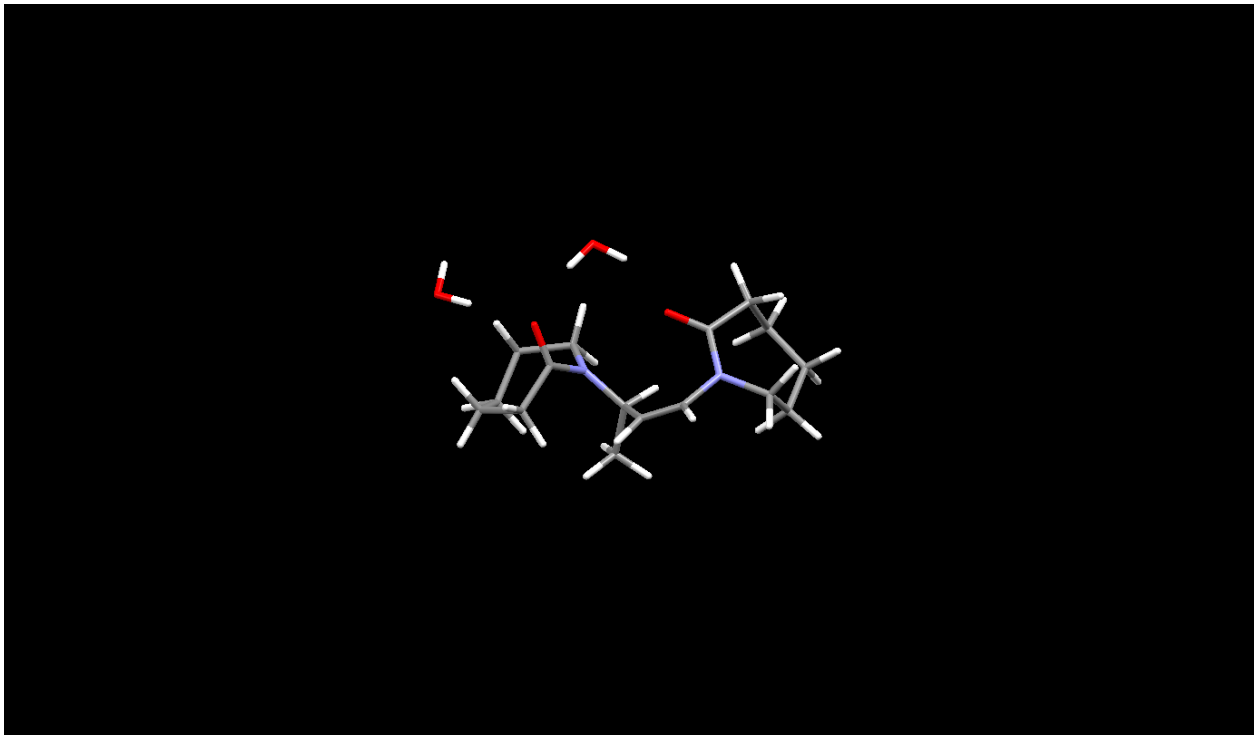


## DFT Calculations

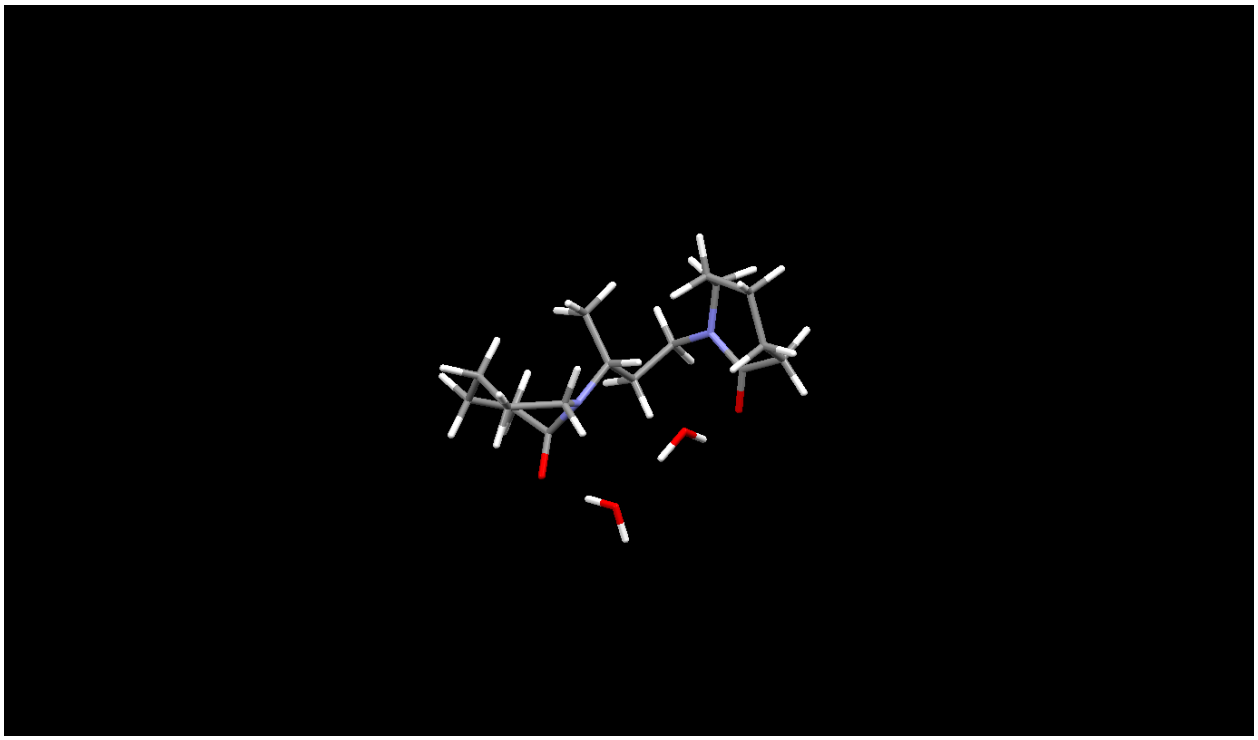
Compound **1**·2$H_2O$ global minimum



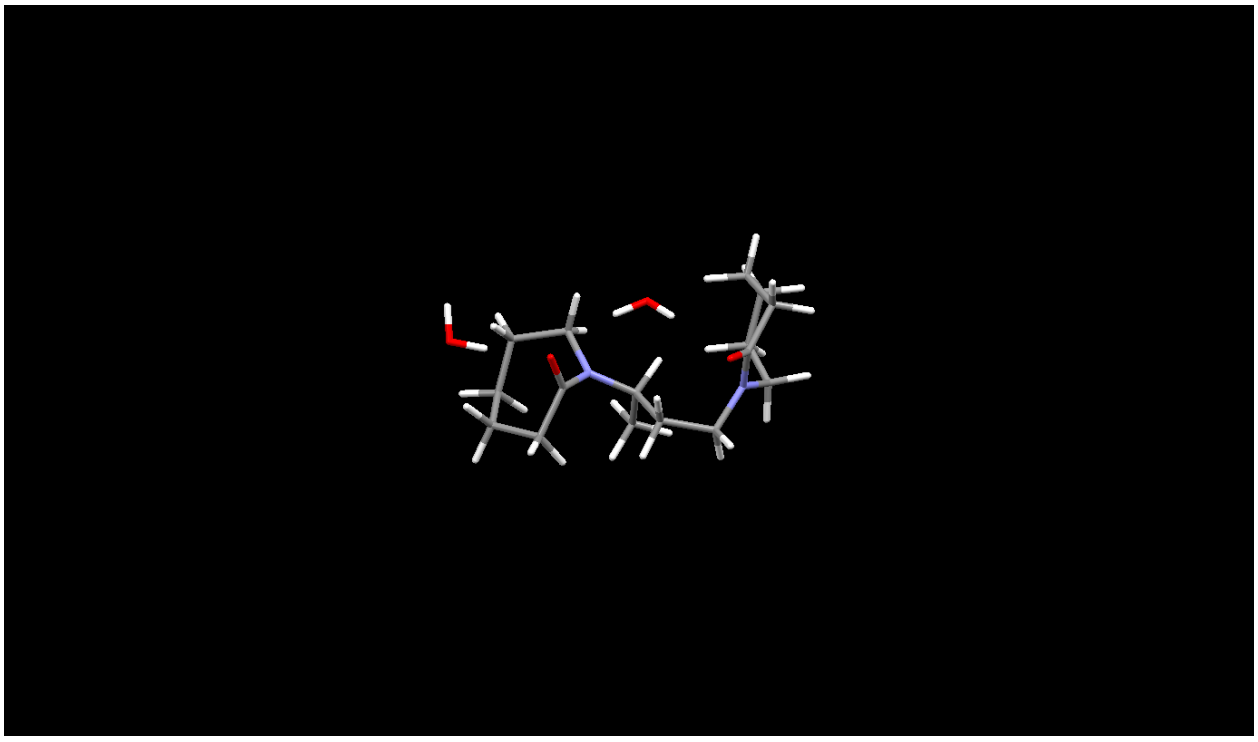
Compound **1**·2$H_2O$ local minimum



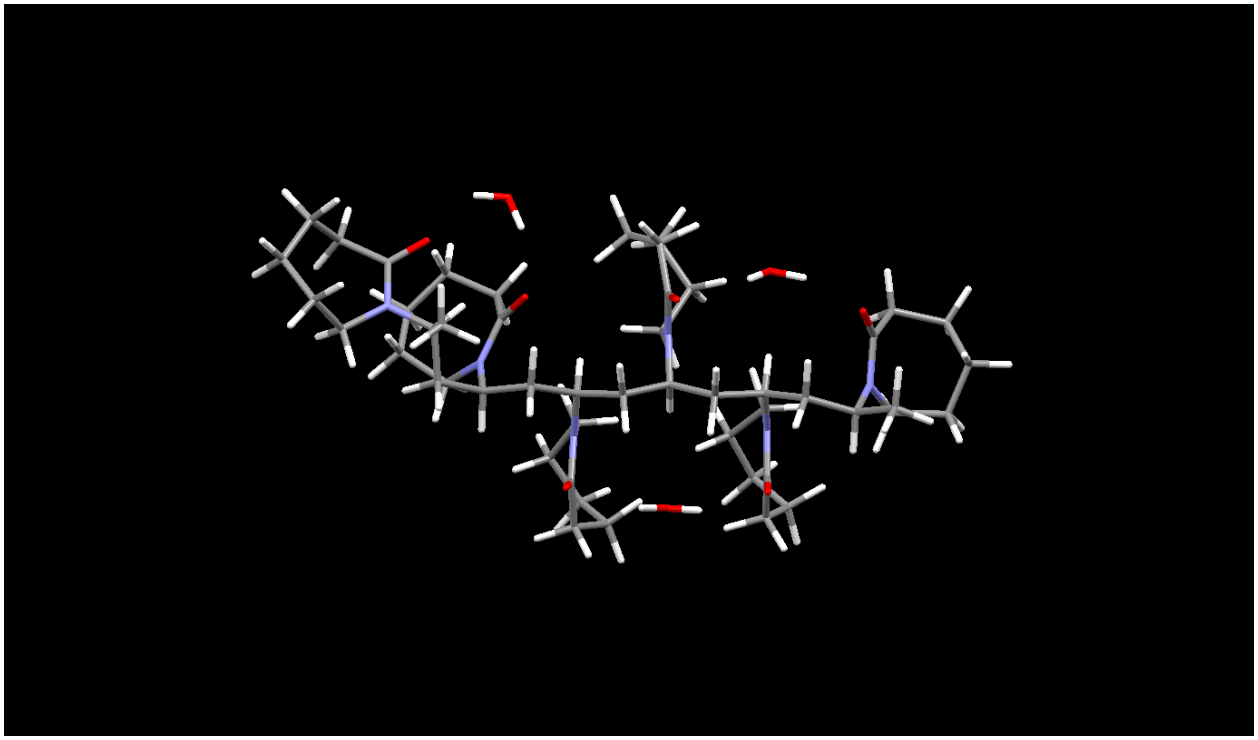
Compound **2**·2$H_2O$ minimum #1



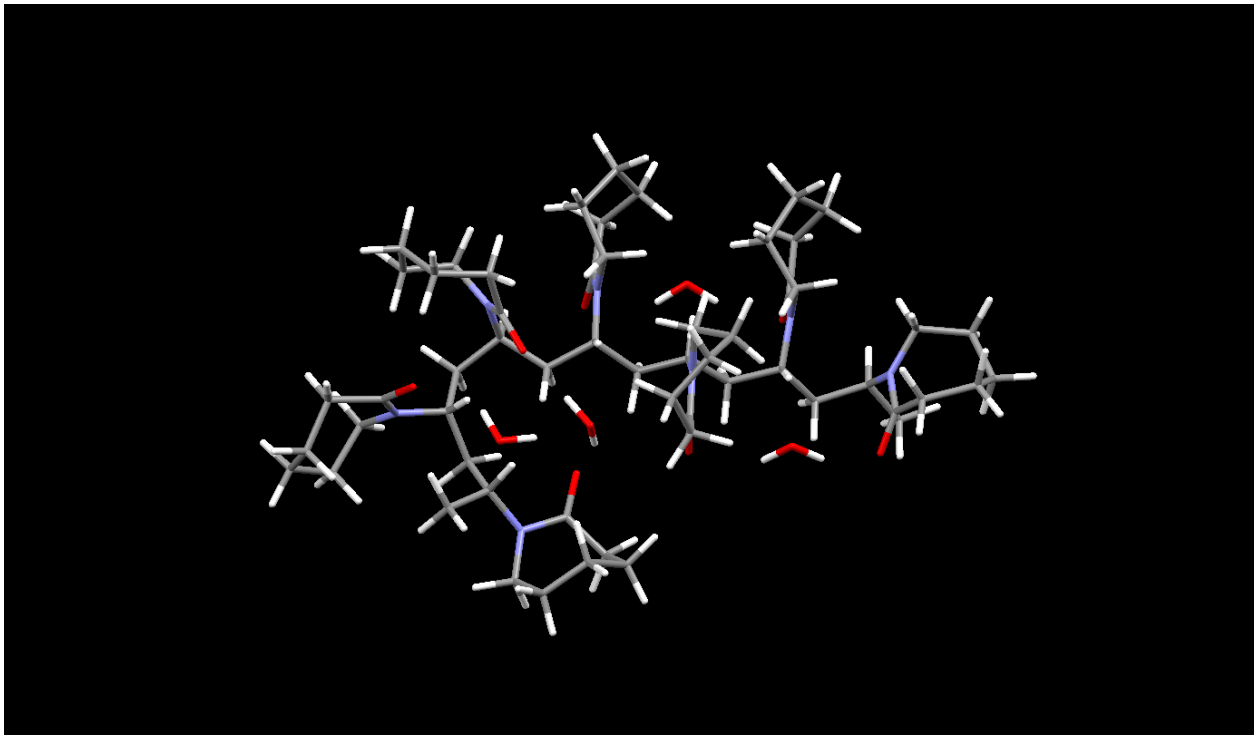
Compound **2**·2$H_2O$ minimum #2



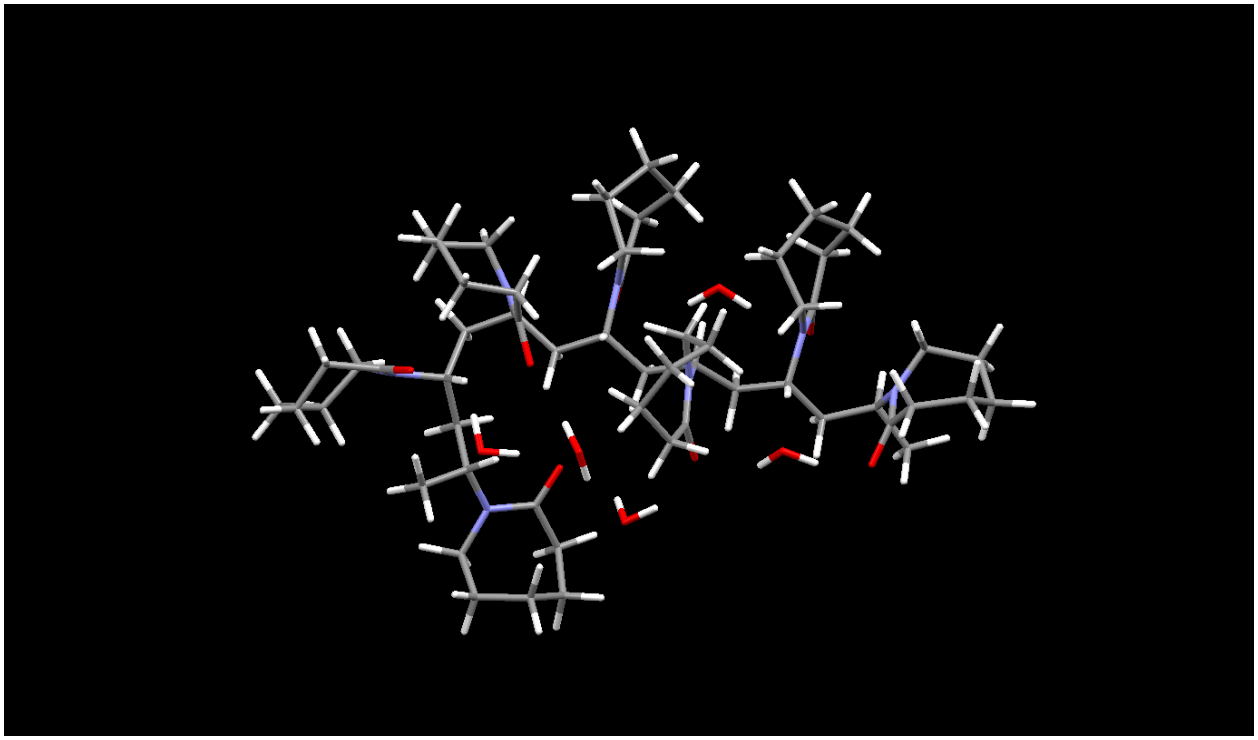
PVCap hexamer segment with three water molecules



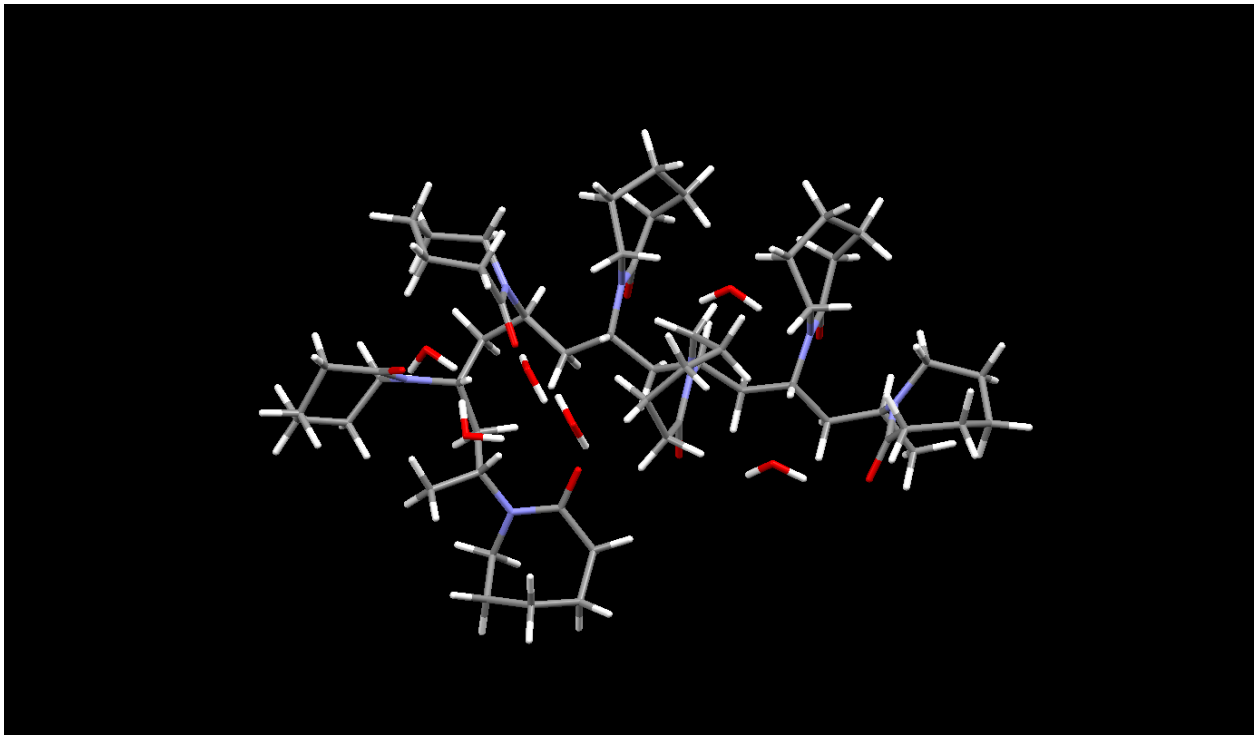
PVCap heptamer segment with four water molecules



PVCap heptamer segment with five water molecules



PVCap heptamer segment with six water molecules



PVCap octamer segment with four water molecules