Electrostatic repulsion between Cucurbit[7]urils can be overcomed in [3]Pseudorotaxane without adding salts

M. Pessêgo, J. A. Moreira, A. M. Rosa da Costa, P. Corrochano, F. J. Poblete, L. Garcia-Rio*

Supporting Information

1- Binding constants for bolaform vs alkyltrimethylammonium surfactants

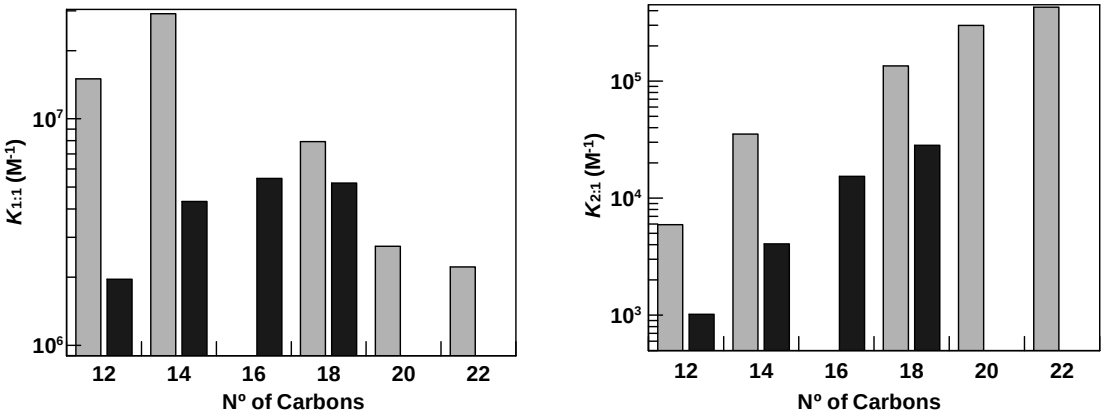


Figure S- 1: Values of the binding constants for C_nTA^+ (black)[1] and for B*n* (grey) 1:1 (left) and 2:1 (right) complexes.

Figure S- 1compares the values of the binding constants of the bolaform (B*n*, dicationic compounds) with published values for alkyltrimethylammonium[1] (C_nTA^+, monocationic compounds). Values of the $K_{1:1}$ binding constants for the bolaform surfactants are higher than those for C_nTA^+ conventional ones due to the interaction with both cationic head groups of the bolaform instead with one in the conventional surfactant (Figure S- 1, left). Moreover, it can be observed that the $K_{1:1}$ binding constants for bolaform approach those of single head surfactants on increasing the length of the alkyl chain in the former. For large hydrocarbon chains a smaller effect of the second head group on $K_{1:1}$, is observed: with the increasing distance between the portal of CB7 and that head group, the forth and back movement of the former becomes slower, and the host mostly located on the other head group. Comparison of the $K_{2:1}$ binding constants show that they increase on increasing the alkyl chain length of the surfactant both for bolaform and conventional ones, with $K_{2:1}$ values being higher for the former (Figure S- 1, right). This difference is a consequence of the different structures of the 2:1 host-guest complexes: in the case of C_nTA^+ the head group of the guest is shared by the hosts, whereas in the case of B*n* each host interacts with a different head group, minimizing the repulsive forces between the portal carbonyl groups of both hosts.

2- NMR Measurements

2.1- ^{1}H NMR spectra

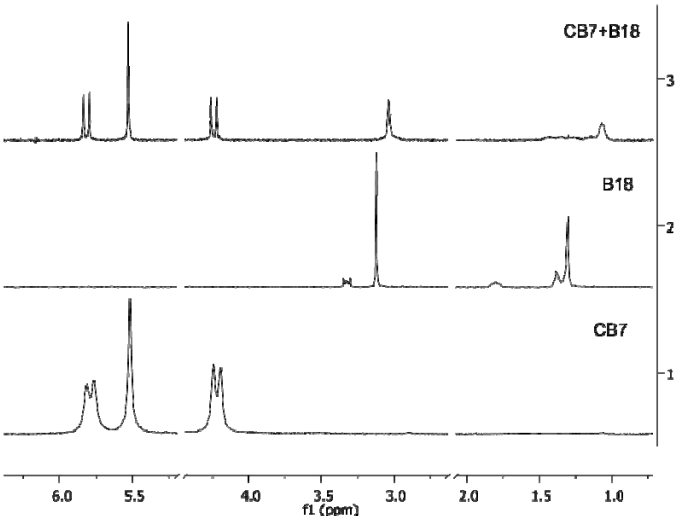


Figure S- 2: ^{1}H NMR spectra of CB7, B18 and CB7+B18

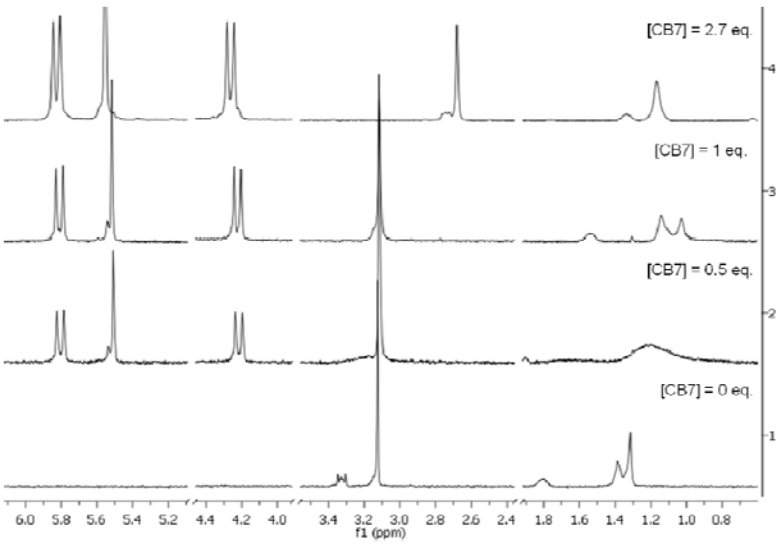


Figure S- 3: ^{1}H spectra of B14 in the absence (1) and in the presence (2-4) of different amounts of CB7.

Table S- 1: Values of $\Delta\delta_{1:1}$ and $\Delta\delta_{2:1}$ for different bolaforms for the signals of $^{+}N(CH_3)_3$.

B*n*	$\Delta\delta_{1:1}$	$\Delta\delta_{2:1}$
B12	0.05	-0.35
B14	-0.02	-0.45
B18	-0.06	-0.38
B20	-0.05	-0.25
B22	-0.02	-0.20

2.2- Diffusion Ordered Spectroscopy (DOSY)

The association process of B*n* with CB7 was studied in detail by preforming ^{1}H and DOSY experiments for a constant concentration of B*n,* below the cmc, with varying concentrations of CB7. The components of the mixture, CB7 and B*n*, present peaks in the spectrum that do not overlap, which makes possible to distinguish individual signals from CB7 and bolaform surfactants (Figure S-1), thus facilitating the evaluation of the data from the self-diffusion experiments. Quantitative analysis of the intensity of a relevant echo peak in the diffusion spectrum provides the translational diffusion coefficient (D) for the corresponding molecule. This was achieved by nonlinear fitting of the signal intensity to the Stejskal-Tanner equation[2]

$$I = I_0 \exp[-D\gamma^2 G^2 \delta^2 (\Delta - \delta/3)] \qquad \textbf{S- 1}$$

where I is the measured signal intensity, I_0 is the signal intensity at the lowest gradient pulse power, γ is the magnetogyric ratio of the observed nucleous and the remaining parameters are defined in the Experimental Section. In all experiments, the intensity decay of the signals gave good fits to equation S- 1, which shows that they represent a single self-diffusion coefficient. A typical plot of intensity decay *vs* $\gamma^2G^2\delta^2(\Delta\text{-}\delta/3)$ from a self-diffusion experiment is given in Figure S- 4.

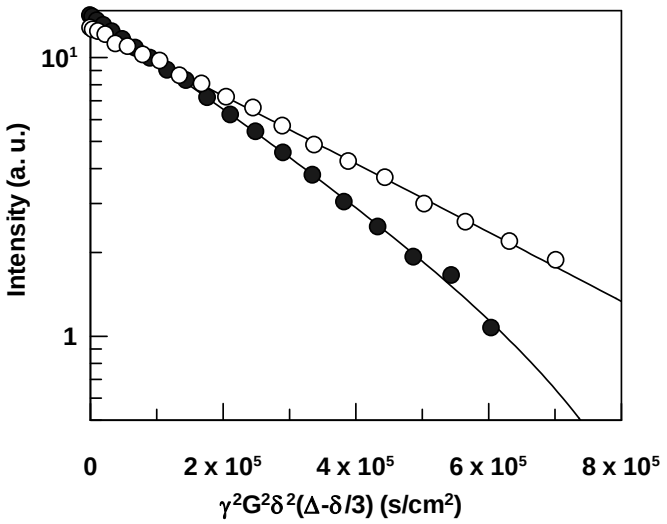


Figure S- 4 Representative echo decays of B18 (1.3 mM) in the absence (●) and in the presence of CB7 (0.9 mM) (○). The data were fitted to an exponential function (solid lines).

All peaks that correspond to CB7 were analyzed and similar results were obtained: for B*n* the peak from the methyl protons of the head groups was used as a reference.

Model of self-diffusion coefficients for the 1:1 and 2:1 complex

On the assumption that complexes of higher order than 1:1 are formed, a second equilibrium is established.

$$\text{CB7} + \text{B}n \overset{K_{1:1}}{\rightleftharpoons} \text{CB7-B}n$$

$$\text{CB7} + \text{CB7-B}n \overset{K_{2:1}}{\rightleftharpoons} (\text{CB7})_2\text{-B}n$$

Scheme S- 1

The observed self-diffusion values can be obtained for the bolaform surfactant and for CB7,

$$D_{Bn,obs} = \chi_{Bn,f} D_{Bn,f} + \chi^{Bn}_{CB7-Bn} D_{CB7-Bn} + \chi^{Bn}_{CB7_2-Bn} D_{CB7_2-Bn}$$

S- 2

$$D_{CB7,obs} = \chi_{CB7,f} D_{CB7,f} + \chi^{CB7}_{CB7-Bn} D_{CB7-Bn} + 2\chi^{CB7}_{CB7_2-Bn} D_{CB7_2-Bn}$$

S- 3

where $D_{Bn,f}$, $D_{CB7,f}$, $D_{CB7\text{-}Bn}$ and $D_{(CB7)2\text{-}Bn}$ are the diffusion coefficients for bolaform surfactant, CB7, 1:1 complex and 2:1 complex, respectively.

Molar fractions for the different species are referred to the total concentration of surfactant as:

$$\chi_{Bn,f} = \frac{[Bn]_f}{C_{Bn}}, \chi^{Bn}_{CB7-Bn} = \frac{[CB7-Bn]}{C_{Bn}}, \chi^{Bn}_{CB7_2\_Bn} = \frac{[CB7_2-Bn]}{C_{Bn}}$$

S- 4

or the total concentration of CB7:

$$\chi_{CB7,f} = \frac{[CB7]_f}{C_{CB7}}, \chi^{CB7}_{CB7-Bn} = \frac{[CB7-Bn]}{C_{CB7}}, \chi^{CB7}_{CB7_2-Bn} = \frac{[CB7_2-Bn]}{C_{CB7}}$$

S- 5

The observed self-diffusion for the bolaform surfactant (equation S- 6) can be expressed in terms of binding constants and total concentration of CB7.

$$D_{Bn,obs} = \frac{D_{Bn,f} + K_{1:1}D_{CB7-Bn}[CB7] + K_{1:1}K_{2:1}D_{CB7_2-Bn}[CB7]^2}{1 + K_{1:1}[CB7] + K_{1:1}K_{2:1}[CB7]^2}$$

S- 6

Figures S-4 to S-7 show the self-diffusion coefficients for B*n* as a function of molar ratio.

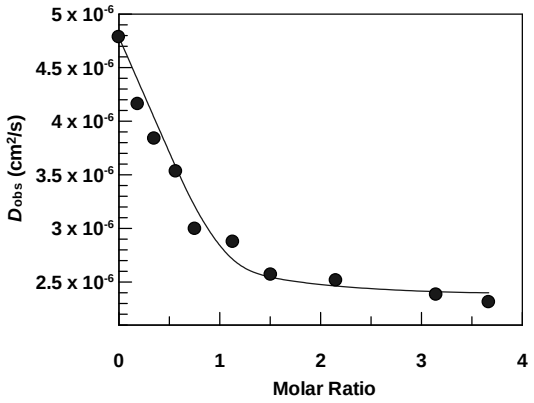


Figure S- 5: Self-diffusion coefficients of B12 (1.3 mM) for varying CB7 concentrations plotted as [CB7]/[B12] molar ratio. The solid line shows the fit to the model of self-diffusion coefficients for the 2:1 complex.

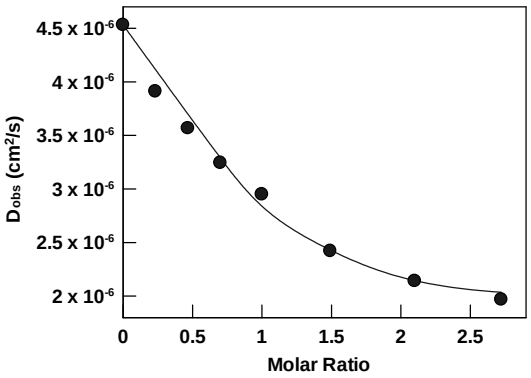


Figure S- 6: Self-diffusion coefficients of B14 (1.3 mM) for varying CB7 concentrations plotted as [CB7]/[B14] molar ratio. The solid line shows the fit to the model of self-diffusion coefficients for the 2:1 complex.

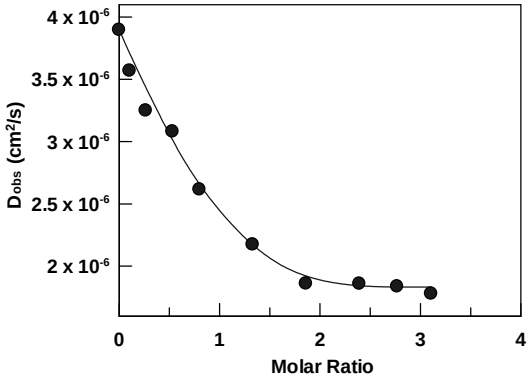


Figure S- 7: Self-diffusion coefficients of B20 (1.3 mM) for varying CB7 concentrations plotted as [CB7]/[B20] molar ratio. The solid line shows the fit to the model of self-diffusion coefficients for the 2:1 complex.

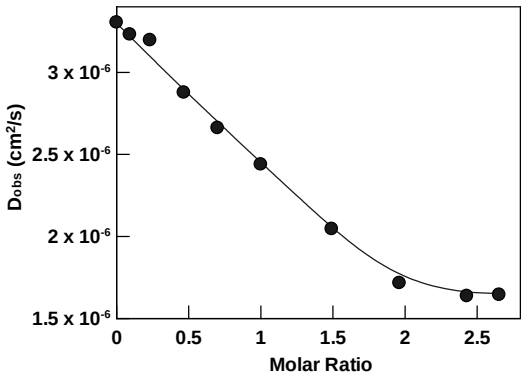


Figure S- 8: Self-diffusion coefficients of B22 (1.3 mM) for varying CB7 concentrations plotted as [CB7]/[B22] molar ratio. The solid line shows the fit to the model of self-diffusion coefficients for the 2:1 complex.

2.3- ^{1}H NMR spectra of bolaform in the presence of CB7.

Bolaform with 12 carbon atoms

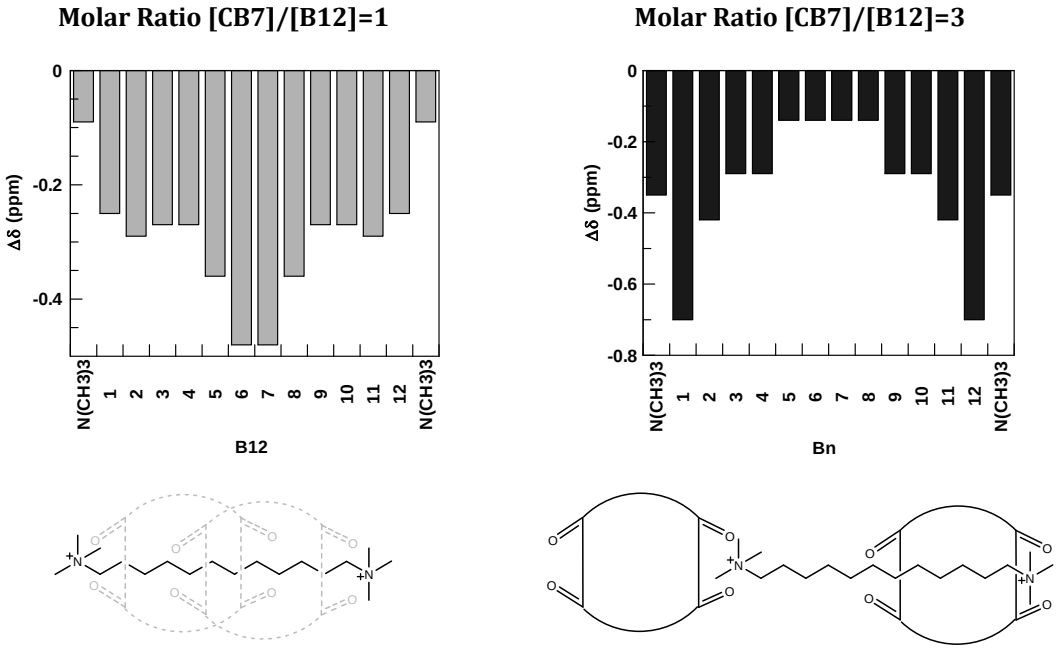


Figure S- 9: CB7-induced chemical shift changes (Δ*δ*, ppm) on the ^{1}H resonances of the protons of B*n* with n=12 for molar ratios of 1 (left) and 3 (right)

Bolaform with 14 carbon atoms

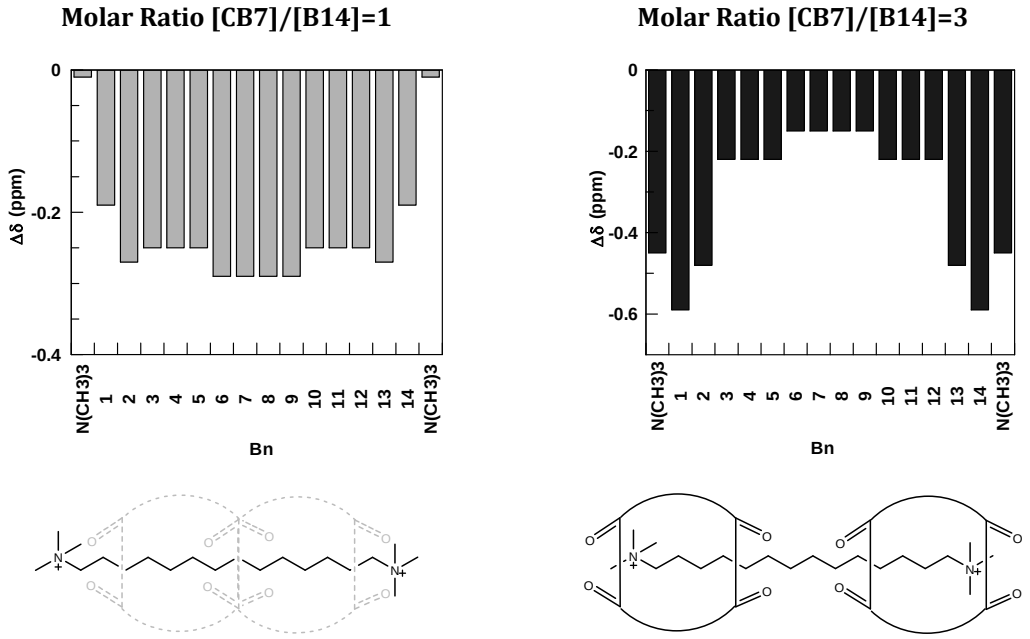


Figure S- 9: CB7-induced chemical shift changes (Δ*δ*, ppm) on the ^{1}H resonances of the protons of B*n* with n=14 for molar ratios of 1 (left) and 3 (right).

Bolaform with 18 carbon atoms

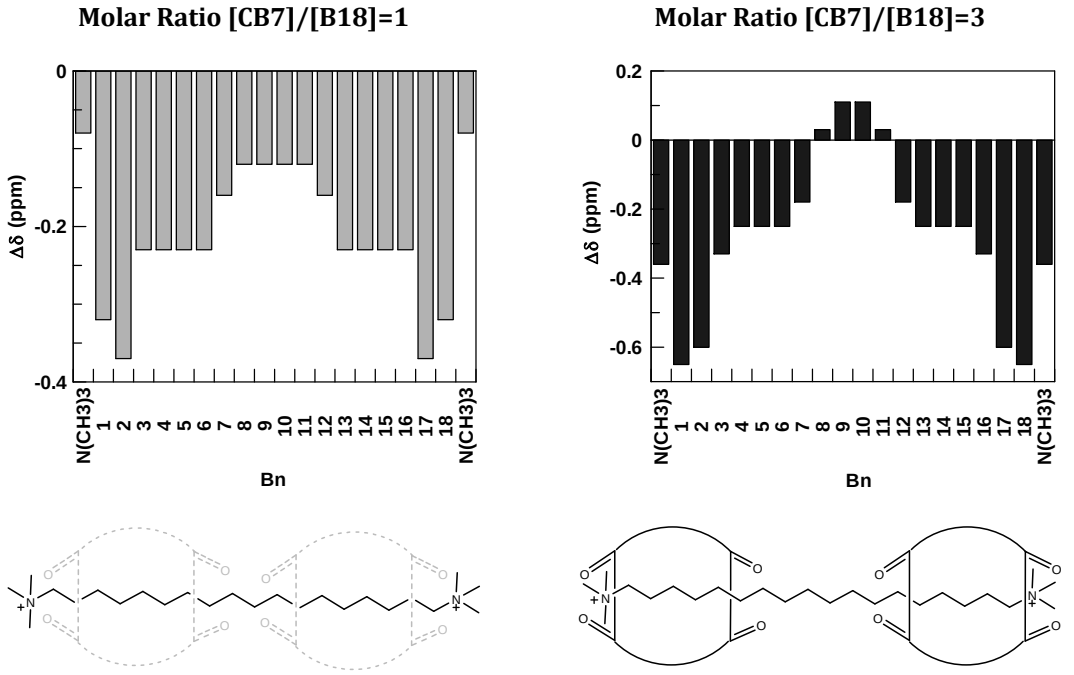


Figure S- 10: CB7-induced chemical shift changes (Δ*δ*, ppm) on the ^{1}H resonances of the protons of B*n* with n=18 for molar ratios of 1 (left) and 3 (right).

Bolaform with 20 carbon atoms

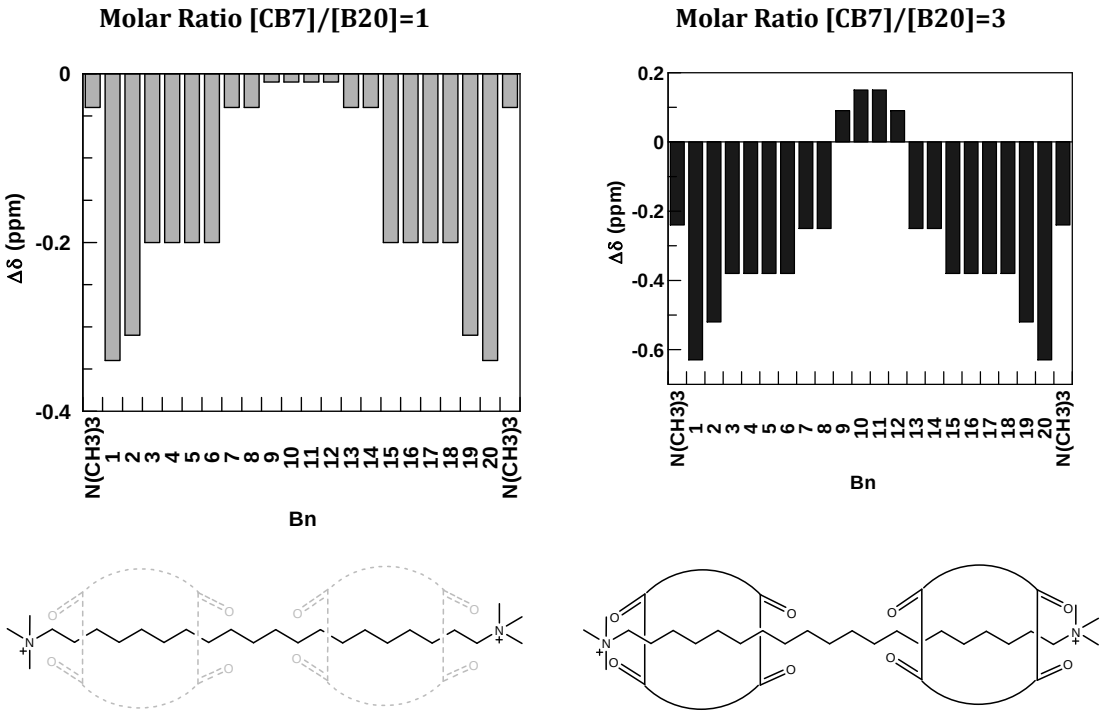


Figure S- 11: CB7-induced chemical shift changes (Δ*δ*, ppm) on the ^{1}H resonances of the protons of B*n* with n=20 for molar ratios of 1 (left) and 3 (right).

Bolaform with 22 carbon atoms

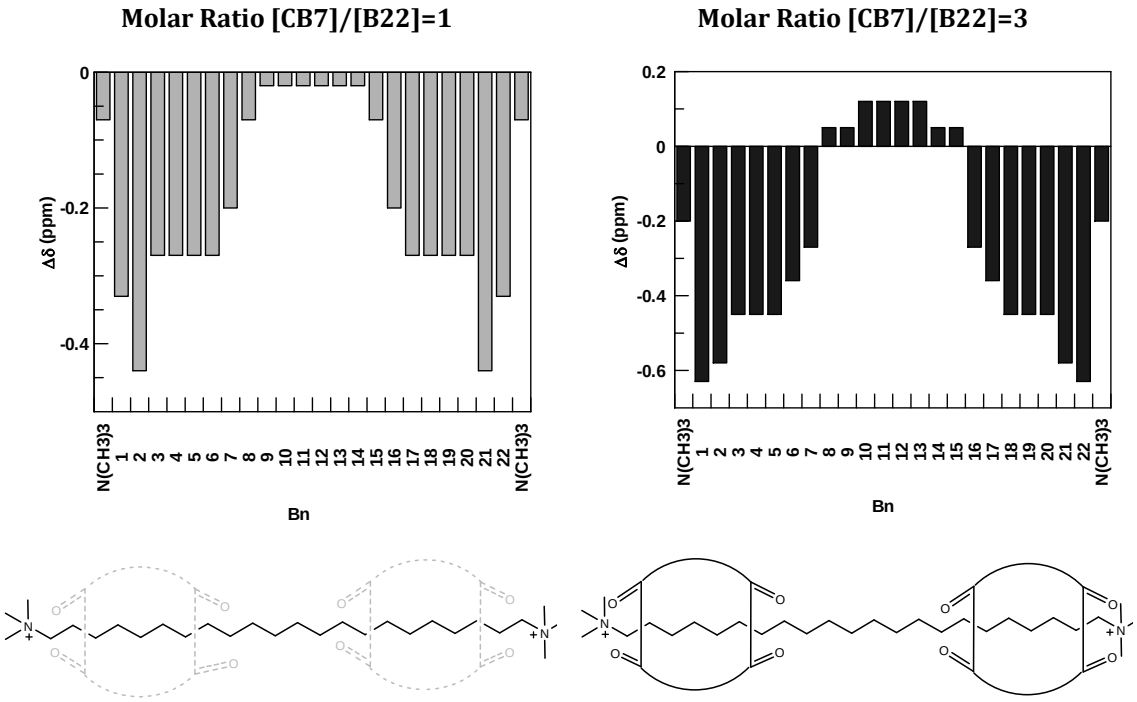


Figure S- 12: CB7-induced chemical shift changes (Δ*δ*, ppm) on the ^{1}H resonances of the protons of B*n* with n=22 for molar ratios of 1 (left) and 3 (right).

3- Kinetic experiments

The influence of CB7 on the rate constant for the solvolysis of MBSC in the absence of B*n* was also studied. Figure S- 13 shows the influence of CB7 concentration on the observed rate constant: it can be seen that the addition of CB7 to the reaction inhibits the hydrolysis of MBSC. The observed inhibition is attributed to the formation of an inclusion complex (MBSC-CB7) between MBSC and CB7 (Scheme S- 2).

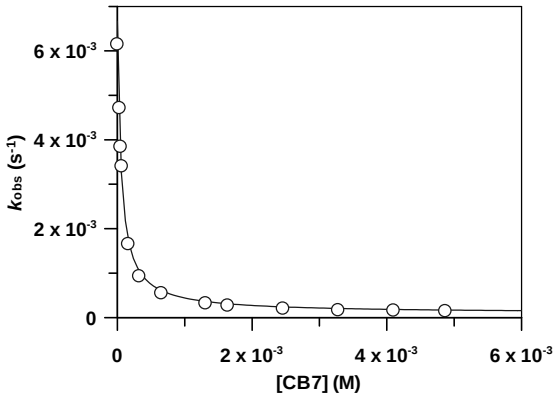
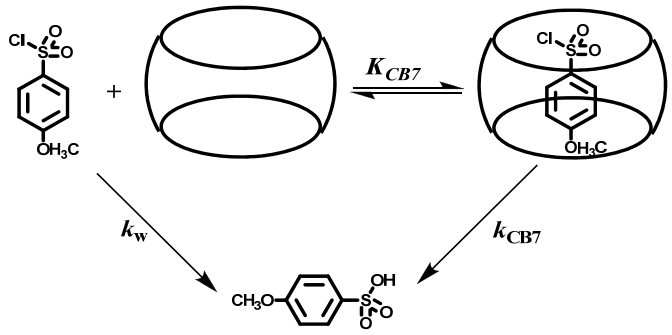


Figure S- 13: Influence of CB7 on the solvolysis recation of MBSC at 25ºC.

The kinetic scheme considers that the solvolysis of MBSC takes place in two well differentiated environments: water, k_w, and the CB7 cavity, k_{CB7}. Equation S- 7 can be obtained from Scheme S- 2.



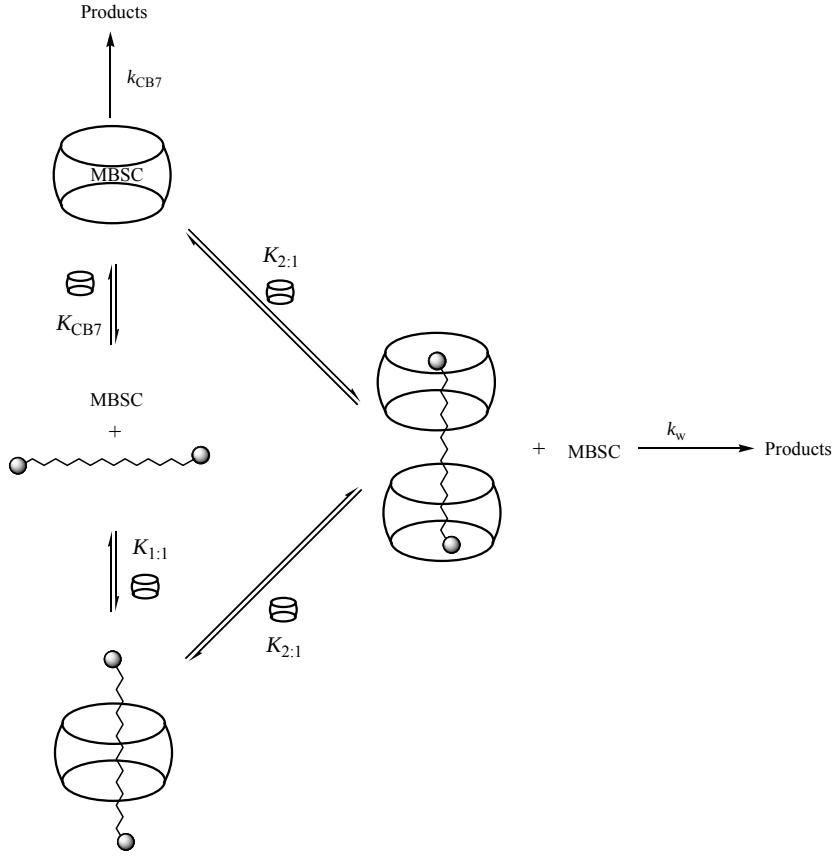
Scheme S- 2

$$k_{obs} = \frac{k_w + k_{CB7} K_{CB7} [CB7]_f}{1 + K_{CB7} [CB7]_f}$$

S- 7

Where K_{CB7} is the equilibrium binding constant of the substrate to CB7, k_{CB7} is the rate constant for the reaction in the cavity of CB7 and k_w is the rate constant for the hydrolysis in aqueous medium. Equation S- 7 gave an excellent fit to the experimental data (Figure S- 13), from which the parameters k_w = (6.44±0.01) × 10^{-3} s^{-1}, K_{CB7} = (1.8±0.1) × 10^4 M^{-1} and k_{CB7} = (6.2±0.1) × 10^{-5} s^{-1} were obtained.

The influence of CB7 on the solvolysis reaction of MBSC in the presence of bolaform surfactants was studied, taking into account that in the structure of 2:1 complex both CB7 host molecules include B*n* within their cavities (Scheme S- 3).



Scheme S- 3

To solve equation S- 7 it is necessary to know the concentration of uncomplexed CB7, $[CB7]_f$, for each surfactant concentration. The concentration of uncomplexed CB7 can be obtained by means of a simulation procedure, assuming that the complex formed between MBSC and CB7 has a stoichiometric ratio of 1:1 and between the latter and the surfactant molecules complexes present 1:1 and 2:1 stoichiometries. The constants for the complexation of the substrate and of the surfactant monomers by CB7 are expressed as (equations S- 8):

$$K_{CB7} = \frac{[CB7 - MBSC]}{[MBSC]_w [CB7]_f}, K_{1:1} = \frac{[CB7 - Bn]}{[Bn][CB7]_f}, K_{2:1} = \frac{[CB7 - Bn - CB7]}{[CB7 - Bn][CB7]_f}$$

S- 8

The mass balance for the total concentrations of CB7, surfactant, and MBSC are given by

$$[CB7]_T = [CB7]_f + [CB7 - MBSC] + [CB7 - Bn] + 2[CB7 - Bn - CB7]$$

S- 9

$$[Bn]_T = [Bn] + [CB7 - Bn] + [CB7 - Bn - CB7]$$

S- 10

$$[MBSC]_T = [MBSC]_w + [CB7 - MBSC]$$

S- 11

Combination of these equations with the binbing constants gives a fourth order equation for the concentration of uncomplexed CB7 (equation S- 12):

$$a[CB7]_f^4 + b[CB7]_f^3 + c[CB7]_f^2 + d[CB7]_f + e = 0$$

S- 12

where

$$a = K_{CB7} K_{1:1} K_{2:1}$$

S- 13

$$b = K_{CB7} K_{1:1} K_{2:1} (2[Bn]_T + [MBSC]_T - [CB7]_T) + K_{CB7} K_{1:1} + K_{1:1} K_{2:1}$$

S- 14

$$c = K_{CB7} K_{1:1} ([Bn]_T + [MBSC]_T - [CB7]_T) + K_{1:1} K_{2:1} (2[Bn]_T - [CB7]_T) + K_{CB7} + K_{1:1}$$

S- 15

$$d = K_{CB7} ([MBSC]_T - [CB7]_T) + K_{1:1} ([Bn]_T - [CB7]_T) + 1$$

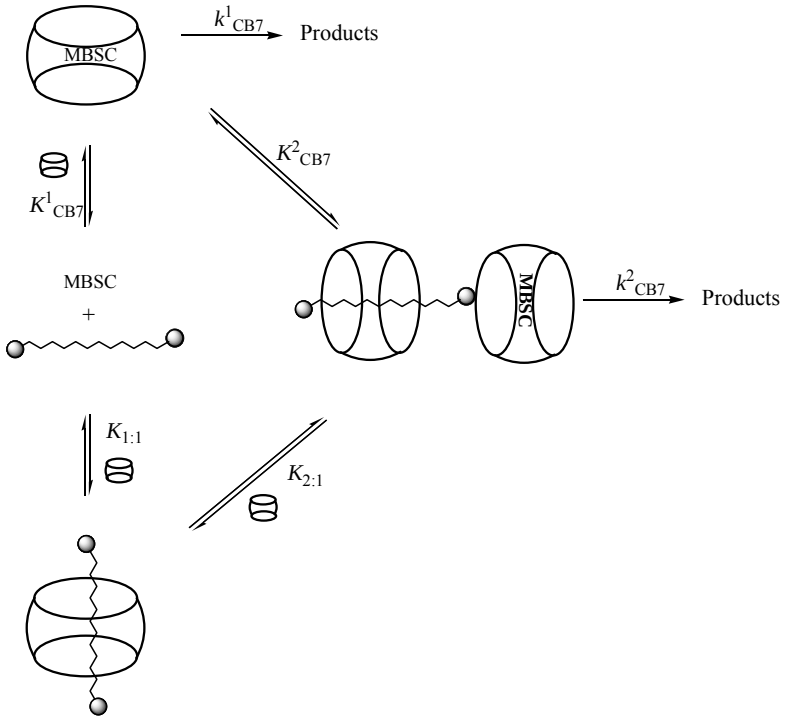
S- 16

$$e = -[CB7]_T$$

S- 17

In order to obtain $[CB7]_f$ we need to solve equation S- 7 using the values of $K_{1:1}$ and $K_{2:1}$ previously obtained and $K_{CB7}=(1.8 \pm 0.1) \times 10^4$ M^{-1}.

Assiming that in the 2:1 complex one of the hosts forms an inclusion complex and the other an external complex with an empty cavity, the latter could form an inclusion complex with the chemical probe, MBSC (Scheme S- 4).This assumption allows us to neglect the formation of a 2:1 complex between the CB7 and the surfactant, since the formation of this type of complex does not affect the reaction rate.



Scheme S- 4

In this case, solvolysis can take place in water, k_w, and in the cavity of CB7, k^1_{CB7} and k^2_{CB7}. Considering the following approaches (equations S- 18), will allow us to obtain equation S- 7.

$$K_{CB7} = K^1_{CB7} = K^2_{CB7}, k_{CB7} = k^1_{CB7} = k^2_{CB7}$$

S- 18

As mentioned previously, to solve equation S- 7 we need to know $[CB7]_f$ for each surfactant concentration by a simulation procedure, which consideres the above approaches and the equilibria present in the system, expressed as:

$$K_{CB7} = \frac{[CB7 - MBSC]}{[MBSC]_w [CB7]_f}, K_{1:1} = \frac{[CB7 - Bn]}{[CB7]_f [Bn]}$$

S- 19

The mass balance for the total concentrations of CB7, surfactant and MBSC are given by

$$[CB7]_T = [CB7]_f + [CB7 - MBSC] + [CB7 - Bn]$$

S- 20

$$[Bn]_T = [Bn] + [CB7 - Bn] + [CB7 - Bn - CB7]$$

S- 21

$$[MBSC]_T = [MBSC]_w + [CB7 - MBSC]$$

S- 22

The combination of these equations with the binding constants gives a third order equation for the concentration of uncomplexed CB7 (equation S- 23):

$$a[CB7]_f^3 + b[CB7]_f^2 + c[CB7]_f + d = 0$$

S- 23

Where

$$a = K_{CB7} K_{1:1}$$

S- 24

$$b = K_{CB7} K_{1:1} ([Bn]_T + [MBSC]_T - [CB7]_T) + K_{CB7} + K_{1:1}$$

S- 25

$$c = K_{CB7} ([MBSC]_T - [CB7]_T) + K_{1:1} ([Bn]_T - [CB7]_T) + 1$$

S- 26

$$d = -[CB7]_T$$

S- 27

4-References

[1] Pessêgo, M.; Moreira, J. A.; Garcia-Rio, L. *Chem. Eur. J.* **2012**, *18*, 7931-7940.

[2] Price, W. S. *Concepts. Nucl. Magn. Reson.* **1998**, *10*, 197-237.