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Rhodium Complexes Non-Covalently Bound to Cyclodextrins: Novel Water-Soluble Supramolecular Catalysts for the Biphasic Hydroformylation of Higher Olefins

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Abstract: A new class of cationic α-cyclodextrins bearing 2-hydroxy-3-trimethylammoniopropyl groups has been synthesised. We investigated their efficiency as mass-transfer promoters in a biphasic hydroformylation reaction catalysed by a rhodium trisulfonated triphenylphosphine system. These cationic α-cyclodextrins greatly increased the reaction rate, the chemoselectivity, and, surprisingly, the linear-to-branched aldehyde ratio. We attributed this unexpected enhancement of the linear-to-branched aldehyde ratio to the in situ formation of new catalytic supramolecular species obtained by ion-exchange between the catalyst ligand and the cationic α-cyclodextrins.

Keywords: cyclodextrins · hydroformylation · phosphanes · rhodium · supramolecular chemistry

Introduction

The use of chemically modified β-cyclodextrins (β-CD) as mass-transfer promoters is an attractive solution to extend the scope of aqueous organometallic catalysis to water-insoluble substrates.[1] Indeed, the β-CD derivatives greatly improve the solubility of highly hydrophobic substrates by forming water-soluble inclusion complexes and, consequently avoid mass-transfer limitations.[2] Formation of inclusion complexes with the phosphine used to solubilise the transition-metal in water can occur in parallel to the complexation of the substrate. The first example of such a phenomenon was reported with the native β-CD and the currently most-used ligand in aqueous organometallic catalysis: the sodium salt of the *meta*-substituted trisulfonated triphenylphosphine ($P(m\text{-}C_6H_4SO_3Na)_3$ (TPPTS)).[3] The geometry of this inclusion complex was deduced from two-dimensional NMR experiments and it was demonstrated that one phenyl ring of the TPPTS was included into the hydrophobic cavity of the β-CD from the side of the secondary hydroxy groups.[4] The affinity between the native β-CD and the ligand is very dependent on the nature of the ligand. Thus, the value of the association constant is particularly high when the ligand possesses a non-sulfonated aromatic ring as in the case of the (3-sodium sulfonatophenyl)diphenylphosphine (TPPMS)[5] and the bis(3-sodium sulfonatophenyl)-[4-(4-*tert*-butylphenyl)phenyl]phosphine.[6] Substitution of one or several hydroxy groups of the β-CD by ionic groups has a major influence on the original inclusion ability of the β-CD towards the ligand. For example, the lowest association constants are observed with β-CD derivatives bearing anionic substituents. Indeed, electronic repulsions between the anionic groups of these β-CD derivatives and the sulfonato groups of the water-soluble phosphine impede the formation of inclusion complexes.[7] Conversely, the presence of cationic groups such as ammonium groups on the β-CD greatly increase the affinity of the CD for the ligand due to attractive electrostatic interactions between the cationic group of the CD and the anionic group of the phosphine. For instance, the value of the association constant for the TPPMS-mono[2-*O*-(2-hydroxy-3-trimethylammoniopropyl)]-β-CD inclusion complex was found to be 105 500 versus 7110 M^{-1} for the TPPMS-β-CD inclusion complex.[8] This inclusion

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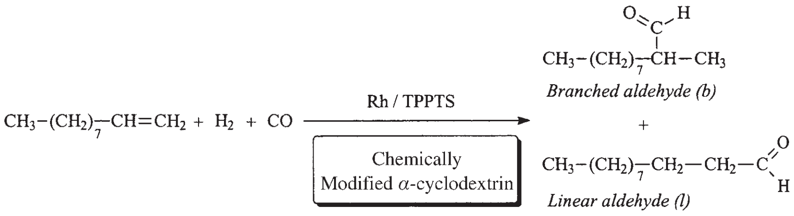
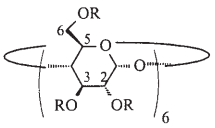
complex was formed in situ by an ion-exchange between the mono[2-*O*-(2-hydroxy-3-trimethylammoniopropyl)]-β-CD chloride and the sodium salt of the TPPMS. The NMR experiments demonstrated that one of the non-sulfonated groups of the TPPMS was included in the host cavity of the CD and that methyl groups of the 2-hydroxy-3-trimethylammoniopropyl substituent were inequivalent due to the formation of the ion pair.

The discovery of this ion-exchange gave us the idea to synthesise water-soluble organometallic catalysts possessing mass-transfer functions by self-assembly. Indeed, if the CD cavity is not occupied by one phenyl ring of the phosphine and remains located near the catalytically active centre owing to the formation of an ion pair between the ligand and the CD, such an organometallic complex could act as an efficient phase-transfer catalyst and/or could lead to unusual selectivity. As we have recently demonstrated that non-charged α-cyclodextrin (α-CD) derivatives cannot form inclusion complexes with the TPPTS due to their cavities being too small,[9] the α-CD derivatives bearing 2-hydroxy-3-trimethylammoniopropyl substituents could be excellent candidates to obtain such catalysts.



Structure of the chemically modified cyclodextrin



Abbreviations	R (*number of R group by CD*)	Carbon bearing the OR group(s)
HP-α-CD	$-CH_2-CH(OH)-CH_3$ *(3.6)*	2
RAME-α-CD	$-CH_3$ *(10.8)*	2, 3, 6
mono-HTMAP-α-CD	$-CH_2-CH(OH)-CH_2-N(CH_3)_3^+Cl^-$ *(1)*	2
mono-MTMAP/Me-α-CD	$-CH_2-CH(OCH_3)-CH_2-N(CH_3)_3^+Cl^-$ *(1)* and $-CH_3$ *(13)*	2, 3, 6
tetra-HTMAP-α-CD	$-CH_2-CH(OH)-CH_2-N(CH_3)_3^+Cl^-$ *(4)*	2, 3, 6
di-MTMAP/Me-α-CD	$-CH_2-CH(OCH_3)-CH_2-N(CH_3)_3^+Cl^-$ *(2)* and $-CH_3$ *(15)*	2, 3, 6

Scheme 1. Rhodium-catalysed hydroformylation of 1-decene in the presence of chemically modified α-cyclodextrins.

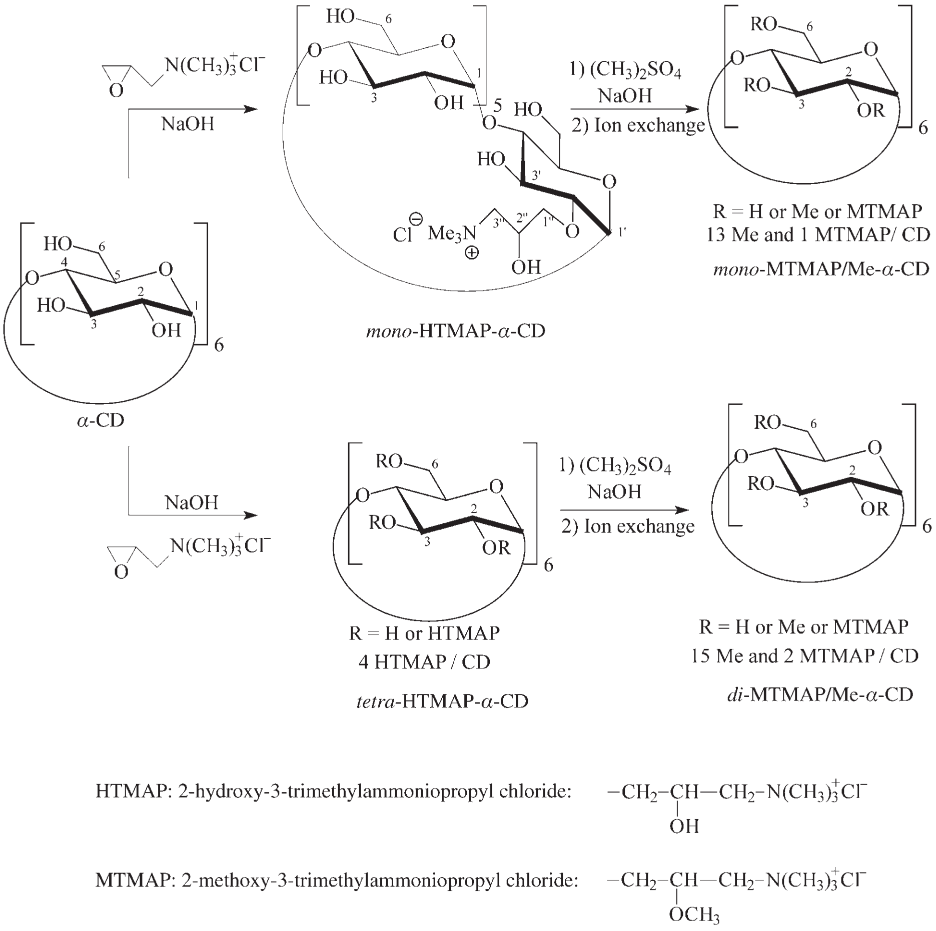
Here we report the synthesis of new α-CD derivatives bearing 2-hydroxy-3-trimethylammoniopropyl substituents. The behaviour of these α-CD derivatives towards the TPPTS ligand was investigated by ^1H and $^{31}P\{^1H\}$ NMR spectroscopy, and the ability of $[Rh(acac)(CO)_2]$/TPPTS/cationic α-CD systems to catalyse the biphasic hydroformylation of 1-decene has been evaluated (Scheme 1).

Results and Discussion

Synthesis of cationic α-CD derivatives: The α-CD derivatives bearing the 2-hydroxy-3-trimethylammoniopropyl (HTMAP) group were synthesised according to a procedure analogous to that described by Deratani and co-workers for β-CD derivatives bearing HTMAP groups.[10]

The native α-CD and 2,3-epoxypropyltrimethylammonium chloride reacted in basic medium to afford the *O*-(2-hydroxy-3-trimethylammoniumpropyl)-α-CD derivatives (mono-HTMAP-α-CD and tetra-HTMAP-α-CD; Scheme 2). For example, attachment of one HTMAP group to the α-CD is evidenced by ^1H NMR spectra showing the presence of new signals assigned to H1′, H2″, H3′, and NMe_3^+ (Figure 1a).

We checked the monosubstitution by comparing the integrated areas of the resonance for the proton H2″ and the protons H1 and H1′. The degree of substitution was also confirmed by ES-MS. The substitution in position 2 of the α-CD was indicated by the presence of H1′ corresponding to the acetalic proton of the glucose unit substituted in position 2. This position was in agreement with the data reported by Deratani and co-workers for the HTMAP-β-CD. We synthesised tetra-HTMAP-α-CD in the same way as mono-HTMAP-α-CD by increasing the quantity of 2,3-epoxypro-



Scheme 2. Synthesis of the cationic α-cyclodextrins used in this work.

pyltrimethylammonium chloride (14 versus 0.7 equivalents). The NMR and ES-MS analyses were in accordance with an average degree of substitution of four. The regioselectivity was not only in the 2 position but either in the 3 or 6 positions.

As methylation of CD enhances the surface active properties[11] of CD and its affinity[12] for long-chain olefins, we envisaged the synthesis of methylated derivatives of the mono-HTMAP-α-CD and the tetra-HTMAP-α-CD. Initial attempts by adding 2,3-epoxypropyltrimethylammonium chloride to randomly methylated-α-CD (RAME-α-CD) in aqueous basic medium, or in *N*,*N*-dimethylformamide containing barium oxide and barium hydroxide, failed due to the poor reactivity of the hydroxy groups of the RAME-α-CD. Fortunately, the target CD derivatives have been obtained from mono-HTMAP-α-CD and tetra-HTMAP-α-CD by using dimethylsulfate as a methylation reagent.[13] The ^{1}H NMR spectrum of the methylated mono-HTMAP-α-CD showed the presence of methyl groups in the 2, 3, and 6 positions. We obtained the average substitution-degree of 13 by ES-MS. It must be pointed out that the hydroxy group of the HTMAP group was also methylated as the signal of the H2′′ proton of the HTMAP group was found upfield in the CD proton pattern (see Figure 1b).

In the same way, the NMR spectrum of the methylated derivative of tetra-HTMAP-α-CD indicates that methylation of the hydroxy group of the HTMAP group has occurred. The average number of methyl groups and methylated HTMAP groups was determined by ES-MS and were found to be 15 and 2, respectively. The number of methylated HTMAP groups was surprisingly lower than the initial number of HTMAP groups in the starting product (2 as opposed to 4). The loss of HTMAP groups during the synthesis was attributed to the high concentration of base required for the methylation. We assume that the degradation proceeds by a Hofmann elimination as we detected the characteristic odour of amine when the reaction was complete.

^{1}H and ^{31}P{^{1}H} NMR studies: The behaviour of the cationic α-CD derivatives toward the TPPTS ligand has been investigated by ^{1}H and ^{31}P{^{1}H} NMR spectroscopy. The ^{1}H and ^{31}P NMR spectra of a stoichiometric mixture of TPPTS and mono-HTMAP-α-CD are displayed in Figures 2–4. ^{1}H and ^{31}P{^{1}H} NMR spectra of TPPTS in the presence of mono-HTMAP-β-CD are also given for comparison, as it was previously shown that the TPPTS ligand can be partially included in the cavity of chemically modified β-CD derivatives.[6]

As expected, inclusion of one phenyl ring of the TPPTS into the cavity of the mono-HTMAP-β-CD induces strong modifications of the ^{1}H NMR spectra of the TPPTS and β-CD. We observed an overlap of the H_p and $H_{o'}$ signals and a shift for H_m and H_o for the TPPTS protons (see Figure 2). Concerning the β-CD protons, the signal at $\delta = 3.25$ ppm corresponding to the three methyl groups of ammonium was split into several signals and the internal protons of the CD (H3 and H5) were shifted to higher field (see Figure 3). ^{31}P{^{1}H} NMR spectra were also indicative of the inclusion complex formation as an important variation of the chemical shift of the TPPTS phosphorus atom was observed in the presence of mono-HTMAP-β-CD ($\delta = -8.8$ ppm as opposed to −5.9 ppm) (Figure 4).

Conversely, when mono-HTMAP-α-CD was added to TPPTS, the ^{1}H and ^{31}P{^{1}H} spectra of the TPPTS were very similar to those observed without CD. We observed a slight change in chemical shift of the phosphorus atom ($\delta =$

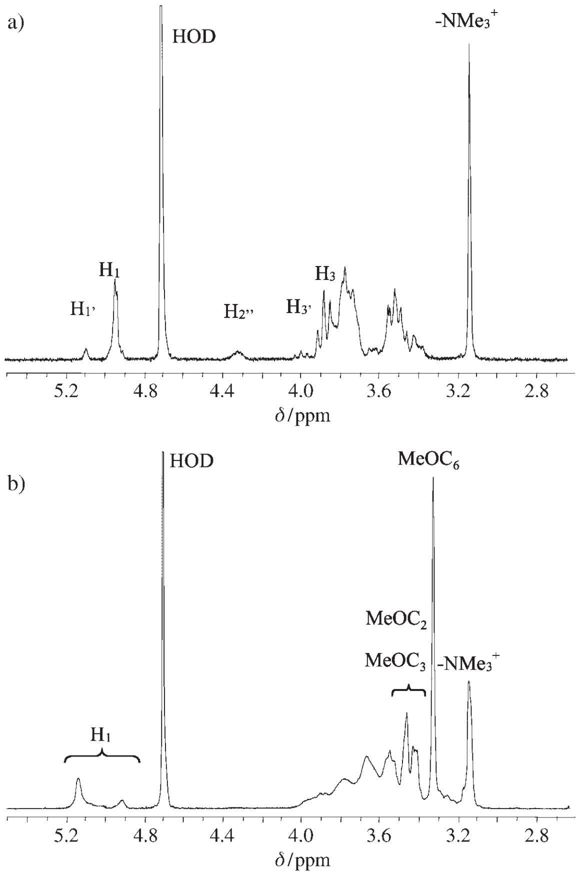


Figure 1. ^1H NMR spectrum of: a) mono-HTMAP-α-CD (3 mм); b) mono-MTMAP/Me-α-CD (3 mм); in D_2O at 298 K.

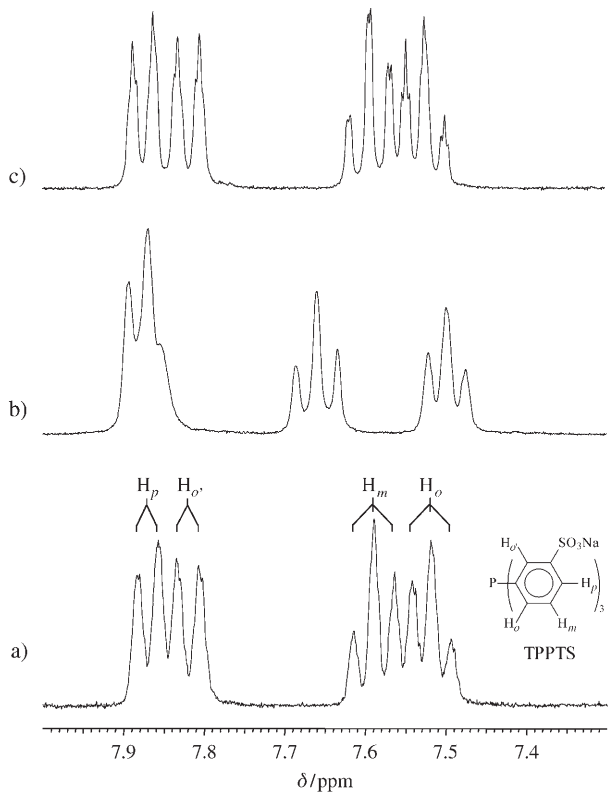


Figure 2. Effect of mono-HTMAP cyclodextrins on the ^1H NMR spectrum of TPPTS (3 mм) in D_2O at 298 K: a) ^1H NMR spectrum of TPPTS without cyclodextrin; b) in the presence of mono-HTMAP-β-CD (3 mм); c) in the presence of mono-HTMAP-α-CD (3 mм).

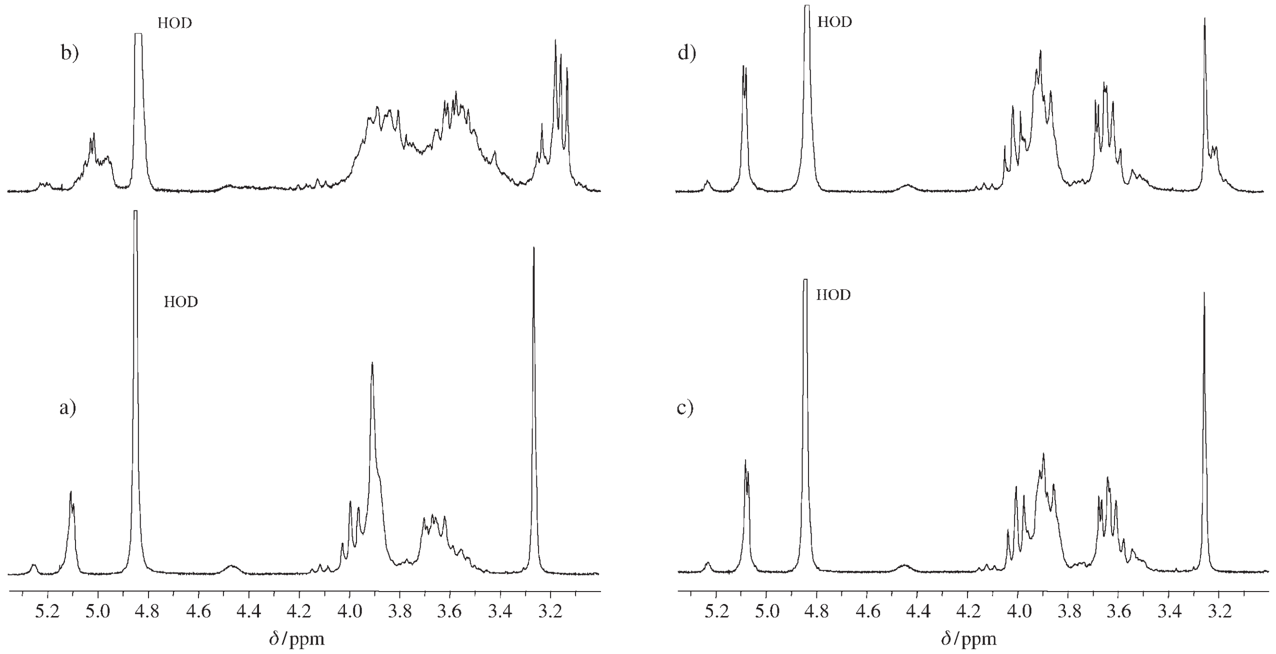


Figure 3. Effect of TPPTS on ^1H NMR spectra of mono-HTMAP cyclodextrins (3 mм) in D_2O at 298 K: a) mono-HTMAP-β-CD; b) mono-HTMAP-β-CD with TPPTS (3 mм); c) mono-HTMAP-α-CD; d) mono-HTMAP-α-CD with TPPTS (3 mм).

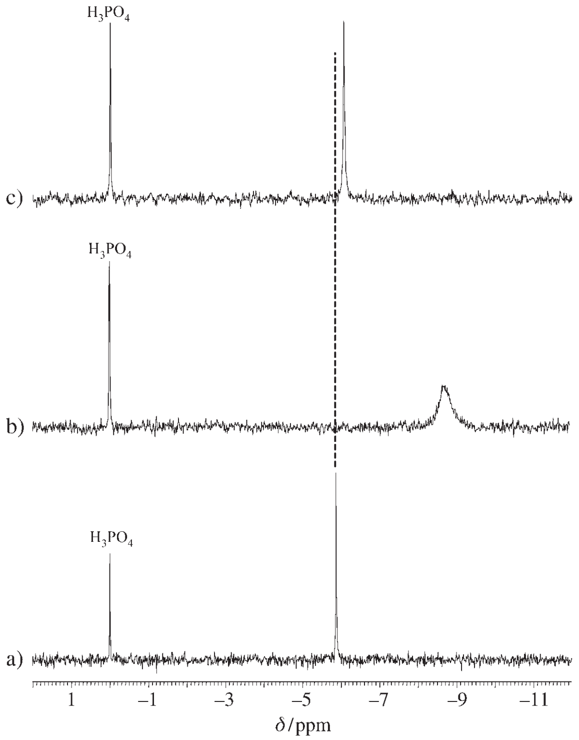


Figure 4. Effect of mono-HTMAP cyclodextrins on the $^{31}P\{^1H\}$ NMR spectrum of TPPTS (3 mM) in D_2O at 298 K with H_3PO_4 as internal reference: a) $^{31}P\{^1H\}$ NMR spectrum of TPPTS without cyclodextrin; b) in the presence of mono-HTMAP-β-CD (3 mM); c) in the presence of mono-HTMAP-α-CD (3 mM).

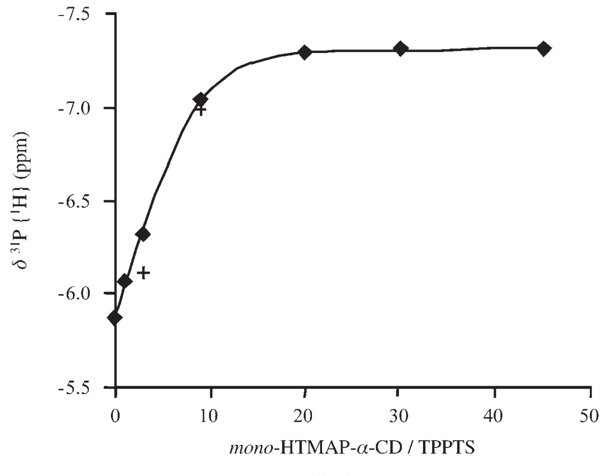


Figure 5. Influence of salts on the $^{31}P\{^1H\}$ chemical shift of TPPTS: (◆) $^{31}P\{^1H\}$ chemical shift of the TPPTS as a function of the mono-HTMAP-α-CD/TPPTS ratio. (+) $^{31}P\{^1H\}$ chemical shift of TPPTS for mono-HTMAP-α-CD/TPPTS ratios of 3 and 9 when NaCl (100 equiv relative to the mono-HTMAP-α-CD) was added to the solution containing the TPPTS and the mono-HTMAP-α-CD.

−0.2 ppm) and a modification of the signal corresponding to the three methyl groups of ammonium ($\delta = 3.25$ ppm) confirming that the cavity of the α-CD is not occupied by a TPPTS phenyl ring. The lack of a phenyl ring in the host cavity was also evidenced by two-dimensional T-ROESY experiments on the stoichiometric mixture as no intense correlation peak was observed between the internal protons of the cavity and the TPPTS ligand. Although no definitive evidence has been obtained, the slight modifications observed in the NMR spectra could result from a partial ion-exchange between the sodium salt of TPPTS and the mono-HTMAP-α-CD. This hypothesis was supported by a $^{31}P\{^1H\}$ NMR study conducted on various TPPTS/mono-HTMAP-α-CD mixtures. Figure 5 displays the chemical shifts of the TPPTS phosphorus atom as a function of the mono-HTMAP-α-CD/TPPTS ratio.

The TPPTS chemical shift was strongly influenced by the presence of mono-HTMAP-α-CD up to a ratio of mono-HTMAP-α-CD/TPPTS of 11–12. At higher ratios, there is almost no additional change in chemical shift suggesting that all sodium cations of the TPPTS have been substituted by the cationic α-CD. We carefully examined the ^1H NMR spectra of the above TPPTS/mono-HTMAP-α-CD mixtures. We observed no change of the CD proton pattern confirming that inclusion of a phenyl ring of the TPPTS did not occur even at high mono-HTMAP-α-CD/TPPTS ratios. We should point out that the influence of the counterion of the TPPTS on the chemical shift of the TPPTS phosphorus atom has also been observed by Hanson and Riisager with non-amphiphilic quaternary ammonium ions.[14] These authors reported that the $^{31}P\{^1H\}$ NMR signal of TPPTS is shifted toward high field in the presence of tetrabutylammonium bromide due to ion-exchange between TPPTS and the ammonium salt.

The stability of the mono-HTMAP-α-CD/TPPTS ion pair was investigated in the presence of inorganic salts. In particular, it is expected that the addition of a large amount of salt such as NaCl to a solution containing the mono-HTMAP-α-CD/TPPTS ion pair could induce dissociation of the ion pair and, consequently, formation of the sodium salt of the TPPTS and the mono-HTMAP-α-CD with the chloride as counteranion. As shown in Figure 5, addition of NaCl (100 equivalents relative to the mono-HTMAP-α-CD) did not induce a total dissociation of the ion pair. Hence the $^{31}P\{^1H\}$ NMR signal of TPPTS for a CD/TPPTS ratio of nine was $\delta = -7.04$ ppm without NaCl and −6.98 ppm in the presence of NaCl (100 equivalents/mono-HTMAP-α-CD). The effect of NaCl was however more marked when the CD/TPPTS ratio was lower. In fact, the chemical shift of the phosphorus atom for a CD/TPPTS ratio of three was found to be $\delta = -6.32$ ppm without NaCl and −6.11 ppm in the presence of NaCl (100 equivalents/mono-HTMAP-α-CD). A similar phenomenon was also observed when Na_2SO_4 (50 equivalents/CD) was added to the solution containing the ion pair, confirming that the mono-HTMAP-α-CD/TPPTS ion pair is relatively stable. Finally, it should be noted that the high stability of TPPTS/ammonium ion pair has also been mentioned in the literature. Numerous authors have attributed the enhancement of activity and selectivity observed when the hydroformylation reaction is conducted in the presence of cetyltrimethylammonium surfactants to

Table 1. Hydroformylation of 1-decene in the presence of different chemically modified α-cyclodextrins.[a]

Entry	CD	Na_2SO_4	Time [h]	Conversion [%]	Selectivity [%]	l/b ratio
1	–	(−)	6	3	59	2.8
2[b]	–	(−)	6	3	67	2.7
3[c]	–	(+)	6	1	60	2.8
4	HP-α-CD	(−)	6	24	88	3.0
5	RAME-α-CD	(−)	6	43	91	2.8
6	RAME-α-CD	(−)	24	65	92	2.8
7	mono-HTMAP-α-CD	(−)	6	13	93	3.6
8[d]	mono-HTMAP-α-CD	(+)	6	9	93	3.6
9[e]	mono-HTMAP-α-CD	(+)	6	4	93	3.6
10	mono-MTMAP/Me-α-CD	(−)	6	43	98	3.1
11	mono-MTMAP/Me-α-CD	(−)	24	89	99	3.1
12	tetra-HTMAP-α-CD	(−)	6	8	88	5.4
13	di-MTMAP/Me-α-CD	(−)	24	16	94	4.7

[a] Experimental conditions: $[Rh(acac)(CO)_2]$ (4.07×10^{-2} mmol), TPPTS (0.21 mmol), CD (0.48 mmol), H_2O (11.5 mL), 1-decene (20.35 mmol), 80 °C, CO/H_2 (1:1, 50 atm). [b] The salt $HOCH_2CH(OH)CH_2N(CH_3)_3^+Cl^-$ (0.48 mmol) was added in the catalytic medium instead of the CD. [c] Na_2SO_4 (2.4 mmol) was added to the solution. [d] Na_2SO_4 (1.2 mmol) was added to the solution. [e] Na_2SO_4 (2.4 mmol) was added to the solution.

strong interactions of the TPPTS sulfonate groups with the surface of micelles composed of surfactant ammonium groups.[15] The strong affinity of the TPPTS for ammonium groups has also been exploited to immobilise rhodium complexes on structurally well-defined microparticles. Mecking and Thomann have reported that the $[HRh(CO)(TPPTS)_3]$ complex can be bound to polyelectrolyte-coated-latex particles through strong interactions between the TPPTS ligand and the ammonium groups of the polyelectrolyte.[16]

Although the spectra are not displayed here, similar results were obtained with the other cationic α-CD derivatives. The ^{1}H NMR spectra of the tetra-HTMAP-α-CD, mono-MTMAP/Me-α-CD and di-MTMAP/Me-α-CD in the presence of TPPTS were very similar to those obtained without TPPTS except for the signal of the trimethylammonium group. As in the case of the mono-HTMAP-α-CD, the ^{31}P NMR signal of TPPTS shifted slightly towards high field in the presence of the three previous α-CD derivatives, suggesting partial cation-exchanges.

Catalytic experiments: The catalytic properties of rhodium catalysts prepared in situ from $[Rh(acac)(CO)_2]$, TPPTS, and cationic α-CD derivatives were studied in the biphasic hydroformylation of 1-decene. We performed preliminary experiments to determine the precise influence of the various cationic α-CD derivatives. Firstly, a control experiment was performed in the absence of CD under standard reaction conditions (Table 1, entry 1).

As expected for a reaction under mass-transfer control, the conversion was very low without CD (3%). Moreover, the aldehyde selectivity was poor since an important part of the terminal decene was converted into internal decene (41%). Finally, the linear-to-branched (l/b) aldehyde ratio was equal to 2.8. For comparison, we performed experiments with non-charged CD derivatives such as the hydroxypropyl-α-CD (HP-α-CD) and the randomly methylated α-CD (RAME-α-CD) (Table 1, entries 4 to 6). It has been reported that these two CD derivatives greatly improved the conversion and selectivity without decreasing the l/b aldehyde ratio.[17]

Addition of mono-HTMAP-α-CD to the reaction medium has a significant influence on the decene conversion as the latter was enhanced by a factor of four in comparison with the control experiment (compare entry 7 with entry 1 in Table 1). However, we observed a lower rate-increase than with the HP-α-CD and RAME-α-CD, probably owing to the ionic nature of the mono-HTMAP-α-CD. Our experiment conducted in the presence of Na_2SO_4 (Table 1, entry 3) and numerous literature data indicate that addition of a non-amphiphilic salt to aqueous catalytic solution has a detrimental effect on the hydroformylation rate.[18] In fact, the solubilising power of the mono-HTMAP-α-CD due to its cavity is partly counterbalanced by a salting out effect. Furthermore, tensiometric measurements indicated that this cationic CD adsorbs weakly at the liquid–liquid interface, which is unfavourable to the mass-transfer between the aqueous and organic phases.[11] The aldehyde selectivity in the presence of mono-HTMAP-α-CD was similar to that observed with the non-charged CD derivatives, confirming the protective effect of the CD cavity towards the isomerisation reaction. Indeed, when the olefin is inside the hydrophobic host cavity of the α-CD, the formation of isomerising species leading to internal olefins by β-hydride elimination is prohibited by the steric hindrance. The l/b aldehyde ratio obtained with the mono-HTMAP-α-CD was more unexpected and was notably increased: 3.6 versus 2.8–3.0 in the presence of non-charged CD derivatives. We experimented to determine the origin of this increase by adding the ammonium salt $HOCH_2CH(OH)CH_2N(CH_3)_3^+Cl^-$ to the catalytic medium instead of the mono-HTMAP-α-CD (see Table 1, entry 2). This ammonium salt was chosen because of its structural similarity with the substituent group of the mono-HTMAP-α-CD and its lack of molecular recognition ability. No increase of the conversion and l/b aldehyde ratio was observed in the presence of this additive, suggesting that the l/b aldehyde ratio increase in the presence of mono-HTMAP-α-CD is not due to a salt effect but to the presence of the host cavity of mono-HTMAP-α-CD. We could explain the beneficial effect of the cavity on the l/b aldehyde ratio by two hypotheses. The first is the formation of a new catalytic species by an in situ ion-exchange between the sodium of TPPTS and the mono-HTMAP-α-CD. As the receptor site of such a supramolecular catalyst is located near the coordination sphere of the catalytically active metal centre, the olefin included into the cavity could adopt a preferential orientation which is favourable to the formation of the linear alkyl rhodium species leading to the linear aldehyde. The second hypothesis is a steric stress of the CD cavity on the substrate compelling the latter to react preferentially by its terminal carbon. We favour the ion-exchange hypothesis as being the most probable. It is difficult to imagine that the presence of only one arm on the CD can constrain the olefin to react by its terminal carbon whereas such a phenomenon is not observed with HP-α-CD that has about 3.6 arms of similar structure without the ammonium group. Experiments performed in the presence of increasing amounts of sodium sulfate salt indicate that the catalytic species obtained by in situ ion-exchange are stable in the reaction medium. As shown in Table 1 entries 7–9, addition of Na_2SO_4 decreased the conversion by a salting out effect but had no effect on the l/b aldehyde ratio. The ratio remained high (3.6 as opposed to 2.8 without CD), suggesting that the screening effect of Na_2SO_4 is lessened due to the strong ionic bonding of the cationic CD to the TPPTS ligand. This hypothesis was totally in agreement with our NMR study of various mono-HTMAP-α-CD/TPPTS mixtures in the presence of salts.

The results obtained with the methylated form of the mono-HTMAP-α-CD are illustrative of the difficulty to anticipate the reactivity of the catalysts involving molecular recognition processes. The conversion and the aldehyde selectivity in the presence of mono-MTMAP/Me-α-CD were much higher that those observed with the mono-HTMAP-α-CD (compare entries 7 and 10) and, appeared even higher than those with the RAME-α-CD, which is the most efficient CD known to date (compare entries 6 and 11 in Table 1). A decrease in the l/b aldehyde ratio was unfortunately observed with this mono-MTMAP/Me-α-CD (3.1 versus 3.6 with the mono-HTMAP-α-CD) even though the l/b aldehyde ratio was higher than that observed with the RAME-α-CD. The conversion and selectivity increases observed with the mono-MTMAP/Me-α-CD can be attributed to the presence of an enlarged hydrophobic cavity able to receive the olefin in a more efficient way and to enhance surface active properties of this cyclodextrin. Unfortunately, the l/b aldehyde ratio decrease cannot be easily rationalised. Indeed, methylation of the mono-HTMAP should not impede the cation exchange between the TPPTS and the cationic CD and should not notably modify the orientation of the olefin in the coordination sphere of catalytic centre.

The results from α-CD derivatives containing several cationic arms confirm the beneficial effect of ammonium groups on the l/b aldehyde ratio (Table 1, entries 12 and 13). Indeed, the highest l/b aldehyde ratios were obtained with these polycationic α-CD derivatives (4.7 for the di-MTMAP/Me-α-CD and 5.4 for of tetra-HTMAP-α-CD). The remarkable l/b aldehyde ratio increase supports our hypothesis concerning the origin of the increase. The presence of several ammonium groups increases the probability of exchange between the sodium salt of TPPTS and the cationic CD and so, the formation of new catalytic species which are non-covalently connected to the CD. Furthermore, the presence of several cationic groups on the CD gives rise to more sterically hindered α-CD derivatives which induce an orientation of olefin in the cavity more efficiently, which is favourable to the formation of the linear alkyl rhodium species. Finally, the poor conversions observed with the di-MTMAP/Me-α-CD and the tetra-HTMAP-α-CD are related to the polycationic nature of these cyclodextrins. Indeed, polycharged CD derivatives do not adsorb strongly at the liquid–liquid interface and consequently have poor phase-transfer properties.

Conclusion

We have shown that α-CD derivatives bearing 2-hydroxy-3-trimethylammoniopropyl groups are efficient mass-transfer promoters for the hydroformylation of higher olefins in biphasic systems as the conversion, the aldehyde selectivity and especially the l/b aldehyde ratio can be significantly increased. The l/b aldehyde ratio increase was attributed to the in situ formation of new catalytic supramolecular species by ion-exchange between the catalyst ligand and the cationic α-CD. Contrary to supramolecular catalysts where the CD is covalently bound to the catalysts,[19] ionic bonding of CD to the organometallic catalyst offers the advantage of a reversible interaction with the catalyst. Consequently, when the CD is used in large excess toward the catalyst, the binding of the substrate–CD inclusion complex to the catalyst is transient and CD could behave as a supramolecular shuttle between the catalytically active centre and the bulk or interface as schematically represented in Figure 6. We are currently investigating the properties of this new class of supramolecular catalytic systems.

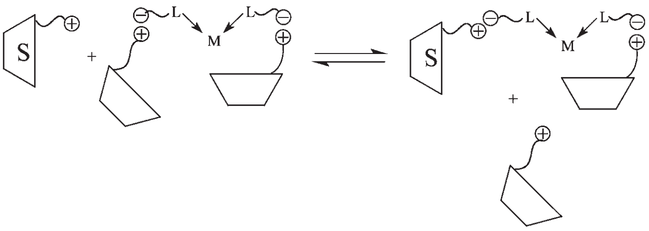


Figure 6. Principle of supramolecular catalysis conducted in the presence of an excess of CD non-covalently bound to the catalysts.

Experimental Section

General remarks: The ^1H and ^{31}P NMR spectra were recorded at 300.13 and 121.49 MHz on a Bruker Avance DRX300 spectrometer, respectively. ^1H and $^{31}P\{^1H\}$ chemical shifts are given in ppm relative to external references: sodium [D_4]3-(trimethylsilyl)propionate (98% atom D) in D_2O for ^1H NMR and H_3PO_4 in D_2O for $^{31}P\{^1H\}$ NMR. ES-MS was performed on a Finnigan LCQ-DUO mass spectrometer. Gas chromatography was carried out on a Shimadzu GC-17 A gas chromatograph equipped with a methylsilicone capillary column (25 m × 0.25 mm) and a flame ionisation detector (GC:FID). The exchange of sulfate by chloride ions was performed with a Dowex 1X8–100 ion-exchange resin. Ion chromatography was conducted on a Dionex DX-120 ion chromatograph equipped with an anionic column (Ion Pac AS14 Anion-Exchange). Dicarbonylacetylacetonatorhodium(I) and organic compounds (undecane, 1-decene, 2,3-epoxypropyltrimethylammonium chloride, native α-CD) were purchased from Strem Chemicals and Aldrich Chemicals in their highest purity and used without further purification. Randomly methylated-α-cyclodextrin (RAME-α-CD) was prepared by adapting a procedure reported by Kenichi and co-workers.[13] This cyclodextrin was partially methylated. Methylation occurred at positions 2, 3, or 6 and 1.8 OH groups per glucopyranose unit were statistically modified. Hydroxypropylated α-cyclodextrin (HP-α-CD) was obtained from Aldrich Chemicals. This cyclodextrin was partially *O*-2-hydroxypropylated; statistically 0.6 OH groups were modified per glucopyranose unit. Tris(3-sodium sulfonatophenyl)phosphine (TPPTS - $P(m\text{-}C_6H_4SO_3Na)_3$) was synthesised as reported by Gärtner and co-workers.[20] The purity of the TPPTS was carefully controlled. In particular, $^{31}P\{^1H\}$ NMR solution spectroscopy indicated that the product was a mixture of phosphine (approximately 98 %) and its oxide (approximately 2 %). Carbon monoxide/hydrogen mixtures (1:1) were used directly from cylinders (>99.9 % pure, Air Liquide). Distilled deionised water was used in all experiments. All catalytic reactions were performed under nitrogen using standard Schlenk techniques. All solvents and liquid reagents were degassed by bubbling with nitrogen for 15 min or by two freeze-pump-thaw cycles before use.

Mono[2-*O*-(2-hydroxy-3-trimethylammoniopropyl)]-α-cyclodextrin chloride (mono-HTMAP-α-CD): An aqueous solution of 2,3-epoxypropyltrimethylammonium chloride (0.53 g, 3.49 mmol, 5 mL) was added dropwise with stirring to a solution of α-CD (5 g, 5.14 mmol) dissolved in aqueous NaOH (0.20 g in 10 mL of water, 5.14 mmol). The reaction mixture was stirred overnight at 50 °C. After the mixture had been allowed to cool, the solution was neutralised with aqueous HCl and the water was evaporated. The residue was taken up in methanol (60 mL) and then refluxed for 1 h. The white product was precipitated by addition of acetone (80 mL) to the filtrate. The product was obtained as a white solid; yield 1.35 g (23 %); ^1H NMR (D_2O): $\delta = 5.08$ (m, H1′), 4.93 (m, H1), 4.30 (m, H2″), 3.98 (t, $J = 9$ Hz, H3′), 3.86 (t, $J = 9$ Hz, H3), 3.85–3.60 (m, H5, H5′, H6, H6′), 3.60–3.30 (H2, H2′, H4, H4′, H3″, H1″), 3.11 ppm (s, $-N^+Me_3$); ES-MS: *m*/*z*: 1088.76 $[M]^+$. The average substitution degree determined by ES-MS was found to be one.

Tetra[*O*-(2-hydroxy-3-trimethylammoniopropyl)]-α-cyclodextrin chloride (tetra-HTMAP-α-CD): An aqueous solution (5 mL) of 2,3-epoxypropyltrimethylammonium chloride (10.9 g, 71.9 mmol) was added dropwise with stirring to a solution of α-CD (5 g, 5.14 mmol) dissolved in aqueous NaOH (0.41 g in 20 mL of water, 10.3 mmol). The reaction mixture was stirred overnight at 50 °C. After the mixture had been allowed to cool, the solution was neutralised with aqueous HCl and the water was evaporated. The residue was taken up in methanol (60 mL), and then refluxed for 1 h. The white product was precipitated by addition of acetone (80 mL) to the filtrate. The product was obtained as a white solid; yield 4.1 g (54 %); ^1H NMR (D_2O): $\delta = 5.09$ and 4.94 (m, H1, H1′), 4.31 (m, H2″), 4.00–3.25 (H3′, H3, H5, H5′, H6, H6′, H2, H2′, H4, H4′, H3″, H1″), 3.10 ppm (s, $-N^+Me_3$); ES-MS: *m*/*z*: 602.6–981.6 $[M]^{2+}$. The average substitution degree determined by ES-MS was found to be four.

Methylated mono[2-*O*-(2-methoxy-3-trimethylammoniopropyl)]-α-cyclodextrin chloride (mono-MTMAP/Me-α-CD): mono-HTMAP-α-CD (5 g, 4.45 mmol) was dissolved in aqueous NaOH solution (32.4 g in 49 mL, 0.8 mol), then dimethyl sulfate (76 mL, 0.8 mol) was added dropwise over 10 h at room temperature. The reaction mixture was stirred for 17 h. At the end of reaction, unreacted dimethyl sulfate was decomposed by addition of concentrated ammonia solution (120 mL) followed by mixing at room temperature for 6 h. mono-MTMAP/Me-α-CD was extracted with chloroform, and the organic layer was washed with water until the washings were of neutral pH and was dried over anhydrous sodium sulfate. After evaporation of chloroform, the product was dissolved in water and was passed through a chloride exchange resin to remove sulfate ions. The total exchange of sulfate by chloride ions was assessed by ion chromatography. The water was distilled and the product was obtained as a white solid; yield 2.3 g (39 %); ^1H NMR (D_2O): $\delta = 5.13$ and 4.90 (m, H1), 3.30 (s, $MeOC_6$), 3.12 (s, $-N^+Me_3$), 4.0–3.35 ppm (other protons); ES-MS: *m*/*z*: 1229.1–1312.6 $[M]^+$. The average substitution degree for MTMAP groups and for methyl groups was 1 and 13, respectively.

Methylated di-[*O*-(2-methoxy-3-trimethylammoniopropyl)]-α-cyclodextrin chloride (di-MTMAP/Me-α-CD): tetra-HTMAP-α-CD (3.5 g, 2.33 mmol) was dissolved in aqueous NaOH solution (22.6 g in 34 mL, 0.56 mol), then dimethyl sulfate (53 mL, 0.56 mol) was added dropwise over 10 h at room temperature. The reaction mixture was stirred for 17 h. At the end of reaction, unreacted dimethyl sulfate was decomposed by addition of concentrated ammonia solution (83 mL) followed by mixing at room temperature for 6 h. di-MTMAP/Me-α-CD was extracted with chloroform, and the organic layer was washed with water until the washings were of neutral pH and dried over anhydrous sodium sulfate. After evaporation of chloroform, the product was dissolved in water and passed through a chloride exchange resin to remove sulfate ions. The total exchange of sulfate by chloride anions was checked by ion chromatography. The water was distilled off and the product was obtained as a white solid; yield 0.6 g (17 %); ^1H NMR (D_2O): $\delta = 5.11$ and 5.00 (m, H1), 3.27 (s, $MeOC_6$), 3.09 (s, $-N^+Me_3$), 4.0–3.35 ppm (other protons); ES-MS: *m*/*z*: 1463.7–1491.7 $[M]^+$. The average substitution degree for MTMAP groups and for methyl groups was 2 and 15, respectively.

Catalytic experiments: $[Rh(acac)(CO)_2]$ (4.07×10^{-2} mmol), TPPTS (0.21 mmol) and the required amount of chemically modified cyclodextrin were dissolved in water (11.5 mL). The resulting aqueous phase and an organic phase composed of olefin (20.35 mmol) and undecane (4 mmol, GC internal standard) were charged under an atmosphere of N_2 into the 50 mL reactor which was heated at 80 °C. A mechanical stirrer equipped with a multipaddle unit was then started (1500 rpm) and the autoclave was pressurised with CO/H_2 (1:1, 50 atm) from a gas reservoir connected to the reactor through a high pressure regulator valve enabling constant pressure in the reactor throughout the whole reaction. The reaction medium was sampled during the reaction for GC analysis of the organic phase after decantation. For kinetic measurements the time corresponding to the addition of the CO/H_2 mixture was considered as the beginning of the reaction.

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