Complexation of monosulfonated triphenylphosphine oxides with β-cyclodextrin: spectroscopic study and consequence on the behaviour of cyclodextrins in aqueous-phase organometallic catalysis

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Interactions between the β-cyclodextrin and the monosulfonated isomers of triphenylphosphine oxide were investigated in aqueous solution by NMR, UV-vis and ESI mass spectroscopy. Titration and continuous variation plots obtained from ^{31}P and ^{1}H NMR data indicate the formation of 1 : 1 inclusion complexes. The structures of these inclusion complexes were proposed from T-ROESY experiments. All inclusion complexes were enthalpy stabilized, but entropy destabilized. Formation of such complexes cannot decrease the efficiency of cyclodextrins in aqueous-phase organometallic catalysis.

Introduction

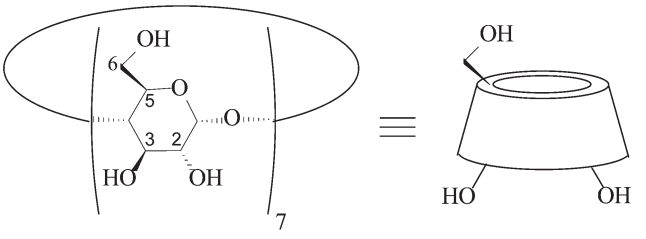
During the last few years, cyclodextrins have been successfully used as mass-transfer promoters in aqueous-phase organometallic catalysis.[1] Indeed, the reaction rates in the presence of these cyclic oligosaccharides can be up to 1000 times higher than those observed without cyclodextrin.[2] These outstanding enhancements of reaction rates were obtained with catalytic amounts of cyclodextrins and were ascribed to an increase in the substrate concentration in the aqueous phase due to the formation of inclusion complexes between the substrate and the cyclodextrin.[3] In these works, it was also demonstrated that the cyclodextrin can bind to water-soluble phosphines used to dissolve the catalyst in the aqueous phase.[4] This interaction was unexpected and has rather negative effects. Thus, the decrease in the selectivity during the rhodium catalyzed hydroformylation reaction,[5] the modification of the catalyst structure[6] and the drop in cyclodextrin activity in particular experimental conditions[7] were attributed to the formation of inclusion complexes between the cyclodextrin and the hydrosoluble phosphine.

As the water-soluble phosphine introduced initially in the medium can be partially oxidized by oxygen traces and/or during the reduction of the catalyst precursor,[8] it is of great interest to know the behaviour of the phosphine oxide towards cyclodextrins. Indeed, if phosphine oxide binds more strongly to the cyclodextrin than the phosphine, the amount of cyclodextrin available to solubilize the substrate in the aqueous phase decreases and, consequently, the mass transfer between the aqueous and organic phases is less efficient.

As no data on the complexation of water-soluble phosphine oxides with cyclodextrins was available in the literature, we decided to study by electrospray ionization mass, NMR and UV-vis spectroscopies the interactions between the β-cyclodextrin (β-CD–Scheme 1) and the potassium salt of *ortho*-, *meta*-, and *para*-substituted monosulfonated triphenylphosphine oxides (OTPPMS–Scheme 2).

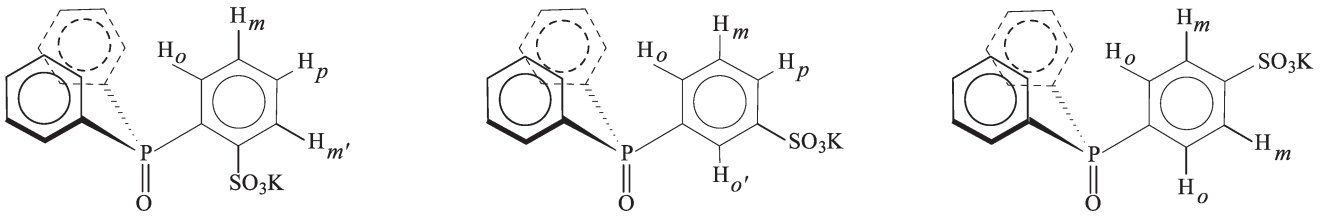
Results and discussion

Interactions between β-CD and OTPPMS were initially investigated by electrospray ionization mass spectrometry.



Scheme 1 Schematic representation of the shape of β-CD. The protons H-3 and H-5 are situated inside the host cavity, whereas protons H-1, H-2 and H-4 point outwards.

Whatever the phosphine oxide, mass spectra indicate the presence of two kinds of adduct containing both β-CD and phosphine oxide. The most abundant adduct contains one molecule of OTPPMS and β-CD (m/z 1569.3; 100% $[\beta\text{-CD} + \text{OTPPMS} + \text{K}]^+$) and the minor adduct two OTPPMS molecules and one β-CD molecule (m/z 1965; $[\beta\text{-CD} + 2\,\text{OTPPMS} + \text{K}]^+$). Besides these two entities, the β-CD adduct (m/z 1173.5; $[\beta\text{-CD} + \text{K}]^+$) and electrostatic aggregates of phosphine oxide (m/z: 435.1 $[\text{OTPPMS} + \text{K}]^+$; 831.1 $[2\,\text{OTPPMS} + \text{K}]^+$ and 1226.9 $[3\,\text{OTPPMS} + \text{K}]^+$) are clearly detected (see for example the Fig. 1). These OTPPMS aggregates that are typical of surface active compounds[9] are formed during the ion spray process and complicate the interpretation of the electrospray mass spectra. Indeed, if the most abundant peak observed at m/z 1569.3 could be assigned to a stable 1 : 1 inclusion complex, the peak at m/z 1965.0 could be due to a 1 : 2 inclusion complex but also to an aggregate of two OTPPMS complexed by a β-CD during the ion spray process. In order to exclude the presence of electrostatic aggregates of OTPPMS and, thus, the formation of non-specific β-CD/OTPPMS aggregates, the spectra were also recorded while varying the potential applied to the orifice from 50 to 130 V with steps of 10 V. Indeed, it is well-known that the breakage of aggregates can take place by increasing the voltage at the orifice.[10] Unfortunately, the spectra obtained at higher voltages were similar to that obtained at 50 V. The electrospray mass spectra of solutions containing low concentrations of OTPPMS and β-CD (up to 0.01 mM each) were also recorded. Once again,



Scheme 2 Representation of the potassium salt of the *ortho*-, *meta*-, and *para*-substituted monosulfonated triphenylphosphine oxides. Protons of the sulfonated aromatic ring have been annotated H-*o*, H-*o*′, H-*m*, H-*m*′ and H-*p*.

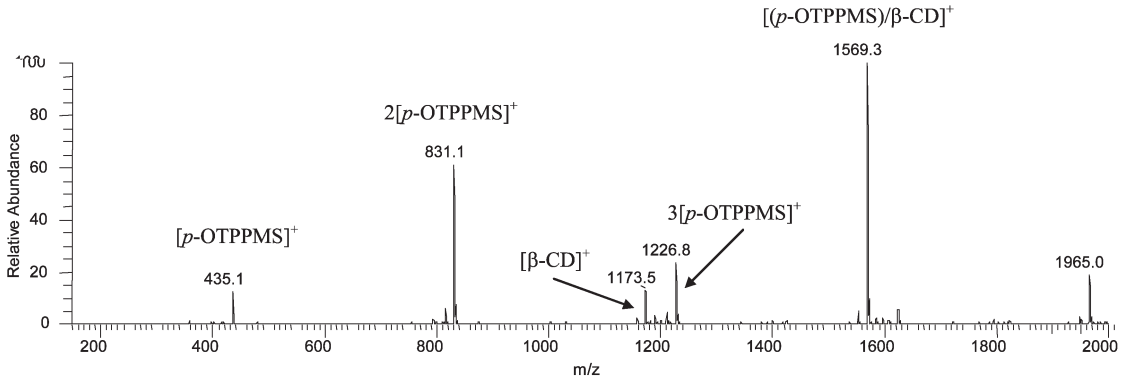


Fig. 1 Electrospray mass spectrum of a mixture of *p*-OTPPMS (10 mM) and β-CD (10 mM) recorded in the positive mode at a 50 V orifice potential.

the undesirable aggregates were observed and the nature of the peak at m/z 1965.0 cannot be clarified.

The undeniable existence of inclusion processes and the stoichiometry of the inclusion complexes were provided by the continuous variation technique (Job's method).[11] For each phosphine oxide, a series of samples containing variable ratios of β-CD and phosphine oxide was prepared keeping the total concentration of species constant. In all cases, the ^{31}P and ^{1}H NMR spectra exhibited chemical shift variations for the phosphorus and protons of the phosphine oxide and for most of the β-CD protons. In particular, the largest differences in the chemical shifts for the β-CD protons are always observed for the protons situated *inside* the hydrophobic cavity (H-3 and H-5), demonstrating the reality of inclusion processes. Furthermore, all Job's plots derived from the corresponding ^{1}H and ^{31}P NMR spectra show a maximum at $r = 0.5$ and highly symmetrical shapes, indicating undoubtedly that the stoichiometry of inclusion complexes is 1 : 1 and that the existence of 1 : 2 inclusion complexes can be negligible[11,12]

The structures of these 1 : 1 inclusion complexes were determined from two-dimensional T-ROESY experiments.[13] The relative intensities of the cross-peaks observed in the T-ROESY spectra of solutions containing β-CD and *o*-OTPPMS or *m*-OTPPMS are shown in Table 1. The strong interactions observed between the H-5 and H-3 protons and the aromatic protons of the non-sulfonated aromatic ring fully prove that a non-sulfonated aromatic ring is included deeply in the β-CD cavity. Furthermore, absence of interaction with the H-6 proton indicates that the two oxides penetrate into the β-CD cavity from the secondary OH group side. All interactions observed between protons of sulfonated aromatic group and the H-3 and H-5 protons confirm that the sulfonated aromatic group lies near the secondary rim of the cavity, outside the cavity in the aqueous bulk phase. The deduced orientations of *o*-OTPPMS or *m*-OTPPMS in the β-CD cavity are shown in Scheme 3.†

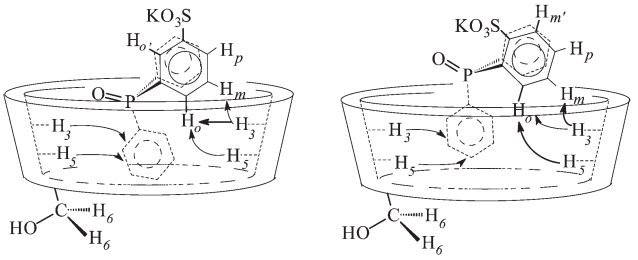
Table 1 Cross-peaks observed in the T-ROESY spectra of solution containing phosphine oxide (2 mM) and β-CD (8 mM) in D_2O at 298 K [a]

Phosphine oxide	Phosphine oxide protons	β-cyclodextrin protons		
		H-3	H-5	H-6
o-OTPPMS	H-*p*	—	—	—
	H-*o*	+	+++	—
	H-*m*	++	—	—
	H-*m'*	—	—	—
	H-*(non sulfonated ring)*	+++	++	—
m-OTPPMS	H-*p*	—	—	—
	H-*o*′	—	—	—
	H-*m*	+	—	—
	H-*o*	++	++	—
	H*(non sulfonated ring)*	+++	+++	—

[a] Relative intensity of the peaks. +++: strong; ++: medium; +: weak; —: no signal.

In the case of *p*-OTPPMS, the inclusion mode appears more complicated. Indeed, the T-ROESY spectrum of a mixture of

† The presence of small amounts of other 1 : 1 inclusion complexes in the case of the *o*- and *m*-OTPPMS cannot be totally excluded since the corresponding cross-peaks may not have large enough intensities and may be buried in the noise. However, the good agreement observed between the association constant values obtained by two different spectroscopic techniques led us to assume that the presence of such species should be negligible.



Scheme 3 Structures proposed for the *m*-OTPPMS/β-CD and *o*-OTPPMS/β-CD complexes. The interactions observed in the T-ROESY spectra are also indicated.

p-OTPPMS and β-CD does not show the typical pattern of a 1 : 1 inclusion complex and suggests that at least two different kinds of 1 : 1 inclusion complex are present in the solution (Fig. 2).

The strong dipolar contacts observed between the aromatic protons of the non-sulfonated aromatic ring and H-5 and H-3 protons on the one hand, and the absence of strong correlation between the phosphine oxide and the H-6 proton on the other hand, indicate that inclusion of one of the non-sulfonated aromatic rings by the secondary face of the β-CD occurs as in the case of the *o*-and *m*-OTPPMS (Complex A in Scheme 4). However, this type of 1 : 1 inclusion complex cannot account for the strong interaction observed between the H-*m* proton and the proton H-5 located deep in the cavity. Such an interaction can only be rationalized by assuming the presence of a second 1 : 1 inclusion complex. This inclusion complex is obtained by penetration of the sulfonated aromatic ring by the secondary rim of the β-CD as schematically represented in Scheme 4 with Complex B. This hypothesis is also consistent with the strong interactions observed between the protons of the sulfonated aromatic ring and the H-3 and H-5 protons. The penetration of a hydrophilic group like the sulfonate moiety in the hydrophobic cavity can seem surprising but it must be pointed out that we have already observed this type of binding in the case of the trisulfonated triphenylphosphine.[4] Indeed, in this inclusion complex, we have demonstrated that the sulfonate group was deeply included in the β-CD cavity and faced the primary hydroxyls. The very weak dipolar contacts observed between H-*o* and H-6 protons on the one hand, and between the protons of non-sulfonated rings and the H-6 protons on the other hand, are unusual and suggest an inclusion by the primary rim of the β-CD (complex C in Scheme 4). To the best of our knowledge, this inclusion mode has never been observed for water-soluble triphenylphosphine derivatives. However,

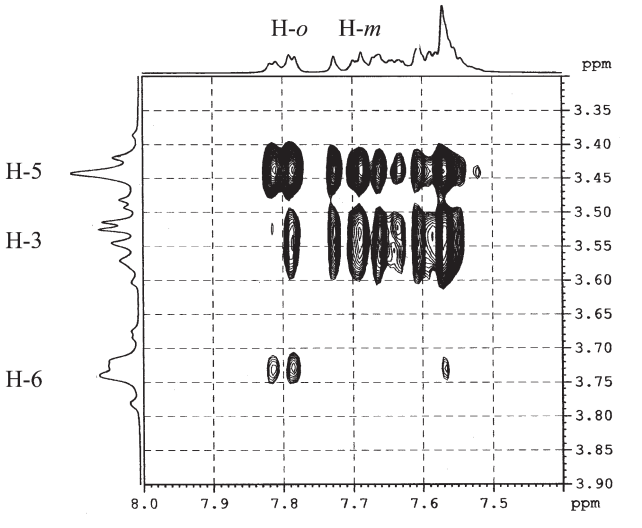
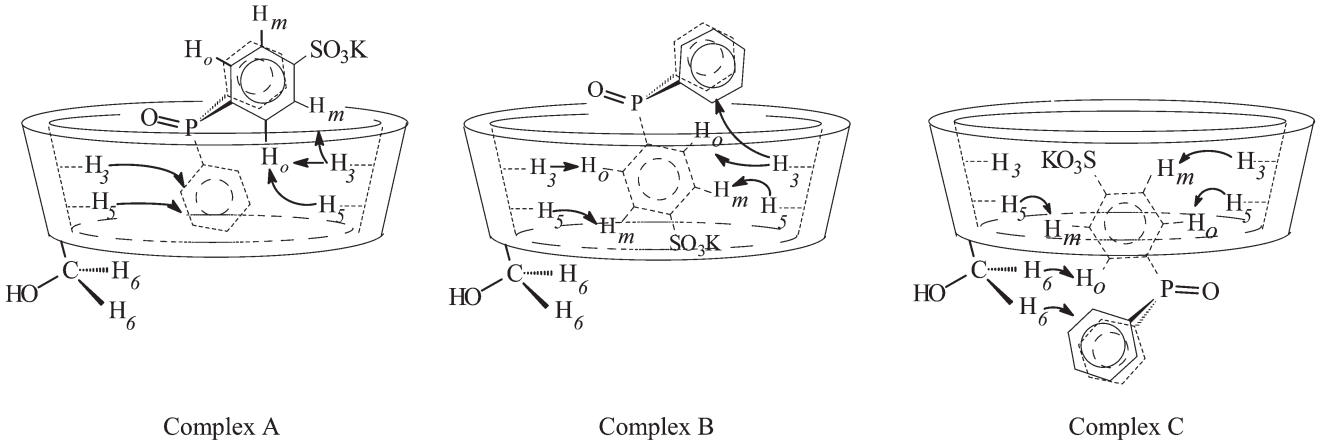


Fig. 2 Partial contour plot of the T-ROESY spectrum of a solution containing β-CD (2 mM) and *p*-OTPPMS (8 mM) in D_2O at 298 K with a 300 ms mixing time.

the percentage of this kind of 1 : 1 inclusion is likely very low in view of the low intensity of the cross-peaks. Surprisingly, it must be noticed that the penetration of a non-sulfonated aromatic ring by the primary rim does not occur. Indeed, no strong dipolar contact has been observed between H-6 and the protons of non-sulfonated aromatic ring. Existence of several inclusion modes for the *para* isomer is ascribable to the high symmetry of the aromatic ring bearing the sulfonate group. Indeed, it is well-known that *para*-disubstitued benzenes fit much better in the β-CD cavity than *ortho*- or *meta*-disubstitued benzenes.[14]

The association constants of each inclusion complex were evaluated at 298 K from ^{31}P NMR spectroscopic data (classical titration method) and from UV-Vis spectroscopic data (titration and spectral displacement methods). For the higher temperatures, the association constants were measured by ^{31}P NMR shift titration method. The values calculated by assuming a 1 : 1 inclusion mechanism are listed in Table 2.

The values obtained at 298 K by NMR and UV-vis measurements for the *o*-OTPPMS/β-CD and *m*-OTPPMS/β-CD complexes are similar and much lower than those found for the corresponding non-oxidized phosphine/β-CD complexes. Indeed, the association constants for *o*-TPPMS/β-CD and *m*-TPPMS/β-CD inclusion complexes were found to be 3890 ± 50 and 7110 ± 890 M^{-1}, respectively.[15] The discrepancy



Scheme 4 Structures proposed for the *p*-OTPPMS/β-CD inclusion complexes. The interactions observed in the T-ROESY spectrum are also indicated.

observed between the association constant values derived by NMR and UV-vis spectroscopy at 298 K in the case of the *p*-OTPPMS is rather surprising and might to be due to the presence of different types of 1 : 1 complexes. However, as in the case of *o*- and *m*-OTPPMS, the association constants of the *p*-OTPPMS/β-CD inclusion complex were significantly lower than that of *p*-TPPMS/β-CD complex ($77\,300 \pm 890$ M^{-1} at 298 K), confirming the poor affinity of phosphine oxides for the β-CD.

Such a reduction of affinity could be due to the decreased mobility of the phosphine oxide *vs.* non-oxidized phosphine. Indeed, introduction of an oxygen atom on the phosphorus atom reduces the conformational mobility of aromatic ring bearing the sulfonate group and, consequently, the number of conformations that can fit properly into the β-CD cavity. This reduction of guest flexibility is particularly unfavorable in the case of the *ortho* and *meta* isomers. Indeed, the formation of an inclusion complex with these two oxides requires the orientation of the sulfonate group toward the water upon encapsulation into the host cavity. This precise orientation is necessary to reduce the steric crowding with the β-CD periphery.

The thermodynamic quantities for phosphine oxide/β-CD inclusion complexes were determined from the temperature dependence of the stability constant K using the van't Hoff relation. As shown in Fig. 3, the van't Hoff plots were apparently linear for the three phosphine oxides within the temperature range considered in our study. Therefore, changes in the heat capacity were neglected in our study. The enthalpies and entropies were determined in the usual manner from the slopes and intercepts of the plots. The results are summarized in Table 3. All complexes have a favorable ΔH° and an unfavorable ΔS°, indicating that the hydrophobic and van der Waals interactions, rather than the entropically favorable desolvation are the major driving forces for the inclusion of phosphine oxides.[16] The negative ΔS° is typical of partial complexation of a large guest into the CD cavity. Indeed, when a part of the guest is outside the cavity in contact with water, the positive contribution to ΔS° from loss of solvation is minimized, and its loss in rotational and translational degrees lead to negative ΔS°.[17] The trends observed for the enthalpies ($\Delta H^\circ_p < \Delta H^\circ_m < \Delta H^\circ_o$) and for the entropies ($\Delta S^\circ_p < \Delta S^\circ_m < \Delta S^\circ_o$) seem to indicate that the further sulfonato group from the phosphorus atom is, the deeper the penetration of the phosphine oxide into the β-CD cavity is. Indeed, a deeper penetration induces stronger van der Waals interactions, giving larger ΔH°, but greatly reduces the guest's freedom, giving more unfavorable ΔS°.[16]

Conclusions

This work has demonstrated that monosulfonated isomers of triphenylphosphine oxide can bind to β-CD to form 1 : 1 complexes. Although the shape and size of phosphines and corresponding oxides are very similar, the values of association constants are clearly different, indicating that the affinity of phosphine derivatives for cyclodextrin is not easily foreseeable. From a point of view of aqueous-phase organometallic catalysis, it appears now that the partial oxidation of phosphine cannot induce a decrease in the amount of cyclodextrin involved in the mass-transfer phenomena. Indeed, the percentage of cyclodextrin trapped by phosphine derivatives cannot be higher when the phosphine initially introduced in the reaction medium is partially oxidized as the phosphine oxide has a lower affinity for the cyclodextrin than the phosphine.

Experimental

General methods

The ^1H and ^{31}P NMR spectra were recorded at 300.13 and 121.49 MHz, respectively, on a Bruker DRX instrument. Chemical shifts are given in ppm relative to sodium [D_4]3-(trimethyl silyl)propionate (98% atom D) in D_2O using external reference. The notation used in NMR assignments of monosulfonated triphenylphosphine oxides is indicated in Scheme 2. T-ROESY experiments were carried out as previously reported.[15] Electrospray ionization mass spectroscopy experiments were performed on a Thermoquest Finnigan LCQ Duo. Phosphine oxide and β-CD in equimolar concentrations were dissolved in pure water. The final concentration varied from 0.01 mM to 10 mM. The samples were introduced through the fused silica inlet capillary at a flow rate of 5 μl min^{-1}. The orifice potential was set at 50 V. The temperature of the interface was set at 200 °C. Positive ion detection mode was used. Calibration was performed with Ultramark 1621. UV-vis spectroscopy was performed on a Perkin Elmer Lamba 19 spectrometer. The cell used was placed in a cuvette holder and the temperature was kept constant at 298 K ± 0.1 by means of a thermostated bath.

Materials

D_2O (99.95% isotopic purity) was obtained from Merck. β-CD was purchased from Aldrich and carefully dried before use. The *o*-, *m*-, and *p*-substituted monosulfonated triphenylphosphine oxides were synthesized from the corresponding non-oxidized monosulfonated triphenylphosphine derivatives.[15] In a typical experiment, the potassium salt of monosulfonated triphenylphosphine (385 mg, 0.967 mmol) was dissolved in 20 ml of water and 0.1 ml of a 30 wt.% solution of H_2O_2 (0.968 mmol) was added. After stirring for 4 hours at room temperature, the water was removed under vacuum. The remaining solid was recrystallized from 1 : 1 water–EtOH mixture to give white crystals.

Potassium salt of the *ortho*-substituted monosulfonated triphenylphosphine oxide (*o*-OTPPMS). Yield 300 mg (75%). ^1H NMR (D_2O): δ 7.49 (m, 12 H, $H_{non\text{-}sulfonated\ ring}$; H_o and $H_{m'}$), 7.74 (t, 1 H, $^3J_{H,H}$ 5.1 Hz, H_p), 8.06 (dd, 1 H, $^3J_{H,H}$ 4.5, $^3J_{H,H}$ 3.3 Hz, H_m) ppm; $^{13}C\{^1H\}$ NMR (D_2O): δ 126.4 (d, $^1J_{P,C}$ 103 Hz, $C_{sulfonated\ ring:\ C\ in\ \alpha\ of\ P}$), 128.9 (d, $^3J_{P,C}$ 13 Hz, $C_{non\text{-}sulfonated\ ring:\ C\ in\ \gamma\ of\ P}$), 129.8 (d, $^2J_{P,C}$ 9 Hz, C_{Ho}), 131.2 (d, $^3J_{P,C}$ 12 Hz, C_{Hm}), 132.0 (d, $^2J_{P,C}$ 10 Hz, $C_{non\text{-}sulfonated\ ring:\ C\ in\ \beta\ of\ P}$), 132.1 (d, $^1J_{P,C}$

Table 2 Association constant (K_f, M^{-1}) of the potassium salt of the *o*-,*m*-,*p*-substituted monosulfonated triphenylphosphine oxides with the β-CD in water at various temperatures

Phosphine oxide	K_f (298 K)[a]	K_f(298 K)[b]	K_f(298 K)[c]	K_f(308 K)[c]	K_f(318 K)[c]	K_f(328 K)[c]	K_f(338 K)[c]
o-OTPPMS	77 ± 2	75 ± 2	76 ± 5	72 ± 3	48 ± 5	48 ± 5	39 ± 3
m-OTPPMS	150 ± 2	150 ± 3	151 ± 2	148 ± 3	113 ± 5	75 ± 6	54 ± 4
p-OTPPMS	1244 ± 7	1200 ± 4	3098 ± 24	1253 ± 8	918 ± 8	497 ± 5	300 ± 5

[a] Determined by UV-Vis shift titration. [b] Determined from UV-Vis spectroscopic data with a spectral displacement method. [c] Determined by ^{31}P NMR shift titration.

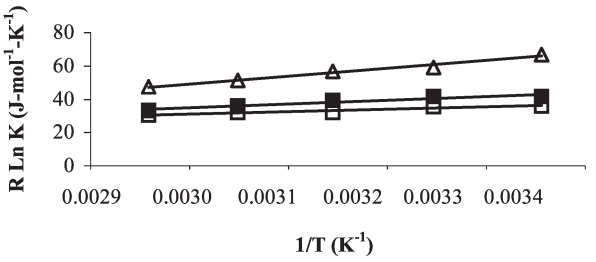


Fig. 3 Van't Hoff plots for the *o*-OTPPMS (□), *m*-OTPPMS (■) and *p*-OTPPMS (△).

111 Hz, $C_{\text{non-sulfonated ring: C in α of P}}$), 132.6 (d, $^4J_{P,C}$ 3 Hz, $C_{\text{non-sulfonated ring: C in δ of P}}$), 133.9 (d, $^4J_{P,C}$ 2 Hz, C_{Hp}), 136.3 (d, $^3J_{P,C}$ 12 Hz, $C_{Hm'}$), 147.1 (d, $^2J_{P,C}$ 6 Hz, C_{SO_3K}) ppm; $^{31}P\{^1H\}$ NMR (D_2O): δ 39.21 (s) ppm.

Potassium salt of the *meta*-substituted monosulfonated triphenylphosphine oxide (*m*-OTPPMS). Yield 360 mg (90%). ^1H NMR (D_2O): δ 7.55 (m, 12 H, $H_{\text{non-sulfonated ring}}$, H_o and H_m), 7.87 (d, 1 H, $^3J_{P,H}$ 12.3 Hz, $H_{o'}$), 7.96 (d, 1 H, $^3J_{H,H}$ 7.7 Hz, H_p) ppm; $^{13}C\{^1H\}$ NMR (D_2O): δ 129.0 (d, $^2J_{P,C}$ 12 Hz, $C_{Ho'}$), 129.1 (d, $^1J_{P,C}$ 107 Hz, $C_{\text{sulfonated ring, C in α of P}}$), 129.5 (d, $^3J_{P,C}$ 12 Hz, $C_{\text{non-sulfonated ring: C in γ of P}}$), 130.2 (d, $^4J_{P,C}$ 2 Hz, C_{Hp}), 130.2 (d, $^2J_{P,C}$ 12 Hz, C_{Ho}), 131.4 (d, $^1J_{P,C}$ 105 Hz, $C_{\text{non-sulfonated ring, C in α of P}}$), 132.3 (d, $^2J_{P,C}$ 11 Hz, $C_{\text{non-sulfonated ring: C in β of P}}$), 133.7 (d, $^4J_{P,C}$ 3 Hz, $C_{\text{non-sulfonated ring: C in δ of P}}$), 135.0 (d, $^3J_{P,C}$ 10 Hz, C_{Hm}), 143.7 (d, $^3J_{P,C}$ 12 Hz, C_{SO_3K}) ppm; $^{31}P\{^1H\}$ NMR (D_2O): δ 36.49 (s) ppm.

Potassium salt of the para-substituted monosulfonated triphenylphosphine oxide (*p*-OTPPMS). Yield: 368 mg (92%). ^1H RMN (D_2O): δ 7.60 (m, 12 H, $H_{\text{non-sulfonated ring}}$, H_m), 7.87 (dd, 2 H, $^3J_{H,H}$ 2.1, $^3J_{P,H}$ 6.0 Hz, H_o) ppm; $^{13}C\{^1H\}$ NMR (D_2O): δ 126.2 (d, $^2J_{P,C}$ 13 Hz, C_{Ho}), 129.2 (d, $^1J_{P,C}$ 107 Hz, $C_{\text{non-sulfonated ring: C in α of P}}$), 129.5 (d, $^3J_{P,C}$ 13 Hz, $C_{\text{non-sulfonated ring: C in γ of P}}$), 132.3 (d, $^2J_{P,C}$ 11 Hz, $C_{\text{non-sulfonated ring: C in β of P}}$), 133.1 (d, $^3J_{P,C}$ 11 Hz, C_{Hm}), 133.5 (d, $^1JP,C$ 104 Hz, $C_{\text{sulfonated ring: C in α of P}}$), 133.7 (d, $^4J_{P,C}$ 2 Hz, $C_{\text{non-sulfonated ring: C in δ of P}}$), 146.9 (d, $^4J_{P,C}$ 3 Hz, C_{SO3K}) ppm; $^{31}P\{^1H\}$ NMR (D_2O): δ 36.66 (s) ppm.

Calculation of association constants by NMR spectroscopy

The phosphorous atom was chosen for evaluating the association constant on the basis that (i) the phosphorus NMR signal cannot be overlapped by any resonance signals and that (ii) the phosphorus chemical shift difference value between free and bound state of the phosphine oxide ($\Delta\delta_{max}$) is very high (8.24 ppm for the *p*-OTPPMS; 4.854 ppm for *m*-OTPPMS and 4.399 ppm for the *o*-OTPPMS at 298 K). This last point is very important as it has been clearly demonstrated that a low $\Delta\delta_{max}$ value induces significant error on the association constant, and that the corresponding titration has to be discarded on a quantitative point of view.[18] Assuming a 1 : 1 inclusion mechanism, the observed chemical shift of the phosphorus atom (δ_{OBS}) and the complex concentration [COMP] are described as follows:

$$\delta_{OBS} = (\delta_{Phos.}[Phos.] + \delta_{COMP}[COMP])/[Phos.]_T \quad (1)$$

$$[COMP] = -1/2\,[(1/K_f + [CD]_T + [Phos.]_T)^2 - 4\,[CD]_T[Phos.]_T]^{1/2} + 1/2\,(1/K_f + [CD]_T + [Phos.]_T) \quad (2)$$

where K_f and $[\,]_T$ stand for binding constant and total, respectively. For a given value of K_f, [COMP] is known and δ_{COMP} may be calculated from eqn. (1) for each $[CD]_T$. Standard deviation over δ_{COMP} is minimized relative to K_f to obtain the 1 : 1 association constant.

Table 3 Thermodynamic parameters for the complexation of the potassium salt of the *o*-, *m*-, and *p*-substituted monosulfonated triphenylphosphine oxides with the β-CD in water at 298 K

Phosphine oxide	$\Delta H°$/kJ mol^{-1}	$\Delta S°$/J mol^{-1} K^{-1}
o-OTPPMS	−14.5 ± 1.3	−12.4 ± 5.7
m-OTPPMS	−30.1 ± 0.6	−55.6 ± 2.5
p-OTPPMS	−43.2 ± 0.9	−79.1 ± 3.9

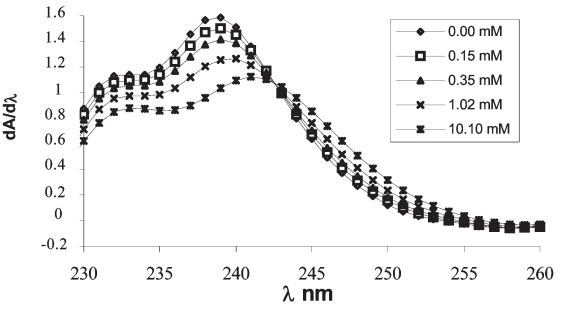


Fig. 4 First derivatives of the absorption spectra of *p*-OTPPMS (0.075 mM) in the presence of varying concentrations of β-CD at 298 K.

Calculation of association constants by UV-vis spectroscopy

The determination of association constants by UV-vis spectroscopy was realised in two different ways.

First, the classical titration method was applied for a fixed concentration of phosphine oxide (0.075 mM), and varying concentration of β-CD (0, 1.5, 2.5, 4.5, 16 mM in the case of the *o*-OTPPMS; 0, 1.47, 2.52, 3.98, 16 mM in the case of *m*-OTPPMS and 0.15, 0.35, 1.02 and 10.10 mM in the case of *p*-OTPPMS) (Fig. 4). An algorithmic treatment similar to one described above was used to calculate the association constant. The algorithmic treatment was applied to UV spectra's derivatives (recorded in the range 230–250 nm for *o*-OTPPMS, in the range 235–245 nm for *m*-OTPPMS and in the range 230–240 nm for *p*-OTPPMS), so that no effect from the refractive index relative to the β-CD was observed.

The second quantitative determination relies on a spectral displacement method with methyl orange (MO) in its basic form.[19] Indeed, the addition of OTPPMS to a solution containing β-CD and MO leads to the formation of the β-CD/OTPPMS complex, thus decreasing the concentration of the β-CD/MO complex initially present. The absorbance variation resulting is directly linked to the added concentration of OTPPMS, but also to the association constant of β-CD/OTPPMS inclusion compound. In practice, spectra were recorded between 520–530 nm. The concentrations for MO, β-CD and OTPPMS were fixed at 0.1 mM, 0.1 mM and 0.3 mM respectively. The first derivatives of these spectra were used for quantitative analysis by an algorithmic treatment described elsewhere.[19]

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